

Active Queue Management (aqm)
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DualQ Coupled AQM for Low Latency, Low Loss and Scalable Throughput
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Abstract

Data Centre TCP (DCTCP) was designed to provide predictably low queuing latency, near-zero loss, and throughput scalability using explicit congestion notification (ECN) and an extremely simple marking behaviour on switches. However, DCTCP does not co-exist with existing TCP traffic---throughput starves. So, until now, DCTCP could only be deployed where a clean-slate environment could be arranged, such as in private data centres. This specification defines 'DualQ Coupled Active Queue Management (AQM)' to allow scalable congestion controls like DCTCP to safely co-exist with classic Internet traffic. The Coupled AQM ensures that a flow runs at about the same rate whether it uses DCTCP or TCP Reno/Cubic, but without inspecting transport layer flow identifiers. When tested in a residential broadband setting, DCTCP achieved sub-millisecond average queuing delay and zero congestion loss under a wide range of mixes of DCTCP and 'Classic' broadband Internet traffic, without compromising the performance of the Classic traffic. The solution also reduces network complexity and eliminates network configuration.

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Table of Contents

1. Introduction	2
1.1. Problem and Scope	2
1.2. Terminology	5
1.3. Features	5
2. DualQ Coupled AQM Algorithm	6
2.1. Coupled AQM	7
2.2. Dual Queue	8
2.3. Traffic Classification	8
2.4. Normative Requirements	8
3. IANA Considerations	9
4. Security Considerations	10
4.1. Overload Handling	10
5. Acknowledgements	11
6. References	11
6.1. Normative References	11
6.2. Informative References	12
Appendix A. Example DualQ Coupled PI2 Algorithm	14
Appendix B. Example DualQ Coupled Curvy RED Algorithm	17
Appendix C. Guidance on Controlling Throughput Equivalence	23
Authors' Addresses	24

1. Introduction

1.1. Problem and Scope

Latency is becoming the critical performance factor for many (most?) applications on the public Internet, e.g. Web, voice, conversational video, gaming, finance apps, remote desktop and cloud-based applications. In the developed world, further increases in access

network bit-rate offer diminishing returns, whereas latency is still a multi-faceted problem. In the last decade or so, much has been done to reduce propagation time by placing caches or servers closer to users. However, queuing remains a major component of latency.

The Diffserv architecture provides Expedited Forwarding [RFC3246], so that low latency traffic can jump the queue of other traffic. However, on access links dedicated to individual sites (homes, small enterprises or mobile devices), often all traffic at any one time will be latency-sensitive. Then Diffserv is of little use. Instead, we need to remove the causes of any unnecessary delay.

The bufferbloat project has shown that excessively-large buffering ('bufferbloat') has been introducing significantly more delay than the underlying propagation time. These delays appear only intermittently--only when a capacity-seeking (e.g. TCP) flow is long enough for the queue to fill the buffer, making every packet in other flows sharing the buffer sit through the queue.

Active queue management (AQM) was originally developed to solve this problem (and others). Unlike Diffserv, which gives low latency to some traffic at the expense of others, AQM controls latency for all traffic in a class. In general, AQMs introduce an increasing level of discard from the buffer the longer the queue persists above a shallow threshold. This gives sufficient signals to capacity-seeking (aka. greedy) flows to keep the buffer empty for its intended purpose: absorbing bursts. However, RED [RFC2309] and other algorithms from the 1990s were sensitive to their configuration and hard to set correctly. So, AQM was not widely deployed.

More recent state-of-the-art AQMs, e.g. fq_CoDel [I-D.ietf-aqm-fq-codel], PIE [I-D.ietf-aqm-pie], Adaptive RED [ARED01], are easier to configure, because they define the queuing threshold in time not bytes, so it is invariant for different link rates. However, no matter how good the AQM, the sawtooth rate of TCP will either cause queuing delay to vary or cause the link to be under-utilized. Even with a perfectly tuned AQM, the additional queuing delay will be of the same order as the underlying speed-of-light delay across the network. Flow-queuing can isolate one flow from another, but it cannot isolate a TCP flow from the delay variations it inflicts on itself, and it has other problems - it overrides the flow rate decisions of variable rate video applications, it does not recognise the flows within IPSec VPN tunnels and it is relatively expensive to implement.

It seems that further changes to the network alone will now yield diminishing returns. Data Centre TCP (DCTCP [I-D.ietf-tcpm-dctcp])

teaches us that a small but radical change to TCP is needed to cut two major outstanding causes of queuing delay variability:

1. the 'sawtooth' varying rate of TCP itself;
2. the smoothing delay deliberately introduced into AQMs to permit bursts without triggering losses.

The former causes a flow's round trip time (RTT) to vary from about 1 to 2 times the base RTT between the machines in question. The latter delays the system's response to change by a worst-case (transcontinental) RTT, which could be hundreds of times the actual RTT of typical traffic from localized CDNs.

Latency is not our only concern:

3. It was known when TCP was first developed that it would not scale to high bandwidth-delay products.

Given regular broadband bit-rates over WAN distances are already [RFC3649] beyond the scaling range of 'classic' TCP Reno, 'less unscalable' Cubic [I-D.ietf-tcpm-cubic] and Compound [I-D.sridharan-tcpm-ctcp] variants of TCP have been successfully deployed. However, these are now approaching their scaling limits. Unfortunately, fully scalable TCPs such as DCTCP cause 'classic' TCP to starve itself, which is why they have been confined to private data centres or research testbeds (until now).

This document specifies a 'DualQ Coupled AQM' extension that solves the problem of coexistence between scalable and classic flows, without having to inspect flow identifiers. The AQM is not like flow-queuing approaches [I-D.ietf-aqm-fq-codel] that classify packets by flow identifier into numerous separate queues in order to isolate sparse flows from the higher latency in the queues assigned to heavier flow. In contrast, the AQM exploits the behaviour of scalable congestion controls like DCTCP so that every packet in every flow sharing the queue for DCTCP-like traffic can be served with very low latency.

This AQM extension can be combined with any single queue AQM that generates a statistical or deterministic mark/drop probability driven by the queue dynamics. In many cases it simplifies the basic control algorithm, and requires little extra processing. Therefore it is believed the Coupled AQM would be applicable and easy to deploy in all types of buffers; buffers in cost-reduced mass-market residential equipment; buffers in end-system stacks; buffers in carrier-scale equipment including remote access servers, routers, firewalls and

Ethernet switches; buffers in network interface cards, buffers in virtualized network appliances, hypervisors, and so on.

The supporting papers [PI216] and [DCTtH15] give the full rationale for the AQM's design, both discursively and in more precise mathematical form.

1.2. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119]. In this document, these words will appear with that interpretation only when in ALL CAPS. Lower case uses of these words are not to be interpreted as carrying RFC-2119 significance.

The DualQ Coupled AQM uses two queues for two services. Each of the following terms identifies both the service and the queue that provides the service:

Classic (denoted by subscript C): The 'Classic' service is intended for all the behaviours that currently co-exist with TCP Reno (TCP Cubic, Compound, SCTP, etc).

Low-Latency, Low-Loss and Scalable (L4S, denoted by subscript L): The 'L4S' service is intended for a set of congestion controls with scalable properties such as DCTCP (e.g. Relentless [Mathis09]).

Either service can cope with a proportion of unresponsive or less-responsive traffic as well (e.g. DNS, VoIP, etc), just as a single queue AQM can. The DualQ Coupled AQM behaviour is similar to a single FIFO queue with respect to unresponsive and overload traffic.

1.3. Features

The AQM couples marking and/or dropping across the two queues such that a flow will get roughly the same throughput whichever it uses. Therefore both queues can feed into the full capacity of a link and no rates need to be configured for the queues. The L4S queue enables scalable congestion controls like DCTCP to give stunningly low and predictably low latency, without compromising the performance of competing 'Classic' Internet traffic. Thousands of tests have been conducted in a typical fixed residential broadband setting. Typical experiments used base round trip delays up to 100ms between the data centre and home network, and large amounts of background traffic in both queues. For every L4S packet, the AQM kept the average queuing delay below 1ms (or 2 packets if serialization delay is bigger for

slow links), and no losses at all were introduced by the AQM. Details of the extensive experiments will be made available [PI216] [DCTtH15].

Subjective testing was also conducted using a demanding panoramic interactive video application run over a stack with DCTCP enabled and deployed on the testbed. Each user could pan or zoom their own high definition (HD) sub-window of a larger video scene from a football match. Even though the user was also downloading large amounts of L4S and Classic data, latency was so low that the picture appeared to stick to their finger on the touchpad (all the L4S data achieved the same ultra-low latency). With an alternative AQM, the video noticeably lagged behind the finger gestures.

Unlike Diffserv Expedited Forwarding, the L4S queue does not have to be limited to a small proportion of the link capacity in order to achieve low delay. The L4S queue can be filled with a heavy load of capacity-seeking flows like DCTCP and still achieve low delay. The L4S queue does not rely on the presence of other traffic in the Classic queue that can be 'overtaken'. It gives low latency to L4S traffic whether or not there is Classic traffic, and the latency of Classic traffic does not suffer when a proportion of the traffic is L4S. The two queues are only necessary because DCTCP-like flows cannot keep latency predictably low and keep utilization high if they are mixed with legacy TCP flows,

The experiments used the Linux implementation of DCTCP that is deployed in private data centres, without any modification despite its known deficiencies. Nonetheless, certain modifications will be necessary before DCTCP is safe to use on the Internet, which are recorded for now in Appendix A of [I-D.briscoe-tsvwg-aqm-tcpm-rmcat-l4s-problem]. However, the focus of this specification is to get the network service in place. Then, without any management intervention, applications can exploit it by migrating to scalable controls like DCTCP, which can then evolve `_while_` their benefits are being enjoyed by everyone on the Internet.

2. DualQ Coupled AQM Algorithm

There are two main aspects to the algorithm:

- o the Coupled AQM that addresses throughput equivalence between Classic (e.g. Reno, Cubic) flows and L4S (e.g. DCTCP) flows
- o the Dual Queue structure that provides latency separation for L4S flows to isolate them from the typically large Classic queue.

2.1. Coupled AQM

In the 1990s, the 'TCP formula' was derived for the relationship between TCP's congestion window, *cwnd*, and its drop probability, *p*. To a first order approximation, *cwnd* of TCP Reno is inversely proportional to the square root of *p*. TCP Cubic implements a Reno-compatibility mode, which is the only relevant mode for typical RTTs under 20ms, while the throughput of a single flow is less than about 500Mb/s. Therefore we can assume that Cubic traffic behaves similar to Reno (but with a slightly different constant of proportionality), and we shall use the term 'Classic' for the collection of Reno and Cubic in Reno mode.

In our supporting paper [PI216], we derive the equivalent rate equation for DCTCP, for which *cwnd* is inversely proportional to *p* (not the square root), where in this case *p* is the ECN marking probability. DCTCP is not the only congestion control that behaves like this, so we use the term 'L4S' traffic for all similar behaviour.

In order to make a DCTCP flow run at roughly the same rate as a Reno TCP flow (all other factors being equal), we make the drop or marking probability for Classic traffic, *p_C* distinct from the marking probability for L4S traffic, *p_L* (in contrast to RFC3168 which requires them to be the same). We make the Classic drop probability *p_C* proportional to the square of the L4S marking probability *p_L*. This is because we need to make the Reno flow rate equal the DCTCP flow rate, so we have to square the square root of *p_C* in the Reno rate equation to make it the same as the straight *p_L* in the DCTCP rate equation.

There is a really simple way to implement the square of a probability - by testing the queue against two random numbers not one. This is the approach adopted in Appendix A and Appendix B.

Stating this as a formula, the relation between Classic drop probability, *p_C*, and L4S marking probability, *p_L* needs to take the form:

$$p_C = (p_L / k)^2 \quad (1)$$

where *k* is the constant of proportionality. Optionally, *k* can be expressed as a power of 2, so $k=2^{k'}$, where *k'* is another constant. Then implementations can avoid costly division by shifting *p_L* by *k'* bits to the right.

2.2. Dual Queue

Classic traffic builds a large queue, so a separate queue is provided for L4S traffic, and it is scheduled with strict priority. Nonetheless, coupled marking ensures that giving priority to L4S traffic still leaves the right amount of spare scheduling time for Classic flows to each get equivalent throughput to DCTCP flows (all other factors such as RTT being equal). The algorithm achieves this without having to inspect flow identifiers.

2.3. Traffic Classification

Both the Coupled AQM and DualQ mechanisms need an identifier to distinguish L4S and C packets. A separate draft [I-D.briscoe-tsvwg-ecn-l4s-id] recommends using the ECT(1) codepoint of the ECN field as this identifier, having assessed various alternatives.

Given L4S work is currently on the experimental track, but the definition of the ECN field is on the standards track [RFC3168], another standards track document has proved necessary to make the ECT(1) codepoint available for experimentation [I-D.black-tsvwg-ecn-experimentation].

2.4. Normative Requirements

In the Dual Queue, L4S packets **MUST** be given priority over Classic, although strict priority **MAY** not be appropriate.

All L4S traffic **MUST** be ECN-capable, although some Classic traffic **MAY** also be ECN-capable.

Whatever identifier is used for L4S traffic, it will still be necessary to agree on the meaning of an ECN marking on L4S traffic, relative to a drop of Classic traffic. In order to prevent starvation of Classic traffic by scalable L4S traffic (e.g. DCTCP) the drop probability of Classic traffic **MUST** be proportional to the square of the marking probability of L4S traffic, In other words, the power to which p_L is raised in Eqn. (1) **MUST** be 2.

The constant of proportionality, k , in Eqn (1) determines the relative flow rates of Classic and L4S flows when the AQM concerned is the bottleneck (all other factors being equal). k does not have to be standardized because differences do not prevent interoperability. However, k has to take some value, and each operator can make that choice.

A value of $k=2$ is currently RECOMMENDED as the default for Internet access networks. Assuming scalable congestion controls for the Internet will be as aggressive as DCTCP, this will ensure their congestion window will be roughly the same as that of a standards track TCP congestion control (Reno) [RFC5681] and other so-called TCP-friendly controls such as TCP Cubic in its TCP-friendly mode.

The requirements for scalable congestion controls on the Internet (termed the TCP Prague requirements) are only in initial draft form [I-D.briscoe-tsvwg-aqm-tcpm-rmcat-l4s-problem] and subject to change. If the aggressiveness of DCTCP is not defined as the benchmark for scalable controls on the Internet, the recommended value of k will also be subject to change.

Whatever value is recommended, the choice of k is a matter of operator policy, and operators MAY choose a different value using Table 1 and the guidelines in Appendix C.

Typically, access network operators isolate customers from each other with some form of layer-2 multiplexing (TDM in DOCSIS, CDMA in 3G) or L3 scheduling (WRR in broadband), rather than relying on TCP to share capacity between customers [RFC0970]. In such cases, the choice of k will solely affect relative flow rates within each customer's access capacity, not between customers. Also, k will not affect relative flow rates at any times when all flows are Classic or all L4S, and it will not affect small flows.

Example DualQ Coupled AQM algorithms called PI2 and Curvy RED are given in Appendix A and Appendix B. Either example AQM can be used to couple packet marking and dropping across a dual Q. Curvy RED requires less operations per packet than RED and can be used if the range of RTTs is limited. PI2 is a simplification of PIE with stable Proportional-Integral control for both Classic and L4S congestion controls. Nonetheless, it would be possible to control the queues with other alternative AQMs, as long as the above normative requirements (those expressed in capitals) are observed, which are intended to be independent of the specific AQM.

{ToDo: Add management and monitoring requirements}

3. IANA Considerations

This specification contains no IANA considerations.

4. Security Considerations

4.1. Overload Handling

Where the interests of users or flows might conflict, it could be necessary to police traffic to isolate any harm to performance. This is a policy issue that needs to be separable from a basic AQM, but an AQM does need to handle overload. A trade-off needs to be made between complexity and the risk of either class harming the other. It is an operator policy to define what must happen if the service time of the classic queue becomes too great. In the following subsections three optional non-exclusive overload protections are defined. Their objective is for the overload behaviour of the DualQ AQM to be similar to a single queue AQM. The example implementation in Appendix A implements the 'delay on overload' policy. Other overload protections can be envisaged:

Minimum throughput service: By replacing the priority scheduler with a weighted round robin scheduler, a minimum throughput service can be guaranteed for Classic traffic. Typically the scheduling weight of the Classic queue will be small (e.g. 5%) to avoid interference with the coupling but big enough to avoid complete starvation of Classic traffic.

Delay on overload: To control milder overload of responsive traffic, particularly when close to the maximum congestion signal, delay can be used as an alternative congestion control mechanism. The Dual Queue Coupled AQM can be made to behave like a single First-In First-Out (FIFO) queue with different service times by replacing the priority scheduler with a very simple scheduler that could be called a "time-shifted FIFO", which is the same as the Modifier Earliest Deadline First (MEDF) scheduler of [MEDF]. The scheduler adds T_m to the queue delay of the next L4S packet, before comparing it with the queue delay of the next Classic packet, then it selects the packet with the greater adjusted queue delay. Under regular conditions, this time-shifted FIFO scheduler behaves just like a strict priority scheduler. But under moderate or high overload it prevents starvation of the Classic queue, because the time-shift defines the maximum extra queuing delay (T_m) of Classic packets relative to L4S.

Drop on overload: On severe overload, e.g. due to non responsive traffic, queues will typically overflow and packet drop will be unavoidable. It is important to avoid unresponsive ECN traffic (either Classic or L4S) driving the AQM to 100% drop and mark probability. Congestion controls that have a minimum congestion window will become unresponsive to ECN marking when the marking probability is high. This situation can be avoided by applying

the drop probability to all packets of all traffic types when it exceeds a certain threshold or by limiting the drop and marking probabilities to a lower maximum value (up to where fairness between the different traffic types is still guaranteed) and rely on delay to control temporary high congestion and eventually queue overflow. If the classic drop probability is applied to all types of traffic when it is higher than a threshold probability the queueing delay can be controlled up to any overload situation, and no further measures are required. If a maximum classic and coupled L4S probability of less than 100% is used, both queues need scheduling opportunities and should eventually experience drop. This can be achieved with a scheduler that guarantees a minimum throughput for each queue, such as a weighted round robin or time-shifted FIFO scheduler. In that case a common queue limit can be configured that will drop packets of both types of traffic.

To keep the throughput of both L4S and Classic flows equal over the full load range, a different control strategy needs to be defined above the point where one congestion control first saturates to a probability of 100% (if $k > 1$, L4S will saturate first). Possible strategies include: also dropping L4S; increasing the queueing delay for both; or ensuring that L4S traffic still responds to marking below a window of 2 segments (see Appendix A of [I-D.briscoe-tsvwg-aqm-tcpm-rmcat-l4s-problem]).

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Appendix A. Example DualQ Coupled PI2 Algorithm

As a first concrete example, the pseudocode below gives the DualQ Coupled AQM algorithm based on the PI2 Classic AQM, we used and tested. For this example only the pseudo code is given. An open source implementation for Linux is available at: <https://github.com/olgabo/dualpi2>.

```
1: dualpi2_enqueue(lq, cq, pkt) { % Test limit and classify lq or cq
2:   stamp(pkt)                  % attach arrival time to packet
3:   if ( lq.len() + cq.len() > limit )
4:     drop(pkt)                  % drop packet if q is full
5:   else {
6:     if ( ecn(pkt) modulo 2 == 0 ) % ECN bits = not-ect or ect(0)
7:       cq.enqueue(pkt)
8:     else                        % ECN bits = ect(1) or ce
9:       lq.enqueue(pkt)
10:  }
11: }
```

Figure 1: Example Enqueue Pseudocode for DualQ Coupled PI2 AQM

```

1: dualpi2_dequeue(lq, cq) { % Couples L4S & Classic queues, lq & cq
2:   while ( lq.len() + cq.len() > 0 )
3:     if ( lq.time() + tshift >= cq.time() ) {
4:       lq.dequeue(pkt)
5:       if ( (pkt.time() > T) or (p > rand()) )
6:         mark(pkt)
7:       return(pkt) % return the packet and stop here
8:     } else {
9:       cq.dequeue(pkt)
10:      if ( p/k > max(rand(), rand()) ) % same as testing (p/k)^2
11:        if ( ecn(pkt) == 0 ) % ECN field = not-ect
12:          drop(pkt) % squared drop, redo loop
13:        else {
14:          mark(pkt) % squared mark
15:          return(pkt) % return the packet and stop here
16:        }
17:      else
18:        return(pkt) % return the packet and stop here
19:    }
20:  }
21:  return(NULL) % no packet to dequeue
22: }

```

Figure 2: Example Dequeue Pseudocode for DualQ Coupled PI2 AQM

```

1: dualpi2_update(lq, cq) { % Update p every Tupdate
2:   curq = cq.time() % use queuing time of first-in Classic packet
3:   alpha_U = alpha * Tupdate % done once when parameters are set
4:   beta_U = beta * Tupdate % done once when parameters are set
5:   p = p + alpha_U * (curq - target) + beta_U * (curq - prevq)
6:   prevq = curq
7: }

```

Figure 3: Example PI-Update Pseudocode for DualQ Coupled PI2 AQM

When packets arrive, first a common queue limit is checked as shown in line 3 of the enqueueing pseudocode in Figure 1. Note that the limit is deliberately tested before enqueue to avoid any bias against larger packets (so the actual buffer has to be one packet larger than limit). If limit is not exceeded, the packet will be classified and enqueued to the Classic or L4S queue dependent on the least significant bit of the ECN field in the IP header (line 6). Packets with a codepoint having an LSB of 0 (Not-ECT and ECT(0)) will be enqueued in the Classic queue. Otherwise, ECT(1) and CE packets will be enqueued in the L4S queue.

The pseudocode in Figure 2 summarises the per packet dequeue implementation of the DualPI2 code. Line 3 implements the time-

shifted FIFO scheduling. It takes the packet that waited the longest, biased by a time-shift of `tshift` for the Classic traffic. If an L4S packet is scheduled, lines 5 and 6 mark the packet if either the L4S threshold `T` is exceeded, or if a random marking decision is drawn according to the probability `p` (maintained by the `dualpi2_update()` function discussed below). If a Classic packet is scheduled, lines 10 to 16 drop or mark the packet based on 2 random decisions resulting in the squared probability $(p/k)^2$ (hence the name PI2 for Classic traffic). Note that `p` is reduced by the factor `k` here. This has 2 effects; first the steady state probability is halved as required to give Classic TCP and DCTCP traffic equal throughput; secondly, the effect of the dynamic gain parameters `alpha` and `beta` are halved as well, which is also needed give Classic TCP and DCTCP control the same stability.

The probability `p` is kept up to date by the core PI algorithm in Figure 3 which is executed every `Tupdate` ([I-D.ietf-aqm-pie] now recommends 16ms, but in our testing so far we have used the earlier recommendation of 32ms). Note that `p` solely depends on the queuing time in the Classic queue. In line 2, the current queuing delay is evaluated by inspecting the timestamp of the next packet to schedule in the Classic queue. The function `cq.time()` subtracts the time stamped at enqueue from the current time and implicitly takes the current queuing delay as 0 if the queue is empty. Line 3 and 4 only need to be executed when the configuration parameters are changed. `Alpha` and `beta` in Hz are gain factors per 1 second. If a briefer update time is configured, `alpha_U` and `beta_U` (`_U` = per `Tupdate`) also have to be reduced, to ensure that the same response is given over time. As such, a smaller `Tupdate` will only result in a response with smaller and finer steps, not a more aggressive response. The new probability is calculated in line 5, where `target` is the target queuing delay, as defined in [I-D.ietf-aqm-pie]. In corner cases, `p` can overflow the range `[0,1]` so the resulting value of `p` has to be bounded (omitted from the pseudocode). Unlike PIE, `alpha_U` and `beta_U` are not tuned dependent on `p`, every `Tupdate`. Instead, in PI2 `alpha_U` and `beta_U` can be constants because the squaring applied to Classic traffic tunes them inherently, as explained in [PI216].

In our experiments so far (building on experiments with PIE) on broadband access links ranging from 4 Mb/s to 200 Mb/s with base RTTs from 5 ms to 100 ms, PI2 achieves good results with the following parameters:

```
tshift = 40ms
```

```
T = max(1ms, serialization time of 2 MTU)
```

```
target = 20ms
```

Tupdate = 32ms

k = 2

alpha = 20Hz (alpha/k = 10Hz for Classic)

beta = 200Hz (beta/k = 100Hz for Classic)

Appendix B. Example DualQ Coupled Curvy RED Algorithm

As another example, the pseudocode below gives the Curvy RED based DualQ Coupled AQM algorithm we used and tested. Although we designed the AQM to be efficient in integer arithmetic, to aid understanding it is first given using real-number arithmetic. Then, one possible optimization for integer arithmetic is given, also in pseudocode. To aid comparison, the line numbers are kept in step between the two by using letter suffixes where the longer code needs extra lines.

```

1: dualq_dequeue(lq, cq) { % Couples L4S & Classic queues, lq & cq
2:   if ( lq.dequeue(pkt) ) {
3a:     p_L = cq.sec() / 2^S_L
3b:     if ( lq.bytt() > T )
3c:       mark(pkt)
3d:     elif ( p_L > maxrand(U) )
4:       mark(pkt)
5:     return(pkt) % return the packet and stop here
6:   }
7:   while ( cq.dequeue(pkt) ) {
8a:     alpha = 2^(-f_C)
8b:     Q_C = alpha * pkt.sec() + (1-alpha)* Q_C % Classic Q EWMA
9a:     sqrt_p_C = Q_C / 2^S_C
9b:     if ( sqrt_p_C > maxrand(2*U) )
10:       drop(pkt) % Squared drop, redo loop
11:     else
12:       return(pkt) % return the packet and stop here
13:   }
14:   return(NULL) % no packet to dequeue
15: }

16: maxrand(u) { % return the max of u random numbers
17:   maxr=0
18:   while (u-- > 0)
19:     maxr = max(maxr, rand()) % 0 <= rand() < 1
20:   return(maxr)
21: }
```

Figure 4: Example Dequeue Pseudocode for DualQ Coupled Curvy RED AQM

Packet classification code is not shown, as it is no different from Figure 1. Potential classification schemes are discussed in Section 2. Overload protection code will be included in a future draft {ToDo}.

At the outer level, the structure of `dualq_dequeue()` implements strict priority scheduling. The code is written assuming the AQM is applied on dequeue (Note 1). Every time `dualq_dequeue()` is called, the if-block in lines 2-6 determines whether there is an L4S packet to dequeue by calling `lq.dequeue(pkt)`, and otherwise the while-block in lines 7-13 determines whether there is a Classic packet to dequeue, by calling `cq.dequeue(pkt)`. (Note 2)

In the lower priority Classic queue, a while loop is used so that, if the AQM determines that a classic packet should be dropped, it continues to test for classic packets deciding whether to drop each until it actually forwards one. Thus, every call to `dualq_dequeue()` returns one packet if at least one is present in either queue, otherwise it returns NULL at line 14. (Note 3)

Within each queue, the decision whether to drop or mark is taken as follows (to simplify the explanation, it is assumed that $U=1$):

L4S: If the test at line 2 determines there is an L4S packet to dequeue, the tests at lines 3a and 3c determine whether to mark it. The first is a simple test of whether the L4S queue (`lq.bytt()` in bytes) is greater than a step threshold T in bytes (Note 4). The second test is similar to the random ECN marking in RED, but with the following differences: i) the marking function does not start with a plateau of zero marking until a minimum threshold, rather the marking probability starts to increase as soon as the queue is positive; ii) marking depends on queuing time, not bytes, in order to scale for any link rate without being reconfigured; iii) marking of the L4S queue does not depend on itself, it depends on the queuing time of the `_other_` (Classic) queue, where `cq.sec()` is the queuing time of the packet at the head of the Classic queue (zero if empty); iv) marking depends on the instantaneous queuing time (of the other Classic queue), not a smoothed average; v) the queue is compared with the maximum of U random numbers (but if $U=1$, this is the same as the single random number used in RED).

Specifically, in line 3a the marking probability p_L is set to the Classic queueing time `qc.sec()` in seconds divided by the L4S scaling parameter 2^{S_L} , which represents the queuing time (in seconds) at which marking probability would hit 100%. Then in line 3d (if $U=1$) the result is compared with a uniformly distributed random number between 0 and 1, which ensures that marking

probability will linearly increase with queueing time. The scaling parameter is expressed as a power of 2 so that division can be implemented as a right bit-shift (>>) in line 3 of the integer variant of the pseudocode (Figure 5).

Classic: If the test at line 7 determines that there is at least one Classic packet to dequeue, the test at line 9b determines whether to drop it. But before that, line 8b updates Q_C , which is an exponentially weighted moving average (Note 5) of the queueing time in the Classic queue, where `pkt.sec()` is the instantaneous queueing time of the current Classic packet and α is the EWMA constant for the classic queue. In line 8a, α is represented as an integer power of 2, so that in line 8 of the integer code the division needed to weight the moving average can be implemented by a right bit-shift (>> f_C).

Lines 9a and 9b implement the drop function. In line 9a the averaged queueing time Q_C is divided by the Classic scaling parameter 2^{S_C} , in the same way that queueing time was scaled for L4S marking. This scaled queueing time is given the variable name `sqrtp_C` because it will be squared to compute Classic drop probability, so before it is squared it is effectively the square root of the drop probability. The squaring is done by comparing it with the maximum out of two random numbers (assuming $U=1$). Comparing it with the maximum out of two is the same as the logical 'AND' of two tests, which ensures drop probability rises with the square of queueing time (Note 6). Again, the scaling parameter is expressed as a power of 2 so that division can be implemented as a right bit-shift in line 9 of the integer pseudocode.

The marking/dropping functions in each queue (lines 3 & 9) are two cases of a new generalization of RED called Curvy RED, motivated as follows. When we compared the performance of our AQM with `fq_CoDel` and PIE, we came to the conclusion that their goal of holding queueing delay to a fixed target is misguided [CRED_Insights]. As the number of flows increases, if the AQM does not allow TCP to increase queueing delay, it has to introduce abnormally high levels of loss. Then loss rather than queueing becomes the dominant cause of delay for short flows, due to timeouts and tail losses.

Curvy RED constrains delay with a softened target that allows some increase in delay as load increases. This is achieved by increasing drop probability on a convex curve relative to queue growth (the square curve in the Classic queue, if $U=1$). Like RED, the curve hugs the zero axis while the queue is shallow. Then, as load increases, it introduces a growing barrier to higher delay. But, unlike RED, it requires only one parameter, the scaling, not three. The diadvantage

of Curvy RED is that it is not adapted to a wide range of RTTs. Curvy RED can be used as is when the RTT range to support is limited otherwise an adaptation mechanism is required.

There follows a summary listing of the two parameters used for each of the two queues:

Classic:

S_C : The scaling factor of the dropping function scales Classic queueing times in the range $[0, 2^{(S_C)}]$ seconds into a dropping probability in the range $[0,1]$. To make division efficient, it is constrained to be an integer power of two;

f_C : To smooth the queueing time of the Classic queue and make multiplication efficient, we use a negative integer power of two for the dimensionless EWMA constant, which we define as $2^{(-f_C)}$.

L4S :

S_L (and k): As for the Classic queue, the scaling factor of the L4S marking function scales Classic queueing times in the range $[0, 2^{(S_L)}]$ seconds into a probability in the range $[0,1]$. Note that $S_L = S_C + k$, where k is the coupling between the queues (Section 2.1). So S_L and k count as only one parameter;

T : The queue size in bytes at which step threshold marking starts in the L4S queue.

{ToDo: These are the raw parameters used within the algorithm. A configuration front-end could accept more meaningful parameters and convert them into these raw parameters.}

From our experiments so far, recommended values for these parameters are: $S_C = -1$; $f_C = 5$; $T = 5 * MTU$ for the range of base RTTs typical on the public Internet. [CRED_Insights] explains why these parameters are applicable whatever rate link this AQM implementation is deployed on and how the parameters would need to be adjusted for a scenario with a different range of RTTs (e.g. a data centre) {ToDo incorporate a summary of that report into this draft}. The setting of k depends on policy (see Section 2.4 and Appendix C respectively for its recommended setting and guidance on alternatives).

There is also a cUrviness parameter, U , which is a small positive integer. It is likely to take the same hard-coded value for all implementations, once experiments have determined a good value. We

have solely used $U=1$ in our experiments so far, but results might be even better with $U=2$ or higher.

Note that the dropping function at line 9 calls `maxrand(2*U)`, which gives twice as much curviness as the call to `maxrand(U)` in the marking function at line 3. This is the trick that implements the square rule in equation (1) (Section 2.1). This is based on the fact that, given a number X from 1 to 6, the probability that two dice throws will both be less than X is the square of the probability that one throw will be less than X . So, when $U=1$, the L4S marking function is linear and the Classic dropping function is squared. If $U=2$, L4S would be a square function and Classic would be quartic. And so on.

The `maxrand(u)` function in lines 16-21 simply generates u random numbers and returns the maximum (Note 7). Typically, `maxrand(u)` could be run in parallel out of band. For instance, if $U=1$, the Classic queue would require the maximum of two random numbers. So, instead of calling `maxrand(2*U)` in-band, the maximum of every pair of values from a pseudorandom number generator could be generated out-of-band, and held in a buffer ready for the Classic queue to consume.

```

1: dualq_dequeue(lq, cq) { % Couples L4S & Classic queues, lq & cq
2:   if ( lq.dequeue(pkt) ) {
3:     if ((lq.bytt() > T) || ((cq.ns() >> (S_L-2)) > maxrand(U)))
4:       mark(pkt)
5:     return(pkt) % return the packet and stop here
6:   }
7:   while ( cq.dequeue(pkt) ) {
8:     Q_C += (pkt.ns() - Q_C) >> f_C % Classic Q EWMA
9:     if ( (Q_C >> (S_C-2)) > maxrand(2*U) )
10:      drop(pkt) % Squared drop, redo loop
11:    else
12:      return(pkt) % return the packet and stop here
13:   }
14:   return(NULL) % no packet to dequeue
15: }
```

Figure 5: Optimised Example Dequeue Pseudocode for Coupled DualQ AQM using Integer Arithmetic

Notes:

1. The drain rate of the queue can vary if it is scheduled relative to other queues, or to cater for fluctuations in a wireless medium. To auto-adjust to changes in drain rate, the queue must be measured in time, not bytes or packets [CoDel]. In our Linux implementation, it was easiest to measure queuing time at

dequeue. Queuing time can be estimated when a packet is enqueued by measuring the queue length in bytes and dividing by the recent drain rate.

2. An implementation has to use priority queueing, but it need not implement strict priority.
3. If packets can be enqueued while processing dequeue code, an implementer might prefer to place the while loop around both queues so that it goes back to test again whether any L4S packets arrived while it was dropping a Classic packet.
4. In order not to change too many factors at once, for now, we keep the marking function for DCTCP-only traffic as similar as possible to DCTCP. However, unlike DCTCP, all processing is at dequeue, so we determine whether to mark a packet at the head of the queue by the byte-length of the queue `_behind_` it. We plan to test whether using queuing time will work in all circumstances, and if we find that the step can cause oscillations, we will investigate replacing it with a steep random marking curve.
5. An EWMA is only one possible way to filter bursts; other more adaptive smoothing methods could be valid and it might be appropriate to decrease the EWMA faster than it increases.
6. In practice at line 10 the Classic queue would probably test for ECN capability on the packet to determine whether to drop or mark the packet. However, for brevity such detail is omitted. All packets classified into the L4S queue have to be ECN-capable, so no dropping logic is necessary at line 3. Nonetheless, L4S packets could be dropped by overload code (see Section 4.1).
7. In the integer variant of the pseudocode (Figure 5) real numbers are all represented as integers scaled up by 2^{32} . In lines 3 & 9 the function `maxrand()` is arranged to return an integer in the range $0 \leq \text{maxrand}() < 2^{32}$. Queuing times are also scaled up by 2^{32} , but in two stages: i) In lines 3 and 8 queuing times `cq.ns()` and `pkt.ns()` are returned in integer nanoseconds, making the values about 2^{30} times larger than when the units were seconds, ii) then in lines 3 and 9 an adjustment of -2 to the right bit-shift multiplies the result by 2^2 , to complete the scaling by 2^{32} .

Appendix C. Guidance on Controlling Throughput Equivalence

RTT_C / RTT_L	Reno	Cubic
1	k=1	k=0
2	k=2	k=1
3	k=2	k=2
4	k=3	k=2
5	k=3	k=3

Table 1: Value of k for which DCTCP throughput is roughly the same as Reno or Cubic, for some example RTT ratios

To determine the appropriate policy, the operator first has to judge whether it wants DCTCP flows to have roughly equal throughput with Reno or with Cubic (because, even in its Reno-compatibility mode, Cubic is about 1.4 times more aggressive than Reno). Then the operator needs to decide at what ratio of RTTs it wants DCTCP and Classic flows to have roughly equal throughput. For example choosing the recommended value of k=0 will make DCTCP throughput roughly the same as Cubic, if their RTTs are the same.

However, even if the base RTTs are the same, the actual RTTs are unlikely to be the same, because Classic (Cubic or Reno) traffic needs a large queue to avoid under-utilization and excess drop, whereas L4S (DCTCP) does not. The operator might still choose this policy if it judges that DCTCP throughput should be rewarded for keeping its own queue short.

On the other hand, the operator will choose one of the higher values for k, if it wants to slow DCTCP down to roughly the same throughput as Classic flows, to compensate for Classic flows slowing themselves down by causing themselves extra queuing delay.

The values for k in the table are derived from the formulae, which was developed in [DCttH15]:

$$2^k = 1.64 (RTT_{reno} / RTT_{dc}) \quad (2)$$

$$2^k = 1.19 (RTT_{cubic} / RTT_{dc}) \quad (3)$$

For localized traffic from a particular ISP's data centre, we used the measured RTTs to calculate that a value of k=3 would achieve throughput equivalence, and our experiments verified the formula very closely.

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Identifying Modified Explicit Congestion Notification (ECN) Semantics
for Ultra-Low Queuing Delay
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Abstract

This specification defines the identifier to be used on IP packets for a new network service called low latency, low loss and scalable throughput (L4S). It is similar to the original (or 'Classic') Explicit Congestion Notification (ECN). 'Classic' ECN marking was required to be equivalent to a drop, both when applied in the network and when responded to by a transport. Unlike 'Classic' ECN marking, for packets carrying the L4S identifier, the network applies marking more immediately and more aggressively than drop, and the transport response to each mark is reduced and smoothed relative to that for drop. The two changes counterbalance each other so that the throughput of an L4S flow will be roughly the same as a 'Classic' flow under the same conditions. However, the much more frequent control signals and the finer responses to them result in ultra-low queuing delay without compromising link utilization, even during high load. Examples of new active queue management (AQM) marking algorithms and examples of new transports (whether TCP-like or real-time) are specified separately. The new L4S identifier is the key piece that enables them to interwork and distinguishes them from 'Classic' traffic. It gives an incremental migration path so that existing 'Classic' TCP traffic will be no worse off, but it can be prevented from degrading the ultra-low delay and loss of the new scalable transports.

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Table of Contents

1. Introduction	3
1.1. Problem	4
1.2. Terminology	5
1.3. Scope	6
2. L4S Packet Identifier	6
2.1. L4S Packet Identification Requirements	6
2.2. L4S Packet Identification	7
2.3. Pre-Requisite Transport Layer Behaviour	8
2.4. L4S Packet Identification by Network Nodes with Transport-Layer Awareness	9
2.5. The Meaning of CE Relative to Drop	10
3. IANA Considerations	10
4. Security Considerations	10
5. Acknowledgements	10
6. References	11
6.1. Normative References	11
6.2. Informative References	11
Appendix A. Alternative Identifiers	15
A.1. ECT(1) and CE codepoints	16
A.2. ECN Plus a Diffserv Codepoint (DSCP)	18
A.3. ECN capability alone	20
A.4. Protocol ID	21
A.5. Source or destination addressing	21
A.6. Summary: Merits of Alternative Identifiers	22

Appendix B. Potential Competing Uses for the ECT(1) Codepoint	23
B.1. Integrity of Congestion Feedback	23
B.2. Notification of Less Severe Congestion than CE	24
Authors' Addresses	24

1. Introduction

This specification defines the identifier to be used on IP packets for a new network service called low latency, low loss and scalable throughput (L4S). It is similar to the original (or 'Classic') Explicit Congestion Notification (ECN). 'Classic' ECN marking was required to be equivalent to a drop, both when applied in the network and when responded to by a transport. Unlike 'Classic' ECN marking, the network applies L4S marking more immediately and more aggressively than drop, and the transport response to each mark is reduced and smoothed relative to that for drop. The two changes counterbalance each other so that the bit-rate of an L4S flow will be roughly the same as a 'Classic' flow under the same conditions. However, the much more frequent control signals and the finer responses to them result in ultra-low queuing delay without compromising link utilization, even during high load.

An example of an active queue management (AQM) marking algorithm that enables the L4S service is the DualQ Coupled AQM defined in a complementary specification [I-D.briscoe-aqm-dualq-coupled]. An example of a scalable transport that would enable the L4S service is Data Centre TCP (DCTCP), which until now has been applicable solely to controlled environments like data centres [I-D.ietf-tcpm-dctcp], because it is too aggressive to co-exist with existing TCP. However, AQMs like DualQ Coupled enable scalable transports like DCTCP to co-exist with existing traffic, each getting roughly the same flow rate when they compete under similar conditions. Note that DCTCP will still not be safe to deploy on the Internet until it satisfies the 'Safety Additions' listed in Appendix A of [I-D.briscoe-tsvwg-aqm-tcpm-rmcat-l4s-problem].

The new L4S identifier is the key piece that enables these two parts to interwork and distinguishes them from 'Classic' traffic. It gives an incremental migration path so that existing 'Classic' TCP traffic will be no worse off, but it can be prevented from degrading the ultra-low delay and loss of the new scalable transports. The performance improvement is so great that it is hoped it will motivate initial deployment of the separate parts of this system.

1.1. Problem

Latency is becoming the critical performance factor for many (most?) applications on the public Internet, e.g. Web, voice, conversational video, gaming, finance apps, remote desktop and cloud-based applications. In the developed world, further increases in access network bit-rate offer diminishing returns, whereas latency is still a multi-faceted problem. In the last decade or so, much has been done to reduce propagation time by placing caches or servers closer to users. However, queuing remains a major component of latency.

The Diffserv architecture provides Expedited Forwarding [RFC3246], so that low latency traffic can jump the queue of other traffic. However, on access links dedicated to individual sites (homes, small enterprises or mobile devices), often all traffic at any one time will be latency-sensitive. Then Diffserv is of little use. Instead, we need to remove the causes of any unnecessary delay.

The bufferbloat project has shown that excessively-large buffering ('bufferbloat') has been introducing significantly more delay than the underlying propagation time. These delays appear only intermittently--only when a capacity-seeking (e.g. TCP) flow is long enough for the queue to fill the buffer, making every packet in other flows sharing the buffer sit through the queue.

Active queue management (AQM) was originally developed to solve this problem (and others). Unlike Diffserv, which gives low latency to some traffic at the expense of others, AQM controls latency for all traffic in a class. In general, AQMs introduce an increasing level of discard from the buffer the longer the queue persists above a shallow threshold. This gives sufficient signals to capacity-seeking (aka. greedy) flows to keep the buffer empty for its intended purpose: absorbing bursts. However, RED [RFC2309] and other algorithms from the 1990s were sensitive to their configuration and hard to set correctly. So, AQM was not widely deployed.

More recent state-of-the-art AQMs, e.g. fq_CoDel [I-D.ietf-aqm-fq-codel], PIE [I-D.ietf-aqm-pie], Adaptive RED [ARED01], are easier to configure, because they define the queuing threshold in time not bytes, so it is invariant for different link rates. However, no matter how good the AQM, the sawtooth rate of TCP will either cause queuing delay to vary or cause the link to be under-utilized. Even with a perfectly tuned AQM, the additional queuing delay will be of the same order as the underlying speed-of-light delay across the network. Flow-queuing can isolate one flow from another, but it cannot isolate a TCP flow from the delay variations it inflicts on itself, and it has other problems - it overrides the flow rate decisions of variable rate video

applications, it does not recognise the flows within IPSec VPN tunnels and it is relatively expensive to implement.

Latency is not our only concern: It was known when TCP was first developed that it would not scale to high bandwidth-delay products. Given regular broadband bit-rates over WAN distances are already [RFC3649] beyond the scaling range of 'Classic' TCP Reno, 'less unscalable' Cubic [I-D.ietf-tcpm-cubic] and Compound [I-D.sridharan-tcpm-ctcp] variants of TCP have been successfully deployed. However, these are now approaching their scaling limits. Unfortunately, fully scalable TCPs such as DCTCP [I-D.ietf-tcpm-dctcp] cause 'Classic' TCP to starve itself, which is why they have been confined to private data centres or research testbeds (until now).

It turns out that a TCP algorithm like DCTCP that solves TCP's scalability problem also solves the latency problem, because the finer sawteeth cause very little queuing delay. A supporting paper [DCttH15] gives the full explanation of why the design solves both the latency and the scaling problems, both in plain English and in more precise mathematical form. The explanation is summarised without the maths in [I-D.briscoe-aqm-dualq-coupled].

1.2. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119]. In this document, these words will appear with that interpretation only when in ALL CAPS. Lower case uses of these words are not to be interpreted as carrying RFC-2119 significance.

Classic service: The 'Classic' service is intended for all the behaviours that currently co-exist with TCP Reno (e.g. TCP Cubic, Compound, SCTP, etc).

Low-Latency, Low-Loss and Scalable (L4S) service: The 'L4S' service is intended for traffic from scalable TCP algorithms such as Data Centre TCP. But it is also more general--it will allow a set of congestion controls with similar scaling properties to DCTCP (e.g. Relentless [Mathis09]) to evolve.

Both Classic and L4S services can cope with a proportion of unresponsive or less-responsive traffic as well (e.g. DNS, VoIP, etc).

Classic ECN: The original Explicit Congestion Notification (ECN) protocol [RFC3168].

1.3. Scope

The new L4S identifier defined in this specification is applicable for IPv4 and IPv6 packets (as for classic ECN [RFC3168]). It is applicable for the unicast, multicast and anycast forwarding modes. It is an orthogonal packet classification to Differentiated Services (Diffserv [RFC2474]), therefore it can be applied to any packet in any Diffserv traffic class. However, as with classic ECN, any particular forwarding node might not implement an active queue management algorithm in all its Diffserv queues.

This document is intended for experimental status, so it does not update any standards track RFCs. Therefore it depends on [I-D.black-tsvwg-ecn-experimentation], which proposes to:

- o update the ECN proposed standard [RFC3168] (in certain specified cases including the present document) to relax the requirement that an ECN mark must be equivalent to a drop, both when applied by the network, and when responded to by the sender;
- o obsolete the experimental ECN nonce [RFC3540] (see Appendix B.1 for rationale);
- o make consequent updates to the following proposed standard RFCs to reflect the above two bullets:
 - * ECN for RTP [RFC6679];
 - * the congestion control specifications of various DCCP CCIDs [RFC4341], [RFC4342], [RFC5622].

2. L4S Packet Identifier

2.1. L4S Packet Identification Requirements

Ideally, the identifier for packets using the Low Latency, Low Loss, Scalable throughput (L4S) service ought to meet the following requirements:

- o it SHOULD survive end-to-end between source and destination applications: across the boundary between host and network, between interconnected networks, and through middleboxes;
- o it SHOULD be common to IPv4 and IPv6 and transport agnostic;
- o it SHOULD be incrementally deployable;

- o it SHOULD enable an AQM to classify packets encapsulated by outer IP or lower-layer headers;
- o it SHOULD consume minimal extra codepoints;
- o it SHOULD not lead to some packets of a transport-layer flow being served by a different queue from others.

Whether the identifier would be recoverable if the experiment failed is a factor that could be taken into account. However, this has not been made a requirement, because that would favour schemes that would be easier to fail, rather than those more likely to succeed.

It is recognised that the chosen identifier is unlikely to satisfy all these requirements, particularly given the limited space left in the IP header. Therefore a compromise will be necessary, which is why all the requirements are expressed with the word 'SHOULD' not 'MUST'. Appendix A discusses the pros and cons of the compromises made in various competing identification schemes against the above requirements. On the basis of this analysis, the "ECT(1) and CE codepoints" is the best compromise. Therefore this scheme is defined in detail in the following section (Section 2.2), while Appendix A has been left to document the rationale for this decision.

2.2. L4S Packet Identification

The L4S treatment is an alternative packet marking treatment [RFC4774] to the classic ECN treatment [RFC3168]. Like classic ECN, it identifies both network and host behaviour: it identifies the marking treatment that network nodes are expected to apply to L4S packets, and it identifies packets that have been sent from hosts that are expected to comply with a broad type of behaviour.

For a packet to receive L4S treatment as it is forwarded, the sender MUST set the ECN field in the IP header (v4 or v6) to the ECT(1) codepoint.

A network node that implements the L4S service MUST classify arriving ECT(1) packets for L4S treatment and it SHOULD classify arriving CE packets for L4S treatment as well. Section 2.4 describes a possible exception to this latter rule.

The L4S AQM treatment follows similar codepoint transition rules to those in RFC 3168. Specifically, the ECT(1) codepoint MUST NOT be changed to any other codepoint than CE, and CE MUST NOT be changed to any other codepoint. An ECT(1) packet is classified as ECN-capable and, if congestion increases, an L4S AQM algorithm will mark the ECN field as CE for an increasing proportion of packets, otherwise

forwarding packets unchanged as ECT(1). The L4S marking treatment is defined in Section 2.5. Under persistent overload conditions, the AQM will follow RFC 3168 and turn off ECN marking, using drop as a congestion signal until the overload episode has subsided.

The L4S treatment is the default for ECT(1) packets in all Diffserv Classes [RFC4774].

For backward compatibility in uncontrolled environments, a network node that implements the L4S treatment MUST also implement a classic AQM treatment. It MUST classify arriving ECT(0) and Not-ECT packets for treatment by the Classic AQM. Classic treatment means that the AQM will mark ECT(0) packets under the same conditions as it would drop Not-ECT packets [RFC3168].

2.3. Pre-Requisite Transport Layer Behaviour

For a host to send packets with the L4S identifier (ECT(1)), it SHOULD implement a congestion control behaviour that ensures the flow rate is inversely proportional to the proportion of bytes in packets marked with the CE codepoint. This is termed a scalable congestion control, because the number of control signals (ECN marks) per round trip remains roughly constant for any flow rate. As with all transport behaviours, a detailed specification will need to be defined for each type of transport or application, including the timescale over which the proportionality is averaged, and control of burstiness. The inverse proportionality requirement above is worded as a 'SHOULD' rather than a 'MUST' to allow reasonable flexibility when defining these specifications.

Data Center TCP (DCTCP [I-D.ietf-tcpm-dctcp]) is an example of a scalable congestion control.

Each sender in a session can use a scalable congestion control independently of the congestion control used by the receiver(s) when they send data. Therefore theoretically there might be ECT(1) packets in one direction and ECT(0) in the other.

In general, a scalable congestion control needs feedback of the extent of CE marking on the forward path. Due to the history of TCP development, when ECN was added it reported no more than one CE mark per round trip. Some transport protocols derived from TCP mimic this behaviour while others report the extent of TCP marking. This means that some transport protocols will need to be updated as a pre-requisite for scalable congestion control. The position for a few well-known transport protocols is given below.

TCP: Support for accurate ECN feedback (AccECN [I-D.ietf-tcpm-accurate-ecn]) by both ends is a pre-requisite for scalable congestion control. However, the reverse does not apply. So even if both ends support AccECN, either of the two ends can choose not to use a scalable congestion control, whatever the other end's choice. Nonetheless, the presence of ECT(1) in the IP headers even in one direction of a TCP connection will imply that both ends support AccECN.

SCTP: An ECN feedback protocol such as that specified in [I-D.stewart-tsvwg-sctp-ecn] would be a pre-requisite for scalable congestion control. That draft would update the ECN feedback protocol sketched out in Appendix A of the standards track specification of SCTP [RFC4960] by adding a field to report the number of CE marks.

RTP over UDP: A pre-requisite for scalable congestion control is for both (all) ends of one media-level hop to signal ECN support using the ecn-capable-rtp attribute [RFC6679]. However, the reverse does not apply, so each end of a media-level hop can independently choose not to use a scalable congestion control, even if both ends support ECN. Nonetheless, the presence of ECT(1) implies that both (all) ends of that hop support ECN.

DCCP: The ACK vector in DCCP [RFC4340] is already sufficient to report the extent of CE marking as needed by a scalable congestion control.

2.4. L4S Packet Identification by Network Nodes with Transport-Layer Awareness

To implement the L4S treatment, a network node does not need to identify transport-layer flows. Nonetheless, if an implementer is willing to identify transport-layer flows at a network node, and if the most recent ECT packet in the same flow was ECT(0), the node MAY classify CE packets for classic ECN [RFC3168] treatment. In all other cases, a network node MUST classify CE packets for L4S treatment. Examples of such other cases are: i) if no ECT packets have yet been identified in a flow; ii) if it is not desirable for a network node to identify transport-layer flows; or iii) if the most recent ECT packet in a flow was ECT(1).

If an implementer uses flow-awareness to classify CE packets, to determine whether the flow is using ECT(0) or ECT(1) it only uses the most recent ECT packet of a flow {ToDo: this advice will need to be verified experimentally}. This is because a sender might have to switch from sending ECT(1) (L4S) packets to sending ECT(0) (Classic) packets, or back again, in the middle of a transport-layer flow.

Such a switch-over is likely to be very rare, but It could be necessary if the path bottleneck moves from a network node that supports L4S to one that only supports Classic ECN. A host ought to be able to detect such a change from a change in RTT variation.

2.5. The Meaning of CE Relative to Drop

The likelihood that an AQM drops a Not-ECT Classic packet (p_C) MUST be roughly proportional to the square of the likelihood that it would have marked it if it had been an L4S packet (p_L). That is

$$p_C \sim (p_L / k)^2$$

The constant of proportionality (k) does not have to be standardised for interoperability, but a value of 2 is RECOMMENDED.

[I-D.briscoe-aqm-dualq-coupled] specifies the essential aspects of an L4S AQM, as well as recommending other aspects. It gives example implementations in appendices.

The term 'likelihood' is used above to allow for marking and dropping to be either probabilistic or deterministic. The example AQMs in [I-D.briscoe-aqm-dualq-coupled] drop and mark probabilistically, so the drop probability is arranged to be the square of the marking probability. Nonetheless, an alternative AQM that dropped and marked deterministically would be valid, as long as the dropping frequency was proportional to the square of the marking frequency.

Note that, contrary to RFC 3168, an AQM implementing the L4S and Classic treatments does not mark an ECT(1) packet under the same conditions that it would have dropped a Not-ECT packet. However, it does mark an ECT(0) packet under the same conditions that it would have dropped a Not-ECT packet.

3. IANA Considerations

This specification contains no IANA considerations.

4. Security Considerations

Two approaches to assure the integrity of signals using the new identifier are introduced in Appendix B.1.

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Appendix A. Alternative Identifiers

This appendix is informative, not normative. It records the pros and cons of various alternative ways to identify L4S packets to record the rationale for the choice of ECT(1) (Appendix A.1) as the L4S identifier. At the end, Appendix A.6 summarises the distinguishing features of the leading alternatives. It is intended to supplement, not replace the detailed text.

The leading solutions all use the ECN field, sometimes in combination with the Diffserv field. Both the ECN and Diffserv fields have the additional advantage that they are no different in either IPv4 or IPv6. A couple of alternatives that use other fields are mentioned at the end, but it is quickly explained why they are not serious contenders.

A.1. ECT(1) and CE codepoints

Definition:

Packets with ECT(1) and conditionally packets with CE would signify L4S semantics as an alternative to the semantics of classic ECN [RFC3168], specifically:

- * The ECT(1) codepoint would signify that the packet was sent by an L4S-capable sender;
- * Given shortage of codepoints, both L4S and classic ECN sides of an AQM would have to use the same CE codepoint to indicate that a packet had experienced congestion. If a packet that had already been marked CE in an upstream buffer arrived at a subsequent AQM, this AQM would then have to guess whether to classify CE packets as L4S or classic ECN. Choosing the L4S treatment would be a safer choice, because then a few classic packets might arrive early, rather than a few L4S packets arriving late;
- * Additional information might be available if the classifier were transport-aware. Then it could classify a CE packet for classic ECN treatment if the most recent ECT packet in the same flow had been marked ECT(0). However, the L4S service ought not to need transport-layer awareness;

Cons:

Consumes the last ECN codepoint: The L4S service is intended to supersede the service provided by classic ECN, therefore using ECT(1) to identify L4S packets could ultimately mean that the ECT(0) codepoint was 'wasted' purely to distinguish one form of ECN from its successor;

ECN hard in some lower layers: It is not always possible to support ECN in an AQM acting in a buffer below the IP layer [I-D.ietf-tsvwg-ecn-encap-guidelines]. In such cases, the L4S service would have to drop rather than mark frames even though they might contain an ECN-capable packet. However, such cases would be unusual.

Risk of reordering classic CE packets: Having to classify all CE packets as L4S risks some classic CE packets arriving early, which is a form of reordering. Reordering can cause the TCP sender to retransmit spuriously. However, one or two packets delivered early does not cause any spurious retransmissions because the subsequent packets continue to move the cumulative acknowledgement

boundary forwards. Anyway, the risk of reordering would be low, because: i) it is quite unusual to experience more than one bottleneck queue on a path; ii) even then, reordering would only occur if there was simultaneous mixing of classic and L4S traffic, which would be more unlikely in an access link, which is where most bottlenecks are located; iii) even then, spurious retransmissions would only occur if a contiguous sequence of three or more classic CE packets from one bottleneck arrived at the next, which should in itself happen very rarely with a good AQM. The risk would be completely eliminated in AQMs that were transport-aware (but they should not need to be);

Non-L4S service for control packets: The classic ECN RFCs [RFC3168] and [RFC5562] require a sender to clear the ECN field to Not-ECT for retransmissions and certain control packets specifically pure ACKs, window probes and SYNs. When L4S packets are classified by the ECN field alone, these control packets would not be classified into an L4S queue, and could therefore be delayed relative to the other packets in the flow. This would not cause re-ordering (because retransmissions are already out of order, and the control packets carry no data). However, it would make critical control packets more vulnerable to loss and delay. To address this problem, [I-D.bagnulo-tswg-generalized-ecn] proposes an experiment in which all TCP control packets and retransmissions are ECN-capable.

Pros:

Should work e2e: The ECN field generally works end-to-end across the Internet. Unlike the DSCP, the setting of the ECN field is at least forwarded unchanged by networks that do not support ECN, and networks rarely clear it to zero;

Should work in tunnels: Unlike Diffserv, ECN is defined to always work across tunnels. However, tunnels do not always implement ECN processing as they should do, particularly because IPsec tunnels were defined differently for a few years.

Could migrate to one codepoint: If all classic ECN senders eventually evolve to use the L4S service, the ECT(0) codepoint could be reused for some future purpose, but only once use of ECT(0) packets had reduced to zero, or near-zero, which might never happen.

A.2. ECN Plus a Diffserv Codepoint (DSCP)

Definition:

For packets with a defined DSCP, all codepoints of the ECN field (except Not-ECT) would signify alternative L4S semantics to those for classic ECN [RFC3168], specifically:

- * The L4S DSCP would signify that the packet came from an L4S-capable sender;
- * ECT(0) and ECT(1) would both signify that the packet was travelling between transport endpoints that were both ECN-capable;
- * CE would signify that the packet had been marked by an AQM implementing the L4S service.

Use of a DSCP is the only approach for alternative ECN semantics given as an example in [RFC4774]. However, it was perhaps considered more for controlled environments than new end-to-end services;

Cons:

Consumes DSCP pairs: A DSCP is obviously not orthogonal to Diffserv. Therefore, wherever the L4S service is applied to multiple Diffserv scheduling behaviours, it would be necessary to replace each DSCP with a pair of DSCPs.

Uses critical lower-layer header space: The resulting increased number of DSCPs might be hard to support for some lower layer technologies, e.g. 802.1p and MPLS both offer only 3-bits for a maximum of 8 traffic class identifiers. Although L4S should reduce and possibly remove the need for some DSCPs intended for differentiated queuing delay, it will not remove the need for Diffserv entirely, because Diffserv is also used to allocate bandwidth, e.g. by prioritising some classes of traffic over others when traffic exceeds available capacity.

Not end-to-end (host-network): Very few networks honour a DSCP set by a host. Typically a network will zero (bleach) the Diffserv field from all hosts. Sometimes networks will attempt to identify applications by some form of packet inspection and, based on network policy, they will set the DSCP considered appropriate for the identified application. Network-based application identification might use some combination of protocol ID, port numbers(s), application layer protocol headers, IP address(es), VLAN ID(s) and even packet timing.

Not end-to-end (network-network): Very few networks honour a DSCP received from a neighbouring network. Typically a network will zero (bleach) the Diffserv field from all neighbouring networks at an interconnection point. Sometimes bilateral arrangements are made between networks, such that the receiving network remarks some DSCPs to those it uses for roughly equivalent services. The likelihood that a DSCP will be bleached or ignored depends on the type of DSCP:

Local-use DSCP: These tend to be used to implement application-specific network policies, but a bilateral arrangement to remark certain DSCPs is often applied to DSCPs in the local-use range simply because it is easier not to change all of a network's internal configurations when a new arrangement is made with a neighbour;

Global-use DSCP: These do not tend to be honoured across network interconnections more than local-use DSCPs. However, if two networks decide to honour certain of each other's DSCPs, the reconfiguration is a little easier if both of their globally recognised services are already represented by the relevant global-use DSCPs.

Note that today a global-use DSCP gives little more assurance of end-to-end service than a local-use DSCP. In future the global-use range might give more assurance of end-to-end service than local-use, but it is unlikely that either assurance will be high, particularly given the hosts are included in the end-to-end path.

Not all tunnels: Diffserv codepoints are often not propagated to the outer header when a packet is encapsulated by a tunnel header. DSCPs are propagated to the outer of uniform mode tunnels, but not pipe mode [RFC2983], and pipe mode is fairly common.

ECN hard in some lower layers:: Because this approach uses both the Diffserv and ECN fields, an AQM will only work at a lower layer if both can be supported. If individual network operators wished to deploy an AQM at a lower layer, they would usually propagate an IP Diffserv codepoint to the lower layer, using for example IEEE 802.1p. However, the ECN capability is harder to propagate down to lower layers because few lower layers support it.

Pros:

Could migrate to e2e: If all usage of classic ECN migrates to usage of L4S, the DSCP would become redundant, and the ECN capability alone could eventually identify L4S packets without the

interconnection problems of Diffserv detailed above, and without having permanently consumed more than one codepoint in the IP header. Although the DSCP does not generally function as an end-to-end identifier (see above), it could be used initially by individual ISPs to introduce the L4S service for their own locally generated traffic;

A.3. ECN capability alone

Definition:

This approach uses ECN capability alone as the L4S identifier. It is only feasible if classic ECN is not widely deployed. The specific definition of codepoints would be:

- * Any ECN codepoint other than Not-ECT would signify an L4S-capable sender;
- * ECN codepoints would not be used for classic [RFC3168] ECN, and the classic network service would only be used for Not-ECT packets.

This approach would only be feasible if

- A. it was generally agreed that there was little chance of any classic [RFC3168] ECN deployment in any network nodes;
- B. it was generally agreed that there was little chance of any client devices being deployed with classic [RFC3168] TCP-ECN on by default (note that classic TCP-ECN is already on-by-default on many servers);
- C. for TCP connections, developers of client OSs would all have to agree not to encourage further deployment of classic ECN. Specifically, at the start of a TCP connection classic ECN could be disabled during negotiation of the ECN capability:
 - + an L4S-capable host would have to disable ECN if the corresponding host did not support accurate ECN feedback [RFC7560], which is a prerequisite for the L4S service;
 - + developers of operating systems for user devices would only enable ECN by default for TCP once the stack implemented L4S and accurate ECN feedback [RFC7560] including requesting accurate ECN feedback by default.

Cons:

Near-infeasible deployment constraints: The constraints for deployment above represent a highly unlikely, but not completely impossible, set of circumstances. If, despite the above measures, a pair of hosts did negotiate to use classic ECN, their packets would be classified into the same queue as L4S traffic, and if they had to compete with a long-running L4S flow they would get a very small capacity share;

ECN hard in some lower layers: See the same issue with "ECT(1) and CE codepoints" (Appendix A.1);

Non-L4S service for control packets: See the same issue with "ECT(1) and CE codepoints" (Appendix A.1).

Pros:

Consumes no additional codepoints: The ECT(1) codepoint and all spare Diffserv codepoints would remain available for future use;

Should work e2e: As with "ECT(1) and CE codepoints" (Appendix A.1);

Should work in tunnels: As with "ECT(1) and CE codepoints" (Appendix A.1).

A.4. Protocol ID

It has been suggested that a new ID in the IPv4 Protocol field or the IPv6 Next Header field could identify L4S packets. However this approach is ruled out by numerous problems:

- o A new protocol ID would need to be paired with the old one for each transport (TCP, SCTP, UDP, etc.);
- o In IPv6, there can be a sequence of Next Header fields, and it would not be obvious which one would be expected to identify a network service like L4S;
- o A new protocol ID would rarely provide an end-to-end service, because It is well-known that new protocol IDs are often blocked by numerous types of middlebox;
- o The approach is not a solution for AQMs below the IP layer;

A.5. Source or destination addressing

Locally, a network operator could arrange for L4S service to be applied based on source or destination addressing, e.g. packets from its own data centre and/or CDN hosts, packets to its business

customers, etc. It could use addressing at any layer, e.g. IP addresses, MAC addresses, VLAN IDs, etc. Although addressing might be a useful tactical approach for a single ISP, it would not be a feasible approach to identify an end-to-end service like L4S. Even for a single ISP, it would require packet classifiers in buffers to be dependent on changing topology and address allocation decisions elsewhere in the network. Therefore this approach is not a feasible solution.

A.6. Summary: Merits of Alternative Identifiers

Table 1 provides a very high level summary of the pros and cons detailed against the schemes described respectively in Appendix A.2, Appendix A.3 and Appendix A.1, for six issues that set them apart.

Issue	DSCP + ECN		ECN	ECT(1) + CE	
	initial	eventual	initial	initial	eventual
end-to-end	N . .	. ? .	. . Y	. . Y	. . Y
tunnels	. O .	. O .	. . ?	. . ?	. . Y
lower layers	N . .	. ? .	. O .	. O .	. . ?
codepoints	N ?	. . Y	N ?
reordering	. . Y	. . Y	. . Y	. O .	. . ?
ctrl pkts	. . Y	. . Y	. O .	. O .	. . ?
			Note 1		

Note 1: Only feasible if classic ECN is obsolete.

Table 1: Comparison of the Merits of Three Alternative Identifiers

The schemes are scored based on both their capabilities now ('initial') and in the long term ('eventual'). The 'ECN' scheme shares the 'eventual' scores of the 'ECT(1) + CE' scheme. The scores are one of 'N, O, Y', meaning 'Poor', 'Ordinary', 'Good' respectively. The same scores are aligned vertically to aid the eye. A score of "?" in one of the positions means that this approach might optimisitically become this good, given sufficient effort. The table summarises the text and is not meant to be understandable without having read the text.

Appendix B. Potential Competing Uses for the ECT(1) Codepoint

The ECT(1) codepoint of the ECN field has already been assigned once for experimental use as the ECN nonce [RFC3540]. ECN is probably the only remaining field in the Internet Protocol that is common to IPv4 and IPv6 and still has potential to work end-to-end, with tunnels and with lower layers. Therefore, ECT(1) should not be reassigned to a different experimental use without carefully assessing competing potential uses. These fall into the following categories:

B.1. Integrity of Congestion Feedback

Receiving hosts can fool a sender into downloading faster by suppressing feedback of ECN marks (or of losses if retransmissions are not necessary or available otherwise). [RFC3540] proposes that a TCP sender could set either of ECT(0) or ECT(1) in each packet of a flow and remember the sequence it had set, termed the ECN nonce. If any packet is lost or congestion marked, the receiver will miss that bit of the sequence. An ECN Nonce receiver has to feed back the least significant bit of the sum, so it cannot suppress feedback of a loss or mark without a 50-50 chance of guessing the sum incorrectly.

As far as is known, the ECN Nonce has never been deployed, and it was only implemented for a couple of testbed evaluations. It would be nearly impossible to deploy now, because any misbehaving receiver can simply opt-out, which would be unremarkable given all receivers currently opt-out.

Other ways to protect TCP feedback integrity have since been developed that do not consume any extra codepoints in the base IP header. For instance:

- o the sender can test the integrity of the receiver's feedback by occasionally setting the IP-ECN field to a value normally only set by the network. Then it can test whether the receiver's feedback faithfully reports what it expects [I-D.moncaster-tcpm-rcv-cheat]. This works for loss and it will work for the accurate ECN feedback [RFC7560] intended for L4S;
- o A network can enforce a congestion response to its ECN markings (or packet losses) by auditing congestion exposure (ConEx) [RFC7713]. Whether the receiver or a downstream network is suppressing congestion feedback or the sender is unresponsive to the feedback, or both, ConEx audit can neutralise any advantage that any of these three parties would otherwise gain.

ECN in RTP [RFC6679] is defined so that the receiver can ask the sender to send all ECT(0); all ECT(1); or both randomly. It

recommends that the receiver asks for ECT(0), which is the default. The sender can choose to ignore the receiver's request. A rather complex but optional nonce mechanism was included in early drafts of RFC 6679, but it was replaced with a statement that a nonce mechanism is not specified, explaining that misbehaving receivers could opt-out anyway. RFC 6679 as published gives no rationale for why ECT(1) or 'random' might be needed, but it warns that 'random' would make header compression highly inefficient. The possibility of using ECT(1) may have been left in the RFC to allow a nonce mechanism to be added later.

Therefore, it seems unlikely that anyone has implemented the optional use of ECT(1) for RTP. Even if they have, it seems even less likely that any deployment actually uses it. However these assumptions will need to be verified.

B.2. Notification of Less Severe Congestion than CE

Various researchers have proposed to use ECT(1) as a less severe congestion notification than CE, particularly to enable flows to fill available capacity more quickly after an idle period, when another flow departs or when a flow starts, e.g. VCP [VCP], Queue View (QV) [QV] {ToDo: consider Jonathan Morton's Explicit Load Regulation (ELR) if relevant, once the promised write-up appears}.

Before assigning ECT(1) as an identifier for L4S, we must carefully consider whether it might be better to hold ECT(1) in reserve for future standardisation of rapid flow acceleration, which is an important and enduring problem [RFC6077].

Pre-Congestion Notification (PCN) is another scheme that assigns alternative semantics to the ECN field. It uses ECT(1) to signify a less severe level of pre-congestion notification than CE [RFC6660]. However, the ECN field only takes on the PCN semantics if packets carry a Diffserv codepoint defined to indicate PCN marking within a controlled environment. PCN is required to be applied solely to the outer header of a tunnel across the controlled region in order not to interfere with any end-to-end use of the ECN field. Therefore a PCN region on the path would not interfere with any of the L4S service identifiers proposed in Appendix A.

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Low Latency, Low Loss, Scalable Throughput (L4S) Internet Service:
Architecture
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Abstract

This document describes the L4S architecture for the provision of a new service that the Internet could provide to eventually replace best efforts for all traffic: Low Latency, Low Loss, Scalable throughput (L4S). It is becoming common for all (or most) applications being run by a user at any one time to require low latency. However, the only solution the IETF can offer for ultra-low queuing delay is Diffserv, which only favours a minority of packets at the expense of others. In extensive testing the new L4S service keeps average queuing delay under a millisecond for all applications even under very heavy load, without sacrificing utilization; and it keeps congestion loss to zero. It is becoming widely recognized that adding more access capacity gives diminishing returns, because latency is becoming the critical problem. Even with a high capacity broadband access, the reduced latency of L4S remarkably and consistently improves performance under load for applications such as interactive video, conversational video, voice, Web, gaming, instant messaging, remote desktop and cloud-based apps (even when all being used at once over the same access link). The insight is that the root cause of queuing delay is in TCP, not in the queue. By fixing the sending TCP (and other transports) queuing latency becomes so much better than today that operators will want to deploy the network part of L4S to enable new products and services. Further, the network part is simple to deploy - incrementally with zero-config. Both parts, sender and network, ensure coexistence with other legacy traffic. At the same time L4S solves the long-recognized problem with the future scalability of TCP throughput.

This document describes the L4S architecture, briefly describing the different components and how the work together to provide the aforementioned enhanced Internet service.

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Table of Contents

1. Introduction	3
2. L4S architecture overview	4
3. Terminology	6
4. L4S architecture components	7
5. Rationale	9
5.1. Why These Primary Components?	9
5.2. Why Not Alternative Approaches?	10
6. Applicability	12
6.1. Use Cases	13
6.2. Deployment Considerations	14
6.2.1. Deployment Topology	15
6.2.2. Deployment Sequences	16
6.2.3. L4S Flow but Non-L4S Bottleneck	18
6.2.4. Other Potential Deployment Issues	19

7. IANA Considerations	19
8. Security Considerations	19
8.1. Traffic (Non-)Policing	19
8.2. 'Latency Friendliness'	20
8.3. Policing Prioritized L4S Bandwidth	20
8.4. ECN Integrity	21
9. Acknowledgements	22
10. References	22
10.1. Normative References	22
10.2. Informative References	22
Appendix A. Required features for scalable transport protocols to be safely deployable in the Internet (a.k.a. TCP Prague requirements)	26
Appendix B. Standardization items	30
Authors' Addresses	33

1. Introduction

It is increasingly common for all of a user's applications at any one time to require low delay: interactive Web, Web services, voice, conversational video, interactive video, instant messaging, online gaming, remote desktop and cloud-based applications. In the last decade or so, much has been done to reduce propagation delay by placing caches or servers closer to users. However, queuing remains a major, albeit intermittent, component of latency. When present it typically doubles the path delay from that due to the base speed-of-light. Low loss is also important because, for interactive applications, losses translate into even longer retransmission delays.

It has been demonstrated that, once access network bit rates reach levels now common in the developed world, increasing capacity offers diminishing returns if latency (delay) is not addressed. Differentiated services (Diffserv) offers Expedited Forwarding [RFC3246] for some packets at the expense of others, but this is not applicable when all (or most) of a user's applications require low latency.

Therefore, the goal is an Internet service with ultra-Low queueing Latency, ultra-Low Loss and Scalable throughput (L4S) - for all traffic. A service for all traffic will need none of the configuration or management baggage (traffic policing, traffic contracts) associated with favouring some packets over others. This document describes the L4S architecture for achieving that goal.

It must be said that queuing delay only degrades performance infrequently [Hohlfeld14]. It only occurs when a large enough capacity-seeking (e.g. TCP) flow is running alongside the user's

traffic in the bottleneck link, which is typically in the access network. Or when the low latency application is itself a large capacity-seeking flow (e.g. interactive video). At these times, the performance improvement must be so remarkable that network operators will be motivated to deploy it.

Active Queue Management (AQM) is part of the solution to queuing under load. AQM improves performance for all traffic, but there is a limit to how much queuing delay can be reduced by solely changing the network; without addressing the root of the problem.

The root of the problem is the presence of standard TCP congestion control (Reno [RFC5681]) or compatible variants (e.g. TCP Cubic [I-D.ietf-tcpm-cubic]). We shall call this family of congestion controls 'Classic' TCP. It has been demonstrated that if the sending host replaces Classic TCP with a 'Scalable' alternative, when a suitable AQM is deployed in the network the performance under load of all the above interactive applications can be stunningly improved. For instance, queuing delay under heavy load with the example DCTCP/DualQ solution cited below is roughly 1 millisecond (1 ms) at the 99th percentile without losing link utilization. This compares with 5 to 20 ms on average with a Classic TCP and current state-of-the-art AQMs such as fq_CoDel [I-D.ietf-aqm-fq-codel] or PIE [RFC8033]. Also, with a Classic TCP, 5 ms of queuing is usually only possible by losing some utilization.

It has been convincingly demonstrated [DCTtH15] that it is possible to deploy such an L4S service alongside the existing best efforts service so that all of a user's applications can shift to it when their stack is updated. Access networks are typically designed with one link as the bottleneck for each site (which might be a home, small enterprise or mobile device), so deployment at a single node should give nearly all the benefit. The L4S approach requires a number of mechanisms in different parts of the Internet to fulfill its goal. This document presents the L4S architecture, by describing the different components and how they interact to provide the scalable low-latency, low-loss, Internet service.

2. L4S architecture overview

There are three main components to the L4S architecture (illustrated in Figure 1):

- 1) Network: The L4S service traffic needs to be isolated from the queuing latency of the Classic service traffic. However, the two should be able to freely share a common pool of capacity. This is because there is no way to predict how many flows at any one time might use each service and capacity in access networks is too

scarce to partition into two. So a 'semi-permeable' membrane is needed that partitions latency but not bandwidth. The Dual Queue Coupled AQM [I-D.briscoe-aqm-dualq-coupled] is an example of such a semi-permeable membrane.

Per-flow queuing such as in [I-D.ietf-aqm-fq-codel] could be used, but it partitions both latency and bandwidth between every end-to-end flow. So it is rather overkill, which brings disadvantages (see Section 5.2), not least that thousands of queues are needed when two are sufficient.

- 2) Protocol: A host needs to distinguish L4S and Classic packets with an identifier so that the network can classify them into their separate treatments. [I-D.briscoe-tsvwg-ecn-l4s-id] considers various alternative identifiers, and concludes that all alternatives involve compromises, but the ECT(1) codepoint of the ECN field is a workable solution.
- 3) Host: Scalable congestion controls already exist. They solve the scaling problem with TCP first pointed out in [RFC3649]. The one used most widely (in controlled environments) is Data Centre TCP (DCTCP [I-D.ietf-tcpm-dctcp]), which has been implemented and deployed in Windows Server Editions (since 2012), in Linux and in FreeBSD. Although DCTCP as-is 'works' well over the public Internet, most implementations lack certain safety features that will be necessary once it is used outside controlled environments like data centres (see later). A similar scalable congestion control will also need to be transplanted into protocols other than TCP (SCTP, RTP/RTCP, RMCAT, etc.)

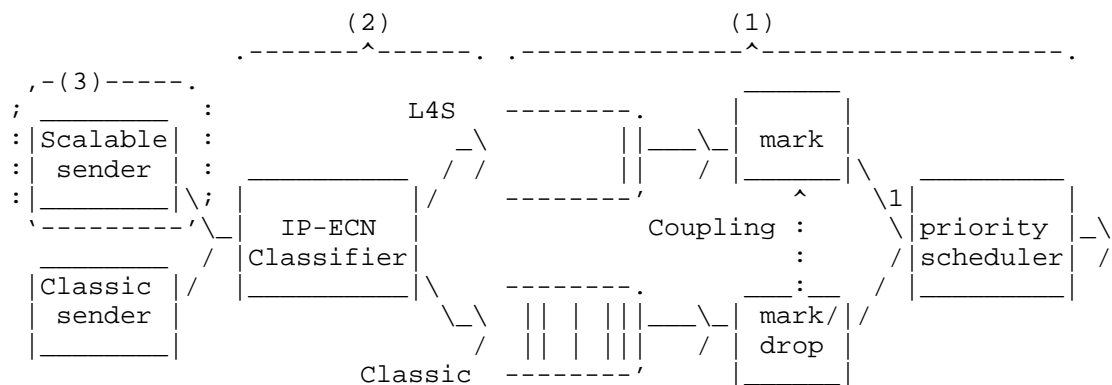


Figure 1: Components of an L4S Solution: 1) Isolation in separate network queues; 2) Packet Identification Protocol; and 3) Scalable Sending Host

3. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119]. In this document, these words will appear with that interpretation only when in ALL CAPS. Lower case uses of these words are not to be interpreted as carrying RFC-2119 significance. COMMENT: Since this will be an information document, This should be removed.

Classic service: The 'Classic' service is intended for all the congestion control behaviours that currently co-exist with TCP Reno (e.g. TCP Cubic, Compound, SCTP, etc).

Low-Latency, Low-Loss and Scalable (L4S) service: The 'L4S' service is intended for traffic from scalable TCP algorithms such as Data Centre TCP. But it is also more general--it will allow a set of congestion controls with similar scaling properties to DCTCP (e.g. Relentless [Mathis09]) to evolve.

Both Classic and L4S services can cope with a proportion of unresponsive or less-responsive traffic as well (e.g. DNS, VoIP, etc).

Scalable Congestion Control: A congestion control where flow rate is inversely proportional to the level of congestion signals. Then, as flow rate scales, the number of congestion signals per round trip remains invariant, maintaining the same degree of control. For instance, DCTCP averages 2 congestion signals per round-trip whatever the flow rate.

Classic Congestion Control: A congestion control with a flow rate compatible with standard TCP Reno [RFC5681]. With Classic congestion controls, as capacity increases enabling higher flow rates, the number of round trips between congestion signals (losses or ECN marks) rises in proportion to the flow rate. So control of queuing and/or utilization becomes very slack. For instance, with 1500 B packets and an RTT of 18 ms, as TCP Reno flow rate increases from 2 to 100 Mb/s the number of round trips between congestion signals rises proportionately, from 2 to 100.

The default congestion control in Linux (TCP Cubic) is Reno-compatible for most scenarios expected for some years. For instance, with a typical domestic round-trip time (RTT) of 18ms, TCP Cubic only switches out of Reno-compatibility mode once the flow rate approaches 1 Gb/s. For a typical data centre RTT of 1 ms, the switch-over point is theoretically 1.3 Tb/s. However, with a less common transcontinental RTT of 100 ms, it only remains

Reno-compatible up to 13 Mb/s. All examples assume 1,500 B packets.

Classic ECN: The original proposed standard Explicit Congestion Notification (ECN) protocol [RFC3168], which requires ECN signals to be treated the same as drops, both when generated in the network and when responded to by the sender.

Site: A home, mobile device, small enterprise or campus, where the network bottleneck is typically the access link to the site. Not all network arrangements fit this model but it is a useful, widely applicable generalisation.

4. L4S architecture components

The L4S architecture is composed by the following elements.

Protocols: The L4S architecture encompass the two protocol changes that we describe next:

- a. [I-D.briscoe-tsvwg-ecn-l4s-id] recommends ECT(1) is used as the identifier to classify L4S and Classic packets into their separate treatments, as required by [RFC4774].
- b. An essential aspect of a scalable congestion control is the use of explicit congestion signals rather than losses, because the signals need to be sent immediately and frequently--too often to use drops. 'Classic' ECN [RFC3168] requires an ECN signal to be treated the same as a drop, both when it is generated in the network and when it is responded to by hosts. L4S allows networks and hosts to support two separate meanings for ECN. So the standards track [RFC3168] will need to be updated to allow ECT(1) packets to depart from the 'same as drop' constraint.

[I-D.ietf-tsvwg-ecn-experimentation] has been prepared as a standards track update to relax specific requirements in RFC 3168 (and certain other standards track RFCs), which clears the way for the above experimental changes proposed for L4S.

[I-D.ietf-tsvwg-ecn-experimentation] also obsoletes the original experimental assignment of the ECT(1) codepoint as an ECN nonce [RFC3540] (it was never deployed, and it offers no security benefit now that deployment is optional).

Network components: The Dual Queue Coupled AQM has been specified as generically as possible [I-D.briscoe-aqm-dualq-coupled] as a 'semi-permeable' membrane without specifying the particular AQMs to use in the two queues. An informational appendix of the draft is provided for pseudocode examples of different possible AQM approaches.

Initially a zero-config variant of RED called Curvy RED was implemented, tested and documented. The aim is for designers to be free to implement diverse ideas. So the brief normative body of the draft only specifies the minimum constraints an AQM needs to comply with to ensure that the L4S and Classic services will coexist. For instance, a variant of PIE called Dual PI Squared [PI2] has been implemented and found to perform better over a wide range of conditions, so it has been documented in a second appendix of [I-D.briscoe-aqm-dualq-coupled].

Host mechanisms: The L4S architecture includes a number of mechanisms in the end host that we enumerate next:

- a. Data Centre TCP is the most widely used example of a scalable congestion control. It is being documented in the TCPM WG as an informational record of the protocol currently in use [I-D.ietf-tcpm-dctcp]. It will be necessary to define a number of safety features for a variant usable on the public Internet. A draft list of these, known as the TCP Prague requirements, has been drawn up (see Appendix A). The list also includes some optional performance improvements.
- b. Transport protocols other than TCP use various congestion controls designed to be friendly with Classic TCP. Before they can use the L4S service, it will be necessary to implement scalable variants of each of these transport behaviours. The following standards track RFCs currently define these protocols: ECN in TCP [RFC3168], in SCTP [RFC4960], in RTP [RFC6679], and in DCCP [RFC4340]. Not all are in widespread use, but those that are will eventually need to be updated to allow a different congestion response, which they will have to indicate by using the ECT(1) codepoint. Scalable variants are under consideration for some new transport protocols that are themselves under development, e.g. QUIC [I-D.johansson-quic-ecn] and certain real-time media congestion avoidance techniques (RMCAT) protocols.
- c. ECN feedback is sufficient for L4S in some transport protocols (RTCP, DCCP) but not others:
 - * For the case of TCP, the feedback protocol for ECN embeds the assumption from Classic ECN that it is the same as drop, making it unusable for a scalable TCP. Therefore, the implementation of TCP receivers will have to be upgraded [RFC7560]. Work to standardize more accurate ECN feedback for TCP (AccECN [I-D.ietf-tcpm-accurate-ecn]) is already in progress.

- * ECN feedback is only roughly sketched in an appendix of the SCTP specification. A fuller specification has been proposed [I-D.stewart-tsvwg-sctpecn], which would need to be implemented and deployed before SCTCP could support L4S.

5. Rationale

5.1. Why These Primary Components?

Explicit congestion signalling (protocol): Explicit congestion signalling is a key part of the L4S approach. In contrast, use of drop as a congestion signal creates a tension because drop is both a useful signal (more would reduce delay) and an impairment (less would reduce delay). Explicit congestion signals can be used many times per round trip, to keep tight control, without any impairment. Under heavy load, even more explicit signals can be applied so the queue can be kept short whatever the load. Whereas state-of-the-art AQMs have to introduce very high packet drop at high load to keep the queue short. Further, TCP's sawtooth reduction can be smaller, and therefore return to the operating point more often, without worrying that this causes more signals (one at the top of each smaller sawtooth). The consequent smaller amplitude sawteeth fit between a very shallow marking threshold and an empty queue, so delay variation can be very low, without risk of under-utilization.

All the above makes it clear that explicit congestion signalling is only advantageous for latency if it does not have to be considered 'the same as' drop (as required with Classic ECN [RFC3168]). Therefore, in a DualQ AQM, the L4S queue uses a new L4S variant of ECN that is not equivalent to drop [I-D.briscoe-tsvwg-ecn-l4s-id], while the Classic queue uses either classic ECN [RFC3168] or drop, which are equivalent.

Before Classic ECN was standardized, there were various proposals to give an ECN mark a different meaning from drop. However, there was no particular reason to agree on any one of the alternative meanings, so 'the same as drop' was the only compromise that could be reached. RFC 3168 contains a statement that:

"An environment where all end nodes were ECN-Capable could allow new criteria to be developed for setting the CE codepoint, and new congestion control mechanisms for end-node reaction to CE packets. However, this is a research issue, and as such is not addressed in this document."

Latency isolation with coupled congestion notification (network):

Using just two queues is not essential to L4S (more would be possible), but it is the simplest way to isolate all the L4S traffic that keeps latency low from all the legacy Classic traffic that does not.

Similarly, coupling the congestion notification between the queues is not necessarily essential, but it is a clever and simple way to allow senders to determine their rate, packet-by-packet, rather than be overridden by a network scheduler. Because otherwise a network scheduler would have to inspect at least transport layer headers, and it would have to continually assign a rate to each flow without any easy way to understand application intent.

L4S packet identifier (protocol): Once there are at least two separate treatments in the network, hosts need an identifier at the IP layer to distinguish which treatment they intend to use.

Scalable congestion notification (host): A scalable congestion control keeps the signalling frequency high so that rate variations can be small when signalling is stable, and rate can track variations in available capacity as rapidly as possible otherwise.

5.2. Why Not Alternative Approaches?

All the following approaches address some part of the same problem space as L4S. In each case, it is shown that L4S complements them or improves on them, rather than being a mutually exclusive alternative:

Diffserv: Diffserv addresses the problem of bandwidth apportionment for important traffic as well as queuing latency for delay-sensitive traffic. L4S solely addresses the problem of queuing latency (as well as loss and throughput scaling). Diffserv will still be necessary where important traffic requires priority (e.g. for commercial reasons, or for protection of critical infrastructure traffic). Nonetheless, if there are Diffserv classes for important traffic, the L4S approach can provide low latency for all traffic within each Diffserv class (including the case where there is only one Diffserv class).

Also, as already explained, Diffserv only works for a small subset of the traffic on a link. It is not applicable when all the applications in use at one time at a single site (home, small business or mobile device) require low latency. Also, because L4S is for all traffic, it needs none of the management baggage (traffic policing, traffic contracts) associated with favouring some packets over others. This baggage has held Diffserv back from widespread end-to-end deployment.

State-of-the-art AQMs: AQMs such as PIE and fq_CoDel give a significant reduction in queuing delay relative to no AQM at all. The L4S work is intended to complement these AQMs, and we definitely do not want to distract from the need to deploy them as widely as possible. Nonetheless, without addressing the large saw-tooth rate variations of Classic congestion controls, AQMs alone cannot reduce queuing delay too far without significantly reducing link utilization. The L4S approach resolves this tension by ensuring hosts can minimize the size of their sawteeth without appearing so aggressive to legacy flows that they starve.

Per-flow queuing: Similarly per-flow queuing is not incompatible with the L4S approach. However, one queue for every flow can be thought of as overkill compared to the minimum of two queues for all traffic needed for the L4S approach. The overkill of per-flow queuing has side-effects:

- A. fq makes high performance networking equipment costly (processing and memory) - in contrast dual queue code can be very simple;
- B. fq requires packet inspection into the end-to-end transport layer, which doesn't sit well alongside encryption for privacy - in contrast a dual queue only operates at the IP layer;
- C. fq isolates the queuing of each flow from the others and it prevents any one flow from consuming more than $1/N$ of the capacity. In contrast, all L4S flows are expected to keep the queue shallow, and policing of individual flows to enforce this may be applied separately, as a policy choice.

An fq scheduler has to decide packet-by-packet which flow to schedule without knowing application intent. Whereas a separate policing function can be configured less strictly, so that senders can still control the instantaneous rate of each flow dependent on the needs of each application (e.g. variable rate video), giving more wriggle-room before a flow is deemed non-compliant. Also policing of queuing and of flow-rates can be applied independently.

Alternative Back-off ECN (ABE): Yet again, L4S is not an alternative to ABE but a complement that introduces much lower queuing delay. ABE [I-D.khademi-tcpm-alternativebackoff-ecn] alters the host behaviour in response to ECN marking to utilize a link better and give ECN flows a faster throughput, but it assumes the network still treats ECN and drop the same. Therefore ABE exploits any lower queuing delay that AQMs can provide. But as explained

above, AQMs still cannot reduce queuing delay too far without losing link utilization (for other non-ABE flows).

6. Applicability

A transport layer that solves the current latency issues will provide new service, product and application opportunities.

With the L4S approach, the following existing applications will immediately experience significantly better quality of experience under load in the best effort class:

- o Gaming
- o VoIP
- o Video conferencing
- o Web browsing
- o (Adaptive) video streaming
- o Instant messaging

The significantly lower queuing latency also enables some interactive application functions to be offloaded to the cloud that would hardly even be usable today:

- o Cloud based interactive video
- o Cloud based virtual and augmented reality

The above two applications have been successfully demonstrated with L4S, both running together over a 40 Mb/s broadband access link loaded up with the numerous other latency sensitive applications in the previous list as well as numerous downloads. A panoramic video of a football stadium can be swiped and pinched so that on the fly a proxy in the cloud generates a sub-window of the match video under the finger-gesture control of each user. At the same time, a virtual reality headset fed from a 360 degree camera in a racing car has been demonstrated, where the user's head movements control the scene generated in the cloud. In both cases, with 7 ms end-to-end base delay, the additional queuing delay of roughly 1 ms is so low that it seems the video is generated locally. See <https://riteproject.eu/dctth/> for videos of these demonstrations.

Using a swiping finger gesture or head movement to pan a video are extremely demanding applications--far more demanding than VoIP.

Because human vision can detect extremely low delays of the order of single milliseconds when delay is translated into a visual lag between a video and a reference point (the finger or the orientation of the head).

If low network delay is not available, all fine interaction has to be done locally and therefore much more redundant data has to be downloaded. When all interactive processing can be done in the cloud, only the data to be rendered for the end user needs to be sent. Whereas, once applications can rely on minimal queues in the network, they can focus on reducing their own latency by only minimizing the application send queue.

6.1. Use Cases

The following use-cases for L4S are being considered by various interested parties:

- o Where the bottleneck is one of various types of access network: DSL, cable, mobile, satellite
 - * Radio links (cellular, WiFi) that are distant from the source are particularly challenging. The radio link capacity can vary rapidly by orders of magnitude, so it is often desirable to hold a buffer to utilise sudden increases of capacity;
 - * cellular networks are further complicated by a perceived need to buffer in order to make hand-overs imperceptible;
 - * Satellite networks generally have a very large base RTT, so even with minimal queuing, overall delay can never be extremely low;
 - * Nonetheless, it is certainly desirable not to hold a buffer purely because of the sawteeth of Classic TCP, when it is more than is needed for all the above reasons.
- o Private networks of heterogeneous data centres, where there is no single administrator that can arrange for all the simultaneous changes to senders, receivers and network needed to deploy DCTCP:
 - * a set of private data centres interconnected over a wide area with separate administrations, but within the same company
 - * a set of data centres operated by separate companies interconnected by a community of interest network (e.g. for the finance sector)

- * multi-tenant (cloud) data centres where tenants choose their operating system stack (Infrastructure as a Service - IaaS)
- o Different types of transport (or application) congestion control:
 - * elastic (TCP/SCTP);
 - * real-time (RTP, RMCAT);
 - * query (DNS/LDAP).
- o Where low delay quality of service is required, but without inspecting or intervening above the IP layer [I-D.you-encrypted-traffic-management]:
 - * mobile and other networks have tended to inspect higher layers in order to guess application QoS requirements. However, with growing demand for support of privacy and encryption, L4S offers an alternative. There is no need to select which traffic to favour for queuing, when L4S gives favourable queuing to all traffic.
- o If queuing delay is minimized, applications with a fixed delay budget can communicate over longer distances, or via a longer chain of service functions [RFC7665] or onion routers.

6.2. Deployment Considerations

The DualQ is, in itself, an incremental deployment framework for L4S AQMs so that L4S traffic can coexist with existing Classic "TCP-friendly" traffic. Section 6.2.1 explains why only deploying AQM in one node at each end of the access link will realize nearly all the benefit.

L4S involves both end systems and the network, so Section 6.2.2 suggests some typical sequences to deploy each part, and why there will be an immediate and significant benefit after deploying just one part.

If an ECN-enabled DualQ AQM has not been deployed at a bottleneck, an L4S flow is required to include a fall-back strategy to Classic behaviour. Section 6.2.3 describes how an L4S flow detects this, and how to minimize the effect of false negative detection.

6.2.1. Deployment Topology

Nonetheless, DualQ AQMs will not have to be deployed throughout the Internet before L4S will work for anyone. Operators of public Internet access networks typically design their networks so that the bottleneck will nearly always occur at one known (logical) link. This confines the cost of queue management technology to one place.

The case of mesh networks is different and will be discussed later. But the known bottleneck case is generally true for Internet access to all sorts of different 'sites', where the word 'site' includes home networks, small-to-medium sized campus or enterprise networks and even cellular devices (Figure 2). Also, this known-bottleneck case tends to be true whatever the access link technology; whether xDSL, cable, cellular, line-of-sight wireless or satellite.

Therefore, the full benefit of the L4S service should be available in the downstream direction when the DualQ AQM is deployed at the ingress to this bottleneck link (or links for multihomed sites). And similarly, the full upstream service will be available once the DualQ is deployed at the upstream ingress.

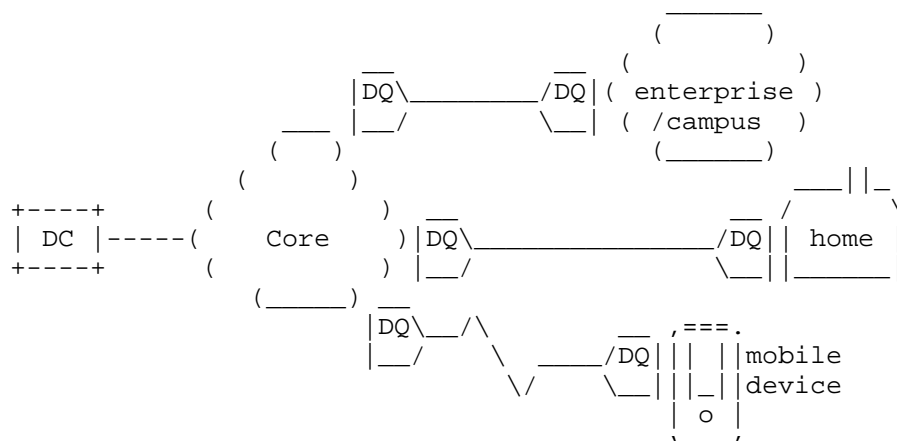


Figure 2: Likely location of DualQ Deployments in common access topologies

Deployment in mesh topologies depends on how over-booked the core is. If the core is non-blocking, or at least generously provisioned so that the edges are nearly always the bottlenecks, it would only be necessary to deploy the DualQ AQM at the edge bottlenecks. For example, some datacentre networks are designed with the bottleneck in

the hypervisor or host NICs, while others bottleneck at the top-of-rack switch (both the output ports facing hosts and those facing the core).

The DualQ would eventually also need to be deployed at any other persistent bottlenecks such as network interconnections, e.g. some public Internet exchange points and the ingress and egress to WAN links interconnecting datacentres.

6.2.2. Deployment Sequences

For any one L4S flow to work, it requires 3 parts to have been deployed. This was the same deployment problem that ECN faced [I-D.iab-protocol-transitions] so we have learned from this.

Firstly, L4S deployment exploits the fact that DCTCP already exists on many Internet hosts (Windows, FreeBSD and Linux); both servers and clients. Therefore, just deploying DualQ AQM at a network bottleneck immediately gives a working deployment of all the L4S parts. DCTCP needs some safety concerns to be fixed for general use over the public Internet (see Appendix A), but DCTCP is not on by default, so these issues can be managed within controlled deployments or controlled trials.

Secondly, the performance improvement with L4S is so significant that it enables new interactive services and products that were not previously possible. It is much easier for companies to initiate new work on deployment if there is budget for a new product trial. If, in contrast, there were only an incremental performance improvement (as with Classic ECN), spending on deployment tends to be much harder to justify.

Thirdly, the L4S identifier is defined so that initially network operators can enable L4S exclusively for certain customers or certain applications. But this is carefully defined so that it does not compromise future evolution towards L4S as an Internet-wide service. This is because the L4S identifier is defined not only as the end-to-end ECN field, but it can also optionally be combined with any other packet header or some status of a customer or their access link. Operators could do this anyway, even if it were not blessed by the IETF. However, it is best for the IETF to specify that they must use their own local identifier in combination with the IETF's identifier. Then, if an operator enables the optional local-use approach, they only have to remove this extra rule to make the service work Internet-wide - it will already traverse middleboxes, peerings, etc.

	Servers or proxies	Access link	Clients
1	DCTCP (existing)	DualQ AQM downstream	DCTCP (existing)
	WORKS DOWNSTREAM FOR CONTROLLED DEPLOYMENTS/TRIALS		
2	TCP Prague		AccECN (already in progress:DCTCP/BBR)
	FULLY	WORKS	DOWNSTREAM
3		DualQ AQM upstream	TCP Prague
	FULLY WORKS UPSTREAM AND DOWNSTREAM		

Figure 3: Example L4S Deployment Sequences

Figure 3 illustrates some example sequences in which the parts of L4S might be deployed. It consists of the following stages:

1. Here, the immediate benefit of a single AQM deployment can be seen, but limited to a controlled trial or controlled deployment. In this example downstream deployment is first, but in other scenarios the upstream might be go first. The DualQ AQM also greatly improves the downstream Classic service, assuming no other AQM has already been deployed.
2. In this stage, the name 'TCP Prague' is used to represent a variant of DCTCP that is safe to use in a production environment. If the application is primarily unidirectional, 'TCP Prague' is only needed at one end. Accurate ECN feedback (AccECN) [I-D.ietf-tcpm-accurate-ecn] is needed at the other end, but it is a generic ECN feedback facility that is already planned to be deployed for other purposes, e.g. DCTCP, BBR [BBR]. The two ends can be deployed in either order, because TCP Prague only enables itself if it has negotiated the use of AccECN feedback with the other end during the connection handshake. Thus, deployment on both ends (and in some cases only one) enables L4S trials to move to a production service, in one direction. This stage might be further motivated by performance improvements between DCTCP and TCP Prague Appendix A.
3. This is a two-move stage to enable L4S upstream. The DualQ or TCP Prague can be deployed in either order as already explained. To motivate the first of two independent moves, the deferred benefit of enabling new services after the second move has to be

worth it to cover the first mover's investment risk. As explained already, the potential for new services provides this motivation. The DualQ AQM also greatly improves the upstream Classic service, assuming no other AQM has already been deployed.

Note that other deployment sequences might occur. For instance: the upstream might be deployed first; a non-TCP protocol might be used end-to-end, e.g. QUIC, RMCAT; a body such as the 3GPP might require L4S to be implemented in 5G user equipment, or other random acts of kindness.

6.2.3. L4S Flow but Non-L4S Bottleneck

If L4S is enabled between two hosts but there is no L4S AQM at the bottleneck, any drop from the bottleneck will trigger the L4S sender to fall back to a 'TCP-Friendly' behaviour (Requirement #4.1 in Appendix A).

Unfortunately, as well as protecting legacy traffic, this rule degrades the L4S service whenever there is a loss, even if the loss was not from a non-DualQ bottleneck (false negative). And unfortunately, prevalent drop can be due to other causes, e.g.:

- o congestion loss at other transient bottlenecks, e.g. due to bursts in shallower queues;
- o transmission errors, e.g. due to electrical interference;
- o rate policing.

Three complementary approaches are in progress, but they are all currently research:

- o In TCP Prague, use a similar approach to BBR [BBR] to ignore selected losses. This could mask any of the above types of loss (requires consensus on how to safely interoperate with drop-based congestion controls).
- o A combination of RACK, reconfigured link retransmission and L4S could address transmission errors (no reference yet);
- o Hybrid ECN/drop policers (see Section 8.3).

L4S deployment scenarios that minimize these issues (e.g. over wireline networks) can proceed in parallel to this research, in the expectation that research success will continually widen L4S applicability.

In recent studies there has been no evidence of Classic ECN support in AQMs on the Internet. If Classic ECN support does materialize, a way to satisfy Requirement #4.2 in Appendix A will have to be added to TCP Prague.

6.2.4. Other Potential Deployment Issues

An L4S AQM uses the ECN field to signal congestion. So, in common with Classic ECN, if the AQM is within a tunnel or at a lower layer, correct functioning of ECN signalling requires correct propagation of the ECN field up the layers [I-D.ietf-tsvwg-ecn-encap-guidelines].

7. IANA Considerations

This specification contains no IANA considerations.

8. Security Considerations

8.1. Traffic (Non-)Policing

Because the L4S service can serve all traffic that is using the capacity of a link, it should not be necessary to police access to the L4S service. In contrast, Diffserv only works if some packets get less favourable treatment than others. So it has to use traffic policers to limit how much traffic can be favoured. In turn, traffic policers require traffic contracts between users and networks as well as pairwise between networks. Because L4S will lack all this management complexity, it is more likely to work end-to-end.

During early deployment (and perhaps always), some networks will not offer the L4S service. These networks do not need to police or remark L4S traffic - they just forward it unchanged as best efforts traffic, as they would already forward traffic with ECT(1) today. At a bottleneck, such networks will introduce some queuing and dropping. When a scalable congestion control detects a drop it will have to respond as if it is a Classic congestion control (see item 3-1 in Appendix A). This will ensure safe interworking with other traffic at the 'legacy' bottleneck, but it will degrade the L4S service to no better (but never worse) than classic best efforts, whenever a legacy (non-L4S) bottleneck is encountered on a path.

Certain network operators might choose to restrict access to the L4S class, perhaps only to customers who have paid a premium. Their packet classifier (item 2 in Figure 1) could identify such customers against some other field (e.g. source address range) as well as ECN. If only the ECN L4S identifier matched, but not the source address (say), the classifier could direct these packets (from non-paying customers) into the Classic queue. Allowing operators to use an

additional local classifier is intended to remove any incentive to bleach the L4S identifier. Then at least the L4S ECN identifier will be more likely to survive end-to-end even though the service may not be supported at every hop. Such arrangements would only require simple registered/not-registered packet classification, rather than the managed application-specific traffic policing against customer-specific traffic contracts that Diffserv requires.

8.2. 'Latency Friendliness'

The L4S service does rely on self-constraint - not in terms of limiting capacity usage, but in terms of limiting burstiness. It is hoped that standardisation of dynamic behaviour (cf. TCP slow-start) and self-interest will be sufficient to prevent transports from sending excessive bursts of L4S traffic, given the application's own latency will suffer most from such behaviour.

Whether burst policing becomes necessary remains to be seen. Without it, there will be potential for attacks on the low latency of the L4S service. However it may only be necessary to apply such policing reactively, e.g. punitively targeted at any deployments of new bursty malware.

8.3. Policing Prioritized L4S Bandwidth

As mentioned in Section 5.2, L4S should remove the need for low latency Diffserv classes. However, those Diffserv classes that give certain applications or users priority over capacity, would still be applicable. Then, within such Diffserv classes, L4S would often be applicable to give traffic low latency and low loss. Within such a class, the bandwidth available to a user or application is often limited by a rate policer. Similarly, in the default Diffserv class, rate policers are used to partition shared capacity.

A classic rate policer drops any packets exceeding a set rate, usually also giving a burst allowance (variant exist where the policer re-marks non-compliant traffic to a discard-eligible Diffserv codepoint, so they may be dropped elsewhere during contention). In networks that deploy L4S and use rate policers, it will be preferable to deploy a policer designed to be more friendly to the L4S service,

This is currently a research area. it might be achieved by setting a threshold where ECN marking is introduced, such that it is just under the policed rate or just under the burst allowance where drop is introduced. This could be applied to various types of policer, e.g. [RFC2697], [RFC2698] or the local (non-ConEx) variant of the ConEx congestion policer [I-D.briscoe-conex-policing]. Otherwise, whenever L4S traffic encounters a rate policer, it will experience drops and

the source will fall back to a Classic congestion control, thus losing all the benefits of L4S.

Further discussion of the applicability of L4S to the various Diffserv classes, and the design of suitable L4S rate policers.

8.4. ECN Integrity

Receiving hosts can fool a sender into downloading faster by suppressing feedback of ECN marks (or of losses if retransmissions are not necessary or available otherwise). [RFC3540] proposes that a TCP sender could pseudorandomly set either of ECT(0) or ECT(1) in each packet of a flow and remember the sequence it had set, termed the ECN nonce. If the receiver supports the nonce, it can prove that it is not suppressing feedback by reflecting its knowledge of the sequence back to the sender. The nonce was proposed on the assumption that receivers might be more likely to cheat congestion control than senders (although senders also have a motive to cheat).

If L4S uses the ECT(1) codepoint of ECN for packet classification, it will have to obsolete the experimental nonce. As far as is known, the ECN Nonce has never been deployed, and it was only implemented for a couple of testbed evaluations. It would be nearly impossible to deploy now, because any misbehaving receiver can simply opt-out, which would be unremarkable given all receivers currently opt-out.

Other ways to protect TCP feedback integrity have since been developed. For instance:

- o the sender can test the integrity of the receiver's feedback by occasionally setting the IP-ECN field to a value normally only set by the network. Then it can test whether the receiver's feedback faithfully reports what it expects [I-D.moncaster-tcpm-rcv-cheat]. This method consumes no extra codepoints. It works for loss and it will work for ECN feedback in any transport protocol suitable for L4S. However, it shares the same assumption as the nonce; that the sender is not cheating and it is motivated to prevent the receiver cheating;
- o A network can enforce a congestion response to its ECN markings (or packet losses) by auditing congestion exposure (ConEx) [RFC7713]. Whether the receiver or a downstream network is suppressing congestion feedback or the sender is unresponsive to the feedback, or both, ConEx audit can neutralise any advantage that any of these three parties would otherwise gain. ConEx is only currently defined for IPv6 and consumes a destination option header. It has been implemented, but not deployed as far as is known.

9. Acknowledgements

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Appendix A. Required features for scalable transport protocols to be safely deployable in the Internet (a.k.a. TCP Prague requirements)

This list contains a list of features, mechanisms and modifications from currently defined behaviour for scalable Transport protocols so that they can be safely deployed over the public Internet. This list of requirements was produced at an ad hoc meeting during IETF-94 in Prague [TCPPrague].

One of such scalable transport protocols is DCTCP, currently specified in [I-D.ietf-tcpm-dctcp]. In its current form, DCTCP is specified to be deployable in controlled environments and deploying it in the public Internet would lead to a number of issues, both from the safety and the performance perspective. In this section, we describe the modifications and additional mechanisms that are required for its deployment over the global Internet. We use DCTCP as a base, but it is likely that most of these requirements equally apply to other scalable transport protocols.

We next provide a brief description of each required feature.

Requirement #4.1: Fall back to Reno/Cubic congestion control on packet loss.

Description: In case of packet loss, the scalable transport MUST react as classic TCP (whatever the classic version of TCP is running in the host, e.g. Reno, Cubic).

Motivation: As part of the safety conditions for deploying a scalable transport over the public Internet is to make sure that it behaves properly when some or all the network devices connecting the two endpoints that implement the scalable transport have not been upgraded. In particular, it may be the case that some of the switches along the path between the two endpoints may only react to congestion by dropping packets (i.e. no ECN marking). It is important that in these cases, the scalable transport react to the congestion signal in the form of a packet drop similarly to classic TCP.

In the particular case of DCTCP, the current DCTCP specification states that "It is RECOMMENDED that an implementation deal with loss episodes in the same way as conventional TCP." For safe deployment in the public Internet of a scalable transport, the above requirement needs to be defined as a MUST.

Packet loss, while rare, may also occur in the case that the bottleneck is L4S capable. In this case, the sender may receive a high number of packets marked with the CE bit set and also experience a loss. Current DCTCP implementations react differently to this situation. At least one implementation reacts only to the drop signal (e.g. by halving the CWND) and at least another DCTCP implementation reacts to both signals (e.g. by halving the CWND due to the drop and also further reducing the CWND based on the proportion of marked packet). We believe that further experimentation is needed to understand what is the best behaviour for the public Internet, which may or not be one of the existent implementations.

Requirement #4.2: Fall back to Reno/Cubic congestion control on classic ECN bottlenecks.

Description: The scalable transport protocol SHOULD/MAY? behave as classic TCP with classic ECN if the path contains a legacy bottleneck which marks both `ect(0)` and `ect(1)` in the same way as drop (non L4S, but ECN capable bottleneck).

Motivation: Similarly to Requirement #3.1, this requirement is a safety condition in case L4S-capable endpoints are communicating over a path that contains one or more non-L4S but ECN capable switches and one of them happens to be the bottleneck. In this case, the scalable transport will attempt to fill in the buffer of the bottleneck switch up to the marking threshold and produce a small sawtooth around that operation point. The result is that the switch will set its operation point with the buffer full and all other non-scalable transports will be starved (as they will react reducing their CWND more aggressively than the scalable transport).

Scalable transports then MUST be able to detect the presence of a classic ECN bottleneck and fall back to classic TCP/classic ECN behaviour in this case.

Discussion: It is not clear at this point if it is possible to design a mechanism that always detect the aforementioned cases. One possibility is to base the detection on an increase on top of a minimum RTT, but it is not yet clear which value should trigger this. Having a delay based fall back response on L4S may as well be beneficial for preserving low latency without legacy network nodes. Even if it possible to design such a mechanism, it may well be that it would encompass additional complexity that implementers may consider unnecessary. The need for this mechanism depends on the extent of classic ECN deployment.

Requirement #4.3: Reduce RTT dependence

Description: Scalable transport congestion control algorithms MUST reduce or eliminate the RTT bias within the range of RTTs available.

Motivation: Classic TCP's throughput is known to be inversely proportional to RTT. One would expect flows over very low RTT paths to nearly starve flows over larger RTTs. However, because Classic TCP induces a large queue, it has never allowed a very low RTT path to exist, so far. For instance, consider two paths with base RTT 1ms and 100ms. If Classic TCP induces a 20ms queue, it turns these RTTs into 21ms and 120ms leading to a throughput ratio of about 1:6. Whereas if a Scalable TCP induces only a 1ms queue, the ratio is

2:101. Therefore, with small queues, long RTT flows will essentially starve.

Scalable transport protocol MUST then accommodate flows across the range of RTTs enabled by the deployment of L4S service over the public Internet.

Requirement #4.4: Scaling down the congestion window.

Description: Scalable transports MUST be responsive to congestion when RTTs are significantly smaller than in the current public Internet.

Motivation: As currently specified, the minimum CWND of TCP (and the scalable extensions such as DCTCP), is set to 2 MSS. Once this minimum CWND is reached, the transport protocol ceases to react to congestion signals (the CWND is not further reduced beyond this minimum size).

L4S mechanisms reduce significantly the queueing delay, achieving smaller RTTs over the Internet. For the same CWND, smaller RTTs imply higher transmission rates. The result is that when scalable transport are used and small RTTs are achieved, the minimum value of the CWND currently defined in 2 MSS may still result in a high transmission rate for a large number of common scenarios. For example, as described in [TCP-sub-mss-w], consider a residential setting with an broadband Internet access of 40Mbps. Suppose now a number of equal TCP flows running in parallel with the Internet access link being the bottleneck. Suppose that for these flows, the RTT is 6ms and the MSS is 1500B. The minimum transmission rate supported by TCP in this scenario is when CWND is set to 2 MSS, which results in 4Mbps for each flow. This means that in this scenario, if the number of flows is higher than 10, the congestion control ceases to be responsive and starts to build up a queue in the network.

In order to address this issue, the congestion control mechanism for scalable transports MUST be responsive for the new range of RTT resulting from the decrease of the queueing delay.

There are several ways how this can be achieved. One possible sub-MSS window mechanism is described in [TCP-sub-mss-w].

In addition to the safety requirements described before, there are some optimizations that while not required for the safe deployment of scalable transports over the public Internet, would results in an optimized performance. We describe them next.

Optimization #5.1: Setting ECT in SYN, SYN/ACK and pure ACK packets.

Description: Scalable transport SHOULD set the ECT bit in SYN, SYN/ACK and pure ACK packets.

Motivation: Failing to set the ECT bit in SYN, SYN/ACK or ACK packets results in these packets being more likely dropped during congestion events. Dropping SYN and SYN/ACK packets is particularly bad for performance as the retransmission timers for these packets are large. [RFC3168] prevents from marking these packets due to security reasons. The arguments provided should be revisited in the context of L4S and evaluate if avoiding marking these packets is still the best approach.

Optimization #5.2: Faster than additive increase.

Description: Scalable transport MAY support faster than additive increase in the congestion avoidance phase.

Motivation: As currently defined, DCTCP supports additive increase in congestion avoidance phase. It would be beneficial for performance to update the congestion control algorithm to increase the CWND more than 1 MSS per RTT during the congestion avoidance phase. In the context of L4S such mechanism, must also provide fairness with other classes of traffic, including classic TCP and possibly scalable TCP that uses additive increase.

Optimization #5.3: Faster convergence to fairness.

Description: Scalable transport SHOULD converge to a fair share allocation of the available capacity as fast as classic TCP or faster.

Motivation: The time required for a new flow to obtain its fair share of the capacity of the bottleneck when there are already ongoing flows using up all the bottleneck capacity is higher in the case of DCTCP than in the case of classic TCP (about a factor of 1,5 and 2 larger according to [Alizadeh-stability]). This is detrimental in general, but it is very harmful for short flows, which performance can be worse than the one obtained with classic TCP. For this reason it is desirable that scalable transport provide convergence times no larger than classic TCP.

Appendix B. Standardization items

The following table includes all the items that should be standardized to provide a full L4S architecture.

The table is too wide for the ASCII draft format, so it has been split into two, with a common column of row index numbers on the left.

The columns in the second part of the table have the following meanings:

WG: The IETF WG most relevant to this requirement. The "tcpm/iccrgr" combination refers to the procedure typically used for congestion control changes, where tcpm owns the approval decision, but uses the iccrgr for expert review [NewCC_Proc];

TCP: Applicable to all forms of TCP congestion control;

DCTCP: Applicable to Data Centre TCP as currently used (in controlled environments);

DCTCP bis: Applicable to an future Data Centre TCP congestion control intended for controlled environments;

XXX Prague: Applicable to a Scalable variant of XXX (TCP/SCTP/RMCA) congestion control.

Req #	Requirement	Reference
0	ARCHITECTURE	
1	L4S IDENTIFIER	[I-D.briscoe-tsvwg-ecn-l4s-id]
2	DUAL QUEUE AQM	[I-D.briscoe-aqm-dualq-coupled]
3	Suitable ECN Feedback	[I-D.ietf-tcpm-accurate-ecn], [I-D.stewart-tsvwg-sctpecn].
	SCALABLE TRANSPORT - SAFETY ADDITIONS	
4-1	Fall back to Reno/Cubic on loss	[I-D.ietf-tcpm-dctcp]
4-2	Fall back to Reno/Cubic if classic ECN bottleneck detected	
4-3	Reduce RTT-dependence	
4-4	Scaling TCP's Congestion Window for Small Round Trip Times	[TCP-sub-mss-w]
	SCALABLE TRANSPORT - PERFORMANCE ENHANCEMENTS	
5-1	Setting ECT in SYN, SYN/ACK and pure ACK packets	draft-bagnulo-tsvwg-generalized-ECN
5-2	Faster-than-additive increase	
5-3	Less drastic exit from slow-start	

#	WG	TCP	DCTCP	DCTCP-bis	TCP Prague	SCTP Prague	RMCAT Prague
0	tsvwg?	Y	Y	Y	Y	Y	Y
1	tsvwg?			Y	Y	Y	Y
2	aqm?	n/a	n/a	n/a	n/a	n/a	n/a
3	tcpm	Y	Y	Y	Y	n/a	n/a
4-1	tcpm		Y	Y	Y	Y	Y
4-2	tcpm/ iccrgr?				Y	Y	?
4-3	tcpm/ iccrgr?			Y	Y	Y	?
4-4	tcpm	Y	Y	Y	Y	Y	?
5-1	tsvwg	Y	Y	Y	Y	n/a	n/a
5-2	tcpm/ iccrgr?			Y	Y	Y	?
5-3	tcpm/ iccrgr?			Y	Y	Y	?

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Requirements for Time-Based Loss Detection

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Abstract

Many protocols must detect packet loss for various reasons (e.g., to ensure reliability using retransmissions or to understand the level of congestion along a network path). While many mechanisms have been designed to detect loss, ultimately, protocols can only count on the passage of time without delivery confirmation to declare a packet "lost". Each implementation of a time-based loss detection mechanism represents a balance between correctness and timeliness and therefore no implementation suits all situations. This document

provides high-level requirements for time-based loss detectors appropriate for general use in unicast communication across the Internet. Within the requirements, implementations have latitude to define particulars that best address each situation.

Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

1 Introduction

As a network of networks, the Internet consists of a large variety of links and systems that support a wide variety of tasks and workloads. The service provided by the network varies from best-effort delivery among loosely connected components to highly predictable delivery within controlled environments (e.g., between physically connected nodes, within a tightly controlled data center). Each path through the network has a set of path properties---e.g., available capacity, delay, packet loss. Given the range of networks that make up the Internet, these properties range from largely static to highly dynamic.

This document provides guidelines for developing an understanding of one path property: packet loss. In particular, we offer guidelines for developing and implementing time-based loss detectors that have been gradually learned over the last several decades. We focus on the general case where the loss properties of a path are (a) unknown a priori and (b) dynamically vary over time. Further, while there are numerous root causes of packet loss, we leverage the conservative notion that loss is an implicit indication of congestion [RFC5681]. While this stance is not always correct, as a general assumption it has historically served us well [Jac88]. As we discuss further in section 2, the guidelines in this document should be viewed as a general default for unicast communication across best-effort networks and not as optimal---or even applicable---for all situations.

Given that packet loss is routine in best-effort networks, loss detection is a crucial activity for many protocols and applications and is generally undertaken for two major reasons:

(1) Ensuring reliable data delivery.

This requires a data sender to develop an understanding of which transmitted packets have not arrived at the receiver. This knowledge allows the sender to retransmit missing data.

(2) Congestion control.

As we mention above, packet loss is often taken as an

implicit indication that the sender is transmitting too fast and is overwhelming some portion of the network path. Data senders can therefore use loss to trigger transmission rate reductions.

Various mechanisms are used to detect losses in a packet stream. Often we use continuous or periodic acknowledgments from the recipient to inform the sender's notion of which pieces of data are missing. However, despite our best intentions and most robust mechanisms we cannot place ultimate faith in receiving such acknowledgments, but can only truly depend on the passage of time. Therefore, our ultimate backstop to ensuring that we detect all loss is a timeout. That is, the sender sets some expectation for how long to wait for confirmation of delivery for a given piece of data. When this time period passes without delivery confirmation the sender concludes the data was lost in transit.

The specifics of time-based loss detection schemes represent a tradeoff between correctness and responsiveness. In other words we wish to simultaneously:

- wait long enough to ensure the detection of loss is correct, and
- minimize the amount of delay we impose on applications (before repairing loss) and the network (before we reduce the congestion).

Serving both of these goals is difficult as they pull in opposite directions [AP99]. By not waiting long enough to accurately determine a packet has been lost we may provide a needed retransmission in a timely manner, but risk sending unnecessary ("spurious") retransmissions and needlessly lowering the transmission rate. By waiting long enough that we are unambiguously certain a packet has been lost we cannot repair losses in a timely manner and we risk prolonging network congestion.

Many protocols and applications---such as TCP [RFC6298], SCTP [RFC4960], SIP [RFC3261]---use their own time-based loss detection mechanisms. At this point, our experience leads to a recognition that often specific tweaks that deviate from standardized time-based loss detectors do not materially impact network safety with respect to congestion control [AP99]. Therefore, in this document we outline a set of high-level protocol-agnostic requirements for time-based loss detection. The intent is to provide a safe foundation on which implementations have the flexibility to instantiate mechanisms that best realize their specific goals.

2 Context

This document is different from the way we ideally like to engineer systems. Usually, we strive to understand high-level requirements as a starting point. We then methodically engineer specific protocols, algorithms and systems that meet these requirements. Within the IETF standards process we have derived many time-based

loss detection schemes without benefit from some over-arching requirements document---because we had no idea how to write such a document! Therefore, we made the best specific decisions we could in response to specific needs.

At this point, however, the community's experience has matured to the point where we can define a set of general, high-level requirements for time-based loss detection schemes. We now understand how to separate the strategies these mechanisms use that are crucial for network safety from those small details that do not materially impact network safety. The requirements in this document may not be appropriate in all cases. In particular, the guidelines in section 4 are concerned with the general case, but specific situations may allow for more flexibility in terms of loss detection because specific facets of the environment are known (e.g., when operating over a single physical link or within a tightly controlled data center). Therefore, variants, deviations or wholly different time-based loss detectors may be necessary or useful in some cases. The correct way to view this document is as the default case and not as a one-size-fits-all that is optimal in all cases.

Adding a requirements umbrella to a body of existing specifications is inherently messy and we run the risk of creating inconsistencies with both past and future mechanisms. Therefore, we make the following statements about the relationship of this document to past and future specifications:

- This document does not update or obsolete any existing RFC. These previous specifications---while generally consistent with the requirements in this document---reflect community consensus and this document does not change that consensus.
- The requirements in this document are meant to provide for network safety and, as such, SHOULD be used by all future time-based loss detection mechanisms.
- The requirements in this document may not be appropriate in all cases and, therefore, deviations and variants may be necessary in the future (hence the "SHOULD" in the last bullet). However, inconsistencies MUST be (a) explained and (b) gather consensus.

3 Scope

The principles we outline in this document are protocol-agnostic and widely applicable. We make the following scope statements about the application of the requirements discussed in Section 4:

- (S.1) While there are a bevy of uses for timers in protocols---from rate-based pacing to connection failure detection and beyond---this document is focused only on loss detection.
- (S.2) The requirements for time-based loss detection mechanisms in this document are for the primary or "last resort" loss detection mechanism whether the mechanism is the sole loss

repair strategy or works in concert with other mechanisms.

While a straightforward time-based loss detector is sufficient for simple protocols like DNS [RFC1034,RFC1035], more complex protocols often use more advanced loss detectors to aid performance. For instance, TCP and SCTP have methods to detect (and repair) loss based on explicit endpoint state sharing [RFC2018,RFC4960,RFC6675]. Such mechanisms often provide more timely and precise loss detection than time-based loss detectors. However, these mechanisms do not obviate the need for a "retransmission timeout" or "RTO" because---as we discuss in Section 1---only the passage of time can ultimately be relied upon to detect loss. In other words, ultimately we cannot count on acknowledgments to arrive at the data sender to indicate which packets never arrived at the receiver. In cases such as these we need a time-based loss detector to functions as a "last resort".

Also, note, that some recent proposals have incorporated time as a component of advanced loss detection methods---either as an aggressive first loss detector in certain situations or in conjunction with endpoint state sharing [DCCM13,CCDJ20,IS20]. While these mechanisms can aid timely loss recovery, the protocol ultimately leans on another more conservative timer to ensure reliability when these mechanisms break down. The requirements in this document are only directly applicable to last resort loss detection. However, we expect that many of the requirements can serve as useful guidelines for more aggressive non-last resort timers, as well.

- (S.3) The requirements in this document apply only to endpoint-to-endpoint unicast communication. Reliable multicast (e.g., [RFC5740]) protocols are explicitly outside the scope of this document.

Protocols such as SCTP [RFC4960] and MP-TCP [RFC6182] that communicate in a unicast fashion with multiple specific endpoints can leverage the requirements in this document provided they track state and follow the requirements for each endpoint independently. I.e., if host A communicates with addresses B and C, A needs to use independent time-based loss detector instances for traffic sent to B and C.

- (S.4) There are cases where state is shared across connections or flows (e.g., [RFC2140], [RFC3124]). State pertaining to time-based loss detection is often discussed as sharable. These situations raise issues that the simple flow-oriented time-based loss detection mechanism discussed in this document does not consider (e.g., how long to preserve state between connections). Therefore, while the general principles given in Section 4 are likely applicable, sharing time-based loss detection information across flows is outside the scope of this document.

4 Requirements

We now list the requirements that apply when designing primary or last resort time-based loss detection mechanisms. For historical reasons and ease of exposition, we refer to the time between sending a packet and determining the packet has been lost due to lack of delivery confirmation as the "retransmission timeout" or "RTO". After the RTO passes without delivery confirmation, the sender may safely assume the packet is lost. However, as discussed above, the detected loss need not be repaired (i.e., the loss could be detected only for congestion control and not reliability purposes).

- (1) As we note above, loss detection happens when a sender does not receive delivery confirmation within some expected period of time. In the absence of any knowledge about the latency of a path, the initial RTO MUST be conservatively set to no less than 1 second.

Correctness is of the utmost importance when transmitting into a network with unknown properties because:

- Premature loss detection can trigger spurious retransmits that could cause issues when a network is already congested.
- Premature loss detection can needlessly cause congestion control to dramatically lower the sender's allowed transmission rate---especially since the rate is already likely low at this stage of the communication. Recovering from such a rate change can take a relatively long time.
- Finally, as discussed below, sometimes using time-based loss detection and retransmissions can cause ambiguities in assessing the latency of a network path. Therefore, it is especially important for the first latency sample to be free of ambiguities such that there is a baseline for the remainder of the communication.

The specific constant (1 second) comes from the analysis of Internet RTTs found in Appendix A of [RFC6298].

- (2) We now specify four requirements that pertain to setting an expected time interval for delivery confirmation.

Often measuring the time required for delivery confirmation is framed as assessing the "round-trip time (RTT)" of the network path. The RTT is the minimum amount of time required to receive delivery confirmation and also often follows protocol behavior whereby acknowledgments are generated quickly after data arrives. For instance, this is the case for the RTO used by TCP [RFC6298] and SCTP [RFC4960]. However, this is somewhat misleading and the expected latency is better framed as the "feedback time" (FT). In other words, the expectation is not always simply a network property, but can include additional time before a sender should reasonably expect a response.

For instance, consider a UDP-based DNS request from a client to a recursive resolver [RFC1035]. When the request can be served from the resolver's cache the FT likely well approximates the network RTT between the client and resolver. However, on a cache miss the resolver will request the needed information from one or more authoritative DNS servers, which will non-trivially increase the FT compared to the network RTT between the client and resolver.

Therefore, we express the requirements in terms of FT. Again, for ease of exposition we use "RTO" to indicate the interval between a packet transmission and the decision the packet has been lost---regardless of whether the packet will be retransmitted.

- (a) The RTO SHOULD be set based on multiple observations of the FT when available.

In other words, the RTO should represent an empirically-derived reasonable amount of time that the sender should wait for delivery confirmation before deciding the given data is lost. Network paths are inherently dynamic and therefore it is crucial to incorporate multiple recent FT samples in the RTO to take into account the delay variation across time.

For example, TCP's RTO [RFC6298] would satisfy this requirement due to its use of an exponentially-weighted moving average (EWMA) to combine multiple FT samples into a "smoothed RTT". In the name of conservativeness, TCP goes further to also include an explicit variance term when computing the RTO.

While multiple FT samples are crucial for capturing the delay dynamics of a path, we explicitly do not tightly specify the process---including the number of FT samples to use and how/when to age samples out of the RTO calculation---as the particulars could depend on the situation and/or goals of each specific loss detector.

Finally, FT samples come from packet exchanges between peers. We encourage protocol designers---especially for new protocols---to strive to ensure the feedback is not easily spoofable by on- or off-path attackers such that they can perturb a host's notion of the FT. Ideally, all messages would be cryptographically secure, but given that this is not always possible---especially in legacy protocols---using a healthy amount of randomness in the packets is encouraged.

- (b) FT observations SHOULD be taken and incorporated into the RTO at least once per RTT or as frequently as data is exchanged in cases where that happens less frequently than once per RTT.

Internet measurements show that taking only a single FT sample per TCP connection results in a relatively poorly performing RTO mechanism [AP99], hence this requirement that the FT be sampled continuously throughout the lifetime of communication.

As an example, TCP takes an FT sample roughly once per RTT, or if using the timestamp option [RFC7323] on each acknowledgment arrival. [AP99] shows that both these approaches result in roughly equivalent performance for the RTO estimator.

- (c) FT observations MAY be taken from non-data exchanges.

Some protocols use non-data exchanges for various reasons---e.g., keepalives, heartbeats, control messages. To the extent that the latency of these exchanges mirrors data exchange, they can be leveraged to take FT samples within the RTO mechanism. Such samples can help protocols keep their RTO accurate during lulls in data transmission. However, given that these messages may not be subject to the same delays as data transmission, we do not take a general view on whether this is useful or not.

- (d) An RTO mechanism MUST NOT use ambiguous FT samples.

Assume two copies of some packet X are transmitted at times t_0 and t_1 and then at time t_2 the sender receives confirmation that X in fact arrived. In some cases, it is not clear which copy of X triggered the confirmation and hence the actual FT is either $t_2 - t_1$ or $t_2 - t_0$, but which is a mystery. Therefore, in this situation an implementation MUST NOT use either version of the FT sample and hence not update the RTO (as discussed in [KP87,RFC6298]).

There are cases where two copies of some data are transmitted in a way whereby the sender can tell which is being acknowledged by an incoming ACK. E.g., TCP's timestamp option [RFC7323] allows for packets to be uniquely identified and hence avoid the ambiguity. In such cases there is no ambiguity and the resulting samples can update the RTO.

- (3) Loss detected by the RTO mechanism MUST be taken as an indication of network congestion and the sending rate adapted using a standard mechanism (e.g., TCP collapses the congestion window to one packet [RFC5681]).

This ensures network safety.

An exception to this rule is if an IETF standardized mechanism determines that a particular loss is due to a non-congestion event (e.g., packet corruption). In such a case a congestion

control action is not required. Additionally, congestion control actions taken based on time-based loss detection could be reversed when a standard mechanism post-facto determines that the cause of the loss was not congestion (e.g., [RFC5682]).

- (4) Each time the RTO is used to detect a loss, the value of the RTO MUST be exponentially backed off such that the next firing requires a longer interval. The backoff SHOULD be removed after either (a) the subsequent successful transmission of non-retransmitted data, or (b) an RTO passes without detecting additional losses. The former will generally be quicker. The latter covers cases where loss is detected, but not repaired.

A maximum value MAY be placed on the RTO. The maximum RTO MUST NOT be less than 60 seconds (as specified in [RFC6298]).

This ensures network safety.

As with guideline (3), an exception to this rule exists if an IETF standardized mechanism determines that a particular loss is not due to congestion.

5 Discussion

We note that research has shown the tension between the responsiveness and correctness of time-based loss detection seems to be a fundamental tradeoff in the context of TCP [AP99]. That is, making the RTO more aggressive (e.g., via changing TCP's exponentially weighted moving average (EWMA) gains, lowering the minimum RTO, etc.) can reduce the time required to detect actual loss. However, at the same time, such aggressiveness leads to more cases of mistakenly declaring packets lost that ultimately arrived at the receiver. Therefore, being as aggressive as the requirements given in the previous section allow in any particular situation may not be the best course of action because detecting loss---even if falsely---carries a requirement to invoke a congestion response which will ultimately reduce the transmission rate.

While the tradeoff between responsiveness and correctness seems fundamental, the tradeoff can be made less relevant if the sender can detect and recover from mistaken loss detection. Several mechanisms have been proposed for this purpose, such as Eifel [RFC3522], F-RTO [RFC5682] and DSACK [RFC2883,RFC3708]. Using such mechanisms may allow a data originator to tip towards being more responsive without incurring (as much of) the attendant costs of mistakenly declaring packets to be lost.

Also, note that, in addition to the experiments discussed in [AP99], the Linux TCP implementation has been using various non-standard RTO mechanisms for many years seemingly without large-scale problems (e.g., using different EWMA gains than specified in [RFC6298]). Further, a number of TCP implementations use a steady-state minimum RTO that is less than the 1 second specified in [RFC6298]. While the implication of these deviations from the standard may be more

spurious retransmits (per [AP99]), we are aware of no large-scale network safety issues caused by this change to the minimum RTO. This informs the guidelines in the last section (e.g., there is no minimum RTO specified).

Finally, we note that while allowing implementations to be more aggressive could in fact increase the number of needless retransmissions, the above requirements fail safe in that they insist on exponential backoff and a transmission rate reduction. Therefore, providing implementers more latitude than they have traditionally been given in IETF specifications of RTO mechanisms does not somehow open the flood gates to aggressive behavior. Since there is a downside to being aggressive, the incentives for proper behavior are retained in the mechanism.

6 Security Considerations

This document does not alter the security properties of time-based loss detection mechanisms. See [RFC6298] for a discussion of these within the context of TCP.

7 IANA Considerations

This document has no IANA considerations.

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Guidelines for Adding Congestion Notification to Protocols that
Encapsulate IP
draft-ietf-tsvwg-ecn-encap-guidelines-16

Abstract

The purpose of this document is to guide the design of congestion notification in any lower layer or tunnelling protocol that encapsulates IP. The aim is for explicit congestion signals to propagate consistently from lower layer protocols into IP. Then the IP internetwork layer can act as a portability layer to carry congestion notification from non-IP-aware congested nodes up to the transport layer (L4). Following these guidelines should assure interworking among IP layer and lower layer congestion notification mechanisms, whether specified by the IETF or other standards bodies. This document updates the advice to subnetwork designers about ECN in RFC 3819.

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Table of Contents

1. Introduction	3
1.1. Update to RFC 3819	5
1.2. Scope	5
2. Terminology	7
3. Modes of Operation	9
3.1. Feed-Forward-and-Up Mode	9
3.2. Feed-Up-and-Forward Mode	11
3.3. Feed-Backward Mode	12
3.4. Null Mode	14
4. Feed-Forward-and-Up Mode: Guidelines for Adding Congestion Notification	14
4.1. IP-in-IP Tunnels with Shim Headers	15
4.2. Wire Protocol Design: Indication of ECN Support	16
4.3. Encapsulation Guidelines	18
4.4. Decapsulation Guidelines	20
4.5. Sequences of Similar Tunnels or Subnets	22
4.6. Reframing and Congestion Markings	22
5. Feed-Up-and-Forward Mode: Guidelines for Adding Congestion Notification	23
6. Feed-Backward Mode: Guidelines for Adding Congestion Notification	24
7. IANA Considerations	25
8. Security Considerations	25
9. Conclusions	26
10. Acknowledgements	27
11. Contributors	27
12. Comments Solicited	27
13. References	27
13.1. Normative References	27
13.2. Informative References	28
Appendix A. Changes in This Version (to be removed by RFC Editor)	33
Authors' Addresses	38

1. Introduction

The benefits of Explicit Congestion Notification (ECN) described in [RFC8087] and summarized below can only be fully realized if support for ECN is added to the relevant subnetwork technology, as well as to IP. When a lower layer buffer drops a packet obviously it does not just drop at that layer; the packet disappears from all layers. In contrast, when active queue management (AQM) at a lower layer marks a packet with ECN, the marking needs to be explicitly propagated up the layers. The same is true if AQM marks the outer header of a packet that encapsulates inner tunnelled headers. Forwarding ECN is not as straightforward as other headers because it has to be assumed ECN may be only partially deployed. If a lower layer header that contains ECN congestion indications is stripped off by a subnet egress that is not ECN-aware, or if the ultimate receiver or sender is not ECN-aware, congestion needs to be indicated by dropping a packet, not marking it.

The purpose of this document is to guide the addition of congestion notification to any subnet technology or tunnelling protocol, so that lower layer AQM algorithms can signal congestion explicitly and it will propagate consistently into encapsulated (higher layer) headers, otherwise the signals will not reach their ultimate destination.

ECN is defined in the IP header (v4 and v6) [RFC3168] to allow a resource to notify the onset of queue build-up without having to drop packets, by explicitly marking a proportion of packets with the congestion experienced (CE) codepoint.

Given a suitable marking scheme, ECN removes nearly all congestion loss and it cuts delays for two main reasons:

- o It avoids the delay when recovering from congestion losses, which particularly benefits small flows or real-time flows, making their delivery time predictably short [RFC2884];
- o As ECN is used more widely by end-systems, it will gradually remove the need to configure a degree of delay into buffers before they start to notify congestion (the cause of bufferbloat). This is because drop involves a trade-off between sending a timely signal and trying to avoid impairment, whereas ECN is solely a signal not an impairment, so there is no harm triggering it earlier.

Some lower layer technologies (e.g. MPLS, Ethernet) are used to form subnetworks with IP-aware nodes only at the edges. These networks are often sized so that it is rare for interior queues to overflow. However, until recently this was more due to the inability of TCP to

saturate the links. For many years, fixes such as window scaling [RFC7323] proved hard to deploy. And the Reno variant of TCP has remained in widespread use despite its inability to scale to high flow rates. However, now that modern operating systems are finally capable of saturating interior links, even the buffers of well-provisioned interior switches will need to signal episodes of queuing.

Propagation of ECN is defined for MPLS [RFC5129], and is being defined for TRILL [RFC7780], [I-D.ietf-trill-ecn-support], but it remains to be defined for a number of other subnetwork technologies.

Similarly, ECN propagation is yet to be defined for many tunnelling protocols. [RFC6040] defines how ECN should be propagated for IP-in-IPv4 [RFC2003], IP-in-IPv6 [RFC2473] and IPsec [RFC4301] tunnels, but there are numerous other tunnelling protocols with a shim and/or a layer 2 header between two IP headers (v4 or v6). Some address ECN propagation between the IP headers, but many do not. This document gives guidance on how to address ECN propagation for future tunnelling protocols, and a companion standards track specification [I-D.ietf-tsvwg-rfc6040update-shim] updates those existing IP-shim-(L2)-IP protocols that are under IETF change control and still widely used.

Incremental deployment is the most delicate aspect when adding support for ECN. The original ECN protocol in IP [RFC3168] was carefully designed so that a congested buffer would not mark a packet (rather than drop it) unless both source and destination hosts were ECN-capable. Otherwise its congestion markings would never be detected and congestion would just build up further. However, to support congestion marking below the IP layer or within tunnels, it is not sufficient to only check that the two layer 4 transport endpoints support ECN; correct operation also depends on the decapsulator at each subnet or tunnel egress faithfully propagating congestion notifications to the higher layer. Otherwise, a legacy decapsulator might silently fail to propagate any ECN signals from the outer to the forwarded header. Then the lost signals would never be detected and again congestion would build up further. The guidelines given later require protocol designers to carefully consider incremental deployment, and suggest various safe approaches for different circumstances.

Of course, the IETF does not have standards authority over every link layer protocol. So this document gives guidelines for designing propagation of congestion notification across the interface between IP and protocols that may encapsulate IP (i.e. that can be layered beneath IP). Each lower layer technology will exhibit different issues and compromises, so the IETF or the relevant standards body

must be free to define the specifics of each lower layer congestion notification scheme. Nonetheless, if the guidelines are followed, congestion notification should interwork between different technologies, using IP in its role as a 'portability layer'.

Therefore, the capitalized terms 'SHOULD' or 'SHOULD NOT' are often used in preference to 'MUST' or 'MUST NOT', because it is difficult to know the compromises that will be necessary in each protocol design. If a particular protocol design chooses not to follow a 'SHOULD (NOT)' given in the advice below, it MUST include a sound justification.

It has not been possible to give common guidelines for all lower layer technologies, because they do not all fit a common pattern. Instead they have been divided into a few distinct modes of operation: feed-forward-and-upward; feed-upward-and-forward; feed-backward; and null mode. These modes are described in Section 3, then in the subsequent sections separate guidelines are given for each mode.

1.1. Update to RFC 3819

This document updates the brief advice to subnetwork designers about ECN in [RFC3819], by replacing the last two paragraphs of Section 13 with the following sentence:

By following the guidelines in [this document], subnetwork designers can enable a layer-2 protocol to participate in congestion control without dropping packets via propagation of explicit congestion notification (ECN [RFC3168]) to receivers.

and adding [this document] as an informative reference. {RFC Editor: Please replace both instances of [this document] above with the number of the present RFC when published.}

1.2. Scope

This document only concerns wire protocol processing of explicit notification of congestion. It makes no changes or recommendations concerning algorithms for congestion marking or for congestion response, because algorithm issues should be independent of the layer the algorithm operates in.

The default ECN semantics are described in [RFC3168] and updated by [RFC8311]. Also the guidelines for AQM designers [RFC7567] clarify the semantics of both drop and ECN signals from AQM algorithms. [RFC4774] is the appropriate best current practice specification of how algorithms with alternative semantics for the ECN field can be

partitioned from Internet traffic that uses the default ECN semantics. There are two main examples for how alternative ECN semantics have been defined in practice:

- o RFC 4774 suggests using the ECN field in combination with a Diffserv codepoint such as in PCN [RFC6660], Voice over 3G [UTRAN] or Voice over LTE (VoLTE) [LTE-RA];
- o RFC 8311 suggests using the ECT(1) codepoint of the ECN field to indicate alternative semantics such as for the experimental Low Latency Low Loss Scalable throughput (L4S) service [I-D.ietf-tsvwg-ecn-l4s-id]).

The aim is that the default rules for encapsulating and decapsulating the ECN field are sufficiently generic that tunnels and subnets will encapsulate and decapsulate packets without regard to how algorithms elsewhere are setting or interpreting the semantics of the ECN field. [RFC6040] updates RFC 4774 to allow alternative encapsulation and decapsulation behaviours to be defined for alternative ECN semantics. However it reinforces the same point - that it is far preferable to try to fit within the common ECN encapsulation and decapsulation behaviours, because expecting all lower layer technologies and tunnels to be updated is likely to be completely impractical.

Alternative semantics for the ECN field can be defined to depend on the traffic class indicated by the DSCP. Therefore correct propagation of congestion signals could depend on correct propagation of the DSCP between the layers and along the path. For instance, if the meaning of the ECN field depends on the DSCP (as in PCN or VoLTE) and if the outer DSCP is stripped on decapsulation, as in the pipe model of [RFC2983], the special semantics of the ECN field would be lost. Similarly, if the DSCP is changed at the boundary between Diffserv domains, the special ECN semantics would also be lost. This is an important implication of the localized scope of most Diffserv arrangements. In this document, correct propagation of traffic class information is assumed, while what 'correct' means and how it is achieved is covered elsewhere (e.g. RFC 2983) and is outside the scope of the present document.

The guidelines in this document do ensure that common encapsulation and decapsulation rules are sufficiently generic to cover cases where ECT(1) is used instead of ECT(0) to identify alternative ECN semantics (as in L4S [I-D.ietf-tsvwg-ecn-l4s-id]) and where ECN marking algorithms use ECT(1) to encode 3 severity levels into the ECN field (e.g. PCN [RFC6660]) rather than the default of 2. All these different semantics for the ECN field work because it has been possible to define common default decapsulation rules that allow for all cases.

Note that the guidelines in this document do not necessarily require the subnet wire protocol to be changed to add support for congestion notification. For instance, the Feed-Up-and-Forward Mode (Section 3.2) and the Null Mode (Section 3.4) do not. Another way to add congestion notification without consuming header space in the subnet protocol might be to use a parallel control plane protocol.

This document focuses on the congestion notification interface between IP and lower layer or tunnel protocols that can encapsulate IP, where the term 'IP' includes v4 or v6, unicast, multicast or anycast. However, it is likely that the guidelines will also be useful when a lower layer protocol or tunnel encapsulates itself, e.g. Ethernet MAC in MAC ([IEEE802.1Q]; previously 802.1ah) or when it encapsulates other protocols. In the feed-backward mode, propagation of congestion signals for multicast and anycast packets is out-of-scope (because the complexity would make it unlikely to be attempted).

2. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

Further terminology used within this document:

Protocol data unit (PDU): Information that is delivered as a unit among peer entities of a layered network consisting of protocol control information (typically a header) and possibly user data (payload) of that layer. The scope of this document includes layer 2 and layer 3 networks, where the PDU is respectively termed a frame or a packet (or a cell in ATM). PDU is a general term for any of these. This definition also includes a payload with a shim header lying somewhere between layer 2 and 3.

Transport: The end-to-end transmission control function, conventionally considered at layer-4 in the OSI reference model. Given the audience for this document will often use the word transport to mean low level bit carriage, whenever the term is used it will be qualified, e.g. 'L4 transport'.

Encapsulator: The link or tunnel endpoint function that adds an outer header to a PDU (also termed the 'link ingress', the 'subnet ingress', the 'ingress tunnel endpoint' or just the 'ingress' where the context is clear).

Decapsulator: The link or tunnel endpoint function that removes an outer header from a PDU (also termed the 'link egress', the 'subnet egress', the 'egress tunnel endpoint' or just the 'egress' where the context is clear).

Incoming header: The header of an arriving PDU before encapsulation.

Outer header: The header added to encapsulate a PDU.

Inner header: The header encapsulated by the outer header.

Outgoing header: The header forwarded by the decapsulator.

CE: Congestion Experienced [RFC3168]

ECT: ECN-Capable (L4) Transport [RFC3168]

Not-ECT: Not ECN-Capable (L4) Transport [RFC3168]

Load Regulator: For each flow of PDUs, the transport function that is capable of controlling the data rate. Typically located at the data source, but in-path nodes can regulate load in some congestion control arrangements (e.g. admission control, policing nodes or transport circuit-breakers [RFC8084]). Note the term "a function capable of controlling the load" deliberately includes a transport that does not actually control the load responsively but ideally it ought to (e.g. a sending application without congestion control that uses UDP).

ECN-PDU: A PDU at the IP layer or below with a capacity to signal congestion that is part of a congestion control feedback loop within which all the nodes necessary to propagate the signal back to the Load Regulator are capable of doing that propagation. An IP packet with a non-zero ECN field implies that the endpoints are ECN-capable, so this would be an ECN-PDU. However, ECN-PDU is intended to be a general term for a PDU at lower layers, as well as at the IP layer.

Not-ECN-PDU: A PDU at the IP layer or below that is part of a congestion control feedback-loop within which at least one node necessary to propagate any explicit congestion notification signals back to the Load Regulator is not capable of doing that propagation.

3. Modes of Operation

This section sets down the different modes by which congestion information is passed between the lower layer and the higher one. It acts as a reference framework for the following sections, which give normative guidelines for designers of explicit congestion notification protocols, taking each mode in turn:

Feed-Forward-and-Up: Nodes feed forward congestion notification towards the egress within the lower layer then up and along the layers towards the end-to-end destination at the transport layer. The following local optimisation is possible:

Feed-Up-and-Forward: A lower layer switch feeds-up congestion notification directly into the higher layer (e.g. into the ECN field in the IP header), irrespective of whether the node is at the egress of a subnet.

Feed-Backward: Nodes feed back congestion signals towards the ingress of the lower layer and (optionally) attempt to control congestion within their own layer.

Null: Nodes cannot experience congestion at the lower layer except at ingress nodes (which are IP-aware or equivalently higher-layer-aware).

3.1. Feed-Forward-and-Up Mode

Like IP and MPLS, many subnet technologies are based on self-contained protocol data units (PDUs) or frames sent unreliably. They provide no feedback channel at the subnetwork layer, instead relying on higher layers (e.g. TCP) to feed back loss signals.

In these cases, ECN may best be supported by standardising explicit notification of congestion into the lower layer protocol that carries the data forwards. Then a specification is needed for how the egress of the lower layer subnet propagates this explicit signal into the forwarded upper layer (IP) header. This signal continues forwards until it finally reaches the destination transport (at L4). Then typically the destination will feed this congestion notification back to the source transport using an end-to-end protocol (e.g. TCP). This is the arrangement that has already been used to add ECN to IP-in-IP tunnels [RFC6040], IP-in-MPLS and MPLS-in-MPLS [RFC5129].

This mode is illustrated in Figure 1. Along the middle of the figure, layers 2, 3 and 4 of the protocol stack are shown, and one packet is shown along the bottom as it progresses across the network from source to destination, crossing two subnets connected by a

router, and crossing two switches on the path across each subnet. Congestion at the output of the first switch (shown as *) leads to a congestion marking in the L2 header (shown as C in the illustration of the packet). The chevrons show the progress of the resulting congestion indication. It is propagated from link to link across the subnet in the L2 header, then when the router removes the marked L2 header, it propagates the marking up into the L3 (IP) header. The router forwards the marked L3 header into subnet 2, and when it adds a new L2 header it copies the L3 marking into the L2 header as well, as shown by the 'C's in both layers (assuming the technology of subnet 2 also supports explicit congestion marking).

Note that there is no implication that each 'C' marking is encoded the same; a different encoding might be used for the 'C' marking in each protocol.

Finally, for completeness, we show the L3 marking arriving at the destination, where the host transport protocol (e.g. TCP) feeds it back to the source in the L4 acknowledgement (the 'C' at L4 in the packet at the top of the diagram).

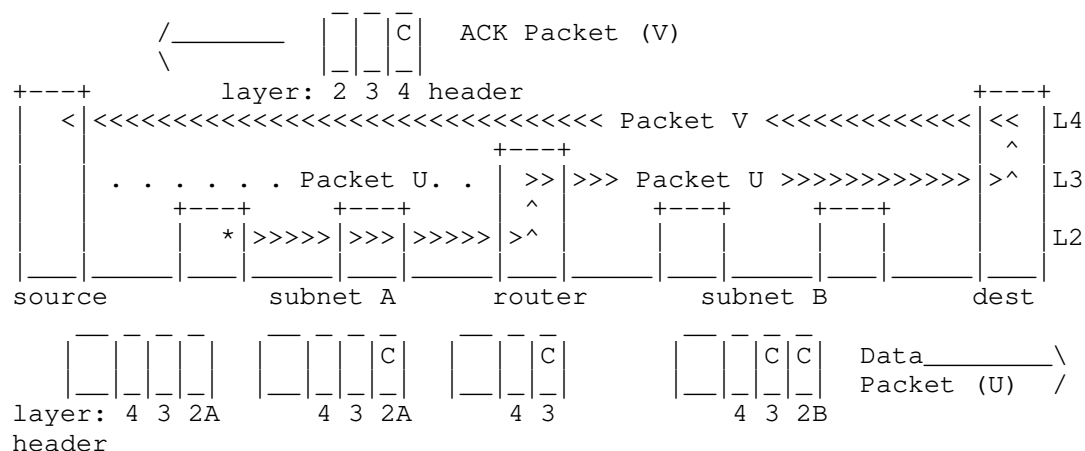


Figure 1: Feed-Forward-and-Up Mode

Of course, modern networks are rarely as simple as this text-book example, often involving multiple nested layers. For example, a 3GPP mobile network may have two IP-in-IP (GTP [GTPv1]) tunnels in series and an MPLS backhaul between the base station and the first router. Nonetheless, the example illustrates the general idea of feeding congestion notification forward then upward whenever a header is removed at the egress of a subnet.

Note that the FECN (forward ECN) bit in Frame Relay [Buck00] and the explicit forward congestion indication (EFCI [ITU-T.I.371]) bit in ATM user data cells follow a feed-forward pattern. However, in ATM, this arrangement is only part of a feed-forward-and-backward pattern at the lower layer, not feed-forward-and-up out of the lower layer--the intention was never to interface to IP ECN at the subnet egress. To our knowledge, Frame Relay FECN is solely used to detect where more capacity should be provisioned.

3.2. Feed-Up-and-Forward Mode

Ethernet is particularly difficult to extend incrementally to support explicit congestion notification. One way to support ECN in such cases has been to use so called 'layer-3 switches'. These are Ethernet switches that dig into the Ethernet payload to find an IP header and manipulate or act on certain IP fields (specifically Diffserv & ECN). For instance, in Data Center TCP [RFC8257], layer-3 switches are configured to mark the ECN field of the IP header within the Ethernet payload when their output buffer becomes congested. With respect to switching, a layer-3 switch acts solely on the addresses in the Ethernet header; it does not use IP addresses, and it does not decrement the TTL field in the IP header.

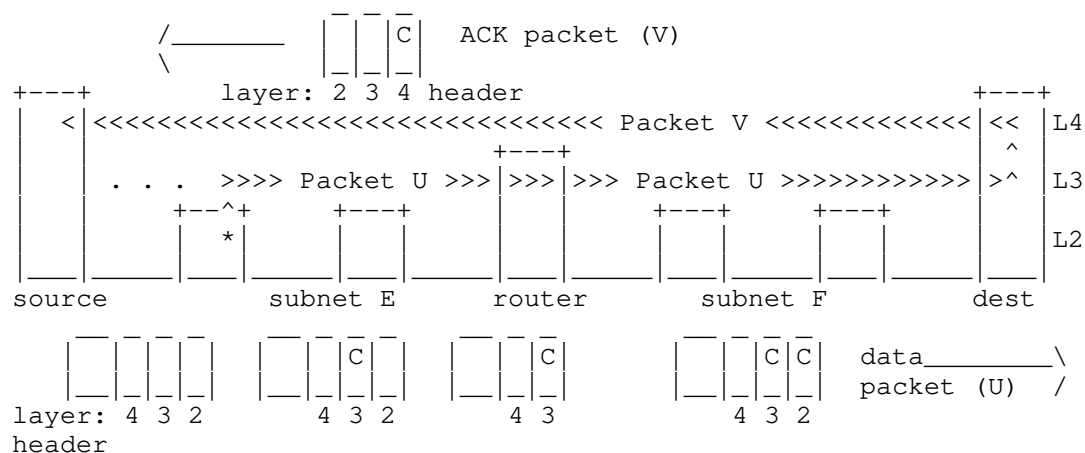


Figure 2: Feed-Up-and-Forward Mode

By comparing Figure 2 with Figure 1, it can be seen that subnet E (perhaps a subnet of layer-3 Ethernet switches) works in feed-up-and-forward mode by notifying congestion directly into L3 at the point of congestion, even though the congested switch does not otherwise act at L3. In this example, the technology in subnet F (e.g. MPLS) does

support ECN natively, so when the router adds the layer-2 header it copies the ECN marking from L3 to L2 as well.

3.3. Feed-Backward Mode

In some layer 2 technologies, explicit congestion notification has been defined for use internally within the subnet with its own feedback and load regulation, but typically the interface with IP for ECN has not been defined.

For instance, for the available bit-rate (ABR) service in ATM, the relative rate mechanism was one of the more popular mechanisms for managing traffic, tending to supersede earlier designs. In this approach ATM switches send special resource management (RM) cells in both the forward and backward directions to control the ingress rate of user data into a virtual circuit. If a switch buffer is approaching congestion or is congested it sends an RM cell back towards the ingress with respectively the No Increase (NI) or Congestion Indication (CI) bit set in its message type field [ATM-TM-ABR]. The ingress then holds or decreases its sending bit-rate accordingly.

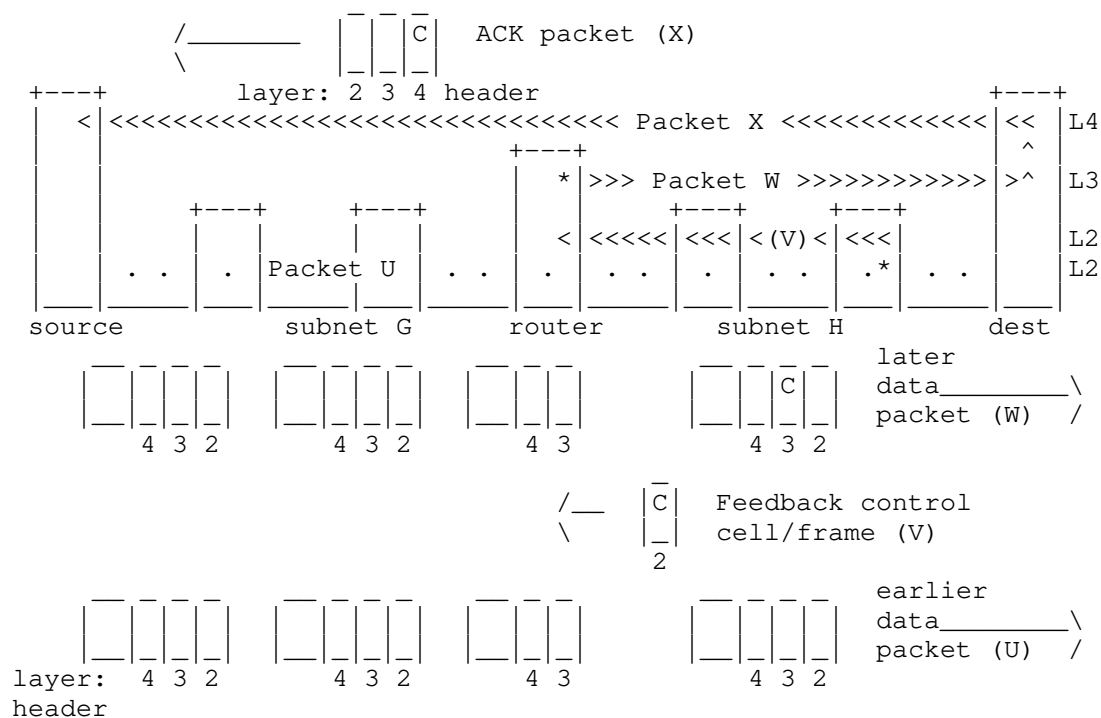


Figure 3: Feed-Backward Mode

ATM's feed-backward approach does not fit well when layered beneath IP's feed-forward approach--unless the initial data source is the same node as the ATM ingress. Figure 3 shows the feed-backward approach being used in subnet H. If the final switch on the path is congested (*), it does not feed-forward any congestion indications on packet (U). Instead it sends a control cell (V) back to the router at the ATM ingress.

However, the backward feedback does not reach the original data source directly because IP does not support backward feedback (and subnet G is independent of subnet H). Instead, the router in the middle throttles down its sending rate but the original data sources don't reduce their rates. The resulting rate mismatch causes the middle router's buffer at layer 3 to back up until it becomes congested, which it signals forwards on later data packets at layer 3 (e.g. packet W). Note that the forward signal from the middle router is not triggered directly by the backward signal. Rather, it is triggered by congestion resulting from the middle router's mismatched rate response to the backward signal.

In response to this later forward signalling, end-to-end feedback at layer-4 finally completes the tortuous path of congestion indications back to the origin data source, as before.

Quantized congestion notification (QCN [IEEE802.1Q]) would suffer from similar problems if extended to multiple subnets. However, from the start QCN was clearly characterized as solely applicable to a single subnet (see Section 6).

3.4. Null Mode

Often link and physical layer resources are 'non-blocking' by design. In these cases congestion notification may be implemented but it does not need to be deployed at the lower layer; ECN in IP would be sufficient.

A degenerate example is a point-to-point Ethernet link. Excess loading of the link merely causes the queue from the higher layer to back up, while the lower layer remains immune to congestion. Even a whole meshed subnetwork can be made immune to interior congestion by limiting ingress capacity and sufficient sizing of interior links, e.g. a non-blocking fat-tree network [Leiserson85]. An alternative to fat links near the root is numerous thin links with multi-path routing to ensure even worst-case patterns of load cannot congest any link, e.g. a Clos network [Clos53].

4. Feed-Forward-and-Up Mode: Guidelines for Adding Congestion Notification

Feed-forward-and-up is the mode already used for signalling ECN up the layers through MPLS into IP [RFC5129] and through IP-in-IP tunnels [RFC6040], whether encapsulating with IPv4 [RFC2003], IPv6 [RFC2473] or IPsec [RFC4301]. These RFCs take a consistent approach and the following guidelines are designed to ensure this consistency continues as ECN support is added to other protocols that encapsulate IP. The guidelines are also designed to ensure compliance with the more general best current practice for the design of alternate ECN schemes given in [RFC4774] and extended by [RFC8311].

The rest of this section is structured as follows:

- o Section 4.1 addresses the most straightforward cases, where [RFC6040] can be applied directly to add ECN to tunnels that are effectively IP-in-IP tunnels, but with shim header(s) between the IP headers.
- o The subsequent sections give guidelines for adding ECN to a subnet technology that uses feed-forward-and-up mode like IP, but it is

not so similar to IP that [RFC6040] rules can be applied directly. Specifically:

- * Sections 4.2, 4.3 and 4.4 respectively address how to add ECN support to the wire protocol and to the encapsulators and decapsulators at the ingress and egress of the subnet.
- * Section 4.5 deals with the special, but common, case of sequences of tunnels or subnets that all use the same technology
- * Section 4.6 deals with the question of reframing when IP packets do not map 1:1 into lower layer frames.

4.1. IP-in-IP Tunnels with Shim Headers

A common pattern for many tunnelling protocols is to encapsulate an inner IP header with shim header(s) then an outer IP header. A shim header is defined as one that is not sufficient alone to forward the packet as an outer header. Another common pattern is for a shim to encapsulate a layer 2 (L2) header, which in turn encapsulates (or might encapsulate) an IP header. [I-D.ietf-tsvwg-rfc6040update-shim] clarifies that RFC 6040 is just as applicable when there are shim(s) and possibly a L2 header between two IP headers.

However, it is not always feasible or necessary to propagate ECN between IP headers when separated by a shim. For instance, it might be too costly to dig to arbitrary depths to find an inner IP header, there may be little or no congestion within the tunnel by design (see null mode in Section 3.4 above), or a legacy implementation might not support ECN. In cases where a tunnel does not support ECN, it is important that the ingress does not copy the ECN field from an inner IP header to an outer. Therefore section 4 of [I-D.ietf-tsvwg-rfc6040update-shim] requires network operators to configure the ingress of a tunnel that does not support ECN so that it zeros the ECN field in the outer IP header.

Nonetheless, in many cases it is feasible to propagate the ECN field between IP headers separated by shim header(s) and/or a L2 header. Particularly in the typical case when the outer IP header and the shim(s) are added (or removed) as part of the same procedure. Even if the shim(s) encapsulate a L2 header, it is often possible to find an inner IP header within the L2 PDU and propagate ECN between that and the outer IP header. This can be thought of as a special case of the feed-up-and-forward mode (Section 3.2), so the guidelines for this mode apply (Section 5).

Numerous shim protocols have been defined for IP tunnelling. More recent ones e.g. Geneve [RFC8926] and Generic UDP Encapsulation (GUE) [I-D.ietf-intarea-gue] cite and follow RFC 6040. And some earlier ones, e.g. CAPWAP [RFC5415] and LISP [RFC6830], cite RFC 3168, which is compatible with RFC 6040.

However, as Section 9.3 of RFC 3168 pointed out, ECN support needs to be defined for many earlier shim-based tunnelling protocols, e.g. L2TPv2 [RFC2661], L2TPv3 [RFC3931], GRE [RFC2784], PPTP [RFC2637], GTP [GTPv1], [GTPv1-U], [GTPv2-C] and Teredo [RFC4380] as well as some recent ones, e.g. VXLAN [RFC7348], NVGRE [RFC7637] and NSH [RFC8300].

All these IP-based encapsulations can be updated in one shot by simple reference to RFC 6040. However, it would not be appropriate to update all these protocols from within the present guidance document. Instead a companion specification [I-D.ietf-tsvwg-rfc6040update-shim] has been prepared that has the appropriate standards track status to update standards track protocols. For those that are not under IETF change control [I-D.ietf-tsvwg-rfc6040update-shim] can only recommend that the relevant body updates them.

4.2. Wire Protocol Design: Indication of ECN Support

This section is intended to guide the redesign of any lower layer protocol that encapsulate IP to add native ECN support at the lower layer. It reflects the approaches used in [RFC6040] and in [RFC5129]. Therefore IP-in-IP tunnels or IP-in-MPLS or MPLS-in-MPLS encapsulations that already comply with [RFC6040] or [RFC5129] will already satisfy this guidance.

A lower layer (or subnet) congestion notification system:

1. SHOULD NOT apply explicit congestion notifications to PDUs that are destined for legacy layer-4 transport implementations that will not understand ECN, and
2. SHOULD NOT apply explicit congestion notifications to PDUs if the egress of the subnet might not propagate congestion notifications onward into the higher layer.

We use the term ECN-PDUs for a PDU on a feedback loop that will propagate congestion notification properly because it meets both the above criteria. And a Not-ECN-PDU is a PDU on a feedback loop that does not meet at least one of the criteria, and will therefore not propagate congestion notification properly. A

corollary of the above is that a lower layer congestion notification protocol:

3. SHOULD be able to distinguish ECN-PDUs from Not-ECN-PDUs.

Note that there is no need for all interior nodes within a subnet to be able to mark congestion explicitly. A mix of ECN and drop signals from different nodes is fine. However, if any interior nodes might generate ECN markings, guideline 2 above says that all relevant egress node(s) SHOULD be able to propagate those markings up to the higher layer.

In IP, if the ECN field in each PDU is cleared to the Not-ECT (not ECN-capable transport) codepoint, it indicates that the L4 transport will not understand congestion markings. A congested buffer must not mark these Not-ECT PDUs, and therefore drops them instead.

The mechanism a lower layer uses to distinguish the ECN-capability of PDUs need not mimic that of IP. The above guidelines merely say that the lower layer system, as a whole, should achieve the same outcome. For instance, ECN-capable feedback loops might use PDUs that are identified by a particular set of labels or tags. Alternatively, logical link protocols that use flow state might determine whether a PDU can be congestion marked by checking for ECN-support in the flow state. Other protocols might depend on out-of-band control signals.

The per-domain checking of ECN support in MPLS [RFC5129] is a good example of a way to avoid sending congestion markings to L4 transports that will not understand them, without using any header space in the subnet protocol.

In MPLS, header space is extremely limited, therefore RFC5129 does not provide a field in the MPLS header to indicate whether the PDU is an ECN-PDU or a Not-ECN-PDU. Instead, interior nodes in a domain are allowed to set explicit congestion indications without checking whether the PDU is destined for a L4 transport that will understand them. Nonetheless, this is made safe by requiring that the network operator upgrades all decapsulating edges of a whole domain at once, as soon as even one switch within the domain is configured to mark rather than drop during congestion. Therefore, any edge node that might decapsulate a packet will be capable of checking whether the higher layer transport is ECN-capable. When decapsulating a CE-marked packet, if the decapsulator discovers that the higher layer (inner header) indicates the transport is not ECN-capable, it drops the packet--effectively on behalf of the earlier congested node (see Decapsulation Guideline 1 in Section 4.4).

It was only appropriate to define such an incremental deployment strategy because MPLS is targeted solely at professional operators, who can be expected to ensure that a whole subnetwork is consistently configured. This strategy might not be appropriate for other link technologies targeted at zero-configuration deployment or deployment by the general public (e.g. Ethernet). For such 'plug-and-play' environments it will be necessary to invent a failsafe approach that ensures congestion markings will never fall into black holes, no matter how inconsistently a system is put together. Alternatively, congestion notification relying on correct system configuration could be confined to flavours of Ethernet intended only for professional network operators, such as Provider Backbone Bridges (PBB [IEEE802.1Q]; previously 802.1ah).

ECN support in TRILL [I-D.ietf-trill-ecn-support] provides a good example of how to add ECN to a lower layer protocol without relying on careful and consistent operator configuration. TRILL provides an extension header word with space for flags of different categories depending on whether logic to understand the extension is critical. The congestion experienced marking has been defined as a 'critical ingress-to-egress' flag. So if a transit RBridge sets this flag and an egress RBridge does not have any logic to process it, it will drop it; which is the desired default action anyway. Therefore TRILL RBridges can be updated with support for ECN in no particular order and, at the egress of the TRILL campus, congestion notification will be propagated to IP as ECN whenever ECN logic has been implemented, or as drop otherwise.

QCN [IEEE802.1Q] is not intended to extend beyond a single subnet, or to interoperate with ECN. Nonetheless, the way QCN indicates to lower layer devices that the end-points will not understand QCN provides another example that a lower layer protocol designer might be able to mimic for their scenario. An operator can define certain Priority Code Points (PCPs [IEEE802.1Q]; previously 802.1p) to indicate non-QCN frames and an ingress bridge is required to map arriving not-QCN-capable IP packets to one of these non-QCN PCPs.

4.3. Encapsulation Guidelines

This section is intended to guide the redesign of any node that encapsulates IP with a lower layer header when adding native ECN support to the lower layer protocol. It reflects the approaches used in [RFC6040] and in [RFC5129]. Therefore IP-in-IP tunnels or IP-in-MPLS or MPLS-in-MPLS encapsulations that already comply with [RFC6040] or [RFC5129] will already satisfy this guidance.

1. Egress Capability Check: A subnet ingress needs to be sure that the corresponding egress of a subnet will propagate any

congestion notification added to the outer header across the subnet. This is necessary in addition to checking that an incoming PDU indicates an ECN-capable (L4) transport. Examples of how this guarantee might be provided include:

- * by configuration (e.g. if any label switches in a domain support ECN marking, [RFC5129] requires all egress nodes to have been configured to propagate ECN)
 - * by the ingress explicitly checking that the egress propagates ECN (e.g. an early attempt to add ECN support to TRILL used IS-IS to check path capabilities before adding ECN extension flags to each frame [RFC7780]).
 - * by inherent design of the protocol (e.g. by encoding ECN marking on the outer header in such a way that a legacy egress that does not understand ECN will consider the PDU corrupt or invalid and discard it, thus at least propagating a form of congestion signal).
2. Egress Fails Capability Check: If the ingress cannot guarantee that the egress will propagate congestion notification, the ingress SHOULD disable ECN at the lower layer when it forwards the PDU. An example of how the ingress might disable ECN at the lower layer would be by setting the outer header of the PDU to identify it as a Not-ECN-PDU, assuming the subnet technology supports such a concept.
 3. Standard Congestion Monitoring Baseline: Once the ingress to a subnet has established that the egress will correctly propagate ECN, on encapsulation it SHOULD encode the same level of congestion in outer headers as is arriving in incoming headers. For example it might copy any incoming congestion notification into the outer header of the lower layer protocol.

This ensures that bulk congestion monitoring of outer headers (e.g. by a network management node monitoring ECN in passing frames) will measure congestion accumulated along the whole upstream path - since the Load Regulator not just since the ingress of the subnet. A node that is not the Load Regulator SHOULD NOT re-initialize the level of CE markings in the outer to zero.

It would still also be possible to measure congestion introduced across one subnet (or tunnel) by subtracting the level of CE markings on inner headers from that on outer headers (see Appendix C of [RFC6040]). For example:

- * If this guideline has been followed and if the level of CE markings is 0.4% on the outer and 0.1% on the inner, 0.4% congestion has been introduced across all the networks since the load regulator, and 0.3% ($= 0.4\% - 0.1\%$) has been introduced since the ingress to the current subnet (or tunnel);
- * Without this guideline, if the subnet ingress had re-initialized the outer congestion level to zero, the outer and inner would measure 0.1% and 0.3%. It would still be possible to infer that the congestion introduced since the Load Regulator was 0.4% ($= 0.1\% + 0.3\%$). But only if the monitoring system somehow knows whether the subnet ingress re-initialized the congestion level.

As long as subnet and tunnel technologies use the standard congestion monitoring baseline in this guideline, monitoring systems will know to use the former approach, rather than having to "somehow know" which approach to use.

4.4. Decapsulation Guidelines

This section is intended to guide the redesign of any node that decapsulates IP from within a lower layer header when adding native ECN support to the lower layer protocol. It reflects the approaches used in [RFC6040] and in [RFC5129]. Therefore IP-in-IP tunnels or IP-in-MPLS or MPLS-in-MPLS encapsulations that already comply with [RFC6040] or [RFC5129] will already satisfy this guidance.

A subnet egress SHOULD NOT simply copy congestion notification from outer headers to the forwarded header. It SHOULD calculate the outgoing congestion notification field from the inner and outer headers using the following guidelines. If there is any conflict, rules earlier in the list take precedence over rules later in the list:

1. If the arriving inner header is a Not-ECN-PDU it implies the L4 transport will not understand explicit congestion markings.
Then:
 - * If the outer header carries an explicit congestion marking, drop is the only indication of congestion that the L4 transport will understand. If the congestion marking is the most severe possible, the packet MUST be dropped. However, if congestion can be marked with multiple levels of severity and the packet's marking is not the most severe, this requirement can be relaxed to: the packet SHOULD be dropped.

- * If the outer is an ECN-PDU that carries no indication of congestion or a Not-ECN-PDU the PDU SHOULD be forwarded, but still as a Not-ECN-PDU.
- 2. If the outer header does not support explicit congestion notification (a Not-ECN-PDU), but the inner header does (an ECN-PDU), the inner header SHOULD be forwarded unchanged.
- 3. In some lower layer protocols congestion may be signalled as a numerical level, such as in the control frames of quantized congestion notification (QCN [IEEE802.1Q]). If such a multi-bit encoding encapsulates an ECN-capable IP data packet, a function will be needed to convert the quantized congestion level into the frequency of congestion markings in outgoing IP packets.
- 4. Congestion indications might be encoded by a severity level. For instance increasing levels of congestion might be encoded by numerically increasing indications, e.g. pre-congestion notification (PCN) can be encoded in each PDU at three severity levels in IP or MPLS [RFC6660] and the default encapsulation and decapsulation rules [RFC6040] are compatible with this interpretation of the ECN field.

If the arriving inner header is an ECN-PDU, where the inner and outer headers carry indications of congestion of different severity, the more severe indication SHOULD be forwarded in preference to the less severe.

- 5. The inner and outer headers might carry a combination of congestion notification fields that should not be possible given any currently used protocol transitions. For instance, if Encapsulation Guideline 3 in Section 4.3 had been followed, it should not be possible to have a less severe indication of congestion in the outer than in the inner. It MAY be appropriate to log unexpected combinations of headers and possibly raise an alarm.

If a safe outgoing codepoint can be defined for such a PDU, the PDU SHOULD be forwarded rather than dropped. Some implementers discard PDUs with currently unused combinations of headers just in case they represent an attack. However, an approach using alarms and policy-mediated drop is preferable to hard-coded drop, so that operators can keep track of possible attacks but currently unused combinations are not precluded from future use through new standards actions.

4.5. Sequences of Similar Tunnels or Subnets

In some deployments, particularly in 3GPP networks, an IP packet may traverse two or more IP-in-IP tunnels in sequence that all use identical technology (e.g. GTP).

In such cases, it would be sufficient for every encapsulation and decapsulation in the chain to comply with RFC 6040. Alternatively, as an optimisation, a node that decapsulates a packet and immediately re-encapsulates it for the next tunnel MAY copy the incoming outer ECN field directly to the outgoing outer and the incoming inner ECN field directly to the outgoing inner. Then the overall behavior across the sequence of tunnel segments would still be consistent with RFC 6040.

Appendix C of RFC6040 describes how a tunnel egress can monitor how much congestion has been introduced within a tunnel. A network operator might want to monitor how much congestion had been introduced within a whole sequence of tunnels. Using the technique in Appendix C of RFC6040 at the final egress, the operator could monitor the whole sequence of tunnels, but only if the above optimisation were used consistently along the sequence of tunnels, in order to make it appear as a single tunnel. Therefore, tunnel endpoint implementations SHOULD allow the operator to configure whether this optimisation is enabled.

When ECN support is added to a subnet technology, consideration SHOULD be given to a similar optimisation between subnets in sequence if they all use the same technology.

4.6. Reframing and Congestion Markings

The guidance in this section is worded in terms of framing boundaries, but it applies equally whether the protocol data units are frames, cells or packets.

Where an AQM marks the ECN field of IP packets as they queue into a layer-2 link, there will be no problem with framing boundaries, because the ECN markings would be applied directly to IP packets. The guidance in this section is only applicable where an ECN capability is being added to a layer-2 protocol so that layer-2 frames can be ECN-marked by an AQM at layer-2. This would only be necessary where AQM will be applied at pure layer-2 nodes (without IP-awareness).

When layer-2 frame headers are stripped off and IP PDUs with different boundaries are forwarded, the provisions in RFC7141 for handling congestion indications when splitting or merging packets

apply (see Section 2.4 of [RFC7141]). Those provisions include: "The general rule to follow is that the number of octets in packets with congestion indications SHOULD be equivalent before and after merging or splitting." See RFC 7141 for the complete provisions and related discussion, including an exception to that general rule.

As also recommended in RFC 7141, the mechanism for propagating congestion indications SHOULD ensure that any new incoming congestion indication is propagated immediately, and not held awaiting possible arrival of further congestion indications sufficient to indicate congestion for all of the octets of an outgoing IP PDU.

5. Feed-Up-and-Forward Mode: Guidelines for Adding Congestion Notification

The guidance in this section is applicable, for example, when IP packets:

- o are encapsulated in Ethernet headers, which have no support for ECN;
- o are forwarded by the eNode-B (base station) of a 3GPP radio access network, which is required to apply ECN marking during congestion, [LTE-RA], [UTRAN], but the Packet Data Convergence Protocol (PDCP) that encapsulates the IP header over the radio access has no support for ECN.

This guidance also generalizes to encapsulation by other subnet technologies with no native support for explicit congestion notification at the lower layer, but with support for finding and processing an IP header. It is unlikely to be applicable or necessary for IP-in-IP encapsulation, where feed-forward-and-up mode based on [RFC6040] would be more appropriate.

Marking the IP header while switching at layer-2 (by using a layer-3 switch) or while forwarding in a radio access network seems to represent a layering violation. However, it can be considered as a benign optimisation if the guidelines below are followed. Feed-up-and-forward is certainly not a general alternative to implementing feed-forward congestion notification in the lower layer, because:

- o IPv4 and IPv6 are not the only layer-3 protocols that might be encapsulated by lower layer protocols
- o Link-layer encryption might be in use, making the layer-2 payload inaccessible

- o Many Ethernet switches do not have 'layer-3 switch' capabilities so they cannot read or modify an IP payload
- o It might be costly to find an IP header (v4 or v6) when it may be encapsulated by more than one lower layer header, e.g. Ethernet MAC in MAC ([IEEE802.1Q]; previously 802.1ah).

Nonetheless, configuring lower layer equipment to look for an ECN field in an encapsulated IP header is a useful optimisation. If the implementation follows the guidelines below, this optimisation does not have to be confined to a controlled environment such as within a data centre; it could usefully be applied on any network--even if the operator is not sure whether the above issues will never apply:

1. If a native lower-layer congestion notification mechanism exists for a subnet technology, it is safe to mix feed-up-and-forward with feed-forward-and-up on other switches in the same subnet. However, it will generally be more efficient to use the native mechanism.
 2. The depth of the search for an IP header SHOULD be limited. If an IP header is not found soon enough, or an unrecognized or unreadable header is encountered, the switch SHOULD resort to an alternative means of signalling congestion (e.g. drop, or the native lower layer mechanism if available).
 3. It is sufficient to use the first IP header found in the stack; the egress of the relevant tunnel can propagate congestion notification upwards to any more deeply encapsulated IP headers later.
6. Feed-Backward Mode: Guidelines for Adding Congestion Notification

It can be seen from Section 3.3 that congestion notification in a subnet using feed-backward mode has generally not been designed to be directly coupled with IP layer congestion notification. The subnet attempts to minimize congestion internally, and if the incoming load at the ingress exceeds the capacity somewhere through the subnet, the layer 3 buffer into the ingress backs up. Thus, a feed-backward mode subnet is in some sense similar to a null mode subnet, in that there is no need for any direct interaction between the subnet and higher layer congestion notification. Therefore no detailed protocol design guidelines are appropriate. Nonetheless, a more general guideline is appropriate:

A subnetwork technology intended to eventually interface to IP SHOULD NOT be designed using only the feed-backward mode, which is certainly best for a stand-alone subnet, but would need to be

modified to work efficiently as part of the wider Internet, because IP uses feed-forward-and-up mode.

The feed-backward approach at least works beneath IP, where the term 'works' is used only in a narrow functional sense because feed-backward can result in very inefficient and sluggish congestion control--except if it is confined to the subnet directly connected to the original data source, when it is faster than feed-forward. It would be valid to design a protocol that could work in feed-backward mode for paths that only cross one subnet, and in feed-forward-and-up mode for paths that cross subnets.

In the early days of TCP/IP, a similar feed-backward approach was tried for explicit congestion signalling, using source-quench (SQ) ICMP control packets. However, SQ fell out of favour and is now formally deprecated [RFC6633]. The main problem was that it is hard for a data source to tell the difference between a spoofed SQ message and a quench request from a genuine buffer on the path. It is also hard for a lower layer buffer to address an SQ message to the original source port number, which may be buried within many layers of headers, and possibly encrypted.

QCN (also known as backward congestion notification, BCN; see Sections 30--33 of [IEEE802.1Q]; previously known as 802.1Qau) uses a feed-backward mode structurally similar to ATM's relative rate mechanism. However, QCN confines its applicability to scenarios such as some data centres where all endpoints are directly attached by the same Ethernet technology. If a QCN subnet were later connected into a wider IP-based internetwork (e.g. when attempting to interconnect multiple data centres) it would suffer the inefficiency shown in Figure 3.

7. IANA Considerations

This memo includes no request to IANA.

8. Security Considerations

If a lower layer wire protocol is redesigned to include explicit congestion signalling in-band in the protocol header, care SHOULD be taken to ensure that the field used is specified as mutable during transit. Otherwise interior nodes signalling congestion would invalidate any authentication protocol applied to the lower layer header--by altering a header field that had been assumed as immutable.

The redesign of protocols that encapsulate IP in order to propagate congestion signals between layers raises potential signal integrity

concerns. Experimental or proposed approaches exist for assuring the end-to-end integrity of in-band congestion signals, e.g.:

- o Congestion exposure (ConEx) for networks to audit that their congestion signals are not being suppressed by other networks or by receivers, and for networks to police that senders are responding sufficiently to the signals, irrespective of the L4 transport protocol used [RFC7713].
- o A test for a sender to detect whether a network or the receiver is suppressing congestion signals (for example see 2nd para of Section 20.2 of [RFC3168]).

Given these end-to-end approaches are already being specified, it would make little sense to attempt to design hop-by-hop congestion signal integrity into a new lower layer protocol, because end-to-end integrity inherently achieves hop-by-hop integrity.

Section 6 gives vulnerability to spoofing as one of the reasons for deprecating feed-backward mode.

9. Conclusions

Following the guidance in this document enables ECN support to be extended to numerous protocols that encapsulate IP (v4 & v6) in a consistent way, so that IP continues to fulfil its role as an end-to-end interoperability layer. This includes:

- o A wide range of tunnelling protocols including those with various forms of shim header between two IP headers, possibly also separated by a L2 header;
- o A wide range of subnet technologies, particularly those that work in the same 'feed-forward-and-up' mode that is used to support ECN in IP and MPLS.

Guidelines have been defined for supporting propagation of ECN between Ethernet and IP on so-called Layer-3 Ethernet switches, using a 'feed-up-and-forward' mode. This approach could enable other subnet technologies to pass ECN signals into the IP layer, even if they do not support ECN natively.

Finally, attempting to add ECN to a subnet technology in feed-backward mode is deprecated except in special cases, due to its likely sluggish response to congestion.

10. Acknowledgements

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12. Comments Solicited

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Appendix A. Changes in This Version (to be removed by RFC Editor)

From ietf-12 to ietf-13

* Following 3rd tsvwg WGLC:

- + Formalized update to RFC 3819 in its own subsection (1.1) and referred to it in the abstract
- + Scope: Clarified that the specification of alternative ECN semantics using ECT(1) was not in RFC 4774, but rather in RFC 8311, and that the problem with using a DSCP to indicate alternative semantics has issues at domain boundaries as well as tunnels.
- + Terminology: tightened up definitions of ECN-PDU and Not-ECN-PDU, and removed definition of Congestion Baseline, given it was only used once.
- + Mentioned QCN where feed-backward is first introduced (S.3), referring forward to where it is discussed more deeply (S.4).
- + Clarified that IS-IS solution to adding ECN support to TRILL was not pursued
- + Completely rewrote the rationale for the guideline about a Standard Congestion Monitoring Baseline, to focus on standardization of the otherwise unknown scenario used, rather than the relative usefulness of the info in each approach
- + Explained the re-framing problem better and added fragmentation as another possible cause of the problem
- + Acknowledged new reviewers
- + Updated references, replaced citations of 802.1Qau and 802.1ah with rolled up 802.1Q, and added citations of Fat trees and Clos Networks
- + Numerous other editorial improvements

From ietf-11 to ietf-12

- * Updated references

From ietf-10 to ietf-11

- * Removed short section (was 3) 'Guidelines for All Cases' because it was out of scope, being covered by RFC 4774. Expanded the Scope section (1.2) to explain all this. Explained that the default encap/decap rules already support certain alternative semantics, particularly all three of the alternative semantics for ECT(1): equivalent to ECT(0) , higher severity than ECT(0), and unmarked but implying different marking semantics from ECT(0).
- * Clarified why the QCN example was being given even though not about increment deployment of ECN
- * Pointed to the spoofing issue with feed-backward mode from the Security Considerations section, to aid security review.
- * Removed any ambiguity in the word 'transport' throughout

From ietf-09 to ietf-10

- * Updated section 5.1 on "IP-in-IP tunnels with Shim Headers" to be consistent with updates to draft-ietf-tsvwg-rfc6040update-shim.
- * Removed reference to the ECN nonce, which has been made historic by RFC 8311
- * Removed "Open Issues" Appendix, given all have been addressed.

From ietf-08 to ietf-09

- * Updated para in Intro that listed all the IP-in-IP tunnelling protocols, to instead refer to draft-ietf-tsvwg-rfc6040update-shim
- * Updated section 5.1 on "IP-in-IP tunnels with Shim Headers" to summarize guidance that has evolved as rfc6040update-shim has developed.

From ietf-07 to ietf-08: Refreshed to avoid expiry. Updated references.

From ietf-06 to ietf-07:

- * Added the people involved in liaisons to the acknowledgements.

From ietf-05 to ietf-06:

- * Introduction: Added GUE and Geneve as examples of tightly coupled shims between IP headers that cite RFC 6040. And added VXLAN to list of those that do not.
- * Replaced normative text about tightly coupled shims between IP headers, with reference to new draft-ietf-tsvwg-rfc6040update-shim
- * Wire Protocol Design: Indication of ECN Support: Added TRILL as an example of a well-design protocol that does not need an indication of ECN support in the wire protocol.
- * Encapsulation Guidelines: In the case of a Not-ECN-PDU with a CE outer, replaced SHOULD be dropped, with explanations of when SHOULD or MUST are appropriate.
- * Feed-Up-and-Forward Mode: Explained examples more carefully, referred to PDCP and cited UTRAN spec as well as E-UTRAN.
- * Updated references.
- * Marked open issues as resolved, but did not delete Open Issues Appendix (yet).

From ietf-04 to ietf-05:

- * Explained why tightly coupled shim headers only "SHOULD" comply with RFC 6040, not "MUST".
- * Updated references

From ietf-03 to ietf-04:

- * Addressed Richard Scheffenegger's review comments: primarily editorial corrections, and addition of examples for clarity.

From ietf-02 to ietf-03:

- * Updated references, ad cited RFC4774.

From ietf-01 to ietf-02:

- * Added Section for guidelines that are applicable in all cases.
- * Updated references.

From ietf-00 to ietf-01: Updated references.

From briscoe-04 to ietf-00: Changed filename following tsvwg adoption.

From briscoe-03 to 04:

- * Re-arranged the introduction to describe the purpose of the document first before introducing ECN in more depth. And clarified the introduction throughout.
- * Added applicability to 3GPP TS 36.300.

From briscoe-02 to 03:

- * Scope section:
 - + Added dependence on correct propagation of traffic class information
 - + For the feed-backward mode, deemed multicast and anycast out of scope
- * Ensured all guidelines referring to subnet technologies also refer to tunnels and vice versa by adding applicability sentences at the start of sections 4.1, 4.2, 4.3, 4.4, 4.6 and 5.
- * Added Security Considerations on ensuring congestion signal fields are classed as immutable and on using end-to-end congestion signal integrity technologies rather than hop-by-hop.

From briscoe-01 to 02:

- * Added authors: JK & PT
- * Added
 - + Section 4.1 "IP-in-IP Tunnels with Tightly Coupled Shim Headers"
 - + Section 4.5 "Sequences of Similar Tunnels or Subnets"
 - + roadmap at the start of Section 4, given the subsections have become quite fragmented.
 - + Section 9 "Conclusions"

- * Clarified why transports are starting to be able to saturate interior links
- * Under Section 1.1, addressed the question of alternative signal semantics and included multicast & anycast.
- * Under Section 3.1, included a 3GPP example.
- * Section 4.2. "Wire Protocol Design":
 - + Altered guideline 2. to make it clear that it only applies to the immediate subnet egress, not later ones
 - + Added a reminder that it is only necessary to check that ECN propagates at the egress, not whether interior nodes mark ECN
 - + Added example of how QCN uses 802.1p to indicate support for QCN.
- * Added references to Appendix C of RFC6040, about monitoring the amount of congestion signals introduced within a tunnel
- * Appendix A: Added more issues to be addressed, including plan to produce a standards track update to IP-in-IP tunnel protocols.
- * Updated acks and references

From briscoe-00 to 01:

- * Intended status: BCP (was Informational) & updates 3819 added.
- * Briefer Introduction: Introductory para justifying benefits of ECN. Moved all but a brief enumeration of modes of operation to their own new section (from both Intro & Scope). Introduced incr. deployment as most tricky part.
- * Tightened & added to terminology section
- * Structured with Modes of Operation, then Guidelines section for each mode.
- * Tightened up guideline text to remove vagueness / passive voice / ambiguity and highlight main guidelines as numbered items.
- * Added Outstanding Document Issues Appendix

* Updated references

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November 13, 2017

Relaxing Restrictions on Explicit Congestion Notification (ECN)
Experimentation
draft-ietf-tsvwg-ecn-experimentation-08

Abstract

This memo updates RFC 3168, which specifies Explicit Congestion Notification (ECN) as an alternative to packet drops for indicating network congestion to endpoints. It relaxes restrictions in RFC 3168 that hinder experimentation towards benefits beyond just removal of loss. This memo summarizes the anticipated areas of experimentation and updates RFC 3168 to enable experimentation in these areas. An Experimental RFC in the IETF document stream is required to take advantage of any of these enabling updates. In addition, this memo makes related updates to the ECN specifications for RTP in RFC 6679 and for DCCP in RFC 4341, RFC 4342 and RFC 5622. This memo also records the conclusion of the ECN nonce experiment in RFC 3540, and provides the rationale for reclassification of RFC 3540 as Historic; this reclassification enables new experimental use of the ECT(1) codepoint.

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Table of Contents

1. Introduction	3
1.1. ECN Terminology	3
1.2. Requirements Language	4
2. ECN Experimentation: Overview	4
2.1. Effective Congestion Control is Required	5
2.2. Network Considerations for ECN Experimentation	5
2.3. Operational and Management Considerations	6
3. ECN Nonce and RFC 3540	7
4. Updates to RFC 3168	8
4.1. Congestion Response Differences	8
4.2. Congestion Marking Differences	9
4.3. TCP Control Packets and Retransmissions	12
5. ECN for RTP Updates to RFC 6679	13
6. ECN for DCCP Updates to RFCs 4341, 4342 and 5622	15
7. Acknowledgements	15
8. IANA Considerations	16
9. Security Considerations	16
10. References	16
10.1. Normative References	16

10.2. Informative References	17
Author's Address	21

1. Introduction

This memo updates RFC 3168 [RFC3168] which specifies Explicit Congestion Notification (ECN) as an alternative to packet drops for indicating network congestion to endpoints. It relaxes restrictions in RFC 3168 that hinder experimentation towards benefits beyond just removal of loss. This memo summarizes the proposed areas of experimentation and updates RFC 3168 to enable experimentation in these areas. An Experimental RFC in the IETF document stream [RFC4844] is required to take advantage of any of these enabling updates. Putting all of these updates into a single document enables experimentation to proceed without requiring a standards process exception for each Experimental RFC that needs changes to RFC 3168, a Proposed Standard RFC.

There is no need for this memo to update RFC 3168 to simplify standardization of protocols and mechanisms that are documented in Standards Track RFCs, as any Standards Track RFC can update RFC 3168 directly without either relying on updates in this memo or using a standards process exception.

In addition, this memo makes related updates to the ECN specification for RTP [RFC6679] and for three DCCP profiles ([RFC4341], [RFC4342] and [RFC5622]) for the same reason. Each experiment is still required to be documented in one or more separate RFCs, but use of Experimental RFCs for this purpose does not require a process exception to modify any of these Proposed Standard RFCs when the modification falls within the bounds established by this memo (RFC 5622 is an Experimental RFC; it is modified by this memo for consistency with modifications to the other two DCCP RFCs).

Some of the anticipated experimentation includes use of the ECT(1) codepoint that was dedicated to the ECN nonce experiment in RFC 3540 [RFC3540]. This memo records the conclusion of the ECN nonce experiment and provides the explanation for reclassification of RFC 3540 as Historic in order to enable new experimental use of the ECT(1) codepoint.

1.1. ECN Terminology

ECT: ECN-Capable Transport. One of the two codepoints ECT(0) or ECT(1) in the ECN field [RFC3168] of the IP header (v4 or v6). An ECN-capable sender sets one of these to indicate that both transport end-points support ECN.

Not-ECT: The ECN codepoint set by senders that indicates that the transport is not ECN-capable.

CE: Congestion Experienced. The ECN codepoint that an intermediate node sets to indicate congestion. A node sets an increasing proportion of ECT packets to CE as the level of congestion increases.

1.2. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119 [RFC2119].

2. ECN Experimentation: Overview

Three areas of ECN experimentation are covered by this memo; the cited Internet-Drafts should be consulted for the detailed goals and rationale of each proposed experiment:

Congestion Response Differences: An ECN congestion indication communicates a higher likelihood than a dropped packet that a short queue exists at the network bottleneck node [I-D.ietf-tcpm-alternativebackoff-ecn]. This difference suggests that for congestion indicated by ECN, a different sender congestion response (e.g., sender backs off by a smaller amount) may be appropriate by comparison to the sender response to congestion indicated by loss. Two examples of proposed sender congestion response changes are described in [I-D.ietf-tcpm-alternativebackoff-ecn] and [I-D.ietf-tsvwg-ecn-l4s-id] - the proposal in the latter draft couples the sender congestion response change to Congestion Marking Differences functionality (see next paragraph). These changes are at variance with RFC 3168's requirement that a sender's congestion control response to ECN congestion indications be the same as to drops. IETF approval, e.g., via an Experimental RFC in the IETF document stream, is required for any sender congestion response used in this area of experimentation. See Section 4.1 for further discussion.

Congestion Marking Differences: Congestion marking at network nodes can be configured to maintain very shallow queues in conjunction with a different sender response to congestion indications (CE marks), e.g., as proposed in [I-D.ietf-tsvwg-ecn-l4s-id]. The traffic involved needs to be identified by the senders to the network nodes in order to avoid damage to other network traffic whose senders do not expect the more frequent congestion marking used to maintain very shallow queues. Use of different ECN

codepoints, specifically ECT(0) and ECT(1), is a promising means of traffic identification for this purpose, but that technique is at variance with RFC 3168's requirement that ECT(0)-marked traffic and ECT(1)-marked traffic not receive different treatment in the network. IETF approval, e.g., via an Experimental RFC in the IETF document stream, is required for any differences in congestion marking or sender congestion response used in this area of experimentation. See Section 4.2 for further discussion.

TCP Control Packets and Retransmissions: RFC 3168 limits the use of ECN with TCP to data packets, excluding retransmissions. With the successful deployment of ECN in large portions of the Internet, there is interest in extending the benefits of ECN to TCP control packets (e.g., SYNs) and retransmitted packets, e.g., as proposed in [I-D.bagnulo-tcpm-generalized-ecn]. This is at variance with RFC 3168's prohibition of use of ECN for TCP control packets and retransmitted packets. See Section 4.3 for further discussion.

The scope of this memo is limited to these three areas of experimentation. This memo expresses no view on the likely outcomes of the proposed experiments and does not specify the experiments in detail. Additional experiments in these areas are possible, e.g., on use of ECN to support deployment of a protocol similar to DCTCP [I-D.ietf-tcpm-dctcp] beyond DCTCP's current applicability that is limited to data center environments. The purpose of this memo is to remove constraints in standards track RFCs that stand in the way of these areas of experimentation.

2.1. Effective Congestion Control is Required

Congestion control remains an important aspect of the Internet architecture [RFC2914]. Any Experimental RFC in the IETF document stream that takes advantage of this memo's updates to any RFC is required to discuss the congestion control implications of the experiment(s) in order to provide assurance that deployment of the experiment(s) does not pose a congestion-based threat to the operation of the Internet.

2.2. Network Considerations for ECN Experimentation

ECN functionality [RFC3168] is becoming widely deployed in the Internet and is being designed into additional protocols such as TRILL [I-D.ietf-trill-ecn-support]. ECN experiments are expected to coexist with deployed ECN functionality, with the responsibility for that coexistence falling primarily upon designers of experimental changes to ECN. In addition, protocol designers and implementers, as well as network operators, may desire to anticipate and/or support

ECN experiments. The following guidelines will help avoid conflicts with the areas of ECN experimentation enabled by this memo:

1. RFC 3168's forwarding behavior remains the preferred approach for routers that are not involved in ECN experiments, in particular continuing to treat the ECT(0) and ECT(1) codepoints as equivalent, as specified in Section 4.2 below.
2. Network nodes that forward packets SHOULD NOT assume that the ECN CE codepoint indicates that the packet would have been dropped if ECN were not in use. This is because Congestion Response Differences experiments employ different congestion responses to dropped packets by comparison to receipt of CE-marked packets (see Section 4.1 below), so CE-marked packets SHOULD NOT be arbitrarily dropped. A corresponding difference in congestion responses already occurs when the ECN field is used for Pre-Congestion Notification (PCN) [RFC6660].
3. A network node MUST NOT originate traffic marked with ECT(1) unless the network node is participating in a Congestion Marking Differences experiment that uses ECT(1), as specified in Section 4.2 below.

Some ECN experiments use ECN with packets where it has not been used previously, specifically TCP control packets and retransmissions, see Section 4.3 below, and in particular its new requirements for middlebox behavior. In general, any system or protocol that inspects or monitors network traffic SHOULD be prepared to encounter ECN usage on packets and traffic that currently do not use ECN.

ECN field handling requirements for tunnel encapsulation and decapsulation are specified in [RFC6040] which is in the process of being updated by [I-D.ietf-tsvwg-rfc6040update-shim]. Related guidance for encapsulations whose outer headers are not IP headers can be found in [I-D.ietf-tsvwg-ecn-encap-guidelines]. These requirements and guidance apply to all traffic, including traffic that is part of any ECN experiment.

2.3. Operational and Management Considerations

Changes in network traffic behavior that result from ECN experimentation are likely to impact network operations and management. Designers of ECN experiments are expected to anticipate possible impacts and consider how they may be dealt with. Specific topics to consider include possible network management changes or extensions, monitoring of the experimental deployment, collection of data for evaluation of the experiment and possible interactions with

other protocols, particularly protocols that encapsulate network traffic.

For further discussion, see [RFC5706]; the questions in Appendix A of RFC 5706 provide a concise survey of some important aspects to consider.

3. ECN Nonce and RFC 3540

As specified in RFC 3168, ECN uses two ECN Capable Transport (ECT) codepoints to indicate that a packet supports ECN, ECT(0) and ECT(1). RFC 3168 assigned the second codepoint, ECT(1), to support ECN nonce functionality that discourages receivers from exploiting ECN to improve their throughput at the expense of other network users. That ECN nonce functionality is fully specified in Experimental RFC 3540 [RFC3540]. This section explains why RFC 3540 is being reclassified as Historic and makes associated updates to RFC 3168.

While the ECN nonce works as specified, and has been deployed in limited environments, widespread usage in the Internet has not materialized. A study of the ECN behaviour of the top one million web servers using 2014 data [Trammell15] found that after ECN was negotiated, none of the 581,711 IPv4 servers tested were using both ECT codepoints, which would have been a possible sign of ECN nonce usage. Of the 17,028 IPv6 servers tested, 4 set both ECT(0) and ECT(1) on data packets. This might have been evidence of use of the ECN nonce by these 4 servers, but might equally have been due to erroneous re-marking of the ECN field by a middlebox or router.

With the emergence of new experimental functionality that depends on use of the ECT(1) codepoint for other purposes, continuing to reserve that codepoint for the ECN nonce experiment is no longer justified. In addition, other approaches to discouraging receivers from exploiting ECN have emerged, see Appendix B.1 of [I-D.ietf-tsvwg-ecn-l4s-id]. Therefore, in support of ECN experimentation with the ECT(1) codepoint, this memo:

- o Declares that the ECN nonce experiment [RFC3540] has concluded, and notes the absence of widespread deployment.
- o Updates RFC 3168 [RFC3168] to remove discussion of the ECN nonce and use of ECT(1) for that nonce.

The four primary updates to RFC 3168 that remove discussion of the ECN nonce and use of ECT(1) for that nonce are:

1. Remove the paragraph in Section 5 that immediately follows Figure 1; this paragraph discusses the ECN nonce as the motivation for two ECT codepoints.
2. Remove Section 11.2 "A Discussion of the ECN nonce." in its entirety.
3. Remove the last paragraph of Section 12, which states that ECT(1) may be used as part of the implementation of the ECN nonce.
4. Remove the first two paragraphs of Section 20.2, which discuss the ECN nonce and alternatives. No changes are made to the rest of Section 20.2, which discusses alternative uses for the fourth ECN codepoint.

In addition, other less substantive RFC 3168 changes are required to remove all other mentions of the ECN nonce and to remove implications that ECT(1) is intended for use by the ECN nonce; these specific text updates are omitted for brevity.

4. Updates to RFC 3168

The following subsections specify updates to RFC 3168 to enable the three areas of experimentation summarized in Section 2.

4.1. Congestion Response Differences

RFC 3168 specifies that senders respond identically to packet drops and ECN congestion indications. ECN congestion indications are predominately originated by Active Queue Management (AQM) mechanisms in intermediate buffers. AQM mechanisms are usually configured to maintain shorter queue lengths than non-AQM based mechanisms, particularly non-AQM drop-based mechanisms such as tail-drop, as AQM mechanisms indicate congestion before the queue overflows. While the occurrence of loss does not easily enable the receiver to determine if AQM is used, the receipt of an ECN Congestion Experienced (CE) mark conveys a strong likelihood that AQM was used to manage the bottleneck queue. Hence an ECN congestion indication communicates a higher likelihood than a dropped packet that a short queue exists at the network bottleneck node [I-D.ietf-tcpm-alternativebackoff-ecn]. This difference suggests that for congestion indicated by ECN, a different sender congestion response (e.g., sender backs off by a smaller amount) may be appropriate by comparison to the sender response to congestion indicated by loss. However, section 5 of RFC 3168 specifies that:

Upon the receipt by an ECN-Capable transport of a single CE packet, the congestion control algorithms followed at the end-

systems MUST be essentially the same as the congestion control response to a **single** dropped packet.

This memo updates this RFC 3168 text to allow the congestion control response (including the TCP Sender's congestion control response) to a CE-marked packet to differ from the response to a dropped packet, provided that the changes from RFC 3168 are documented in an Experimental RFC in the IETF document stream. The specific change to RFC 3168 is to insert the words "unless otherwise specified by an Experimental RFC in the IETF document stream" at the end of the sentence quoted above.

RFC 4774 [RFC4774] quotes the above text from RFC 3168 as background, but does not impose requirements based on that text. Therefore no update to RFC 4774 is required to enable this area of experimentation.

Section 6.1.2 of RFC 3168 specifies that:

If the sender receives an ECN-Echo (ECE) ACK packet (that is, an ACK packet with the ECN-Echo flag set in the TCP header), then the sender knows that congestion was encountered in the network on the path from the sender to the receiver. The indication of congestion should be treated just as a congestion loss in non-ECN-Capable TCP. That is, the TCP source halves the congestion window "cwnd" and reduces the slow start threshold "ssthresh".

This memo also updates this RFC 3168 text to allow the congestion control response (including the TCP Sender's congestion control response) to a CE-marked packet to differ from the response to a dropped packet, provided that the changes from RFC 3168 are documented in an Experimental RFC in the IETF document stream. The specific change to RFC 3168 is to insert the words "Unless otherwise specified by an Experimental RFC in the IETF document stream" at the beginning of the second sentence quoted above.

4.2. Congestion Marking Differences

Taken to its limit, an AQM algorithm that uses ECN congestion indications can be configured to maintain very shallow queues, thereby reducing network latency by comparison to maintaining a larger queue. Significantly more aggressive sender responses to ECN are needed to make effective use of such very shallow queues; Datacenter TCP (DCTCP) [I-D.ietf-tcpm-dctcp] provides an example. In this case, separate network node treatments are essential, both to prevent the aggressive low latency traffic from starving conventional traffic (if present) and to prevent any conventional traffic disruption to any lower latency service that uses the very shallow

queues. Use of different ECN codepoints is a promising means of identifying these two classes of traffic to network nodes, and hence this area of experimentation is based on the use of the ECT(1) codepoint to request ECN congestion marking behavior in the network that differs from ECT(0). It is essential that any such change in ECN congestion marking behavior be counterbalanced by use of a different IETF-approved congestion response to CE marks at the sender, e.g., as proposed in [I-D.ietf-tsvwg-ecn-l4s-id].

Section 5 of RFC 3168 specifies that:

Routers treat the ECT(0) and ECT(1) codepoints as equivalent.

This memo updates RFC 3168 to allow routers to treat the ECT(0) and ECT(1) codepoints differently, provided that the changes from RFC 3168 are documented in an Experimental RFC in the IETF document stream. The specific change to RFC 3168 is to insert the words "unless otherwise specified by an Experimental RFC in the IETF document stream" at the end of the above sentence.

When an AQM is configured to use ECN congestion indications to maintain a very shallow queue, congestion indications are marked on packets that would not have been dropped if ECN was not in use. Section 5 of RFC 3168 specifies that:

For a router, the CE codepoint of an ECN-Capable packet SHOULD only be set if the router would otherwise have dropped the packet as an indication of congestion to the end nodes. When the router's buffer is not yet full and the router is prepared to drop a packet to inform end nodes of incipient congestion, the router should first check to see if the ECT codepoint is set in that packet's IP header. If so, then instead of dropping the packet, the router MAY instead set the CE codepoint in the IP header.

This memo updates RFC 3168 to allow congestion indications that are not equivalent to drops, provided that the changes from RFC 3168 are documented in an Experimental RFC in the IETF document stream. The specific change is to change "For a router," to "Unless otherwise specified by an Experimental RFC in the IETF document stream" at the beginning of the first sentence of the above paragraph.

A larger update to RFC 3168 is necessary to enable sender usage of ECT(1) to request network congestion marking behavior that maintains very shallow queues at network nodes. When using loss as a congestion signal, the number of signals provided should be reduced to a minimum and hence only presence or absence of congestion is communicated. In contrast, ECN can provide a richer signal, e.g., to indicate the current level of congestion, without the disadvantage of

a larger number of packet losses. A proposed experiment in this area, Low Latency Low Loss Scalable throughput (L4S) [I-D.ietf-tsvwg-ecn-l4s-id] significantly increases the CE marking probability for ECT(1)-marked traffic in a fashion that would interact badly with existing sender congestion response functionality because that functionality assumes that the network marks ECT packets as frequently as it would drop Not-ECT packets. If network traffic that uses such a conventional sender congestion response were to encounter L4S's increased marking probability (and hence rate) at a network bottleneck queue, the resulting traffic throughput is likely to be much less than intended for the level of congestion at the bottleneck queue.

This memo updates RFC 3168 to remove that interaction for ECT(1). The specific update to Section 5 of RFC 3168 is to replace the following two paragraphs:

Senders are free to use either the ECT(0) or the ECT(1) codepoint to indicate ECT, on a packet-by-packet basis.

The use of both the two codepoints for ECT, ECT(0) and ECT(1), is motivated primarily by the desire to allow mechanisms for the data sender to verify that network elements are not erasing the CE codepoint, and that data receivers are properly reporting to the sender the receipt of packets with the CE codepoint set, as required by the transport protocol. Guidelines for the senders and receivers to differentiate between the ECT(0) and ECT(1) codepoints will be addressed in separate documents, for each transport protocol. In particular, this document does not address mechanisms for TCP end-nodes to differentiate between the ECT(0) and ECT(1) codepoints. Protocols and senders that only require a single ECT codepoint SHOULD use ECT(0).

with this paragraph:

Protocols and senders MUST use the ECT(0) codepoint to indicate ECT unless otherwise specified by an Experimental RFC in the IETF document stream. Protocols and senders MUST NOT use the ECT(1) codepoint to indicate ECT unless otherwise specified by an Experimental RFC in the IETF document stream. Guidelines for senders and receivers to differentiate between the ECT(0) and ECT(1) codepoints will be addressed in separate documents, for each transport protocol. In particular, this document does not address mechanisms for TCP end-nodes to differentiate between the ECT(0) and ECT(1) codepoints.

Congestion Marking Differences experiments SHOULD modify the network behavior for ECT(1)-marked traffic rather than ECT(0)-marked traffic

if network behavior for only one ECT codepoint is modified. Congestion Marking Differences experiments MUST NOT modify the network behavior for ECT(0)-marked traffic in a fashion that requires changes to sender congestion response to obtain desired network behavior. If a Congestion Marking Differences experiment modifies the network behavior for ECT(1)-marked traffic, e.g., CE-marking behavior, in a fashion that requires changes to sender congestion response to obtain desired network behavior, then the Experimental RFC in the IETF document stream for that experiment MUST specify:

- o The sender congestion response to CE marking in the network, and
- o Router behavior changes, or the absence thereof, in forwarding CE-marked packets that are part of the experiment.

In addition, this memo updates RFC 3168 to remove discussion of the ECN nonce, as noted in Section 3 above.

4.3. TCP Control Packets and Retransmissions

With the successful use of ECN for traffic in large portions of the Internet, there is interest in extending the benefits of ECN to TCP control packets (e.g., SYNs) and retransmitted packets, e.g., as proposed by ECN++ [I-D.bagnulo-tcpm-generalized-ecn].

RFC 3168 prohibits use of ECN for TCP control packets and retransmitted packets in a number of places:

- o "To ensure the reliable delivery of the congestion indication of the CE codepoint, an ECT codepoint MUST NOT be set in a packet unless the loss of that packet in the network would be detected by the end nodes and interpreted as an indication of congestion." (Section 5.2)
- o "A host MUST NOT set ECT on SYN or SYN-ACK packets." (Section 6.1.1)
- o "pure acknowledgement packets (e.g., packets that do not contain any accompanying data) MUST be sent with the not-ECT codepoint." (Section 6.1.4)
- o "This document specifies ECN-capable TCP implementations MUST NOT set either ECT codepoint (ECT(0) or ECT(1)) in the IP header for retransmitted data packets, and that the TCP data receiver SHOULD ignore the ECN field on arriving data packets that are outside of the receiver's current window." (Section 6.1.5)

- o "the TCP data sender MUST NOT set either an ECT codepoint or the CWR bit on window probe packets." (Section 6.1.6)

This memo updates RFC 3168 to allow the use of ECT codepoints on SYN and SYN-ACK packets, pure acknowledgement packets, window probe packets and retransmissions of packets that were originally sent with an ECT codepoint, provided that the changes from RFC 3168 are documented in an Experimental RFC in the IETF document stream. The specific change to RFC 3168 is to insert the words "unless otherwise specified by an Experimental RFC in the IETF document stream" at the end of each sentence quoted above.

In addition, beyond requiring TCP senders not to set ECT on TCP control packets and retransmitted packets, RFC 3168 is silent on whether it is appropriate for a network element, e.g. a firewall, to discard such a packet as invalid. For this area of ECN experimentation to be useful, middleboxes ought not to do that, therefore RFC 3168 is updated by adding the following text to the end of Section 6.1.1.1 on Middlebox Issues:

Unless otherwise specified by an Experimental RFC in the IETF document stream, middleboxes SHOULD NOT discard TCP control packets and retransmitted TCP packets solely because the ECN field in the IP header does not contain Not-ECT. An exception to this requirement occurs in responding to an attack that uses ECN codepoints other than Not-ECT. For example, as part of the response, it may be appropriate to drop ECT-marked TCP SYN packets with higher probability than TCP SYN packets marked with not-ECT. Any such exceptional discarding of TCP control packets and retransmitted TCP packets in response to an attack MUST NOT be done routinely in the absence of an attack and SHOULD only be done if it is determined that the use of ECN is contributing to the attack.

5. ECN for RTP Updates to RFC 6679

RFC 6679 [RFC6679] specifies use of ECN for RTP traffic; it allows use of both the ECT(0) and ECT(1) codepoints, and provides the following guidance on use of these codepoints in section 7.3.1 :

The sender SHOULD mark packets as ECT(0) unless the receiver expresses a preference for ECT(1) or for a random ECT value using the "ect" parameter in the "a=ecn-capable-rtp:" attribute.

The Congestion Marking Differences area of experimentation increases the potential consequences of using ECT(1) instead of ECT(0), and hence the above guidance is updated by adding the following two sentences:

Random ECT values MUST NOT be used, as that may expose RTP to differences in network treatment of traffic marked with ECT(1) and ECT(0) and differences in associated endpoint congestion responses. In addition, ECT(0) MUST be used unless otherwise specified in an Experimental RFC in the IETF document stream.

Section 7.3.3 of RFC 6679 specifies RTP's response to receipt of CE marked packets as being identical to the response to dropped packets:

The reception of RTP packets with ECN-CE marks in the IP header is a notification that congestion is being experienced. The default reaction on the reception of these ECN-CE-marked packets MUST be to provide the congestion control algorithm with a congestion notification that triggers the algorithm to react as if packet loss had occurred. There should be no difference in congestion response if ECN-CE marks or packet drops are detected.

In support of Congestion Response Differences experimentation, this memo updates this text in a fashion similar to RFC 3168 to allow the RTP congestion control response to a CE-marked packet to differ from the response to a dropped packet, provided that the changes from RFC 6679 are documented in an Experimental RFC in the IETF document stream. The specific change to RFC 6679 is to insert the words "Unless otherwise specified by an Experimental RFC in the IETF document stream" and reformat the last two sentences to be subject to that condition, i.e.:

The reception of RTP packets with ECN-CE marks in the IP header is a notification that congestion is being experienced. Unless otherwise specified by an Experimental RFC in the IETF document stream:

- * The default reaction on the reception of these ECN-CE-marked packets MUST be to provide the congestion control algorithm with a congestion notification that triggers the algorithm to react as if packet loss had occurred.
- * There should be no difference in congestion response if ECN-CE marks or packet drops are detected.

The second sentence of the immediately following paragraph in RFC 6679 requires a related update:

Other reactions to ECN-CE may be specified in the future, following IETF Review. Detailed designs of such additional reactions MUST be specified in a Standards Track RFC and be reviewed to ensure they are safe for deployment under any restrictions specified.

The update is to change "Standards Track RFC" to "Standards Track RFC or Experimental RFC in the IETF document stream" for consistency with the first update.

6. ECN for DCCP Updates to RFCs 4341, 4342 and 5622

The specifications of the three DCCP Congestion Control IDs (CCIDs) 2 [RFC4341], 3 [RFC4342] and 4 [RFC5622] contain broadly the same wording as follows:

each DCCP-Data and DCCP-DataAck packet is sent as ECN Capable with either the ECT(0) or the ECT(1) codepoint set.

This memo updates these sentences in each of the three RFCs as follows:

each DCCP-Data and DCCP-DataAck packet is sent as ECN Capable. Unless otherwise specified by an Experimental RFC in the IETF document stream, such DCCP senders MUST set the ECT(0) codepoint.

In support of Congestion Marking Differences experimentation (as noted in Section 3), this memo also updates all three of these RFCs to remove discussion of the ECN nonce. The specific text updates are omitted for brevity.

7. Acknowledgements

The content of this draft, including the specific portions of RFC 3168 that are updated draws heavily from [I-D.khademi-tsvwg-ecn-response], whose authors are gratefully acknowledged. The authors of the Internet Drafts describing the experiments have motivated the production of this memo - their interest in innovation is welcome and heartily acknowledged. Colin Perkins suggested updating RFC 6679 on RTP and provided guidance on where to make the updates.

The draft has been improved as a result of comments from a number of reviewers, including Ben Campbell, Brian Carpenter, Benoit Claise, Spencer Dawkins, Gorby Fairhurst, Sue Hares, Ingemar Johansson, Naeem Khademi, Mirja Kuehlewind, Karen Nielsen, Hilarie Orman, Eric Rescorla, Adam Roach and Michael Welzl. Bob Briscoe's thorough reviews of multiple versions of this memo resulted in numerous improvements including addition of the updates to the DCCP RFCs.

8. IANA Considerations

To reflect the reclassification of RFC 3540 as Historic, IANA is requested to update the Transmission Control Protocol (TCP) Header Flags registry (<https://www.iana.org/assignments/tcp-header-flags/tcp-header-flags.xhtml#tcp-header-flags-1>) to remove the registration of bit 7 as the NS (Nonce Sum) bit and add an annotation to the registry to state that bit 7 was used by Historic RFC 3540 as the NS (Nonce Sum) bit.

9. Security Considerations

As a process memo that only relaxes restrictions on experimentation, there are no protocol security considerations, as security considerations for any experiments that take advantage of the relaxed restrictions are discussed in the Internet-Drafts that propose the experiments.

However, effective congestion control is crucial to the continued operation of the Internet, and hence this memo places the responsibility for not breaking Internet congestion control on the experiments and the experimenters who propose them. This responsibility includes the requirement to discuss congestion control implications in an IETF document stream Experimental RFC for each experiment, as stated in Section 2.1; review of that discussion by the IETF community and the IESG prior to RFC publication is intended to provide assurance that each experiment does not break Internet congestion control.

See Appendix C.1 of [I-D.ietf-tsvwg-ecn-l4s-id] for discussion of alternatives to the ECN nonce.

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In Proc Passive & Active Measurement (PAM'15) Conference (2015)

Appendix A. Change History

[To be removed before RFC publication.]

Changes from draft-ietf-tsvwg-ecn-experimentation-00 to -01:

- o Add mention of DCTCP as another protocol that could benefit from ECN experimentation (near end of Section 2).

Changes from draft-ietf-tsvwg-ecn-experimentation-01 to -02:

- o Generalize to describe rationale for areas of experimentation, with less focus on individual experiments
- o Add ECN terminology section
- o Change name of "ECT Differences" experimentation area to "Congestion Marking Differences"
- o Add overlooked RFC 3168 modification to Section 4.1
- o Clarify text for Experimental RFC exception to ECT(1) non-usage requirement

- o Add explanation of exception to "SHOULD NOT drop" requirement in 4.3
- o Rework RFC 3540 status change text to provide rationale for a separate status change document that makes RFC 3540 Historic. Don't obsolete RFC 3540.
- o Significant editorial changes based on reviews by Mirja Kuehlewind, Michael Welzl and Bob Briscoe.

Changes from draft-ietf-tsvwg-ecn-experimentation-02 to -03:

- o Remove change history prior to WG adoption.
- o Update L4S draft reference to reflect TSVWG adoption of draft.
- o Change the "SHOULD" for DCCP sender use of ECT(0) to a "MUST" (overlooked in earlier editing).
- o Other minor edits.

Changes from draft-ietf-tsvwg-ecn-experimentation-03 to -04:

- o Change name of "Generalized ECN" experimentation area to "TCP Control Packets and Retransmissions."
- o Add IANA Considerations text to request removal of the registration of the NS bit in the TCP header.

Changes from draft-ietf-tsvwg-ecn-experimentation-04 to -05:

- o Minor editorial changes from Area Director review

Changes from draft-ietf-tsvwg-ecn-experimentation-05 to -06:

- o Add summary of RFC 3168 changes to remove the ECN nonce, and use lower-case "nonce" instead of "Nonce" to match RFC 3168 usage.
- o Add security considerations sentence to indicate that review of Experimental RFCs prior to publication approval is the means to ensure that congestion control is not broken by experiments.
- o Other minor editorial changes from IETF Last Call

Changes from draft-ietf-tsvwg-ecn-experimentation-06 to -07:

- o Change draft title to make scope clear - this only covers relaxing of restrictions on ECN experimentation.

- o Any Experimental RFC that takes advantage of this memo has to be in the IETF document stream.
- o Added sections 2.2 and 2.3 on considerations for other protocols and O&M, relocated discussion of congestion control requirement to section 2.1 from section 4.4
- o Remove text indicating that ECT(1) may be assigned to L4S - the requirement for an Experimental RFC suffices to ensure that coordination with L4S will occur.
- o Improve explanation of attack response exception to not dropping packets "solely because the ECN field in the IP header does not contain Not-ECT" in Section 4.3
- o Fix L4S draft reference for discussion of ECN Nonce alternatives - it's Appendix C.1, not B.1.
- o Numerous additional editorial changes from IESG Evaluation

Changes from draft-ietf-tsvwg-ecn-experimentation-07 to -08:

- o Edits from another careful review by Bob Briscoe. The primary change is an editorial rewrite of Section 2.2 including changing its name to better reflect its content.

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Stream Control Transmission Protocol (SCTP) Network Address Translation
Support
draft-ietf-tsvwg-natsupp-23

Abstract

The Stream Control Transmission Protocol (SCTP) provides a reliable communications channel between two end-hosts in many ways similar to the Transmission Control Protocol (TCP). With the widespread deployment of Network Address Translators (NAT), specialized code has been added to NAT functions for TCP that allows multiple hosts to reside behind a NAT function and yet share a single IPv4 address, even when two hosts (behind a NAT function) choose the same port numbers for their connection. This additional code is sometimes classified as Network Address and Port Translation (NAPT).

This document describes the protocol extensions needed for the SCTP endpoints and the mechanisms for NAT functions necessary to provide similar features of NAPT in the single point and multipoint traversal scenario.

Finally, a YANG module for SCTP NAT is defined.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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Table of Contents

1. Introduction	3
2. Conventions	5
3. Terminology	5
4. Motivation and Overview	6
4.1. SCTP NAT Traversal Scenarios	6
4.1.1. Single Point Traversal	7
4.1.2. Multipoint Traversal	7
4.2. Limitations of Classical NAPT for SCTP	8
4.3. The SCTP-Specific Variant of NAT	8
5. Data Formats	13
5.1. Modified Chunks	13
5.1.1. Extended ABORT Chunk	13
5.1.2. Extended ERROR Chunk	14
5.2. New Error Causes	14
5.2.1. VTag and Port Number Collision Error Cause	14
5.2.2. Missing State Error Cause	15
5.2.3. Port Number Collision Error Cause	15
5.3. New Parameters	16
5.3.1. Disable Restart Parameter	16
5.3.2. VTags Parameter	17
6. Procedures for SCTP Endpoints and NAT Functions	18
6.1. Association Setup Considerations for Endpoints	19
6.2. Handling of Internal Port Number and Verification Tag Collisions	19
6.2.1. NAT Function Considerations	19
6.2.2. Endpoint Considerations	20
6.3. Handling of Internal Port Number Collisions	20
6.3.1. NAT Function Considerations	20
6.3.2. Endpoint Considerations	21
6.4. Handling of Missing State	21
6.4.1. NAT Function Considerations	22
6.4.2. Endpoint Considerations	22

6.5.	Handling of Fragmented SCTP Packets by NAT Functions . .	24
6.6.	Multi Point Traversal Considerations for Endpoints . . .	24
7.	SCTP NAT YANG Module	24
7.1.	Tree Structure	24
7.2.	YANG Module	25
8.	Various Examples of NAT Traversals	27
8.1.	Single-homed Client to Single-homed Server	28
8.2.	Single-homed Client to Multi-homed Server	30
8.3.	Multihomed Client and Server	32
8.4.	NAT Function Loses Its State	35
8.5.	Peer-to-Peer Communications	37
9.	Socket API Considerations	42
9.1.	Get or Set the NAT Friendliness (SCTP_NAT_FRIENDLY) . . .	43
10.	IANA Considerations	43
10.1.	New Chunk Flags for Two Existing Chunk Types	43
10.2.	Three New Error Causes	45
10.3.	Two New Chunk Parameter Types	46
10.4.	One New URI	46
10.5.	One New YANG Module	46
11.	Security Considerations	46
12.	Normative References	47
13.	Informative References	48
	Acknowledgments	51
	Authors' Addresses	51

1. Introduction

Stream Control Transmission Protocol (SCTP) [RFC4960] provides a reliable communications channel between two end-hosts in many ways similar to TCP [RFC0793]. With the widespread deployment of Network Address Translators (NAT), specialized code has been added to NAT functions for TCP that allows multiple hosts to reside behind a NAT function using private-use addresses (see [RFC6890]) and yet share a single IPv4 address, even when two hosts (behind a NAT function) choose the same port numbers for their connection. This additional code is sometimes classified as Network Address and Port Translation (NAPT). Please note that this document focuses on the case where the NAT function maps a single or multiple internal addresses to a single external address and vice versa.

To date, specialized code for SCTP has not yet been added to most NAT functions so that only a translation of IP addresses is supported. The end result of this is that only one SCTP-capable host can successfully operate behind such a NAT function and this host can only be single-homed. The only alternative for supporting legacy NAT functions is to use UDP encapsulation as specified in [RFC6951].

The NAT function in the document refers to NAPT functions described in Section 2.2 of [RFC3022], NAT64 [RFC6146], or DS-Lite AFTR [RFC6333].

This document specifies procedures allowing a NAT function to support SCTP by providing similar features to those provided by a NAPT for TCP (see [RFC5382] and [RFC7857]), UDP (see [RFC4787] and [RFC7857]), and ICMP (see [RFC5508] and [RFC7857]). This document also specifies a set of data formats for SCTP packets and a set of SCTP endpoint procedures to support NAT traversal. An SCTP implementation supporting these procedures can assure that in both single-homed and multi-homed cases a NAT function will maintain the appropriate state without the NAT function needing to change port numbers.

It is possible and desirable to make these changes for a number of reasons:

- * It is desirable for SCTP internal end-hosts on multiple platforms to be able to share a NAT function's external IP address in the same way that a TCP session can use a NAT function.
- * If a NAT function does not need to change any data within an SCTP packet, it will reduce the processing burden of NAT'ing SCTP by not needing to execute the CRC32c checksum used by SCTP.
- * Not having to touch the IP payload makes the processing of ICMP messages by NAT functions easier.

An SCTP-aware NAT function will need to follow these procedures for generating appropriate SCTP packet formats.

When considering SCTP-aware NAT it is possible to have multiple levels of support. At each level, the Internal Host, Remote Host, and NAT function does or does not support the procedures described in this document. The following table illustrates the results of the various combinations of support and if communications can occur between two endpoints.

Internal Host	NAT Function	Remote Host	Communication
Support	Support	Support	Yes
Support	Support	No Support	Limited
Support	No Support	Support	None
Support	No Support	No Support	None
No Support	Support	Support	Limited
No Support	Support	No Support	Limited
No Support	No Support	Support	None
No Support	No Support	No Support	None

Table 1: Communication possibilities

From the table it can be seen that no communication can occur when a NAT function does not support SCTP-aware NAT. This assumes that the NAT function does not handle SCTP packets at all and all SCTP packets sent from behind a NAT function are discarded by the NAT function. In some cases, where the NAT function supports SCTP-aware NAT, but one of the two hosts does not support the feature, communication can possibly occur in a limited way. For example, only one host can have a connection when a collision case occurs.

2. Conventions

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

3. Terminology

This document uses the following terms, which are depicted in Figure 1. Familiarity with the terminology used in [RFC4960] and [RFC5061] is assumed.

Internal-Address (Int-Addr)

An internal address that is known to the internal host.

Internal-Port (Int-Port)
The port number that is in use by the host holding the Internal-Address.

Internal-VTag (Int-VTag)
The SCTP Verification Tag (VTag) (see Section 3.1 of [RFC4960]) that the internal host has chosen for an association. The VTag is a unique 32-bit tag that accompanies any incoming SCTP packet for this association to the Internal-Address.

Remote-Address (Rem-Addr)
The address that an internal host is attempting to contact.

Remote-Port (Rem-Port)
The port number used by the host holding the Remote-Address.

Remote-VTag (Rem-VTag)
The Verification Tag (VTag) (see Section 3.1 of [RFC4960]) that the host holding the Remote-Address has chosen for an association. The VTag is a unique 32-bit tag that accompanies any outgoing SCTP packet for this association to the Remote-Address.

External-Address (Ext-Addr)
An external address assigned to the NAT function, that it uses as a source address when sending packets towards a Remote-Address.

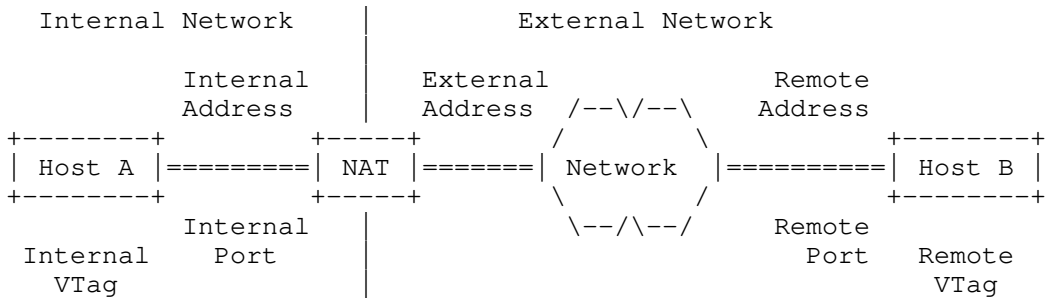


Figure 1: Basic Network Setup

4. Motivation and Overview

4.1. SCTP NAT Traversal Scenarios

This section defines the notion of single and multipoint NAT traversal.

4.1.1. Single Point Traversal

In this case, all packets in the SCTP association go through a single NAT function, as shown in Figure 2.

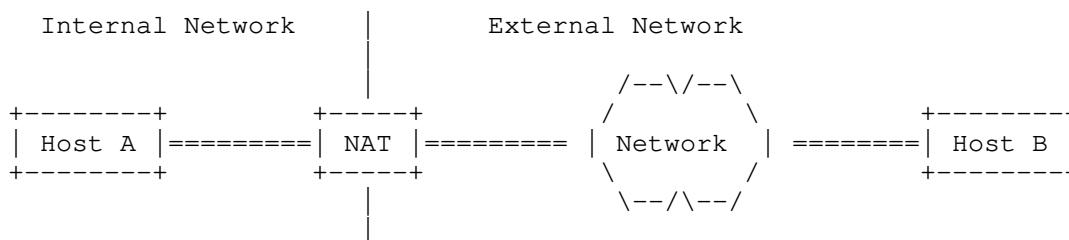


Figure 2: Single NAT Function Scenario

A variation of this case is shown in Figure 3, i.e., multiple NAT functions in the forwarding path between two endpoints.

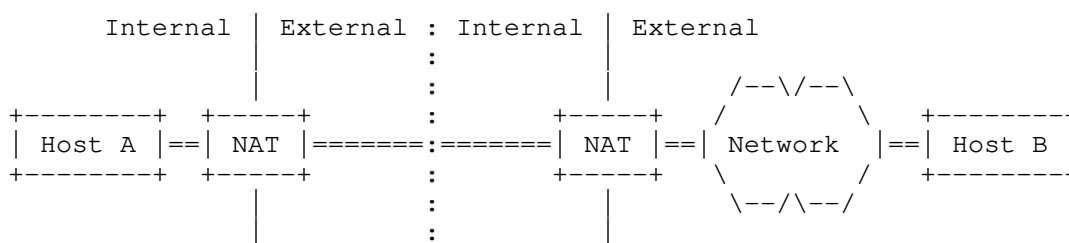


Figure 3: Serial NAT Functions Scenario

Although one of the main benefits of SCTP multi-homing is redundant paths, in the single point traversal scenario the NAT function represents a single point of failure in the path of the SCTP multi-homed association. However, the rest of the path can still benefit from path diversity provided by SCTP multi-homing.

The two SCTP endpoints in this case can be either single-homed or multi-homed. However, the important thing is that the NAT function in this case sees all the packets of the SCTP association.

4.1.2. Multipoint Traversal

This case involves multiple NAT functions and each NAT function only sees some of the packets in the SCTP association. An example is shown in Figure 4.

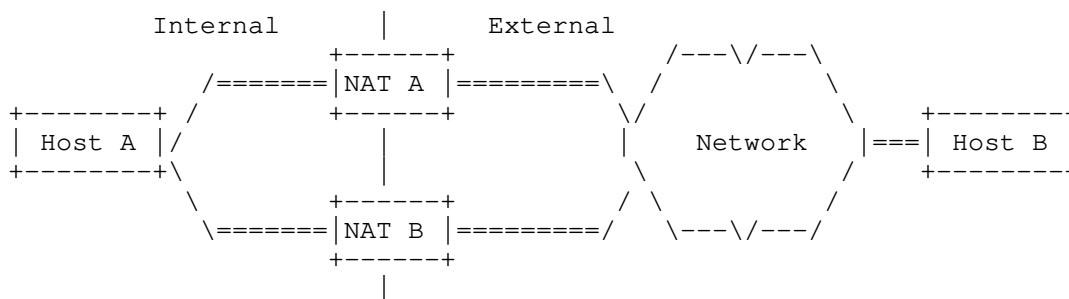


Figure 4: Parallel NAT Functions Scenario

This case does not apply to a single-homed SCTP association (i.e., both endpoints in the association use only one IP address). The advantage here is that the existence of multiple NAT traversal points can preserve the path diversity of a multi-homed association for the entire path. This in turn can improve the robustness of the communication.

4.2. Limitations of Classical NAPT for SCTP

Using classical NAPT possibly results in changing one of the SCTP port numbers during the processing, which requires the recomputation of the transport layer checksum by the NAPT function. Whereas for UDP and TCP this can be done very efficiently, for SCTP the checksum (CRC32c) over the entire packet needs to be recomputed (see Appendix B of [RFC4960] for details of the CRC32c computation). This would considerably add to the NAT computational burden, however hardware support can mitigate this in some implementations.

An SCTP endpoint can have multiple addresses but only has a single port number to use. To make multipoint traversal work, all the NAT functions involved need to recognize the packets they see as belonging to the same SCTP association and perform port number translation in a consistent way. One possible way of doing this is to use a pre-defined table of port numbers and addresses configured within each NAT function. Other mechanisms could make use of NAT to NAT communication. Such mechanisms have not been deployed on a wide scale base and thus are not a preferred solution. Therefore an SCTP variant of NAT function has been developed (see Section 4.3).

4.3. The SCTP-Specific Variant of NAT

In this section it is allowed that there are multiple SCTP capable hosts behind a NAT function that share one External-Address. Furthermore, this section focuses on the single point traversal scenario (see Section 4.1.1).

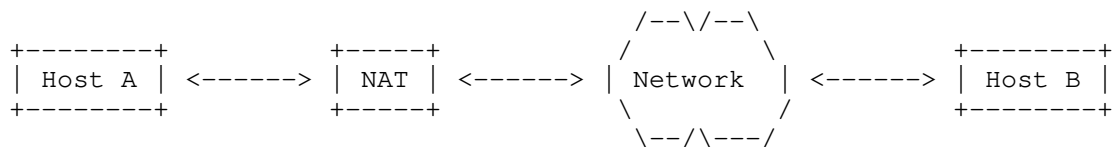
The modification of outgoing SCTP packets sent from an internal host is simple: the source address of the packets has to be replaced with the External-Address. It might also be necessary to establish some state in the NAT function to later handle incoming packets.

Typically, the NAT function has to maintain a NAT binding table of Internal-VTag, Internal-Port, Remote-VTag, Remote-Port, Internal-Address, and whether the restart procedure is disabled or not. An entry in that NAT binding table is called a NAT-State control block. The function Create() obtains the just mentioned parameters and returns a NAT-State control block. A NAT function MAY allow creating NAT-State control blocks via a management interface.

For SCTP packets coming from the external realm of the NAT function the destination address of the packets has to be replaced with the Internal-Address of the host to which the packet has to be delivered, if a NAT state entry is found. The lookup of the Internal-Address is based on the Remote-VTag, Remote-Port, Internal-VTag and the Internal-Port.

The entries in the NAT binding table need to fulfill some uniqueness conditions. There can not be more than one entry NAT binding table with the same pair of Internal-Port and Remote-Port. This rule can be relaxed, if all NAT binding table entries with the same Internal-Port and Remote-Port have the support for the restart procedure disabled (see Section 5.3.1). In this case there can not be no more than one entry with the same Internal-Port, Remote-Port and Remote-VTag and no more than one NAT binding table entry with the same Internal-Port, Remote-Port, and Int-VTag.

The processing of outgoing SCTP packets containing an INIT chunk is illustrated in the following figure. This scenario is valid for all message flows in this section.



```

INIT[Initiate-Tag]
Int-Addr:Int-Port -----> Rem-Addr:Rem-Port
Rem-VTag=0

Create(Initiate-Tag, Int-Port, 0, Rem-Port, Int-Addr,
      IsRestartDisabled)
Returns(NAT-State control block)

```

Translate To:

```

INIT[Initiate-Tag]
Ext-Addr:Int-Port -----> Rem-Addr:Rem-Port
Rem-VTag=0

```

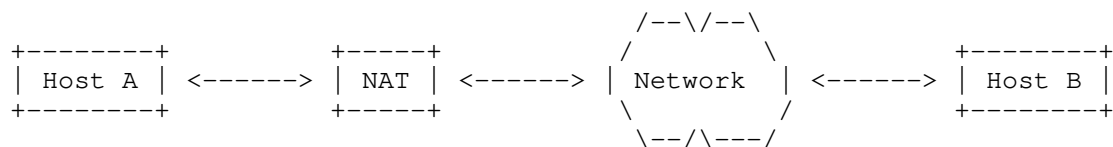
Normally a NAT binding table entry will be created.

However, it is possible that there is already a NAT binding table entry with the same Remote-Port, Internal-Port, and Internal-VTag but different Internal-Address and the restart procedure is disabled. In this case the packet containing the INIT chunk MUST be dropped by the NAT and a packet containing an ABORT chunk SHOULD be sent to the SCTP host that originated the packet with the M bit set and 'VTag and Port Number Collision' error cause (see Section 5.1.1 for the format). The source address of the packet containing the ABORT chunk MUST be the destination address of the packet containing the INIT chunk.

If an outgoing SCTP packet contains an INIT or ASCONF chunk and a matching NAT binding table entry is found, the packet is processed as a normal outgoing packet.

It is also possible that a NAT binding table entry with the same Remote-Port and Internal-Port exists without an Internal-VTag conflict but there exists a NAT binding table entry with the same port numbers but a different Internal-Address and the restart procedure is not disabled. In such a case the packet containing the INIT chunk MUST be dropped by the NAT function and a packet containing an ABORT chunk SHOULD be sent to the SCTP host that originated the packet with the M bit set and 'Port Number Collision' error cause (see Section 5.1.1 for the format).

The processing of outgoing SCTP packets containing no INIT chunks is described in the following figure.

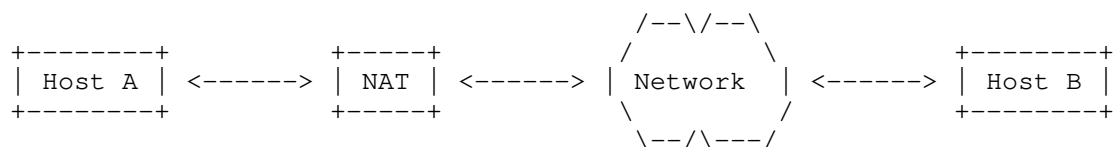


Int-Addr:Int-Port -----> Rem-Addr:Rem-Port
 Rem-VTag

Translate To:

Ext-Addr:Int-Port -----> Rem-Addr:Rem-Port
 Rem-VTag

The processing of incoming SCTP packets containing an INIT ACK chunk is illustrated in the following figure. The Lookup() function has as input the Internal-VTag, Internal-Port, Remote-VTag, and Remote-Port. It returns the corresponding entry of the NAT binding table and updates the Remote-VTag by substituting it with the value of the Initiate-Tag of the INIT ACK chunk. The wildcard character signifies that the parameter's value is not considered in the Lookup() function or changed in the Update() function, respectively.



INIT ACK[Initiate-Tag]
 Ext-Addr:Int-Port <---- Rem-Addr:Rem-Port
 Int-VTag

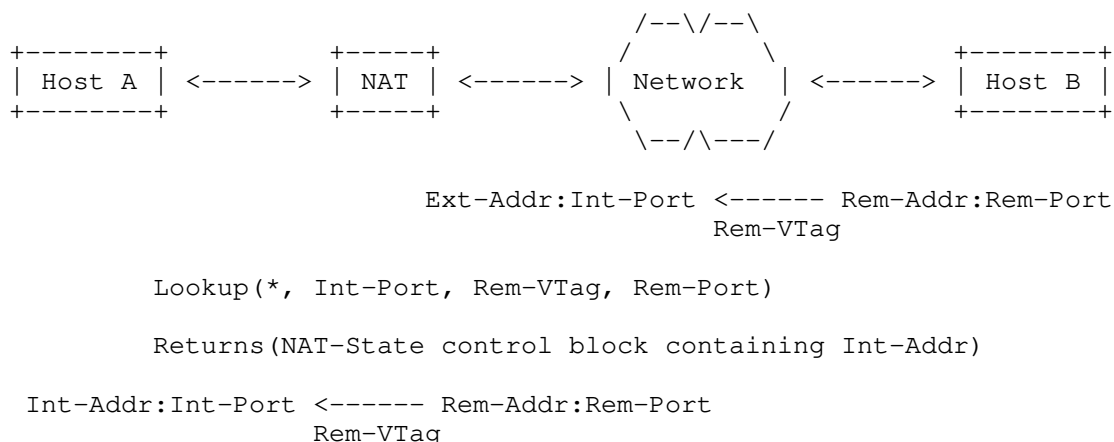
Lookup(Int-VTag, Int-Port, *, Rem-Port)
 Update(*, *, Initiate-Tag, *)

Returns(NAT-State control block containing Int-Addr)

INIT ACK[Initiate-Tag]
 Int-Addr:Int-Port <----- Rem-Addr:Rem-Port
 Int-VTag

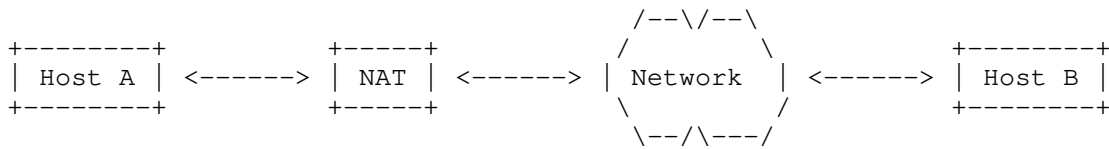
In the case where the Lookup function fails because it does not find an entry, the SCTP packet is dropped. If it succeeds, the Update routine inserts the Remote-VTag (the Initiate-Tag of the INIT ACK chunk) in the NAT-State control block.

The processing of incoming SCTP packets containing an ABORT or SHUTDOWN COMPLETE chunk with the T bit set is illustrated in the following figure.



For an incoming packet containing an INIT chunk a table lookup is made only based on the addresses and port numbers. If an entry with a Remote-VTag of zero is found, it is considered a match and the Remote-VTag is updated. If an entry with a non-matching Remote-VTag is found or no entry is found, the incoming packet is silently dropped. If an entry with a matching Remote-VTag is found, the incoming packet is forwarded. This allows the handling of INIT collision through NAT functions.

The processing of other incoming SCTP packets is described in the following figure.



Ext-Addr: Int-Port <----- Rem-Addr: Rem-Port
Int-VTag

Lookup(Int-VTag, Int-Port, *, Rem-Port)

Returns(NAT-State control block containing Internal-Address)

Int-Addr: Int-Port <----- Rem-Addr: Rem-Port
Int-VTag

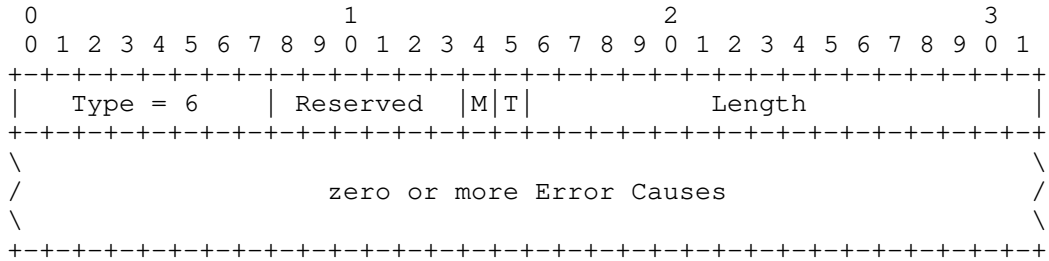
5. Data Formats

This section defines the formats used to support NAT traversal. Section 5.1 and Section 5.2 describe chunks and error causes sent by NAT functions and received by SCTP endpoints. Section 5.3 describes parameters sent by SCTP endpoints and used by NAT functions and SCTP endpoints.

5.1. Modified Chunks

This section presents existing chunks defined in [RFC4960] for which additional flags are specified by this document.

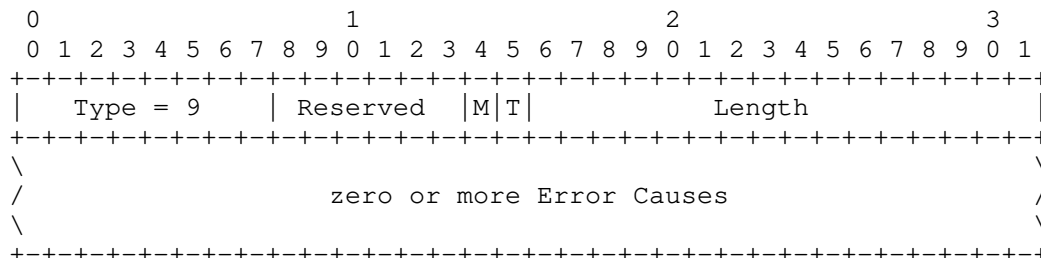
5.1.1. Extended ABORT Chunk



The ABORT chunk is extended to add the new 'M bit'. The M bit indicates to the receiver of the ABORT chunk that the chunk was not generated by the peer SCTP endpoint, but instead by a middle box (e.g., NAT).

[NOTE to RFC-Editor: Assignment of M bit to be confirmed by IANA.]

5.1.2. Extended ERROR Chunk



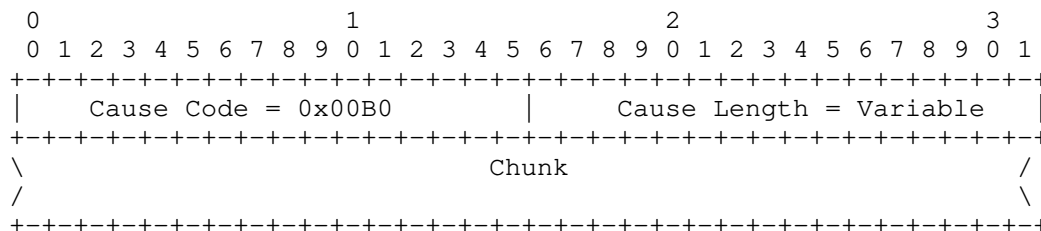
The ERROR chunk defined in [RFC4960] is extended to add the new 'M bit'. The M bit indicates to the receiver of the ERROR chunk that the chunk was not generated by the peer SCTP endpoint, but instead by a middle box.

[NOTE to RFC-Editor: Assignment of M bit to be confirmed by IANA.]

5.2. New Error Causes

This section defines the new error causes added by this document.

5.2.1. VTag and Port Number Collision Error Cause



Cause Code: 2 bytes (unsigned integer)

This field holds the IANA defined cause code for the 'VTag and Port Number Collision' Error Cause. IANA is requested to assign the value 0x00B0 for this cause code.

Cause Length: 2 bytes (unsigned integer)

This field holds the length in bytes of the error cause. The value MUST be the length of the Cause-Specific Information plus 4.

Chunk: variable length

The Cause-Specific Information is filled with the chunk that caused this error. This can be an INIT, INIT ACK, or ASCONF chunk. Note that if the entire chunk will not fit in the ERROR chunk or ABORT chunk being sent then the bytes that do not fit are truncated.

[NOTE to RFC-Editor: Assignment of cause code to be confirmed by IANA.]

5.2.2. Missing State Error Cause

0										1										2										3									
0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1								
Cause Code = 0x00B1										Cause Length = Variable																													
Original Packet																																							

Cause Code: 2 bytes (unsigned integer)

This field holds the IANA defined cause code for the 'Missing State' Error Cause. IANA is requested to assign the value 0x00B1 for this cause code.

Cause Length: 2 bytes (unsigned integer)

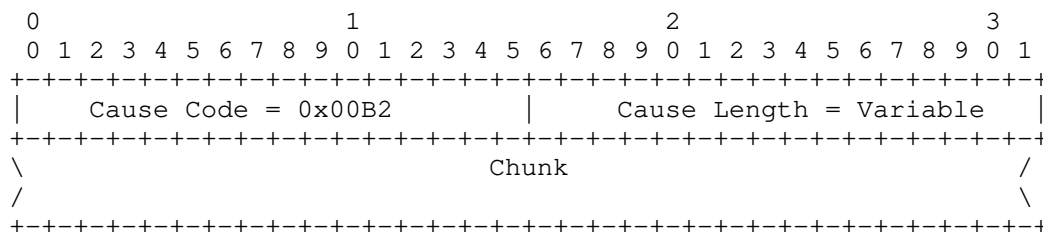
This field holds the length in bytes of the error cause. The value MUST be the length of the Cause-Specific Information plus 4.

Original Packet: variable length

The Cause-Specific Information is filled with the IPv4 or IPv6 packet that caused this error. The IPv4 or IPv6 header MUST be included. Note that if the packet will not fit in the ERROR chunk or ABORT chunk being sent then the bytes that do not fit are truncated.

[NOTE to RFC-Editor: Assignment of cause code to be confirmed by IANA.]

5.2.3. Port Number Collision Error Cause



Cause Code: 2 bytes (unsigned integer)

This field holds the IANA defined cause code for the 'Port Number Collision' Error Cause. IANA is requested to assign the value 0x00B2 for this cause code.

Cause Length: 2 bytes (unsigned integer)

This field holds the length in bytes of the error cause. The value MUST be the length of the Cause-Specific Information plus 4.

Chunk: variable length

The Cause-Specific Information is filled with the chunk that caused this error. This can be an INIT, INIT ACK, or ASCONF chunk. Note that if the entire chunk will not fit in the ERROR chunk or ABORT chunk being sent then the bytes that do not fit are truncated.

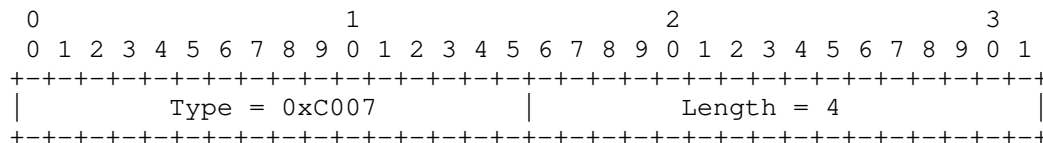
[NOTE to RFC-Editor: Assignment of cause code to be confirmed by IANA.]

5.3. New Parameters

This section defines new parameters and their valid appearance defined by this document.

5.3.1. Disable Restart Parameter

This parameter is used to indicate that the restart procedure is requested to be disabled. Both endpoints of an association MUST include this parameter in the INIT chunk and INIT ACK chunk when establishing an association and MUST include it in the ASCONF chunk when adding an address to successfully disable the restart procedure.



Parameter Type: 2 bytes (unsigned integer)

This field holds the IANA defined parameter type for the Disable Restart Parameter. IANA is requested to assign the value 0xC007 for this parameter type.

Parameter Length: 2 bytes (unsigned integer)

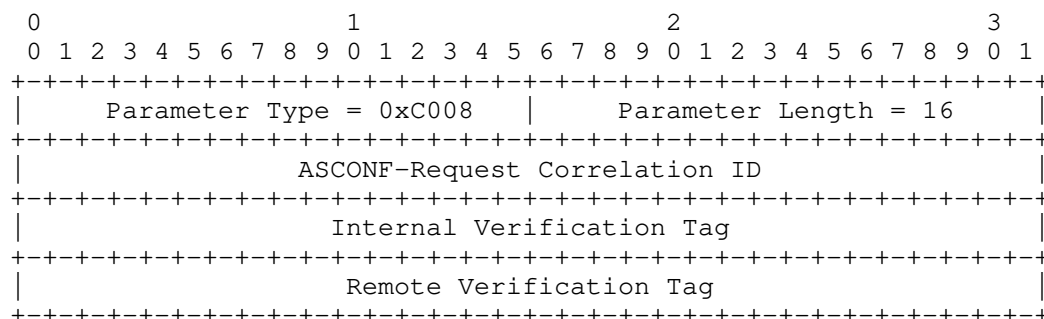
This field holds the length in bytes of the parameter. The value MUST be 4.

[NOTE to RFC-Editor: Assignment of parameter type to be confirmed by IANA.]

The Disable Restart Parameter MAY appear in INIT, INIT ACK and ASCONF chunks and MUST NOT appear in any other chunk.

5.3.2. VTags Parameter

This parameter is used to help a NAT function to recover from state loss.



Parameter Type: 2 bytes (unsigned integer)

This field holds the IANA defined parameter type for the VTags Parameter. IANA is requested to assign the value 0xC008 for this parameter type.

Parameter Length: 2 bytes (unsigned integer)

This field holds the length in bytes of the parameter. The value MUST be 16.

ASCONF-Request Correlation ID: 4 bytes (unsigned integer)

This is an opaque integer assigned by the sender to identify each request parameter. The receiver of the ASCONF Chunk will copy this 32-bit value into the ASCONF Response Correlation ID field of the ASCONF ACK response parameter. The sender of the packet containing the ASCONF chunk can use this same value in the ASCONF ACK chunk to find which request the response is for. The receiver MUST NOT change the value of the ASCONF-Request Correlation ID.

Internal Verification Tag: 4 bytes (unsigned integer)

The Verification Tag that the internal host has chosen for the association. The Verification Tag is a unique 32-bit tag that accompanies any incoming SCTP packet for this association to the Internal-Address.

Remote Verification Tag: 4 bytes (unsigned integer)

The Verification Tag that the host holding the Remote-Address has chosen for the association. The VTag is a unique 32-bit tag that accompanies any outgoing SCTP packet for this association to the Remote-Address.

[NOTE to RFC-Editor: Assignment of parameter type to be confirmed by IANA.]

The VTags Parameter MAY appear in ASCONF chunks and MUST NOT appear in any other chunk.

6. Procedures for SCTP Endpoints and NAT Functions

If an SCTP endpoint is behind an SCTP-aware NAT, a number of problems can arise as it tries to communicate with its peers:

- * IP addresses can not be included in the SCTP packet. This is discussed in Section 6.1.
- * More than one host behind a NAT function could select the same VTag and source port number when communicating with the same peer server. This creates a situation where the NAT function will not be able to tell the two associations apart. This situation is discussed in Section 6.2.
- * If an SCTP endpoint is a server communicating with multiple peers and the peers are behind the same NAT function, then these peers cannot be distinguished by the server. This case is discussed in Section 6.3.
- * A restart of a NAT function during a conversation could cause a loss of its state. This problem and its solution is discussed in Section 6.4.
- * NAT functions need to deal with SCTP packets being fragmented at the IP layer. This is discussed in Section 6.5.
- * An SCTP endpoint can be behind two NAT functions in parallel providing redundancy. The method to set up this scenario is discussed in Section 6.6.

The mechanisms to solve these problems require additional chunks and parameters, defined in this document, and modified handling procedures from those specified in [RFC4960] as described below.

6.1. Association Setup Considerations for Endpoints

The association setup procedure defined in [RFC4960] allows multi-homed SCTP endpoints to exchange its IP-addresses by using IPv4 or IPv6 address parameters in the INIT and INIT ACK chunks. However, this does not work when NAT functions are present.

Every association setup from a host behind a NAT function MUST NOT use multiple internal addresses. The INIT chunk MUST NOT contain an IPv4 Address parameter, IPv6 Address parameter, or Supported Address Types parameter. The INIT ACK chunk MUST NOT contain any IPv4 Address parameter or IPv6 Address parameter using non-global addresses. The INIT chunk and the INIT ACK chunk MUST NOT contain any Host Name parameters.

If the association is intended to be finally multi-homed, the procedure in Section 6.6 MUST be used.

The INIT and INIT ACK chunk SHOULD contain the Disable Restart parameter defined in Section 5.3.1.

6.2. Handling of Internal Port Number and Verification Tag Collisions

Consider the case where two hosts in the Internal-Address space want to set up an SCTP association with the same service provided by some remote hosts. This means that the Remote-Port is the same. If they both choose the same Internal-Port and Internal-VTag, the NAT function cannot distinguish between incoming packets anymore. However, this is unlikely. The Internal-VTags are chosen at random and if the Internal-Ports are also chosen from the ephemeral port range at random (see [RFC6056]) this gives a 46-bit random number that has to match.

The same can happen with the Remote-VTag when a packet containing an INIT ACK chunk or an ASCONF chunk is processed by the NAT function.

6.2.1. NAT Function Considerations

If the NAT function detects a collision of internal port numbers and verification tags, it SHOULD send a packet containing an ABORT chunk with the M bit set if the collision is triggered by a packet containing an INIT or INIT ACK chunk. If such a collision is triggered by a packet containing an ASCONF chunk, it SHOULD send a packet containing an ERROR chunk with the M bit. The M bit is a new

bit defined by this document to express to SCTP that the source of this packet is a "middle" box, not the peer SCTP endpoint (see Section 5.1.1). If a packet containing an INIT ACK chunk triggers the collision, the corresponding packet containing the ABORT chunk MUST contain the same source and destination address and port numbers as the packet containing the INIT ACK chunk. If a packet containing an INIT chunk or an ASCONF chunk, the source and destination address and port numbers MUST be swapped.

The sender of the packet containing an ERROR or ABORT chunk MUST include the error cause with cause code 'VTag and Port Number Collision' (see Section 5.2.1).

6.2.2. Endpoint Considerations

The sender of the packet containing the INIT chunk or the receiver of a packet containing the INIT ACK chunk, upon reception of a packet containing an ABORT chunk with M bit set and the appropriate error cause code for colliding NAT binding table state is included, SHOULD reinitiate the association setup procedure after choosing a new initiate tag, if the association is in COOKIE-WAIT state. In any other state, the SCTP endpoint MUST NOT respond.

The sender of the packet containing the ASCONF chunk, upon reception of a packet containing an ERROR chunk with M bit set, MUST stop adding the path to the association.

6.3. Handling of Internal Port Number Collisions

When two SCTP hosts are behind an SCTP-aware NAT it is possible that two SCTP hosts in the Internal-Address space will want to set up an SCTP association with the same server running on the same remote host. If the two hosts choose the same internal port, this is considered an internal port number collision.

For the NAT function, appropriate tracking can be performed by assuring that the VTags are unique between the two hosts.

6.3.1. NAT Function Considerations

The NAT function, when processing the packet containing the INIT ACK chunk, SHOULD note in its NAT binding table if the association supports the disable restart extension. This note is used when establishing future associations (i.e. when processing a packet containing an INIT chunk from an internal host) to decide if the connection can be allowed. The NAT function does the following when processing a packet containing an INIT chunk:

- * If the packet containing the INIT chunk is originating from an internal port to a remote port for which the NAT function has no matching NAT binding table entry, it MUST allow the packet containing the INIT chunk creating an NAT binding table entry.
- * If the packet containing the INIT chunk matches an existing NAT binding table entry, it MUST validate that the disable restart feature is supported and, if it does, allow the packet containing the INIT chunk to be forwarded.
- * If the disable restart feature is not supported, the NAT function SHOULD send a packet containing an ABORT chunk with the M bit set.

The 'Port Number Collision' error cause (see Section 5.2.3) MUST be included in the ABORT chunk sent in response to the packet containing an INIT chunk.

If the collision is triggered by a packet containing an ASCONF chunk, a packet containing an ERROR chunk with the 'Port Number Collision' error cause SHOULD be sent in response to the packet containing the ASCONF chunk.

6.3.2. Endpoint Considerations

For the remote SCTP server this means that the Remote-Port and the Remote-Address are the same. If they both have chosen the same Internal-Port the server cannot distinguish between both associations based on the address and port numbers. For the server it looks like the association is being restarted. To overcome this limitation the client sends a Disable Restart parameter in the INIT chunk.

When the server receives this parameter it does the following:

- * It MUST include a Disable Restart parameter in the INIT ACK to inform the client that it will support the feature.
- * It MUST disable the restart procedures defined in [RFC4960] for this association.

Servers that support this feature will need to be capable of maintaining multiple connections to what appears to be the same peer (behind the NAT function) differentiated only by the VTags.

6.4. Handling of Missing State

6.4.1. NAT Function Considerations

If the NAT function receives a packet from the internal network for which the lookup procedure does not find an entry in the NAT binding table, a packet containing an ERROR chunk SHOULD be sent back with the M bit set. The source address of the packet containing the ERROR chunk MUST be the destination address of the packet received from the internal network. The verification tag is reflected and the T bit is set. Such a packet containing an ERROR chunk SHOULD NOT be sent if the received packet contains an ASCONF chunk with the VTags parameter or an ABORT, SHUTDOWN COMPLETE or INIT ACK chunk. A packet containing an ERROR chunk MUST NOT be sent if the received packet contains an ERROR chunk with the M bit set. In any case, the packet SHOULD NOT be forwarded to the remote address.

If the NAT function receives a packet from the internal network for which it has no NAT binding table entry and the packet contains an ASCONF chunk with the VTags parameter, the NAT function MUST update its NAT binding table according to the verification tags in the VTags parameter and, if present, the Disable Restart parameter.

When sending a packet containing an ERROR chunk, the error cause 'Missing State' (see Section 5.2.2) MUST be included and the M bit of the ERROR chunk MUST be set (see Section 5.1.2).

6.4.2. Endpoint Considerations

Upon reception of this packet containing the ERROR chunk by an SCTP endpoint the receiver takes the following actions:

- * It SHOULD validate that the verification tag is reflected by looking at the VTag that would have been included in an outgoing packet. If the validation fails, discard the received packet containing the ERROR chunk.
- * It SHOULD validate that the peer of the SCTP association supports the dynamic address extension. If the validation fails, discard the received packet containing the ERROR chunk.
- * It SHOULD generate a packet containing a new ASCONF chunk containing the VTags parameter (see Section 5.3.2) and the Disable Restart parameter (see Section 5.3.1) if the association is using the disable restart feature. By processing this packet the NAT function can recover the appropriate state. The procedures for generating an ASCONF chunk can be found in [RFC5061].

The peer SCTP endpoint receiving such a packet containing an ASCONF chunk SHOULD add the address and respond with an acknowledgment if the address is new to the association (following all procedures defined in [RFC5061]). If the address is already part of the association, the SCTP endpoint MUST NOT respond with an error, but instead SHOULD respond with a packet containing an ASCONF ACK chunk acknowledging the address and take no action (since the address is already in the association).

Note that it is possible that upon receiving a packet containing an ASCONF chunk containing the VTags parameter the NAT function will realize that it has an 'Internal Port Number and Verification Tag collision'. In such a case the NAT function SHOULD send a packet containing an ERROR chunk with the error cause code set to 'VTag and Port Number Collision' (see Section 5.2.1).

If an SCTP endpoint receives a packet containing an ERROR chunk with 'Internal Port Number and Verification Tag collision' as the error cause and the packet in the Error Chunk contains an ASCONF with the VTags parameter, careful examination of the association is necessary. The endpoint does the following:

- * It MUST validate that the verification tag is reflected by looking at the VTag that would have been included in the outgoing packet. If the validation fails, it MUST discard the packet.
- * It MUST validate that the peer of the SCTP association supports the dynamic address extension. If the peer does not support this extension, it MUST discard the received packet containing the ERROR chunk.
- * If the association is attempting to add an address (i.e. following the procedures in Section 6.6) then the endpoint MUST NOT consider the address part of the association and SHOULD make no further attempt to add the address (i.e. cancel any ASCONF timers and remove any record of the path), since the NAT function has a VTag collision and the association cannot easily create a new VTag (as it would if the error occurred when sending a packet containing an INIT chunk).
- * If the endpoint has no other path, i.e. the procedure was executed due to missing a state in the NAT function, then the endpoint MUST abort the association. This would occur only if the local NAT function restarted and accepted a new association before attempting to repair the missing state (Note that this is no different than what happens to all TCP connections when a NAT function loses its state).

6.5. Handling of Fragmented SCTP Packets by NAT Functions

SCTP minimizes the use of IP-level fragmentation. However, it can happen that using IP-level fragmentation is needed to continue an SCTP association. For example, if the path MTU is reduced and there are still some DATA chunk in flight, which require packets larger than the new path MTU. If IP-level fragmentation can not be used, the SCTP association will be terminated in a non-graceful way. See [RFC8900] for more information about IP fragmentation.

Therefore, a NAT function MUST be able to handle IP-level fragmented SCTP packets. The fragments MAY arrive in any order.

When an SCTP packet can not be forwarded by the NAT function due to MTU issues and the IP header forbids fragmentation, the NAT MUST send back a "Fragmentation needed and DF set" ICMPv4 or PTB ICMPv6 message to the internal host. This allows for a faster recovery from this packet drop.

6.6. Multi Point Traversal Considerations for Endpoints

If a multi-homed SCTP endpoint behind a NAT function connects to a peer, it MUST first set up the association single-homed with only one address causing the first NAT function to populate its state. Then it SHOULD add each IP address using packets containing ASCONF chunks sent via their respective NAT functions. The address used in the Add IP address parameter is the wildcard address (0.0.0.0 or ::0) and the address parameter in the ASCONF chunk SHOULD also contain the VTags parameter and optionally the Disable Restart parameter.

7. SCTP NAT YANG Module

This section defines a YANG module for SCTP NAT.

The terminology for describing YANG data models is defined in [RFC7950]. The meaning of the symbols in tree diagrams is defined in [RFC8340].

7.1. Tree Structure

This module augments NAT YANG module [RFC8512] with SCTP specifics. The module supports both classical SCTP NAT (that is, rewrite port numbers) and SCTP-specific variant where the ports numbers are not altered. The YANG "feature" is used to indicate whether SCTP-specific variant is supported.

The tree structure of the SCTP NAT YANG module is provided below:

```

module: ietf-nat-sctp
  augment /nat:nat/nat:instances/nat:instance
    /nat:policy/nat:timers:
      +--rw sctp-timeout?  uint32
  augment /nat:nat/nat:instances/nat:instance
    /nat:mapping-table/nat:mapping-entry:
      +--rw int-VTag?      uint32 {sctp-nat}?
      +--rw rem-VTag?      uint32 {sctp-nat}?

```

Concretely, the SCTP NAT YANG module augments the NAT YANG module (policy, in particular) with the following:

- * The sctp-timeout is used to control the SCTP inactivity timeout. That is, the time an SCTP mapping will stay active without SCTP packets traversing the NAT. This timeout can be set only for SCTP. Hence, `"/nat:nat/nat:instances/nat:instance/nat:policy/nat:transport-protocols/nat:protocol-id"` MUST be set to `'132'` (SCTP).

In addition, the SCTP NAT YANG module augments the mapping entry with the following parameters defined in Section 3. These parameters apply only for SCTP NAT mapping entries (i.e., `"/nat/instances/instance/mapping-table/mapping-entry/transport-protocol"` MUST be set to `'132'`);

- * The Internal Verification Tag (Int-VTag)
- * The Remote Verification Tag (Rem-VTag)

7.2. YANG Module

```

<CODE BEGINS> file "ietf-nat-sctp@2020-11-02.yang"
module ietf-nat-sctp {
  yang-version 1.1;
  namespace "urn:ietf:params:xml:ns:yang:ietf-nat-sctp";
  prefix nat-sctp;

  import ietf-nat {
    prefix nat;
    reference
      "RFC 8512: A YANG Module for Network Address Translation
       (NAT) and Network Prefix Translation (NPT)";
  }

  organization
    "IETF TSVWG Working Group";
  contact
    "WG Web:  <https://datatracker.ietf.org/wg/tsvwg/>

```

WG List: <mailto:tsvwg@ietf.org>

Author: Mohamed Boucadair
<mailto:mohamed.boucadair@orange.com>;

description

"This module augments NAT YANG module with Stream Control Transmission Protocol (SCTP) specifics. The extension supports both a classical SCTP NAT (that is, rewrite port numbers) and a, SCTP-specific variant where the ports numbers are not altered.

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This version of this YANG module is part of RFC XXXX; see the RFC itself for full legal notices.";

```
revision 2019-11-18 {
  description
    "Initial revision.";
  reference
    "RFC XXXX: Stream Control Transmission Protocol (SCTP)
      Network Address Translation Support";
}

feature sctp-nat {
  description
    "This feature means that SCTP-specific variant of NAT
      is supported. That is, avoid rewriting port numbers.";
  reference
    "Section 4.3 of RFC XXXX.";
}

augment "/nat:nat/nat:instances/nat:instance"
  + "/nat:policy/nat:timers" {
  when "/nat:nat/nat:instances/nat:instance"
    + "/nat:policy/nat:transport-protocols"
    + "/nat:protocol-id = 132";
  description
    "Extends NAT policy with a timeout for SCTP mapping
      entries.";
```

```
    leaf sctp-timeout {
      type uint32;
      units "seconds";
      description
        "SCTP inactivity timeout. That is, the time an SCTP
        mapping entry will stay active without packets
        traversing the NAT.";
    }
  }

  augment "/nat:nat/nat:instances/nat:instance"
    + "/nat:mapping-table/nat:mapping-entry" {
    when "nat:transport-protocol = 132";
    if-feature "sctp-nat";
    description
      "Extends the mapping entry with SCTP specifics.";

    leaf int-VTag {
      type uint32;
      description
        "The Internal Verification Tag that the internal
        host has chosen for this communication.";
    }
    leaf rem-VTag {
      type uint32;
      description
        "The Remote Verification Tag that the remote
        peer has chosen for this communication.";
    }
  }
}
<CODE ENDS>
```

8. Various Examples of NAT Traversals

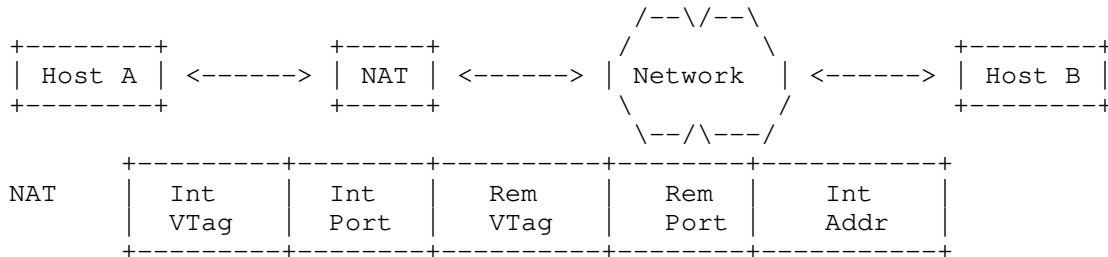
Please note that this section is informational only.

The addresses being used in the following examples are IPv4 addresses for private-use networks and for documentation as specified in [RFC6890]. However, the method described here is not limited to this NAT44 case.

The NAT binding table entries shown in the following examples do not include the flag indicating whether the restart procedure is supported or not. This flag is not relevant for these examples.

8.1. Single-homed Client to Single-homed Server

The internal client starts the association with the remote server via a four-way-handshake. Host A starts by sending a packet containing an INIT chunk.



```
INIT[Initiate-Tag = 1234]
10.0.0.1:1 -----> 203.0.113.1:2
    Rem-VTtag = 0
```

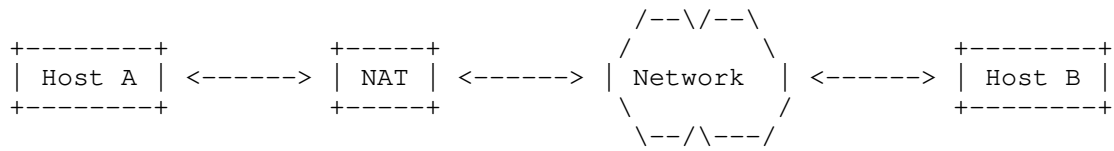
A NAT binding tabled entry is created, the source address is substituted and the packet is sent on:

NAT function creates entry:

NAT	Int VTag	Int Port	Rem VTag	Rem Port	Int Addr
	1234	1	0	2	10.0.0.1

```
INIT[Initiate-Tag = 1234]
192.0.2.1:1 -----> 203.0.113.1:2
    Rem-VTtag = 0
```

Host B receives the packet containing an INIT chunk and sends a packet containing an INIT ACK chunk with the NAT's Remote-address as destination address.



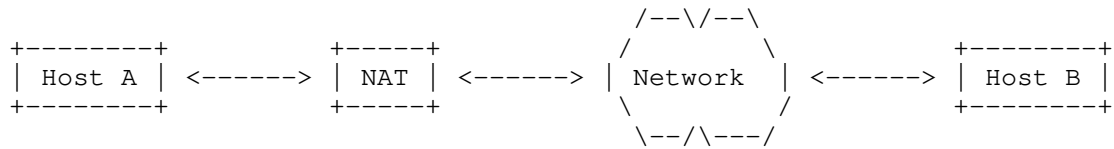
INIT ACK[Initiate-Tag = 5678]
 192.0.2.1:1 <----- 203.0.113.1:2
 Int-VTag = 1234

NAT function updates entry:

NAT	Int VTag	Int Port	Rem VTag	Rem Port	Int Addr
	1234	1	5678	2	10.0.0.1

INIT ACK[Initiate-Tag = 5678]
 10.0.0.1:1 <----- 203.0.113.1:2
 Int-VTag = 1234

The handshake finishes with a COOKIE ECHO acknowledged by a COOKIE ACK.



COOKIE ECHO
 10.0.0.1:1 -----> 203.0.113.1:2
 Rem-VTag = 5678

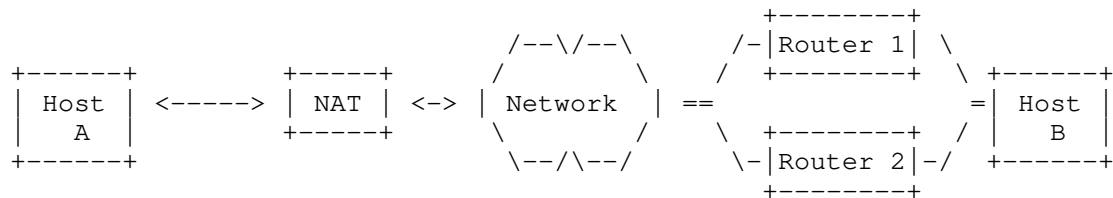
COOKIE ECHO
 192.0.2.1:1 -----> 203.0.113.1:2
 Rem-VTag = 5678

COOKIE ACK
 192.0.2.1:1 <----- 203.0.113.1:2
 Int-VTag = 1234

COOKIE ACK
 10.0.0.1:1 <----- 203.0.113.1:2
 Int-VTag = 1234

8.2. Single-homed Client to Multi-homed Server

The internal client is single-homed whereas the remote server is multi-homed. The client (Host A) sends a packet containing an INIT chunk like in the single-homed case.



NAT	Int VTag	Int Port	Rem VTag	Rem Port	Int Addr
-----	-------------	-------------	-------------	-------------	-------------

```

INIT[Initiate-Tag = 1234]
10.0.0.1:1 ---> 203.0.113.1:2
Rem-VTag = 0
  
```

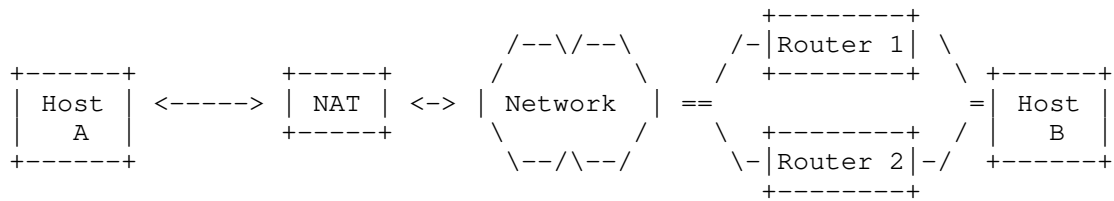
NAT function creates entry:

NAT	Int VTag	Int Port	Rem VTag	Rem Port	Int Addr
	1234	1	0	2	10.0.0.1

```

INIT[Initiate-Tag = 1234]
192.0.2.1:1 -----> 203.0.113.1:2
Rem-VTag = 0
  
```

The server (Host B) includes its two addresses in the INIT ACK chunk.



```

INIT ACK[Initiate-tag = 5678, IP-Addr = 203.0.113.129]
192.0.2.1:1 <----- 203.0.113.1:2
                Int-VTag = 1234

```

The NAT function does not need to change the NAT binding table for the second address:

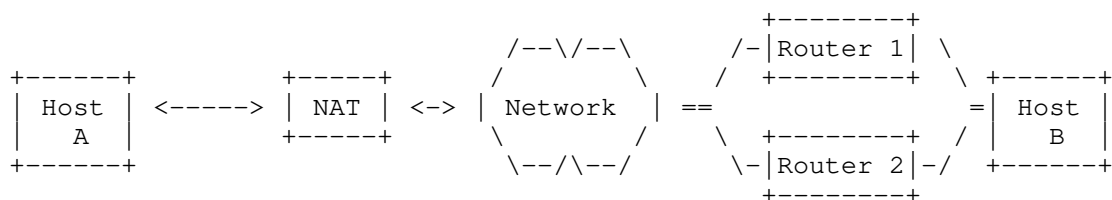
NAT					
	Int VTag	Int Port	Rem VTag	Rem Port	Int Addr
	1234	1	5678	2	10.0.0.1

```

INIT ACK[Initiate-Tag = 5678]
10.0.0.1:1 <--- 203.0.113.1:2
        Int-VTag = 1234

```

The handshake finishes with a COOKIE ECHO acknowledged by a COOKIE ACK.



COOKIE ECHO
 10.0.0.1:1 ---> 203.0.113.1:2
 Rem-VTag = 5678

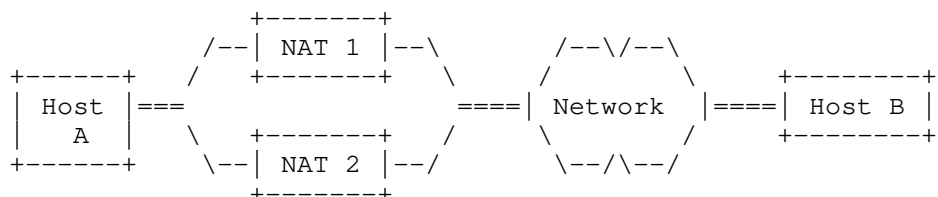
COOKIE ECHO
 192.0.2.1:1 -----> 203.0.113.1:2
 Rem-VTag = 5678

COOKIE ACK
 192.0.2.1:1 <----- 203.0.113.1:2
 Int-VTag = 1234

COOKIE ACK
 10.0.0.1:1 <--- 203.0.113.1:2
 Int-VTag = 1234

8.3. Multihomed Client and Server

The client (Host A) sends a packet containing an INIT chunk to the server (Host B), but does not include the second address.



NAT 1	Int VTag	Int Port	Rem VTag	Rem Port	Int Addr

INIT[Initiate-Tag = 1234]
 10.0.0.1:1 -----> 203.0.113.1:2
 Rem-VTag = 0

NAT function 1 creates entry:

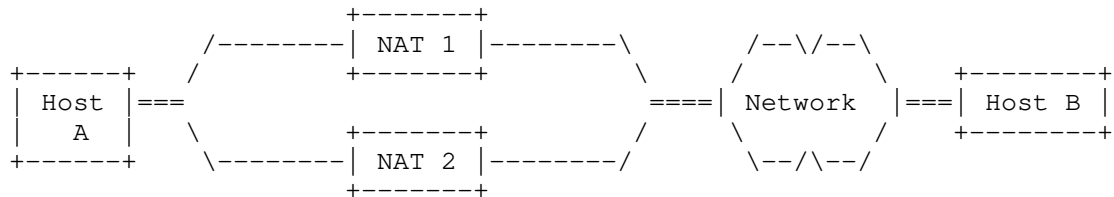
NAT 1	Int VTag	Int Port	Rem VTag	Rem Port	Int Addr
	1234	1	0	2	10.0.0.1

```

                                INIT[Initiate-Tag = 1234]
192.0.2.1:1 -----> 203.0.113.1:2
                                Rem-VTag = 0

```

Host B includes its second address in the INIT ACK.



```

INIT ACK[Initiate-Tag = 5678, IP-Addr = 203.0.113.129]
192.0.2.1:1 <----- 203.0.113.1:2
                                Int-VTag = 1234

```

NAT function 1 does not need to update the NAT binding table for the second address:

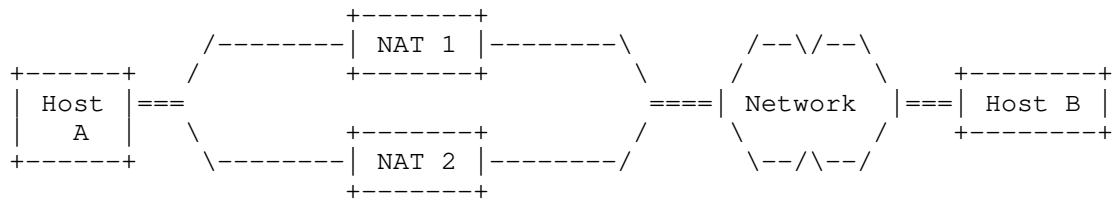
NAT 1	Int VTag	Int Port	Rem VTag	Rem Port	Int Addr
	1234	1	5678	2	10.0.0.1

```

INIT ACK[Initiate-Tag = 5678]
10.0.0.1:1 <----- 203.0.113.1:2
                                Int-VTag = 1234

```

The handshake finishes with a COOKIE ECHO acknowledged by a COOKIE ACK.



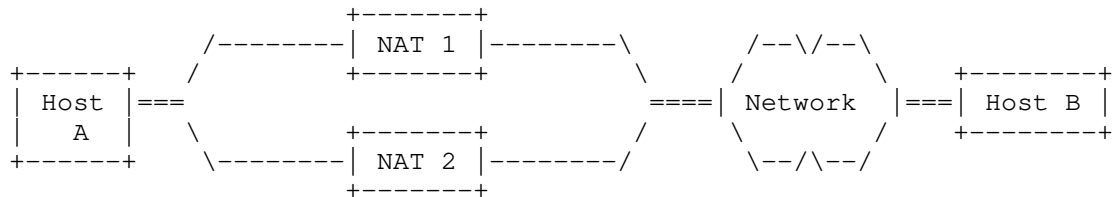
COOKIE ECHO
 10.0.0.1:1 -----> 203.0.113.1:2
 Rem-VTag = 5678

COOKIE ECHO
 192.0.2.1:1 -----> 203.0.113.1:2
 Rem-VTag = 5678

COOKIE ACK
 192.0.2.1:1 <----- 203.0.113.1:2
 Int-VTag = 1234

COOKIE ACK
 10.0.0.1:1 <----- 203.0.113.1:2
 Int-VTag = 1234

Host A announces its second address in an ASCONF chunk. The address parameter contains a wildcard address (0.0.0.0 or ::0) to indicate that the source address has to be added. The address parameter within the ASCONF chunk will also contain the pair of VTags (remote and internal) so that the NAT function can populate its NAT binding table entry completely with this single packet.



ASCONF [ADD-IP=0.0.0.0, INT-VTag=1234, Rem-VTag = 5678]
 10.1.0.1:1 -----> 203.0.113.129:2
 Rem-VTag = 5678

NAT function 2 creates a complete entry:

NAT 2	+-----+				
	Int	Int	Rem	Rem	Int
	VTag	Port	VTag	Port	Addr
	1234	1	5678	2	10.1.0.1
	+-----+				

```

ASCONF [ADD-IP, Int-VTag=1234, Rem-VTag = 5678]
192.0.2.129:1 -----> 203.0.113.129:2
                        Rem-VTag = 5678

```

```

                        ASCONF ACK
192.0.2.129:1 <----- 203.0.113.129:2
                        Int-VTag = 1234

```

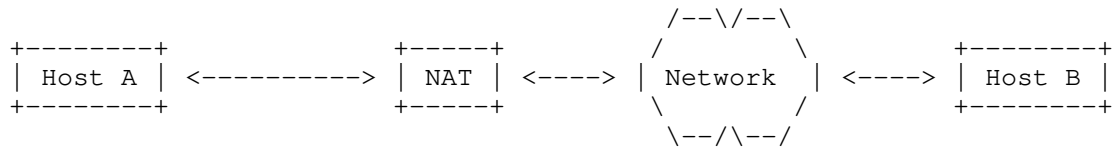
```

                        ASCONF ACK
10.1.0.1:1 <----- 203.0.113.129:2
                        Int-VTag = 1234

```

8.4. NAT Function Loses Its State

Association is already established between Host A and Host B, when the NAT function loses its state and obtains a new external address. Host A sends a DATA chunk to Host B.



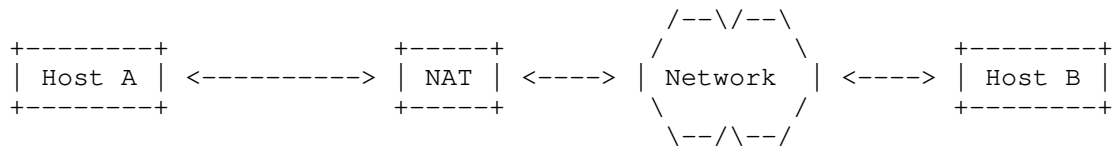
NAT	+-----+				
	Int	Int	Rem	Rem	Int
	VTag	Port	VTag	Port	Addr
	+-----+				

```

                        DATA
10.0.0.1:1 -----> 203.0.113.1:2
                        Rem-VTag = 5678

```

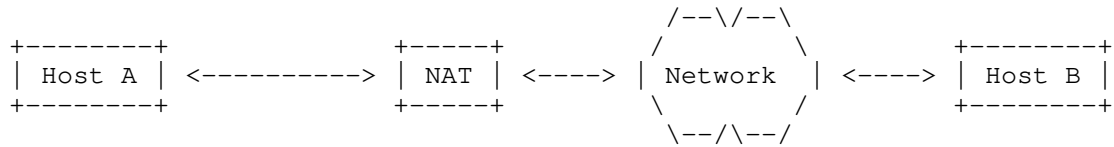
The NAT function cannot find an entry in the NAT binding table for the association. It sends a packet containing an ERROR chunk with the M bit set and the cause "NAT state missing".



```

ERROR [M bit, NAT state missing]
10.0.0.1:1 <----- 203.0.113.1:2
      Rem-VTag = 5678
  
```

On reception of the packet containing the ERROR chunk, Host A sends a packet containing an ASCONF chunk indicating that the former information has to be deleted and the source address of the actual packet added.



```

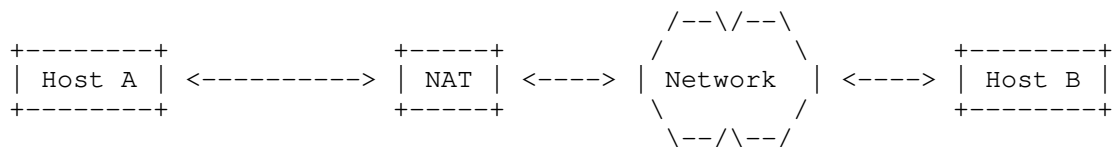
ASCONF [ADD-IP, DELETE-IP, Int-VTag=1234, Rem-VTag = 5678]
10.0.0.1:1 -----> 203.0.113.129:2
      Rem-VTag = 5678
  
```

NAT	Int VTag	Int Port	Rem VTag	Rem Port	Int Addr
	1234	1	5678	2	10.0.0.1

```

ASCONF [ADD-IP, DELETE-IP, Int-VTag=1234, Rem-VTag = 5678]
      192.0.2.2:1 -----> 203.0.113.129:2
      Rem-VTag = 5678
  
```

Host B adds the new source address to this association and deletes all other addresses from this association.



```

                                ASCONF ACK
                                192.0.2.2:1 <----- 203.0.113.129:2
                                Int-VTag = 1234

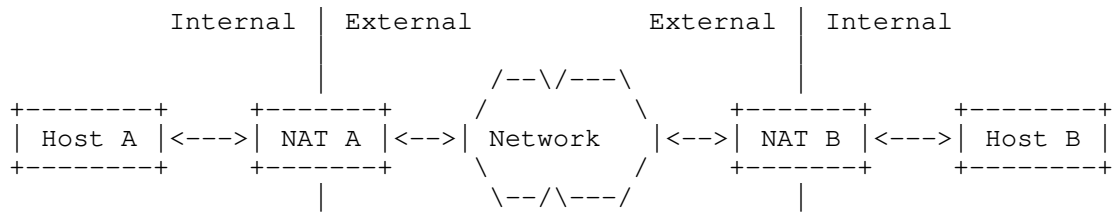
                                ASCONF ACK
                                10.1.0.1:1 <----- 203.0.113.129:2
                                Int-VTag = 1234

                                DATA
                                10.0.0.1:1 -----> 203.0.113.1:2
                                Rem-VTag = 5678

                                DATA
                                192.0.2.2:1 -----> 203.0.113.129:2
                                Rem-VTag = 5678
  
```

8.5. Peer-to-Peer Communications

If two hosts, each of them behind a NAT function, want to communicate with each other, they have to get knowledge of the peer's external address. This can be achieved with a so-called rendezvous server. Afterwards the destination addresses are external, and the association is set up with the help of the INIT collision. The NAT functions create their entries according to their internal peer's point of view. Therefore, NAT function A's Internal-VTag and Internal-Port are NAT function B's Remote-VTag and Remote-Port, respectively. The naming (internal/remote) of the verification tag in the packet flow is done from the sending host's point of view.



NAT Binding Tables

NAT A	Int VTag	Int Port	Rem VTag	Rem Port	Int Addr
-------	-------------	-------------	-------------	-------------	-------------

NAT B	Int v-tag	Int port	Rem v-tag	Rem port	Int Addr
-------	--------------	-------------	--------------	-------------	-------------

```

INIT[Initiate-Tag = 1234]
10.0.0.1:1 --> 203.0.113.1:2
    Rem-VTag = 0
  
```

NAT function A creates entry:

NAT A	Int VTag	Int Port	Rem VTag	Rem Port	Int Addr
	1234	1	0	2	10.0.0.1

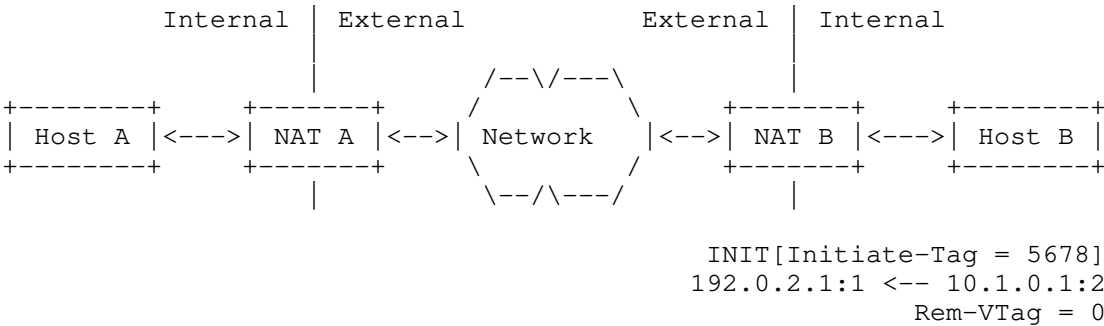
```

INIT[Initiate-Tag = 1234]
192.0.2.1:1 -----> 203.0.113.1:2
    Rem-VTag = 0
  
```

NAT function B processes the packet containing the INIT chunk, but cannot find an entry. The SCTP packet is silently discarded and leaves the NAT binding table of NAT function B unchanged.

NAT B	Int VTag	Int Port	Rem VTag	Rem Port	Int Addr
-------	-------------	-------------	-------------	-------------	-------------

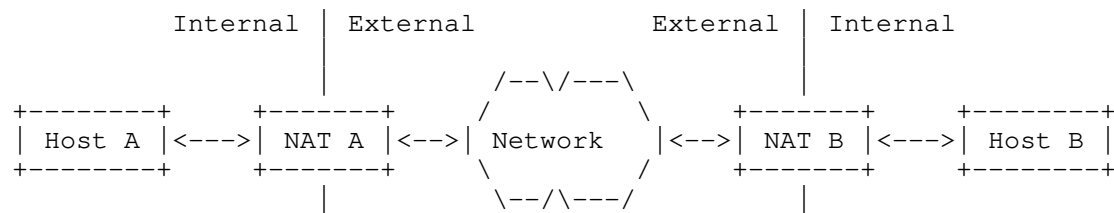
Now Host B sends a packet containing an INIT chunk, which is processed by NAT function B. Its parameters are used to create an entry.



NAT B	Int	Int	Rem	Rem	Int
	VTag	Port	VTag	Port	Addr
	5678	2	0	1	10.1.0.1

INIT[Initiate-Tag = 5678]
192.0.2.1:1 <----- 203.0.113.1:2
Rem-VTag = 0

NAT function A processes the packet containing the INIT chunk. As the outgoing packet containing an INIT chunk of Host A has already created an entry, the entry is found and updated:

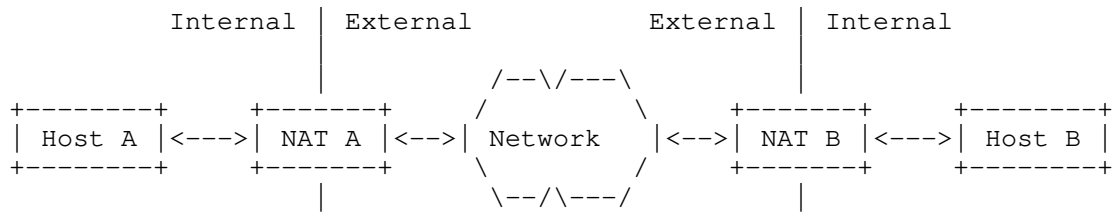


VTag != Int-VTag, but Rem-VTag == 0, find entry.

NAT A	Int VTag	Int Port	Rem VTag	Rem Port	Int Addr
	1234	1	5678	2	10.0.0.1

```
INIT[Initiate-tag = 5678]
10.0.0.1:1 <-- 203.0.113.1:2
    Rem-VTag = 0
```

Host A sends a packet containing an INIT ACK chunk, which can pass through NAT function B:



```

INIT ACK[Initiate-Tag = 1234]
10.0.0.1:1 --> 203.0.113.1:2
    Rem-VTag = 5678

```

```

        INIT ACK[Initiate-Tag = 1234]
192.0.2.1:1 -----> 203.0.113.1:2
        Rem-VTag = 5678

```

NAT function B updates entry:

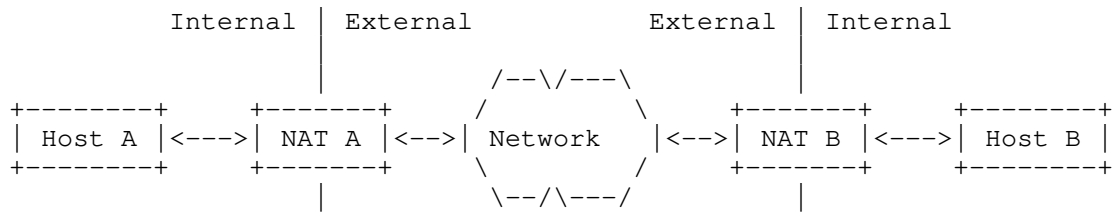
NAT B	Int VTag	Int Port	Rem VTag	Rem Port	Int Addr
	-----	-----	-----	-----	-----
	5678	2	1234	1	10.1.0.1

```

INIT ACK[Initiate-Tag = 1234]
192.0.2.1:1 --> 10.1.0.1:2
    Rem-VTag = 5678

```

The lookup for COOKIE ECHO and COOKIE ACK is successful.



COOKIE ECHO
 192.0.2.1:1 <-- 10.1.0.1:2
 Rem-VTag = 1234

COOKIE ECHO
 192.0.2.1:1 <----- 203.0.113.1:2
 Rem-VTag = 1234

COOKIE ECHO
 10.0.0.1:1 <-- 203.0.113.1:2
 Rem-VTag = 1234

COOKIE ACK
 10.0.0.1:1 --> 203.0.113.1:2
 Rem-VTag = 5678

COOKIE ACK
 192.0.2.1:1 -----> 203.0.113.1:2
 Rem-VTag = 5678

COOKIE ACK
 192.0.2.1:1 --> 10.1.0.1:2
 Rem-VTag = 5678

9. Socket API Considerations

This section describes how the socket API defined in [RFC6458] is extended to provide a way for the application to control NAT friendliness.

Please note that this section is informational only.

A socket API implementation based on [RFC6458] is extended by supporting one new read/write socket option.

9.1. Get or Set the NAT Friendliness (SCTP_NAT_FRIENDLY)

This socket option uses the option_level IPPROTO_SCTP and the option_name SCTP_NAT_FRIENDLY. It can be used to enable/disable the NAT friendliness for future associations and retrieve the value for future and specific ones.

```
struct sctp_assoc_value {  
    sctp_assoc_t assoc_id;  
    uint32_t assoc_value;  
};
```

assoc_id

This parameter is ignored for one-to-one style sockets. For one-to-many style sockets the application can fill in an association identifier or SCTP_FUTURE_ASSOC for this query. It is an error to use SCTP_{CURRENT|ALL}_ASSOC in assoc_id.

assoc_value

A non-zero value indicates a NAT-friendly mode.

10. IANA Considerations

[NOTE to RFC-Editor: "RFCXXXX" is to be replaced by the RFC number you assign this document.]

[NOTE to RFC-Editor: The requested values for the chunk type and the chunk parameter types are tentative and to be confirmed by IANA.]

This document (RFCXXXX) is the reference for all registrations described in this section. The requested changes are described below.

10.1. New Chunk Flags for Two Existing Chunk Types

As defined in [RFC6096] two chunk flags have to be assigned by IANA for the ERROR chunk. The requested value for the T bit is 0x01 and for the M bit is 0x02.

This requires an update of the "ERROR Chunk Flags" registry for SCTP:

ERROR Chunk Flags

Chunk Flag Value	Chunk Flag Name	Reference
0x01	T bit	[RFCXXXX]
0x02	M bit	[RFCXXXX]
0x04	Unassigned	
0x08	Unassigned	
0x10	Unassigned	
0x20	Unassigned	
0x40	Unassigned	
0x80	Unassigned	

Table 2

As defined in [RFC6096] one chunk flag has to be assigned by IANA for the ABORT chunk. The requested value of the M bit is 0x02.

This requires an update of the "ABORT Chunk Flags" registry for SCTP:

ABORT Chunk Flags

Chunk Flag Value	Chunk Flag Name	Reference
0x01	T bit	[RFC4960]
0x02	M bit	[RFCXXXX]
0x04	Unassigned	
0x08	Unassigned	
0x10	Unassigned	
0x20	Unassigned	
0x40	Unassigned	
0x80	Unassigned	

Table 3

10.2. Three New Error Causes

Three error causes have to be assigned by IANA. It is requested to use the values given below.

This requires three additional lines in the "Error Cause Codes" registry for SCTP:

Error Cause Codes

Value	Cause Code	Reference
176	VTag and Port Number Collision	[RFCXXXX]
177	Missing State	[RFCXXXX]
178	Port Number Collision	[RFCXXXX]

Table 4

10.3. Two New Chunk Parameter Types

Two chunk parameter types have to be assigned by IANA. IANA is requested to assign these values from the pool of parameters with the upper two bits set to '11' and to use the values given below.

This requires two additional lines in the "Chunk Parameter Types" registry for SCTP:

Chunk Parameter Types

ID Value	Chunk Parameter Type	Reference
49159	Disable Restart (0xC007)	[RFCXXXX]
49160	VTags (0xC008)	[RFCXXXX]

Table 5

10.4. One New URI

An URI in the "ns" subregistry within the "IETF XML" registry has to be assigned by IANA ([RFC3688]):

URI: urn:ietf:params:xml:ns:yang:ietf-nat-sctp
 Registrant Contact: The IESG.
 XML: N/A; the requested URI is an XML namespace.

10.5. One New YANG Module

An YANG module in the "YANG Module Names" subregistry within the "YANG Parameters" registry has to be assigned by IANA ([RFC6020]):

Name: ietf-nat-sctp
 Namespace: urn:ietf:params:xml:ns:yang:ietf-nat-sctp
 Maintained by IANA: N
 Prefix: nat-sctp
 Reference: RFCXXXX

11. Security Considerations

State maintenance within a NAT function is always a subject of possible Denial Of Service attacks. This document recommends that at a minimum a NAT function runs a timer on any SCTP state so that old association state can be cleaned up.

Generic issues related to address sharing are discussed in [RFC6269] and apply to SCTP as well.

For SCTP endpoints not disabling the restart procedure, this document does not add any additional security considerations to the ones given in [RFC4960], [RFC4895], and [RFC5061].

SCTP endpoints disabling the restart procedure, need to monitor the status of all associations to mitigate resource exhaustion attacks by establishing a lot of associations sharing the same IP addresses and port numbers.

In any case, SCTP is protected by the verification tags and the usage of [RFC4895] against off-path attackers.

For IP-level fragmentation and reassembly related issues see [RFC4963].

The YANG module specified in this document defines a schema for data that is designed to be accessed via network management protocols such as NETCONF [RFC6241] or RESTCONF [RFC8040]. The lowest NETCONF layer is the secure transport layer, and the mandatory-to-implement secure transport is Secure Shell (SSH) [RFC6242]. The lowest RESTCONF layer is HTTPS, and the mandatory-to-implement secure transport is TLS [RFC8446].

The Network Configuration Access Control Model (NACM) [RFC8341] provides the means to restrict access for particular NETCONF or RESTCONF users to a preconfigured subset of all available NETCONF or RESTCONF protocol operations and content.

All data nodes defined in the YANG module that can be created, modified, and deleted (i.e., config true, which is the default) are considered sensitive. Write operations (e.g., edit-config) applied to these data nodes without proper protection can negatively affect network operations. An attacker who is able to access the SCTP NAT function can undertake various attacks, such as:

- * Setting a low timeout for SCTP mapping entries to cause failures to deliver incoming SCTP packets.
- * Instantiating mapping entries to cause NAT collision.

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RFC 4960 Errata and Issues
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Abstract

This document is a compilation of issues found since the publication of RFC4960 in September 2007 based on experience with implementing, testing, and using SCTP along with the suggested fixes. This document provides deltas to RFC4960 and is organized in a time ordered way. The issues are listed in the order they were brought up. Because some text is changed several times the last delta in the text is the one which should be applied. In addition to the delta a description of the problem and the details of the solution are also provided.

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Table of Contents

1. Introduction	3
2. Conventions	4
3. Corrections to RFC 4960	4
3.1. Path Error Counter Threshold Handling	4
3.2. Upper Layer Protocol Shutdown Request Handling	5
3.3. Registration of New Chunk Types	6
3.4. Variable Parameters for INIT Chunks	7
3.5. CRC32c Sample Code on 64-bit Platforms	8
3.6. Endpoint Failure Detection	9
3.7. Data Transmission Rules	10
3.8. T1-Cookie Timer	11
3.9. Miscellaneous Typos	12
3.10. CRC32c Sample Code	19
3.11. partial_bytes_acked after T3-rtx Expiration	20
3.12. Order of Adjustments of partial_bytes_acked and cwnd	21
3.13. HEARTBEAT ACK and the association error counter	22
3.14. Path for Fast Retransmission	23
3.15. Transmittal in Fast Recovery	24
3.16. Initial Value of ssthresh	25
3.17. Automatically Confirmed Addresses	26
3.18. Only One Packet after Retransmission Timeout	27
3.19. INIT ACK Path for INIT in COOKIE-WAIT State	28
3.20. Zero Window Probing and Unreachable Primary Path	29
3.21. Normative Language in Section 10	30
3.22. Increase of partial_bytes_acked in Congestion Avoidance	33
3.23. Inconsistency in Notifications Handling	34
3.24. SACK.Delay Not Listed as a Protocol Parameter	40
3.25. Processing of Chunks in an Incoming SCTP Packet	42
3.26. CWND Increase in Congestion Avoidance Phase	43
3.27. Refresh of cwnd and ssthresh after Idle Period	46
3.28. Window Updates After Receiver Window Opens Up	47
3.29. Path of DATA and Reply Chunks	48
3.30. Outstanding Data, Flightsize and Data In Flight Key Terms	50
3.31. CWND Degradation due to Max.Burst	52
3.32. Reduction of RTO.Initial	53
3.33. Ordering of Bundled SACK and ERROR Chunks	55
3.34. Undefined Parameter Returned by RECEIVE Primitive	56
3.35. DSCP Changes	57

3.36. Inconsistent Handling of ICMPv4 and ICMPv6 Messages . . .	58
3.37. Handling of Soft Errors	60
3.38. Honoring CWND	60
3.39. Zero Window Probing	62
3.40. Updating References Regarding ECN	64
3.41. Host Name Address Parameter Deprecated	66
3.42. Conflicting Text Regarding the Supported Address Types Parameter	70
3.43. Integration of RFC 6096	71
3.44. Integration of RFC 6335	73
3.45. Integration of RFC 7053	75
3.46. CRC32c Code Improvements	79
3.47. Clarification of Gap Ack Blocks in SACK Chunks	89
3.48. Handling of SSN Wrap Arounds	91
3.49. Update RFC 2119 Boilerplate	92
3.50. Missed Text Removal	93
4. IANA Considerations	94
5. Security Considerations	94
6. Acknowledgments	94
7. References	95
7.1. Normative References	95
7.2. Informative References	95
Authors' Addresses	96

1. Introduction

This document contains a compilation of all defects found up until the publication of this document for [RFC4960] specifying the Stream Control Transmission Protocol (SCTP). These defects may be of an editorial or technical nature. This document may be thought of as a companion document to be used in the implementation of SCTP to clarify errors in the original SCTP document.

This document provides a history of the changes that will be compiled into a BIS document for [RFC4960]. It is structured similar to [RFC4460].

Each error will be detailed within this document in the form of:

- o The problem description,
- o The text quoted from [RFC4960],
- o The replacement text that should be placed into an upcoming BIS document,
- o A description of the solution.

Note that when reading this document one must use care to assure that a field or item is not updated further on within the document. Since this document is a historical record of the sequential changes that

have been found necessary at various inter-op events and through discussion on the list, the last delta in the text is the one which should be applied.

2. Conventions

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

3. Corrections to RFC 4960

[NOTE to RFC-Editor:

References to obsoleted RFCs are in OLD TEXT sections and have the corresponding references to the obsoleting RFCs in the NEW TEXT sections. In addition to this, there are some references to the obsoleted [RFC2960], which are intended.

]

3.1. Path Error Counter Threshold Handling

3.1.1. Description of the Problem

The handling of the 'Path.Max.Retrans' parameter is described in Section 8.2 and Section 8.3 of [RFC4960] in an inconsistent way. Whereas Section 8.2 describes that a path is marked inactive when the path error counter exceeds the threshold, Section 8.3 says the path is marked inactive when the path error counter reaches the threshold.

This issue was reported as an Errata for [RFC4960] with Errata ID 1440.

3.1.2. Text Changes to the Document

Old text: (Section 8.3)

When the value of this counter reaches the protocol parameter 'Path.Max.Retrans', the endpoint should mark the corresponding destination address as inactive if it is not so marked, and may also optionally report to the upper layer the change of reachability of this destination address. After this, the endpoint should continue HEARTBEAT on this destination address but should stop increasing the counter.

New text: (Section 8.3)

When the value of this counter exceeds the protocol parameter 'Path.Max.Retrans', the endpoint SHOULD mark the corresponding destination address as inactive if it is not so marked, and MAY also optionally report to the upper layer the change of reachability of this destination address. After this, the endpoint SHOULD continue HEARTBEAT on this destination address but SHOULD stop increasing the counter.

This text has been modified by multiple errata. It is further updated in Section 3.23.

3.1.3. Solution Description

The intended state change should happen when the threshold is exceeded.

3.2. Upper Layer Protocol Shutdown Request Handling

3.2.1. Description of the Problem

Section 9.2 of [RFC4960] describes the handling of received SHUTDOWN chunks in the SHUTDOWN-RECEIVED state instead of the handling of shutdown requests from its upper layer in this state.

This issue was reported as an Errata for [RFC4960] with Errata ID 1574.

3.2.2. Text Changes to the Document

Old text: (Section 9.2)

Once an endpoint has reached the SHUTDOWN-RECEIVED state, it MUST NOT send a SHUTDOWN in response to a ULP request, and should discard subsequent SHUTDOWN chunks.

New text: (Section 9.2)

Once an endpoint has reached the SHUTDOWN-RECEIVED state, it MUST ignore ULP shutdown requests, but MUST continue responding to SHUTDOWN chunks from its peer.

This text is in final form, and is not further updated in this document.

3.2.3. Solution Description

The text never intended the SCTP endpoint to ignore SHUTDOWN chunks from its peer. If it did, the endpoints could never gracefully terminate associations in some cases.

3.3. Registration of New Chunk Types

3.3.1. Description of the Problem

Section 14.1 of [RFC4960] should deal with new chunk types, however, the text refers to parameter types.

This issue was reported as an Errata for [RFC4960] with Errata ID 2592.

3.3.2. Text Changes to the Document

Old text: (Section 14.1)

The assignment of new chunk parameter type codes is done through an IETF Consensus action, as defined in [RFC2434]. Documentation of the chunk parameter MUST contain the following information:

New text: (Section 14.1)

The assignment of new chunk type codes is done through an IETF Consensus action, as defined in [RFC8126]. Documentation of the chunk type MUST contain the following information:

This text has been modified by multiple errata. It is further updated in Section 3.43.

3.3.3. Solution Description

Refer to chunk types as intended and change reference to [RFC8126].

3.4. Variable Parameters for INIT Chunks

3.4.1. Description of the Problem

Newlines in wrong places break the layout of the table of variable parameters for the INIT chunk in Section 3.3.2 of [RFC4960].

This issue was reported as an Errata for [RFC4960] with Errata ID 3291 and Errata ID 3804.

3.4.2. Text Changes to the Document

 Old text: (Section 3.3.2)

Variable Parameters	Status	Type	Value
IPv4 Address (Note 1)	Optional	5	IPv6 Address (Note 1)
Optional 9	Optional	6	Cookie Preservative
Reserved for ECN Capable (Note 2)	Optional	9	Reserved for ECN Capable (Note 2)
32768 (0x8000) Host Name Address (Note 3)	Optional	11	Host Name Address (Note 3)
11 Supported Address Types (Note 4)	Optional	12	Supported Address Types (Note 4)

 New text: (Section 3.3.2)

Variable Parameters	Status	Type	Value
IPv4 Address (Note 1)	Optional	5	
IPv6 Address (Note 1)	Optional	6	
Cookie Preservative	Optional	9	
Reserved for ECN Capable (Note 2)	Optional	32768	(0x8000)
Host Name Address (Note 3)	Optional	11	
Supported Address Types (Note 4)	Optional	12	

This text is in final form, and is not further updated in this document.

3.4.3. Solution Description

Fix the formatting of the table.

3.5. CRC32c Sample Code on 64-bit Platforms

3.5.1. Description of the Problem

The sample code for computing the CRC32c provided in [RFC4960] assumes that a variable of type unsigned long uses 32 bits. This is not true on some 64-bit platforms (for example the ones using LP64).

This issue was reported as an Errata for [RFC4960] with Errata ID 3423.

3.5.2. Text Changes to the Document

Old text: (Appendix C)

```
unsigned long
generate_crc32c(unsigned char *buffer, unsigned int length)
{
    unsigned int i;
    unsigned long crc32 = ~0L;
```

New text: (Appendix C)

```
unsigned long
generate_crc32c(unsigned char *buffer, unsigned int length)
{
    unsigned int i;
    unsigned long crc32 = 0xffffffffL;
```

This text has been modified by multiple errata. It is further updated in Section 3.10 and in Section 3.46.

3.5.3. Solution Description

Use 0xffffffffL instead of ~0L which gives the same value on platforms using 32 bits or 64 bits for variables of type unsigned long.

3.6. Endpoint Failure Detection

3.6.1. Description of the Problem

The handling of the association error counter defined in Section 8.1 of [RFC4960] can result in an association failure even if the path used for data transmission is available, but idle.

This issue was reported as an Errata for [RFC4960] with Errata ID 3788.

3.6.2. Text Changes to the Document

Old text: (Section 8.1)

An endpoint shall keep a counter on the total number of consecutive retransmissions to its peer (this includes retransmissions to all the destination transport addresses of the peer if it is multi-homed), including unacknowledged HEARTBEAT chunks.

New text: (Section 8.1)

An endpoint SHOULD keep a counter on the total number of consecutive retransmissions to its peer (this includes data retransmissions to all the destination transport addresses of the peer if it is multi-homed), including the number of unacknowledged HEARTBEAT chunks observed on the path which is currently used for data transfer. Unacknowledged HEARTBEAT chunks observed on paths different from the path currently used for data transfer SHOULD NOT increment the association error counter, as this could lead to association closure even if the path which is currently used for data transfer is available (but idle).

This text has been modified by multiple errata. It is further updated in Section 3.23.

3.6.3. Solution Description

A more refined handling for the association error counter is defined.

3.7. Data Transmission Rules

3.7.1. Description of the Problem

When integrating the changes to Section 6.1 A) of [RFC2960] as described in Section 2.15.2 of [RFC4460] some text was duplicated and became the final paragraph of Section 6.1 A) of [RFC4960].

This issue was reported as an Errata for [RFC4960] with Errata ID 4071.

3.7.2. Text Changes to the Document

Old text: (Section 6.1 A)

The sender MUST also have an algorithm for sending new DATA chunks to avoid silly window syndrome (SWS) as described in [RFC0813]. The algorithm can be similar to the one described in Section 4.2.3.4 of [RFC1122].

However, regardless of the value of `rwnd` (including if it is 0), the data sender can always have one DATA chunk in flight to the receiver if allowed by `cwnd` (see rule B below). This rule allows the sender to probe for a change in `rwnd` that the sender missed due to the SACK having been lost in transit from the data receiver to the data sender.

New text: (Section 6.1 A)

The sender MUST also have an algorithm for sending new DATA chunks to avoid silly window syndrome (SWS) as described in [RFC1122]. The algorithm can be similar to the one described in Section 4.2.3.4 of [RFC1122].

This text is in final form, and is not further updated in this document.

3.7.3. Solution Description

Last paragraph of Section 6.1 A) removed as intended in Section 2.15.2 of [RFC4460].

3.8. T1-Cookie Timer

3.8.1. Description of the Problem

Figure 4 of [RFC4960] illustrates the SCTP association setup. However, it incorrectly shows that the `T1-init` timer is used in the `COOKIE-ECHOED` state whereas the `T1-cookie` timer should have been used instead.

This issue was reported as an Errata for [RFC4960] with Errata ID 4400.

3.8.2. Text Changes to the Document

 Old text: (Section 5.1.6, Figure 4)

```

COOKIE ECHO [Cookie_Z] -----\
(Start T1-init timer)          \
(Enter COOKIE-ECHOED state)    \---> (build TCB enter ESTABLISHED
                                   state)
                                   /---- COOKIE-ACK
                                   /
(Cancel T1-init timer, <-----/
  Enter ESTABLISHED state)

```

 New text: (Section 5.1.6, Figure 4)

```

COOKIE ECHO [Cookie_Z] -----\
(Start T1-cookie timer)       \
(Enter COOKIE-ECHOED state)    \---> (build TCB enter ESTABLISHED
                                   state)
                                   /---- COOKIE-ACK
                                   /
(Cancel T1-cookie timer, <----/
  Enter ESTABLISHED state)

```

This text has been modified by multiple errata. It is further updated in Section 3.9.

3.8.3. Solution Description

Change the figure such that the T1-cookie timer is used instead of the T1-init timer.

3.9. Miscellaneous Typos

3.9.1. Description of the Problem

While processing [RFC4960] some typos were not caught.

One typo was reported as an Errata for [RFC4960] with Errata ID 5003.

3.9.2. Text Changes to the Document

Old text: (Section 1.6)

Transmission Sequence Numbers wrap around when they reach $2^{32} - 1$. That is, the next TSN a DATA chunk MUST use after transmitting $TSN = 2^{32} - 1$ is $TSN = 0$.

New text: (Section 1.6)

Transmission Sequence Numbers wrap around when they reach $2^{32} - 1$. That is, the next TSN a DATA chunk MUST use after transmitting $TSN = 2^{32} - 1$ is $TSN = 0$.

This text is in final form, and is not further updated in this document.

Old text: (Section 3.3.10.9)

No User Data: This error cause is returned to the originator of a DATA chunk if a received DATA chunk has no user data.

New text: (Section 3.3.10.9)

No User Data: This error cause is returned to the originator of a DATA chunk if a received DATA chunk has no user data.

This text is in final form, and is not further updated in this document.

Old text: (Section 6.7, Figure 9)

```

Endpoint A                                Endpoint Z {App
sends 3 messages; strm 0} DATA [TSN=6,Strm=0,Seq=2] -----
-----> (ack delayed) (Start T3-rtx timer)

DATA [TSN=7,Strm=0,Seq=3] -----> X (lost)

DATA [TSN=8,Strm=0,Seq=4] -----> (gap detected,
                                   immediately send ack)
                                   /----- SACK [TSN Ack=6,Block=1,
                                   /
                                   <-----/ (remove 6 from out-queue,
and mark 7 as "1" missing report)

```

New text: (Section 6.7, Figure 9)

```

Endpoint A                                Endpoint Z
{App sends 3 messages; strm 0}
DATA [TSN=6,Strm=0,Seq=2] -----> (ack delayed)
(Start T3-rtx timer)

DATA [TSN=7,Strm=0,Seq=3] -----> X (lost)

DATA [TSN=8,Strm=0,Seq=4] -----> (gap detected,
                                   immediately send ack)
                                   /----- SACK [TSN Ack=6,Block=1,
                                   /
                                   <-----/
(remove 6 from out-queue,
and mark 7 as "1" missing report)

```

This text is in final form, and is not further updated in this document.

Old text: (Section 6.10)

An endpoint bundles chunks by simply including multiple chunks in one outbound SCTP packet. The total size of the resultant IP datagram, including the SCTP packet and IP headers, MUST be less than or equal to the current Path MTU.

New text: (Section 6.10)

An endpoint bundles chunks by simply including multiple chunks in one outbound SCTP packet. The total size of the resultant IP datagram, including the SCTP packet and IP headers, MUST be less than or equal to the current PMTU.

This text is in final form, and is not further updated in this document.

Old text: (Section 10.1 O))

o Receive Unacknowledged Message

Format: RECEIVE_UNACKED(data retrieval id, buffer address, buffer size, [,stream id] [, stream sequence number] [,partial flag] [,payload protocol-id])

New text: (Section 10.1 O))

O) Receive Unacknowledged Message

Format: RECEIVE_UNACKED(data retrieval id, buffer address, buffer size [,stream id] [,stream sequence number] [,partial flag] [,payload protocol-id])

This text is in final form, and is not further updated in this document.

Old text: (Section 10.1 M)

M) Set Protocol Parameters

Format: SETPROTOCOLPARAMETERS(association id,
[,destination transport address,]
protocol parameter list)

New text: (Section 10.1 M)

M) Set Protocol Parameters

Format: SETPROTOCOLPARAMETERS(association id,
[destination transport address,]
protocol parameter list)

This text is in final form, and is not further updated in this document.

Old text: (Appendix C)

ICMP2) An implementation MAY ignore all ICMPv6 messages where the type field is not "Destination Unreachable", "Parameter Problem", or "Packet Too Big".

New text: (Appendix C)

ICMP2) An implementation MAY ignore all ICMPv6 messages where the type field is not "Destination Unreachable", "Parameter Problem", or "Packet Too Big".

This text is in final form, and is not further updated in this document.

Old text: (Appendix C)

ICMP7) If the ICMP message is either a v6 "Packet Too Big" or a v4 "Fragmentation Needed", an implementation MAY process this information as defined for PATH MTU discovery.

New text: (Appendix C)

ICMP7) If the ICMP message is either a v6 "Packet Too Big" or a v4 "Fragmentation Needed", an implementation MAY process this information as defined for PMTU discovery.

This text is in final form, and is not further updated in this document.

Old text: (Section 5.4)

2) For the receiver of the COOKIE ECHO, the only CONFIRMED address is the one to which the INIT-ACK was sent.

New text: (Section 5.4)

2) For the receiver of the COOKIE ECHO, the only CONFIRMED address is the one to which the INIT ACK was sent.

This text is in final form, and is not further updated in this document.

 Old text: (Section 5.1.6, Figure 4)

```

COOKIE ECHO [Cookie_Z] -----\
(Start T1-init timer)           \
(Enter COOKIE-ECHOED state)      \---> (build TCB enter ESTABLISHED
                                         state)
                                   /---- COOKIE-ACK
                                   /
(Cancel T1-init timer, <-----/
  Enter ESTABLISHED state)

```

 New text: (Section 5.1.6, Figure 4)

```

COOKIE ECHO [Cookie_Z] -----\
(Start T1-cookie timer)        \
(Enter COOKIE-ECHOED state)     \---> (build TCB enter ESTABLISHED
                                         state)
                                   /---- COOKIE ACK
                                   /
(Cancel T1-cookie timer, <---/
  Enter ESTABLISHED state)

```

This text has been modified by multiple errata. It includes modifications from Section 3.8. It is in final form, and is not further updated in this document.

 Old text: (Section 5.2.5)

5.2.5. Handle Duplicate COOKIE-ACK.

 New text: (Section 5.2.5)

5.2.5. Handle Duplicate COOKIE ACK.

This text is in final form, and is not further updated in this document.

Old text: (Section 8.3)

By default, an SCTP endpoint SHOULD monitor the reachability of the idle destination transport address(es) of its peer by sending a HEARTBEAT chunk periodically to the destination transport address(es). HEARTBEAT sending MAY begin upon reaching the ESTABLISHED state and is discontinued after sending either SHUTDOWN or SHUTDOWN-ACK. A receiver of a HEARTBEAT MUST respond to a HEARTBEAT with a HEARTBEAT-ACK after entering the COOKIE-ECHOED state (INIT sender) or the ESTABLISHED state (INIT receiver), up until reaching the SHUTDOWN-SENT state (SHUTDOWN sender) or the SHUTDOWN-ACK-SENT state (SHUTDOWN receiver).

New text: (Section 8.3)

By default, an SCTP endpoint SHOULD monitor the reachability of the idle destination transport address(es) of its peer by sending a HEARTBEAT chunk periodically to the destination transport address(es). HEARTBEAT sending MAY begin upon reaching the ESTABLISHED state and is discontinued after sending either SHUTDOWN or SHUTDOWN ACK. A receiver of a HEARTBEAT MUST respond to a HEARTBEAT with a HEARTBEAT ACK after entering the COOKIE-ECHOED state (INIT sender) or the ESTABLISHED state (INIT receiver), up until reaching the SHUTDOWN-SENT state (SHUTDOWN sender) or the SHUTDOWN-ACK-SENT state (SHUTDOWN receiver).

This text is in final form, and is not further updated in this document.

3.9.3. Solution Description

Typos fixed.

3.10. CRC32c Sample Code

3.10.1. Description of the Problem

The CRC32c computation is described in Appendix B of [RFC4960]. However, the corresponding sample code and its explanation appears at the end of Appendix C, which deals with ICMP handling.

3.10.2. Text Changes to the Document

Move all of Appendix C starting with the following sentence to the end of Appendix B.

The following non-normative sample code is taken from an open-source CRC generator [WILLIAMS93], using the "mirroring" technique and yielding a lookup table for SCTP CRC32c with 256 entries, each 32 bits wide.

This text has been modified by multiple errata. It includes modifications from Section 3.5. It is further updated in Section 3.46.

3.10.3. Solution Description

Text moved to the appropriate location.

3.11. partial_bytes_acked after T3-rtx Expiration

3.11.1. Description of the Problem

Section 7.2.3 of [RFC4960] explicitly states that partial_bytes_acked should be reset to 0 after packet loss detection from SACK but the same is missed for T3-rtx timer expiration.

3.11.2. Text Changes to the Document

Old text: (Section 7.2.3)

When the T3-rtx timer expires on an address, SCTP should perform slow start by:

```
ssthresh = max(cwnd/2, 4*MTU)
cwnd = 1*MTU
```

New text: (Section 7.2.3)

When the T3-rtx timer expires on an address, SCTP SHOULD perform slow start by:

```
ssthresh = max(cwnd/2, 4*MTU)
cwnd = 1*MTU
partial_bytes_acked = 0
```

This text is in final form, and is not further updated in this document.

3.11.3. Solution Description

Specify that `partial_bytes_acked` should be reset to 0 after `T3-rtx` timer expiration.

3.12. Order of Adjustments of `partial_bytes_acked` and `cwnd`

3.12.1. Description of the Problem

Section 7.2.2 of [RFC4960] likely implies the wrong order of adjustments applied to `partial_bytes_acked` and `cwnd` in the congestion avoidance phase.

3.12.2. Text Changes to the Document

Old text: (Section 7.2.2)

- o When `partial_bytes_acked` is equal to or greater than `cwnd` and before the arrival of the SACK the sender had `cwnd` or more bytes of data outstanding (i.e., before arrival of the SACK, `flightsize` was greater than or equal to `cwnd`), increase `cwnd` by MTU, and reset `partial_bytes_acked` to `(partial_bytes_acked - cwnd)`.

New text: (Section 7.2.2)

- o When `partial_bytes_acked` is equal to or greater than `cwnd` and before the arrival of the SACK the sender had `cwnd` or more bytes of data outstanding (i.e., before arrival of the SACK, `flightsize` was greater than or equal to `cwnd`), `partial_bytes_acked` is reset to `(partial_bytes_acked - cwnd)`. Next, `cwnd` is increased by `1*MTU`.

This text has been modified by multiple errata. It is further updated in Section 3.26.

3.12.3. Solution Description

The new text defines the exact order of adjustments of `partial_bytes_acked` and `cwnd` in the congestion avoidance phase.

3.13. HEARTBEAT ACK and the association error counter

3.13.1. Description of the Problem

Section 8.1 and Section 8.3 of [RFC4960] prescribe that the receiver of a HEARTBEAT ACK must reset the association overall error counter. In some circumstances, e.g. when a router discards DATA chunks but not HEARTBEAT chunks due to the larger size of the DATA chunk, it might be better to not clear the association error counter on reception of the HEARTBEAT ACK and reset it only on reception of the SACK to avoid stalling the association.

3.13.2. Text Changes to the Document

Old text: (Section 8.1)

The counter shall be reset each time a DATA chunk sent to that peer endpoint is acknowledged (by the reception of a SACK) or a HEARTBEAT ACK is received from the peer endpoint.

New text: (Section 8.1)

The counter MUST be reset each time a DATA chunk sent to that peer endpoint is acknowledged (by the reception of a SACK). When a HEARTBEAT ACK is received from the peer endpoint, the counter SHOULD also be reset. The receiver of the HEARTBEAT ACK MAY choose not to clear the counter if there is outstanding data on the association. This allows for handling the possible difference in reachability based on DATA chunks and HEARTBEAT chunks.

This text is in final form, and is not further updated in this document.

Old text: (Section 8.3)

Upon the receipt of the HEARTBEAT ACK, the sender of the HEARTBEAT should clear the error counter of the destination transport address to which the HEARTBEAT was sent, and mark the destination transport address as active if it is not so marked. The endpoint may optionally report to the upper layer when an inactive destination address is marked as active due to the reception of the latest HEARTBEAT ACK. The receiver of the HEARTBEAT ACK must also clear the association overall error count as well (as defined in Section 8.1).

New text: (Section 8.3)

Upon the receipt of the HEARTBEAT ACK, the sender of the HEARTBEAT MUST clear the error counter of the destination transport address to which the HEARTBEAT was sent, and mark the destination transport address as active if it is not so marked. The endpoint MAY optionally report to the upper layer when an inactive destination address is marked as active due to the reception of the latest HEARTBEAT ACK. The receiver of the HEARTBEAT ACK SHOULD also clear the association overall error counter (as defined in Section 8.1).

This text has been modified by multiple errata. It is further updated in Section 3.23.

3.13.3. Solution Description

The new text provides a possibility to not reset the association overall error counter when a HEARTBEAT ACK is received if there are valid reasons for it.

3.14. Path for Fast Retransmission

3.14.1. Description of the Problem

[RFC4960] clearly describes where to retransmit data that is timed out when the peer is multi-homed but the same is not stated for fast retransmissions.

3.14.2. Text Changes to the Document

Old text: (Section 6.4)

Furthermore, when its peer is multi-homed, an endpoint SHOULD try to retransmit a chunk that timed out to an active destination transport address that is different from the last destination address to which the DATA chunk was sent.

New text: (Section 6.4)

Furthermore, when its peer is multi-homed, an endpoint SHOULD try to retransmit a chunk that timed out to an active destination transport address that is different from the last destination address to which the DATA chunk was sent.

When its peer is multi-homed, an endpoint SHOULD send fast retransmissions to the same destination transport address where the original data was sent to. If the primary path has been changed and the original data was sent to the old primary path before the fast retransmit, the implementation MAY send it to the new primary path.

This text is in final form, and is not further updated in this document.

3.14.3. Solution Description

The new text clarifies where to send fast retransmissions.

3.15. Transmittal in Fast Recovery

3.15.1. Description of the Problem

The Fast Retransmit on Gap Reports algorithm intends that only the very first packet may be sent regardless of cwnd in the Fast Recovery phase but rule 3) of [RFC4960], Section 7.2.4, misses this clarification.

3.15.2. Text Changes to the Document

Old text: (Section 7.2.4)

- 3) Determine how many of the earliest (i.e., lowest TSN) DATA chunks marked for retransmission will fit into a single packet, subject to constraint of the path MTU of the destination transport address to which the packet is being sent. Call this value K. Retransmit those K DATA chunks in a single packet. When a Fast Retransmit is being performed, the sender SHOULD ignore the value of cwnd and SHOULD NOT delay retransmission for this single packet.

New text: (Section 7.2.4)

- 3) If not in Fast Recovery, determine how many of the earliest (i.e., lowest TSN) DATA chunks marked for retransmission will fit into a single packet, subject to constraint of the PMTU of the destination transport address to which the packet is being sent. Call this value K. Retransmit those K DATA chunks in a single packet. When a Fast Retransmit is being performed, the sender SHOULD ignore the value of cwnd and SHOULD NOT delay retransmission for this single packet.

This text is in final form, and is not further updated in this document.

3.15.3. Solution Description

The new text explicitly specifies to send only the first packet in the Fast Recovery phase disregarding cwnd limitations.

3.16. Initial Value of ssthresh

3.16.1. Description of the Problem

The initial value of ssthresh should be set arbitrarily high. Using the advertised receiver window of the peer is inappropriate if the peer increases its window after the handshake. Furthermore, use a higher requirements level, since not following the advice may result in performance problems.

3.16.2. Text Changes to the Document

Old text: (Section 7.2.1)

- o The initial value of ssthresh MAY be arbitrarily high (for example, implementations MAY use the size of the receiver advertised window).

New text: (Section 7.2.1)

- o The initial value of ssthresh SHOULD be arbitrarily high (e.g., the size of the largest possible advertised window).

This text is in final form, and is not further updated in this document.

3.16.3. Solution Description

Use the same value as suggested in [RFC5681], Section 3.1, as an appropriate initial value. Furthermore, use the same requirements level.

3.17. Automatically Confirmed Addresses

3.17.1. Description of the Problem

The Path Verification procedure of [RFC4960] prescribes that any address passed to the sender of the INIT by its upper layer is automatically CONFIRMED. This, however, is unclear if only addresses in the request to initiate association establishment are considered or any addresses provided by the upper layer in any requests (e.g. in 'Set Primary').

3.17.2. Text Changes to the Document

Old text: (Section 5.4)

- 1) Any address passed to the sender of the INIT by its upper layer is automatically considered to be CONFIRMED.

New text: (Section 5.4)

- 1) Any addresses passed to the sender of the INIT by its upper layer in the request to initialize an association are automatically considered to be CONFIRMED.

This text is in final form, and is not further updated in this document.

3.17.3. Solution Description

The new text clarifies that only addresses provided by the upper layer in the request to initialize an association are automatically confirmed.

3.18. Only One Packet after Retransmission Timeout

3.18.1. Description of the Problem

[RFC4960] is not completely clear when it describes data transmission after T3-rtx timer expiration. Section 7.2.1 does not specify how many packets are allowed to be sent after T3-rtx timer expiration if more than one packet fit into cwnd. At the same time, Section 7.2.3 has the text without normative language saying that SCTP should ensure that no more than one packet will be in flight after T3-rtx timer expiration until successful acknowledgment. It makes the text inconsistent.

3.18.2. Text Changes to the Document

Old text: (Section 7.2.1)

- o The initial cwnd after a retransmission timeout MUST be no more than 1*MTU.

New text: (Section 7.2.1)

- o The initial cwnd after a retransmission timeout MUST be no more than 1*MTU and only one packet is allowed to be in flight until successful acknowledgement.

This text is in final form, and is not further updated in this document.

3.18.3. Solution Description

The new text clearly specifies that only one packet is allowed to be sent after T3-rtx timer expiration until successful acknowledgement.

3.19. INIT ACK Path for INIT in COOKIE-WAIT State

3.19.1. Description of the Problem

In case of an INIT received in the COOKIE-WAIT state [RFC4960] prescribes to send an INIT ACK to the same destination address to which the original INIT has been sent. This text does not address the possibility of the upper layer to provide multiple remote IP addresses while requesting the association establishment. If the upper layer has provided multiple IP addresses and only a subset of these addresses are supported by the peer then the destination address of the original INIT may be absent in the incoming INIT and sending INIT ACK to that address is useless.

3.19.2. Text Changes to the Document

Old text: (Section 5.2.1)

Upon receipt of an INIT in the COOKIE-WAIT state, an endpoint MUST respond with an INIT ACK using the same parameters it sent in its original INIT chunk (including its Initiate Tag, unchanged). When responding, the endpoint MUST send the INIT ACK back to the same address that the original INIT (sent by this endpoint) was sent.

New text: (Section 5.2.1)

Upon receipt of an INIT in the COOKIE-WAIT state, an endpoint MUST respond with an INIT ACK using the same parameters it sent in its original INIT chunk (including its Initiate Tag, unchanged). When responding, the following rules MUST be applied:

- 1) The INIT ACK MUST only be sent to an address passed by the upper layer in the request to initialize the association.
- 2) The INIT ACK MUST only be sent to an address reported in the incoming INIT.
- 3) The INIT ACK SHOULD be sent to the source address of the received INIT.

This text is in final form, and is not further updated in this document.

3.19.3. Solution Description

The new text requires sending INIT ACK to a destination address that is passed by the upper layer and reported in the incoming INIT. If the source address of the INIT meets these conditions, sending the INIT ACK to the source address of the INIT is the preferred behavior.

3.20. Zero Window Probing and Unreachable Primary Path

3.20.1. Description of the Problem

Section 6.1 of [RFC4960] states that when sending zero window probes, SCTP should neither increment the association counter nor increment the destination address error counter if it continues to receive new packets from the peer. However, the reception of new packets from the peer does not guarantee the peer's reachability and, if the destination address becomes unreachable during zero window probing,

SCTP cannot get an updated rwnd until it switches the destination address for probes.

3.20.2. Text Changes to the Document

Old text: (Section 6.1)

If the sender continues to receive new packets from the receiver while doing zero window probing, the unacknowledged window probes should not increment the error counter for the association or any destination transport address. This is because the receiver MAY keep its window closed for an indefinite time. Refer to Section 6.2 on the receiver behavior when it advertises a zero window.

New text: (Section 6.1)

If the sender continues to receive SACKs from the peer while doing zero window probing, the unacknowledged window probes SHOULD NOT increment the error counter for the association or any destination transport address. This is because the receiver could keep its window closed for an indefinite time. Section 6.2 describes the receiver behavior when it advertises a zero window.

This text is in final form, and is not further updated in this document.

3.20.3. Solution Description

The new text clarifies that if the receiver continues to send SACKs, the sender of probes should not increment the error counter of the association and the destination address even if the SACKs do not acknowledge the probes.

3.21. Normative Language in Section 10

3.21.1. Description of the Problem

Section 10 of [RFC4960] is informative and, therefore, normative language such as MUST and MAY cannot be used there. However, there are several places in Section 10 where MUST and MAY are used.

3.21.2. Text Changes to the Document

Old text: (Section 10.1 E))

- o no-bundle flag - instructs SCTP not to bundle this user data with other outbound DATA chunks. SCTP MAY still bundle even when this flag is present, when faced with network congestion.

New text: (Section 10.1 E))

- o no-bundle flag - instructs SCTP not to bundle this user data with other outbound DATA chunks. SCTP may still bundle even when this flag is present, when faced with network congestion.

This text is in final form, and is not further updated in this document.

Old text: (Section 10.1 G))

- o Stream Sequence Number - the Stream Sequence Number assigned by the sending SCTP peer.
- o partial flag - if this returned flag is set to 1, then this Receive contains a partial delivery of the whole message. When this flag is set, the stream id and Stream Sequence Number MUST accompany this receive. When this flag is set to 0, it indicates that no more deliveries will be received for this Stream Sequence Number.

New text: (Section 10.1 G))

- o stream sequence number - the Stream Sequence Number assigned by the sending SCTP peer.
- o partial flag - if this returned flag is set to 1, then this primitive contains a partial delivery of the whole message. When this flag is set, the stream id and stream sequence number must accompany this primitive. When this flag is set to 0, it indicates that no more deliveries will be received for this stream sequence number.

This text is in final form, and is not further updated in this document.

Old text: (Section 10.1 N)

- o Stream Sequence Number - this value is returned indicating the Stream Sequence Number that was associated with the message.
- o partial flag - if this returned flag is set to 1, then this message is a partial delivery of the whole message. When this flag is set, the stream id and Stream Sequence Number MUST accompany this receive. When this flag is set to 0, it indicates that no more deliveries will be received for this Stream Sequence Number.

New text: (Section 10.1 N)

- o stream sequence number - this value is returned indicating the Stream Sequence Number that was associated with the message.
- o partial flag - if this returned flag is set to 1, then this message is a partial delivery of the whole message. When this flag is set, the stream id and stream sequence number must accompany this primitive. When this flag is set to 0, it indicates that no more deliveries will be received for this stream sequence number.

This text is in final form, and is not further updated in this document.

Old text: (Section 10.1 O)

- o Stream Sequence Number - this value is returned indicating the Stream Sequence Number that was associated with the message.
- o partial flag - if this returned flag is set to 1, then this message is a partial delivery of the whole message. When this flag is set, the stream id and Stream Sequence Number MUST accompany this receive. When this flag is set to 0, it indicates that no more deliveries will be received for this Stream Sequence Number.

New text: (Section 10.1 O)

- o stream sequence number - this value is returned indicating the Stream Sequence Number that was associated with the message.
- o partial flag - if this returned flag is set to 1, then this message is a partial delivery of the whole message. When this flag is set, the stream id and stream sequence number must accompany this primitive. When this flag is set to 0, it indicates that no more deliveries will be received for this stream sequence number.

This text is in final form, and is not further updated in this document.

3.21.3. Solution Description

The normative language is removed from Section 10. In addition, the consistency of the text has been improved.

3.22. Increase of partial_bytes_acked in Congestion Avoidance

3.22.1. Description of the Problem

Two issues have been discovered with the partial_bytes_acked handling described in Section 7.2.2 of [RFC4960]:

- o If the Cumulative TSN Ack Point is not advanced but the SACK chunk acknowledges new TSNs in the Gap Ack Blocks, these newly acknowledged TSNs are not considered for partial_bytes_acked although these TSNs were successfully received by the peer.

- o Duplicate TSNs are not considered in `partial_bytes_acked` although they confirm that the DATA chunks were successfully received by the peer.

3.22.2. Text Changes to the Document

Old text: (Section 7.2.2)

- o Whenever `cwnd` is greater than `ssthresh`, upon each SACK arrival that advances the Cumulative TSN Ack Point, increase `partial_bytes_acked` by the total number of bytes of all new chunks acknowledged in that SACK including chunks acknowledged by the new Cumulative TSN Ack and by Gap Ack Blocks.

New text: (Section 7.2.2)

- o Whenever `cwnd` is greater than `ssthresh`, upon each SACK arrival, increase `partial_bytes_acked` by the total number of bytes of all new chunks acknowledged in that SACK including chunks acknowledged by the new Cumulative TSN Ack, by Gap Ack Blocks and by the number of bytes of duplicated chunks reported in Duplicate TSNs.

This text has been modified by multiple errata. It is further updated in Section 3.26.

3.22.3. Solution Description

Now `partial_bytes_acked` is increased by TSNs reported as duplicated as well as TSNs newly acknowledged in Gap Ack Blocks even if the Cumulative TSN Ack Point is not advanced.

3.23. Inconsistency in Notifications Handling

3.23.1. Description of the Problem

[RFC4960] uses inconsistent normative and non-normative language when describing rules for sending notifications to the upper layer. E.g. Section 8.2 of [RFC4960] says that when a destination address becomes inactive due to an unacknowledged DATA chunk or HEARTBEAT chunk, SCTP SHOULD send a notification to the upper layer while Section 8.3 of [RFC4960] says that when a destination address becomes inactive due to an unacknowledged HEARTBEAT chunk, SCTP may send a notification to the upper layer.

This makes the text inconsistent.

3.23.2. Text Changes to the Document

Old text: (Section 8.1)

An endpoint shall keep a counter on the total number of consecutive retransmissions to its peer (this includes retransmissions to all the destination transport addresses of the peer if it is multi-homed), including unacknowledged HEARTBEAT chunks.

New text: (Section 8.1)

An endpoint SHOULD keep a counter on the total number of consecutive retransmissions to its peer (this includes data retransmissions to all the destination transport addresses of the peer if it is multi-homed), including the number of unacknowledged HEARTBEAT chunks observed on the path which currently is used for data transfer. Unacknowledged HEARTBEAT chunks observed on paths different from the path currently used for data transfer SHOULD NOT increment the association error counter, as this could lead to association closure even if the path which currently is used for data transfer is available (but idle). If the value of this counter exceeds the limit indicated in the protocol parameter 'Association.Max.Retrans', the endpoint SHOULD consider the peer endpoint unreachable and SHALL stop transmitting any more data to it (and thus the association enters the CLOSED state). In addition, the endpoint SHOULD report the failure to the upper layer and optionally report back all outstanding user data remaining in its outbound queue. The association is automatically closed when the peer endpoint becomes unreachable.

This text has been modified by multiple errata. It includes modifications from Section 3.6. It is in final form, and is not further updated in this document.

Old text: (Section 8.2)

When an outstanding TSN is acknowledged or a HEARTBEAT sent to that address is acknowledged with a HEARTBEAT ACK, the endpoint shall clear the error counter of the destination transport address to which the DATA chunk was last sent (or HEARTBEAT was sent). When the peer endpoint is multi-homed and the last chunk sent to it was a retransmission to an alternate address, there exists an ambiguity as to whether or not the acknowledgement should be credited to the address of the last chunk sent. However, this ambiguity does not seem to bear any significant consequence to SCTP behavior. If this ambiguity is undesirable, the transmitter may choose not to clear the error counter if the last chunk sent was a retransmission.

New text: (Section 8.2)

When an outstanding TSN is acknowledged or a HEARTBEAT sent to that address is acknowledged with a HEARTBEAT ACK, the endpoint SHOULD clear the error counter of the destination transport address to which the DATA chunk was last sent (or HEARTBEAT was sent), and SHOULD also report to the upper layer when an inactive destination address is marked as active. When the peer endpoint is multi-homed and the last chunk sent to it was a retransmission to an alternate address, there exists an ambiguity as to whether or not the acknowledgement could be credited to the address of the last chunk sent. However, this ambiguity does not seem to bear any significant consequence to SCTP behavior. If this ambiguity is undesirable, the transmitter MAY choose not to clear the error counter if the last chunk sent was a retransmission.

This text is in final form, and is not further updated in this document.

Old text: (Section 8.3)

When the value of this counter reaches the protocol parameter 'Path.Max.Retrans', the endpoint should mark the corresponding destination address as inactive if it is not so marked, and may also optionally report to the upper layer the change of reachability of this destination address. After this, the endpoint should continue HEARTBEAT on this destination address but should stop increasing the counter.

New text: (Section 8.3)

When the value of this counter exceeds the protocol parameter 'Path.Max.Retrans', the endpoint SHOULD mark the corresponding destination address as inactive if it is not so marked, and SHOULD also report to the upper layer the change of reachability of this destination address. After this, the endpoint SHOULD continue HEARTBEAT on this destination address but SHOULD stop increasing the counter.

This text has been modified by multiple errata. It includes modifications from Section 3.1. It is in final form, and is not further updated in this document.

Old text: (Section 8.3)

Upon the receipt of the HEARTBEAT ACK, the sender of the HEARTBEAT should clear the error counter of the destination transport address to which the HEARTBEAT was sent, and mark the destination transport address as active if it is not so marked. The endpoint may optionally report to the upper layer when an inactive destination address is marked as active due to the reception of the latest HEARTBEAT ACK. The receiver of the HEARTBEAT ACK must also clear the association overall error count as well (as defined in Section 8.1).

New text: (Section 8.3)

Upon the receipt of the HEARTBEAT ACK, the sender of the HEARTBEAT SHOULD clear the error counter of the destination transport address to which the HEARTBEAT was sent, and mark the destination transport address as active if it is not so marked. The endpoint SHOULD report to the upper layer when an inactive destination address is marked as active due to the reception of the latest HEARTBEAT ACK. The receiver of the HEARTBEAT ACK SHOULD also clear the association overall error counter (as defined in Section 8.1).

This text has been modified by multiple errata. It includes modifications from Section 3.13. It is in final form, and is not further updated in this document.

Old text: (Section 9.2)

An endpoint should limit the number of retransmissions of the SHUTDOWN chunk to the protocol parameter 'Association.Max.Retrans'. If this threshold is exceeded, the endpoint should destroy the TCB and MUST report the peer endpoint unreachable to the upper layer (and thus the association enters the CLOSED state).

New text: (Section 9.2)

An endpoint SHOULD limit the number of retransmissions of the SHUTDOWN chunk to the protocol parameter 'Association.Max.Retrans'. If this threshold is exceeded, the endpoint SHOULD destroy the TCB and SHOULD report the peer endpoint unreachable to the upper layer (and thus the association enters the CLOSED state).

This text is in final form, and is not further updated in this document.

Old text: (Section 9.2)

The sender of the SHUTDOWN ACK should limit the number of retransmissions of the SHUTDOWN ACK chunk to the protocol parameter 'Association.Max.Retrans'. If this threshold is exceeded, the endpoint should destroy the TCB and may report the peer endpoint unreachable to the upper layer (and thus the association enters the CLOSED state).

New text: (Section 9.2)

The sender of the SHUTDOWN ACK SHOULD limit the number of retransmissions of the SHUTDOWN ACK chunk to the protocol parameter 'Association.Max.Retrans'. If this threshold is exceeded, the endpoint SHOULD destroy the TCB and SHOULD report the peer endpoint unreachable to the upper layer (and thus the association enters the CLOSED state).

This text is in final form, and is not further updated in this document.

3.23.3. Solution Description

The inconsistencies are removed by using consistently SHOULD.

3.24. SACK.Delay Not Listed as a Protocol Parameter

3.24.1. Description of the Problem

SCTP as specified in [RFC4960] supports delaying SACKs. The timer value for this is a parameter and Section 6.2 of [RFC4960] specifies a default and maximum value for it. However, defining a name for this parameter and listing it in the table of protocol parameters in Section 15 of [RFC4960] is missing.

This issue was reported as an Errata for [RFC4960] with Errata ID 4656.

3.24.2. Text Changes to the Document

Old text: (Section 6.2)

An implementation MUST NOT allow the maximum delay to be configured to be more than 500 ms. In other words, an implementation MAY lower this value below 500 ms but MUST NOT raise it above 500 ms.

New text: (Section 6.2)

An implementation MUST NOT allow the maximum delay (protocol parameter 'SACK.Delay') to be configured to be more than 500 ms. In other words, an implementation MAY lower the value of SACK.Delay below 500 ms but MUST NOT raise it above 500 ms.

This text is in final form, and is not further updated in this document.

Old text: (Section 15)

The following protocol parameters are RECOMMENDED:

RTO.Initial - 3 seconds
RTO.Min - 1 second
RTO.Max - 60 seconds
Max.Burst - 4
RTO.Alpha - 1/8
RTO.Beta - 1/4
Valid.Cookie.Life - 60 seconds
Association.Max.Retrans - 10 attempts
Path.Max.Retrans - 5 attempts (per destination address)
Max.Init.Retransmits - 8 attempts
HB.interval - 30 seconds
HB.Max.Burst - 1

New text: (Section 15)

The following protocol parameters are RECOMMENDED:

RTO.Initial - 3 seconds
RTO.Min - 1 second
RTO.Max - 60 seconds
Max.Burst - 4
RTO.Alpha - 1/8
RTO.Beta - 1/4
Valid.Cookie.Life - 60 seconds
Association.Max.Retrans - 10 attempts
Path.Max.Retrans - 5 attempts (per destination address)
Max.Init.Retransmits - 8 attempts
HB.interval - 30 seconds
HB.Max.Burst - 1
SACK.Delay - 200 milliseconds

This text has been modified by multiple errata. It is further updated in Section 3.32.

3.24.3. Solution Description

The parameter was given a name and added to the list of protocol parameters.

3.25. Processing of Chunks in an Incoming SCTP Packet

3.25.1. Description of the Problem

There are a few places in [RFC4960] where the receiver of a packet must discard it while processing the chunks of the packet. It is unclear whether the receiver has to rollback state changes already performed while processing the packet or not.

The intention of [RFC4960] is to process an incoming packet chunk by chunk and not to perform any prescreening of chunks in the received packet. Thus, by discarding one chunk the receiver also causes discarding of all further chunks.

3.25.2. Text Changes to the Document

Old text: (Section 3.2)

- 00 - Stop processing this SCTP packet and discard it, do not process any further chunks within it.
- 01 - Stop processing this SCTP packet and discard it, do not process any further chunks within it, and report the unrecognized chunk in an 'Unrecognized Chunk Type'.

New text: (Section 3.2)

- 00 - Stop processing this SCTP packet, discard the unrecognized chunk and all further chunks.
- 01 - Stop processing this SCTP packet, discard the unrecognized chunk and all further chunks, and report the unrecognized chunk in an 'Unrecognized Chunk Type'.

This text is in final form, and is not further updated in this document.

Old text: (Section 11.3)

It is helpful for some firewalls if they can inspect just the first fragment of a fragmented SCTP packet and unambiguously determine whether it corresponds to an INIT chunk (for further information, please refer to [RFC1858]). Accordingly, we stress the requirements, stated in Section 3.1, that (1) an INIT chunk MUST NOT be bundled with any other chunk in a packet, and (2) a packet containing an INIT chunk MUST have a zero Verification Tag. Furthermore, we require that the receiver of an INIT chunk MUST enforce these rules by silently discarding an arriving packet with an INIT chunk that is bundled with other chunks or has a non-zero verification tag and contains an INIT-chunk.

New text: (Section 11.3)

It is helpful for some firewalls if they can inspect just the first fragment of a fragmented SCTP packet and unambiguously determine whether it corresponds to an INIT chunk (for further information, please refer to [RFC1858]). Accordingly, we stress the requirements, stated in Section 3.1, that (1) an INIT chunk MUST NOT be bundled with any other chunk in a packet, and (2) a packet containing an INIT chunk MUST have a zero Verification Tag. The receiver of an INIT chunk MUST silently discard the INIT chunk and all further chunks if the INIT chunk is bundled with other chunks or the packet has a non-zero verification tag.

This text is in final form, and is not further updated in this document.

3.25.3. Solution Description

The new text makes it clear that chunks can be processed from the beginning to the end and no rollback or pre-screening is required.

3.26. CWND Increase in Congestion Avoidance Phase

3.26.1. Description of the Problem

[RFC4960] in Section 7.2.2 prescribes to increase cwnd by 1*MTU per RTT if the sender has cwnd or more bytes of data outstanding to the corresponding address in the Congestion Avoidance phase. However, this is described without normative language. Moreover, Section 7.2.2 includes an algorithm how an implementation can achieve

this but this algorithm is underspecified and actually allows increasing cwnd by more than 1*MTU per RTT.

3.26.2. Text Changes to the Document

Old text: (Section 7.2.2)

When cwnd is greater than ssthresh, cwnd should be incremented by 1*MTU per RTT if the sender has cwnd or more bytes of data outstanding for the corresponding transport address.

New text: (Section 7.2.2)

When cwnd is greater than ssthresh, cwnd SHOULD be incremented by 1*MTU per RTT if the sender has cwnd or more bytes of data outstanding for the corresponding transport address. The basic guidelines for incrementing cwnd during congestion avoidance are:

- o Sctp MAY increment cwnd by 1*MTU.
- o Sctp SHOULD increment cwnd by one 1*MTU once per RTT when the sender has cwnd or more bytes of data outstanding for the corresponding transport address.
- o Sctp MUST NOT increment cwnd by more than 1*MTU per RTT.

This text is in final form, and is not further updated in this document.

Old text: (Section 7.2.2)

- o Whenever `cwnd` is greater than `ssthresh`, upon each SACK arrival that advances the Cumulative TSN Ack Point, increase `partial_bytes_acked` by the total number of bytes of all new chunks acknowledged in that SACK including chunks acknowledged by the new Cumulative TSN Ack and by Gap Ack Blocks.
- o When `partial_bytes_acked` is equal to or greater than `cwnd` and before the arrival of the SACK the sender had `cwnd` or more bytes of data outstanding (i.e., before arrival of the SACK, `flightsize` was greater than or equal to `cwnd`), increase `cwnd` by MTU, and reset `partial_bytes_acked` to `(partial_bytes_acked - cwnd)`.

New text: (Section 7.2.2)

- o Whenever `cwnd` is greater than `ssthresh`, upon each SACK arrival, increase `partial_bytes_acked` by the total number of bytes of all new chunks acknowledged in that SACK including chunks acknowledged by the new Cumulative TSN Ack, by Gap Ack Blocks and by the number of bytes of duplicated chunks reported in Duplicate TSNs.
- o When `partial_bytes_acked` is greater than `cwnd` and before the arrival of the SACK the sender had less than `cwnd` bytes of data outstanding (i.e., before arrival of the SACK, `flightsize` was less than `cwnd`), reset `partial_bytes_acked` to `cwnd`.
- o When `partial_bytes_acked` is equal to or greater than `cwnd` and before the arrival of the SACK the sender had `cwnd` or more bytes of data outstanding (i.e., before arrival of the SACK, `flightsize` was greater than or equal to `cwnd`), `partial_bytes_acked` is reset to `(partial_bytes_acked - cwnd)`. Next, `cwnd` is increased by `1*MTU`.

This text has been modified by multiple errata. It includes modifications from Section 3.12 and Section 3.22. It is in final form, and is not further updated in this document.

3.26.3. Solution Description

The basic guidelines for incrementing `cwnd` during the congestion avoidance phase are added into Section 7.2.2. The guidelines include the normative language and are aligned with [RFC5681].

The algorithm from Section 7.2.2 is improved to not allow increasing cwnd by more than 1*MTU per RTT.

3.27. Refresh of cwnd and ssthresh after Idle Period

3.27.1. Description of the Problem

[RFC4960] prescribes to adjust cwnd per RTO if the endpoint does not transmit data on a given transport address. In addition to that, it prescribes to set cwnd to the initial value after a sufficiently long idle period. The latter is excessive. Moreover, it is unclear what is a sufficiently long idle period.

[RFC4960] doesn't specify the handling of ssthresh in the idle case. If ssthresh is reduced due to a packet loss, ssthresh is never recovered. So traffic can end up in Congestion Avoidance all the time, resulting in a low sending rate and bad performance. The problem is even more serious for SCTP because in a multi-homed SCTP association traffic that switches back to the previously failed primary path will also lead to the situation where traffic ends up in Congestion Avoidance.

3.27.2. Text Changes to the Document

Old text: (Section 7.2.1)

- o The initial cwnd before DATA transmission or after a sufficiently long idle period MUST be set to min(4*MTU, max (2*MTU, 4380 bytes)).

New text: (Section 7.2.1)

- o The initial cwnd before DATA transmission MUST be set to min(4*MTU, max (2*MTU, 4380 bytes)).

Old text: (Section 7.2.1)

- o When the endpoint does not transmit data on a given transport address, the cwnd of the transport address should be adjusted to $\max(\text{cwnd}/2, 4 \cdot \text{MTU})$ per RTO.

New text: (Section 7.2.1)

- o While the endpoint does not transmit data on a given transport address, the cwnd of the transport address SHOULD be adjusted to $\max(\text{cwnd}/2, 4 \cdot \text{MTU})$ once per RTO. Before the first cwnd adjustment, the ssthresh of the transport address SHOULD be set to the cwnd.

This text is in final form, and is not further updated in this document.

3.27.3. Solution Description

A rule about cwnd adjustment after a sufficiently long idle period is removed.

The text is updated to describe the ssthresh handling. When the idle period is detected, the cwnd value is stored to the ssthresh value.

3.28. Window Updates After Receiver Window Opens Up

3.28.1. Description of the Problem

The sending of SACK chunks for window updates is only indirectly referenced in [RFC4960], Section 6.2, where it is stated that an SCTP receiver must not generate more than one SACK for every incoming packet, other than to update the offered window.

However, the sending of window updates when the receiver window opens up is necessary to avoid performance problems.

3.28.2. Text Changes to the Document

Old text: (Section 6.2)

An SCTP receiver MUST NOT generate more than one SACK for every incoming packet, other than to update the offered window as the receiving application consumes new data.

New text: (Section 6.2)

An SCTP receiver MUST NOT generate more than one SACK for every incoming packet, other than to update the offered window as the receiving application consumes new data. When the window opens up, an SCTP receiver SHOULD send additional SACK chunks to update the window even if no new data is received. The receiver MUST avoid sending a large number of window updates, in particular large bursts of them. One way to achieve this is to send a window update only if the window can be increased by at least a quarter of the receive buffer size of the association.

This text is in final form, and is not further updated in this document.

3.28.3. Solution Description

The new text makes clear that additional SACK chunks for window updates should be sent as long as excessive bursts are avoided.

3.29. Path of DATA and Reply Chunks

3.29.1. Description of the Problem

Section 6.4 of [RFC4960] describes the transmission policy for multi-homed SCTP endpoints. However, there are the following issues with it:

- o It states that a SACK should be sent to the source address of an incoming DATA. However, it is known that other SACK policies (e.g. sending SACKs always to the primary path) may be more beneficial in some situations.
- o Initially it states that an endpoint should always transmit DATA chunks to the primary path. Then it states that the rule for transmittal of reply chunks should also be followed if the endpoint is bundling DATA chunks together with the reply chunk which contradicts with the first statement to always transmit DATA

chunks to the primary path. Some implementations were having problems with it and sent DATA chunks bundled with reply chunks to a different destination address than the primary path that caused many gaps.

3.29.2. Text Changes to the Document

Old text: (Section 6.4)

An endpoint SHOULD transmit reply chunks (e.g., SACK, HEARTBEAT ACK, etc.) to the same destination transport address from which it received the DATA or control chunk to which it is replying. This rule should also be followed if the endpoint is bundling DATA chunks together with the reply chunk.

However, when acknowledging multiple DATA chunks received in packets from different source addresses in a single SACK, the SACK chunk may be transmitted to one of the destination transport addresses from which the DATA or control chunks being acknowledged were received.

New text: (Section 6.4)

An endpoint SHOULD transmit reply chunks (e.g., INIT ACK, COOKIE ACK, HEARTBEAT ACK, etc.) in response to control chunks to the same destination transport address from which it received the control chunk to which it is replying.

The selection of the destination transport address for packets containing SACK chunks is implementation dependent. However, an endpoint SHOULD NOT vary the destination transport address of a SACK when it receives DATA chunks coming from the same source address.

When acknowledging multiple DATA chunks received in packets from different source addresses in a single SACK, the SACK chunk MAY be transmitted to one of the destination transport addresses from which the DATA or control chunks being acknowledged were received.

This text is in final form, and is not further updated in this document.

3.29.3. Solution Description

The SACK transmission policy is left implementation dependent but it is specified to not vary the destination address of a packet containing a SACK chunk unless there are reasons for it as it may negatively impact RTT measurement.

A confusing statement that prescribes to follow the rule for transmittal of reply chunks when the endpoint is bundling DATA chunks together with the reply chunk is removed.

3.30. Outstanding Data, Flightsize and Data In Flight Key Terms

3.30.1. Description of the Problem

[RFC4960] uses outstanding data, flightsize and data in flight key terms in formulas and statements but their definitions are not provided in Section 1.3. Furthermore, outstanding data does not include DATA chunks which are classified as lost but which have not been retransmitted yet and there is a paragraph in Section 6.1 of [RFC4960] where this statement is broken.

3.30.2. Text Changes to the Document

Old text: (Section 1.3)

- o Congestion window (cwnd): An SCTP variable that limits the data, in number of bytes, a sender can send to a particular destination transport address before receiving an acknowledgement.

...

- o Outstanding TSN (at an SCTP endpoint): A TSN (and the associated DATA chunk) that has been sent by the endpoint but for which it has not yet received an acknowledgement.

New text: (Section 1.3)

- o Outstanding TSN (at an SCTP endpoint): A TSN (and the associated DATA chunk) that has been sent by the endpoint but for which it has not yet received an acknowledgement.
- o Outstanding data (or Data outstanding or Data in flight): The total amount of the DATA chunks associated with outstanding TSNs. A retransmitted DATA chunk is counted once in outstanding data. A DATA chunk which is classified as lost but which has not been retransmitted yet is not in outstanding data.
- o Flightsize: The amount of bytes of outstanding data to a particular destination transport address at any given time.
- o Congestion window (cwnd): An SCTP variable that limits outstanding data, in number of bytes, a sender can send to a particular destination transport address before receiving an acknowledgement.

This text is in final form, and is not further updated in this document.

Old text: (Section 6.1)

- C) When the time comes for the sender to transmit, before sending new DATA chunks, the sender MUST first transmit any outstanding DATA chunks that are marked for retransmission (limited by the current cwnd).

New text: (Section 6.1)

- C) When the time comes for the sender to transmit, before sending new DATA chunks, the sender MUST first transmit any DATA chunks that are marked for retransmission (limited by the current cwnd).

This text is in final form, and is not further updated in this document.

3.30.3. Solution Description

Now Section 1.3, Key Terms, includes explanations of outstanding data, data in flight and flightsize key terms. Section 6.1 is corrected to properly use the outstanding data term.

3.31. CWND Degradation due to Max.Burst

3.31.1. Description of the Problem

Some implementations were experiencing a degradation of cwnd because of the Max.Burst limit. This was due to misinterpretation of the suggestion in [RFC4960], Section 6.1, on how to use the Max.Burst parameter when calculating the number of packets to transmit.

3.31.2. Text Changes to the Document

Old text: (Section 6.1)

- D) When the time comes for the sender to transmit new DATA chunks, the protocol parameter Max.Burst SHOULD be used to limit the number of packets sent. The limit MAY be applied by adjusting cwnd as follows:

```
if((flightsize + Max.Burst*MTU) < cwnd) cwnd = flightsize +
Max.Burst*MTU
```

Or it MAY be applied by strictly limiting the number of packets emitted by the output routine.

New text: (Section 6.1)

- D) When the time comes for the sender to transmit new DATA chunks, the protocol parameter Max.Burst SHOULD be used to limit the number of packets sent. The limit MAY be applied by adjusting cwnd temporarily as follows:

```
if ((flightsize + Max.Burst*MTU) < cwnd)
    cwnd = flightsize + Max.Burst*MTU
```

Or it MAY be applied by strictly limiting the number of packets emitted by the output routine. When calculating the number of packets to transmit and particularly using the formula above, cwnd SHOULD NOT be changed permanently.

This text is in final form, and is not further updated in this document.

3.31.3. Solution Description

The new text clarifies that cwnd should not be changed when applying the Max.Burst limit. This mitigates packet bursts related to the reception of SACK chunks, but not bursts related to an application sending a burst of user messages.

3.32. Reduction of RTO.Initial

3.32.1. Description of the Problem

[RFC4960] uses 3 seconds as the default value for RTO.Initial in accordance with Section 4.3.2.1 of [RFC1122]. [RFC6298] updates [RFC1122] and lowers the initial value of the retransmission timer from 3 seconds to 1 second.

3.32.2. Text Changes to the Document

Old text: (Section 15)

The following protocol parameters are RECOMMENDED:

RTO.Initial - 3 seconds
RTO.Min - 1 second
RTO.Max - 60 seconds
Max.Burst - 4
RTO.Alpha - 1/8
RTO.Beta - 1/4
Valid.Cookie.Life - 60 seconds
Association.Max.Retrans - 10 attempts
Path.Max.Retrans - 5 attempts (per destination address)
Max.Init.Retransmits - 8 attempts
HB.interval - 30 seconds
HB.Max.Burst - 1

New text: (Section 15)

The following protocol parameters are RECOMMENDED:

RTO.Initial - 1 second
RTO.Min - 1 second
RTO.Max - 60 seconds
Max.Burst - 4
RTO.Alpha - 1/8
RTO.Beta - 1/4
Valid.Cookie.Life - 60 seconds
Association.Max.Retrans - 10 attempts
Path.Max.Retrans - 5 attempts (per destination address)
Max.Init.Retransmits - 8 attempts
HB.interval - 30 seconds
HB.Max.Burst - 1
SACK.Delay - 200 milliseconds

This text has been modified by multiple errata. It includes modifications from Section 3.24. It is in final form, and is not further updated in this document.

3.32.3. Solution Description

The value `RTO.Initial` has been lowered to 1 second to be in tune with [RFC6298].

3.33. Ordering of Bundled SACK and ERROR Chunks

3.33.1. Description of the Problem

When an SCTP endpoint receives a DATA chunk with an invalid stream identifier it shall acknowledge it by sending a SACK chunk and indicate that the stream identifier was invalid by sending an ERROR chunk. These two chunks may be bundled. However, [RFC4960] requires in case of bundling that the ERROR chunk follows the SACK chunk. This restriction of the ordering is not necessary and might only limit interoperability.

3.33.2. Text Changes to the Document

Old text: (Section 6.5)

Every DATA chunk MUST carry a valid stream identifier. If an endpoint receives a DATA chunk with an invalid stream identifier, it shall acknowledge the reception of the DATA chunk following the normal procedure, immediately send an ERROR chunk with cause set to "Invalid Stream Identifier" (see Section 3.3.10), and discard the DATA chunk. The endpoint may bundle the ERROR chunk in the same packet as the SACK as long as the ERROR follows the SACK.

New text: (Section 6.5)

Every DATA chunk MUST carry a valid stream identifier. If an endpoint receives a DATA chunk with an invalid stream identifier, it SHOULD acknowledge the reception of the DATA chunk following the normal procedure, immediately send an ERROR chunk with cause set to "Invalid Stream Identifier" (see Section 3.3.10), and discard the DATA chunk. The endpoint MAY bundle the ERROR chunk and the SACK Chunk in the same packet.

This text is in final form, and is not further updated in this document.

3.33.3. Solution Description

The unnecessary restriction regarding the ordering of the SACK and ERROR chunk has been removed.

3.34. Undefined Parameter Returned by RECEIVE Primitive

3.34.1. Description of the Problem

[RFC4960] provides a description of an abstract API. In the definition of the RECEIVE primitive an optional parameter with name "delivery number" is mentioned. However, no definition of this parameter is given in [RFC4960] and the parameter is unnecessary.

3.34.2. Text Changes to the Document

Old text: (Section 10.1 G))

G) Receive

Format: RECEIVE(association id, buffer address, buffer size
[,stream id])

-> byte count [,transport address] [,stream id] [,stream sequence
number] [,partial flag] [,delivery number] [,payload protocol-id]

New text: (Section 10.1 G))

G) Receive

Format: RECEIVE(association id, buffer address, buffer size
[,stream id])

-> byte count [,transport address] [,stream id] [,stream sequence
number] [,partial flag] [,payload protocol-id]

This text is in final form, and is not further updated in this document.

3.34.3. Solution Description

The undefined parameter has been removed.

3.35. DSCP Changes

3.35.1. Description of the Problem

The upper layer can change the Differentiated Services Code Point (DSCP) used for packets being sent. A change of the DSCP can result in packets hitting different queues on the path and, therefore, the congestion control should be initialized when the DSCP is changed by the upper layer. This is not described in [RFC4960].

3.35.2. Text Changes to the Document

New text: (Section 7.2.5)

7.2.5. Change of Differentiated Services Code Points

SCTP implementations MAY allow an application to configure the Differentiated Services Code Point (DSCP) used for sending packets. If a DSCP change might result in outgoing packets being queued in different queues, the congestion control parameters for all affected destination addresses MUST be reset to their initial values.

This text is in final form, and is not further updated in this document.

Old text: (Section 10.1 M)

Mandatory attributes:

- o association id - local handle to the SCTP association.
- o protocol parameter list - the specific names and values of the protocol parameters (e.g., Association.Max.Retrans; see Section 15) that the SCTP user wishes to customize.

New text: (Section 10.1 M)

Mandatory attributes:

- o association id - local handle to the SCTP association.
- o protocol parameter list - the specific names and values of the protocol parameters (e.g., Association.Max.Retrans; see Section 15, or other parameters like the DSCP) that the SCTP user wishes to customize.

This text is in final form, and is not further updated in this document.

3.35.3. Solution Description

Text describing the required action on DSCP changes has been added.

3.36. Inconsistent Handling of ICMPv4 and ICMPv6 Messages

3.36.1. Description of the Problem

Appendix C of [RFC4960] describes the handling of ICMPv4 and ICMPv6 messages. The handling of ICMP messages indicating that the port number is unreachable described in the enumeration is not consistent with the description given in [RFC4960] after the enumeration. Furthermore, the text explicitly describes the handling of ICMPv6 packets indicating reachability problems, but does not do the same for the corresponding ICMPv4 packets.

3.36.2. Text Changes to the Document

Old text: (Appendix C)

ICMP3) An implementation MAY ignore any ICMPv4 messages where the code does not indicate "Protocol Unreachable" or "Fragmentation Needed".

New text: (Appendix C)

ICMP3) An implementation SHOULD ignore any ICMP messages where the code indicates "Port Unreachable".

This text is in final form, and is not further updated in this document.

Old text: (Appendix C)

ICMP9) If the ICMPv6 code is "Destination Unreachable", the implementation MAY mark the destination into the unreachable state or alternatively increment the path error counter.

New text: (Appendix C)

ICMP9) If the ICMP type is "Destination Unreachable", the implementation MAY mark the destination into the unreachable state or alternatively increment the path error counter.

This text has been modified by multiple errata. It is further updated in Section 3.37.

3.36.3. Solution Description

The text has been changed to describe the intended handling of ICMP messages indicating that the port number is unreachable by replacing the third rule. Furthermore, remove the limitation to ICMPv6 in the ninth rule.

3.37. Handling of Soft Errors

3.37.1. Description of the Problem

[RFC1122] defines the handling of soft errors and hard errors for TCP. Appendix C of [RFC4960] only deals with hard errors.

3.37.2. Text Changes to the Document

Old text: (Appendix C)

ICMP9) If the ICMPv6 code is "Destination Unreachable", the implementation MAY mark the destination into the unreachable state or alternatively increment the path error counter.

New text: (Appendix C)

ICMP9) If the ICMP type is "Destination Unreachable", the implementation MAY mark the destination into the unreachable state or alternatively increment the path error counter. SCTP MAY provide information to the upper layer indicating the reception of ICMP messages when reporting a network status change.

This text has been modified by multiple errata. It includes modifications from Section 3.36. It is in final form, and is not further updated in this document.

3.37.3. Solution Description

Text has been added allowing SCTP to notify the application in case of soft errors.

3.38. Honoring CWND

3.38.1. Description of the Problem

When using the slow start algorithm, SCTP increases the congestion window only when it is being fully utilized. Since SCTP uses DATA chunks and does not use the congestion window to fragment user messages, this requires that some overbooking of the congestion window is allowed.

3.38.2. Text Changes to the Document

Old text: (Section 6.1)

- B) At any given time, the sender MUST NOT transmit new data to a given transport address if it has cwnd or more bytes of data outstanding to that transport address.

New text: (Section 6.1)

- B) At any given time, the sender MUST NOT transmit new data to a given transport address if it has cwnd + (PMTU - 1) or more bytes of data outstanding to that transport address. If data is available the sender SHOULD exceed cwnd by up to (PMTU-1) bytes on a new data transmission if the flightsize does not currently reach cwnd. The breach of cwnd MUST constitute one packet only.

This text is in final form, and is not further updated in this document.

Old text: (Section 7.2.1)

- o Whenever cwnd is greater than zero, the endpoint is allowed to have cwnd bytes of data outstanding on that transport address.

New text: (Section 7.2.1)

- o Whenever cwnd is greater than zero, the endpoint is allowed to have cwnd bytes of data outstanding on that transport address. A limited overbooking as described in B) of Section 6.1 SHOULD be supported.

This text is in final form, and is not further updated in this document.

3.38.3. Solution Description

Text was added to clarify how the cwnd limit should be handled.

3.39. Zero Window Probing

3.39.1. Description of the Problem

The text describing zero window probing was not clearly handling the case where the window was not zero, but too small for the next DATA chunk to be transmitted. Even in this case, zero window probing has to be performed to avoid deadlocks.

3.39.2. Text Changes to the Document

Old text: (Section 6.1)

- A) At any given time, the data sender MUST NOT transmit new data to any destination transport address if its peer's `rwnd` indicates that the peer has no buffer space (i.e., `rwnd` is 0; see Section 6.2.1). However, regardless of the value of `rwnd` (including if it is 0), the data sender can always have one DATA chunk in flight to the receiver if allowed by `cwnd` (see rule B, below). This rule allows the sender to probe for a change in `rwnd` that the sender missed due to the SACK's having been lost in transit from the data receiver to the data sender.

When the receiver's advertised window is zero, this probe is called a zero window probe. Note that a zero window probe SHOULD only be sent when all outstanding DATA chunks have been cumulatively acknowledged and no DATA chunks are in flight. Zero window probing MUST be supported.

New text: (Section 6.1)

- A) At any given time, the data sender MUST NOT transmit new data to any destination transport address if its peer's `rwnd` indicates that the peer has no buffer space (i.e., `rwnd` is smaller than the size of the next DATA chunk; see Section 6.2.1). However, regardless of the value of `rwnd` (including if it is 0), the data sender can always have one DATA chunk in flight to the receiver if allowed by `cwnd` (see rule B, below). This rule allows the sender to probe for a change in `rwnd` that the sender missed due to the SACK's having been lost in transit from the data receiver to the data sender.

When the receiver has no buffer space, this probe is called a zero window probe. Note that a zero window probe SHOULD only be sent when all outstanding DATA chunks have been cumulatively acknowledged and no DATA chunks are in flight. Zero window probing MUST be supported.

This text is in final form, and is not further updated in this document.

3.39.3. Solution Description

The terminology is used in a cleaner way.

3.40. Updating References Regarding ECN

3.40.1. Description of the Problem

[RFC4960] refers for ECN only to [RFC3168], which will be updated by [RFC8311]. This needs to be reflected when referring to ECN.

3.40.2. Text Changes to the Document

Old text: (Appendix A)

ECN [RFC3168] describes a proposed extension to IP that details a method to become aware of congestion outside of datagram loss.

New text: (Appendix A)

ECN as specified in [RFC3168] updated by [RFC8311] describes an extension to IP that details a method to become aware of congestion outside of datagram loss.

This text is in final form, and is not further updated in this document.

Old text: (Appendix A)

In general, [RFC3168] should be followed with the following exceptions.

New text: (Appendix A)

In general, [RFC3168] updated by [RFC8311] SHOULD be followed with the following exceptions.

This text is in final form, and is not further updated in this document.

Old text: (Appendix A)

[RFC3168] details negotiation of ECN during the SYN and SYN-ACK stages of a TCP connection.

New text: (Appendix A)

[RFC3168] updated by [RFC8311] details negotiation of ECN during the SYN and SYN-ACK stages of a TCP connection.

This text is in final form, and is not further updated in this document.

Old text: (Appendix A)

[RFC3168] details a specific bit for a receiver to send back in its TCP acknowledgements to notify the sender of the Congestion Experienced (CE) bit having arrived from the network.

New text: (Appendix A)

[RFC3168] updated by [RFC8311] details a specific bit for a receiver to send back in its TCP acknowledgements to notify the sender of the Congestion Experienced (CE) bit having arrived from the network.

This text is in final form, and is not further updated in this document.

Old text: (Appendix A)

[RFC3168] details a specific bit for a sender to send in the header of its next outbound TCP segment to indicate to its peer that it has reduced its congestion window.

New text: (Appendix A)

[RFC3168] updated by [RFC8311] details a specific bit for a sender to send in the header of its next outbound TCP segment to indicate to its peer that it has reduced its congestion window.

This text is in final form, and is not further updated in this document.

3.40.3. Solution Description

References to [RFC8311] have been added. While there, some wordsmithing has been performed.

3.41. Host Name Address Parameter Deprecated

3.41.1. Description of the Problem

[RFC4960] defines three types of address parameters to be used with INIT and INIT ACK chunks:

1. IPv4 Address parameters.
2. IPv6 Address parameters.
3. Host Name Address parameters.

The first two are supported by the SCTP kernel implementations of FreeBSD, Linux and Solaris, but the third one is not. In addition, the first two were successfully tested in all nine interoperability tests for SCTP, but the third one has never been successfully tested. Therefore, the Host Name Address parameter should be deprecated.

3.41.2. Text Changes to the Document

Old text: (Section 3.3.2)

Note 3: An INIT chunk MUST NOT contain more than one Host Name Address parameter. Moreover, the sender of the INIT MUST NOT combine any other address types with the Host Name Address in the INIT. The receiver of INIT MUST ignore any other address types if the Host Name Address parameter is present in the received INIT chunk.

New text: (Section 3.3.2)

Note 3: An INIT chunk MUST NOT contain the Host Name Address parameter. The receiver of an INIT chunk containing a Host Name Address parameter MUST send an ABORT and MAY include an Error Cause indicating an Unresolvable Address.

This text is in final form, and is not further updated in this document.

Old text: (Section 3.3.2.1)

The sender of INIT uses this parameter to pass its Host Name (in place of its IP addresses) to its peer. The peer is responsible for resolving the name. Using this parameter might make it more likely for the association to work across a NAT box.

New text: (Section 3.3.2.1)

The sender of an INIT chunk MUST NOT include this parameter. The usage of the Host Name Address parameter is deprecated.

This text is in final form, and is not further updated in this document.

Old text: (Section 3.3.2.1)

Address Type: 16 bits (unsigned integer)

This is filled with the type value of the corresponding address TLV (e.g., IPv4 = 5, IPv6 = 6, Host name = 11).

New text: (Section 3.3.2.1)

Address Type: 16 bits (unsigned integer)

This is filled with the type value of the corresponding address TLV (e.g., IPv4 = 5, IPv6 = 6). The value indicating the Host Name Address parameter (Host name = 11) MUST NOT be used.

This text is in final form, and is not further updated in this document.

Old text: (Section 3.3.3)

Note 3: The INIT ACK chunks MUST NOT contain more than one Host Name Address parameter. Moreover, the sender of the INIT ACK MUST NOT combine any other address types with the Host Name Address in the INIT ACK. The receiver of the INIT ACK MUST ignore any other address types if the Host Name Address parameter is present.

New text: (Section 3.3.3)

Note 3: An INIT ACK chunk MUST NOT contain the Host Name Address parameter. The receiver of INIT ACK chunks containing a Host Name Address parameter MUST send an ABORT and MAY include an Error Cause indicating an Unresolvable Address.

This text is in final form, and is not further updated in this document.

Old text: (Section 5.1.2)

B) If there is a Host Name parameter present in the received INIT or

INIT ACK chunk, the endpoint shall resolve that host name to a list of IP address(es) and derive the transport address(es) of this peer by combining the resolved IP address(es) with the SCTP source port.

The endpoint MUST ignore any other IP Address parameters if they are also present in the received INIT or INIT ACK chunk.

The time at which the receiver of an INIT resolves the host name has potential security implications to SCTP. If the receiver of an INIT resolves the host name upon the reception of the chunk, and the mechanism the receiver uses to resolve the host name involves potential long delay (e.g., DNS query), the receiver may open itself up to resource attacks for the period of time while it is waiting for the name resolution results before it can build the State Cookie and release local resources.

Therefore, in cases where the name translation involves potential long delay, the receiver of the INIT MUST postpone the name resolution till the reception of the COOKIE ECHO chunk from the peer. In such a case, the receiver of the INIT SHOULD build the State Cookie using the received Host Name (instead of destination transport addresses) and send the INIT ACK to the source IP address from which the INIT was received.

The receiver of an INIT ACK shall always immediately attempt to resolve the name upon the reception of the chunk.

The receiver of the INIT or INIT ACK MUST NOT send user data (piggy-backed or stand-alone) to its peer until the host name is successfully resolved.

If the name resolution is not successful, the endpoint MUST immediately send an ABORT with "Unresolvable Address" error cause to its peer. The ABORT shall be sent to the source IP address from which the last peer packet was received.

New text: (Section 5.1.2)

- B) If there is a Host Name parameter present in the received INIT or INIT ACK chunk, the endpoint MUST immediately send an ABORT and MAY include an Error Cause indicating an Unresolvable Address to its peer. The ABORT SHALL be sent to the source IP address from which the last peer packet was received.

This text is in final form, and is not further updated in this document.

Old text: (Section 11.2.4.1)

The use of the host name feature in the INIT chunk could be used to flood a target DNS server. A large backlog of DNS queries, resolving the host name received in the INIT chunk to IP addresses, could be accomplished by sending INITs to multiple hosts in a given domain. In addition, an attacker could use the host name feature in an indirect attack on a third party by sending large numbers of INITs to random hosts containing the host name of the target. In addition to the strain on DNS resources, this could also result in large numbers of INIT ACKs being sent to the target. One method to protect against this type of attack is to verify that the IP addresses received from DNS include the source IP address of the original INIT. If the list of IP addresses received from DNS does not include the source IP address of the INIT, the endpoint MAY silently discard the INIT. This last option will not protect against the attack against the DNS.

New text: (Section 11.2.4.1)

The support of the Host Name Address parameter has been removed from the protocol. Endpoints receiving INIT or INIT ACK chunks containing the Host Name Address parameter MUST send an ABORT chunk in response and MAY include an Error Cause indicating an Unresolvable Address.

This text is in final form, and is not further updated in this document.

3.41.3. Solution Description

The usage of the Host Name Address parameter has been deprecated.

3.42. Conflicting Text Regarding the Supported Address Types Parameter

3.42.1. Description of the Problem

When receiving an SCTP packet containing an INIT chunk sent from an address for which the corresponding address type is not listed in the Supported Address Types, there is conflicting text in Section 5.1.2 of [RFC4960]. It is stated that the association MUST be aborted and also that the association SHOULD be established and there SHOULD NOT be any error indication.

3.42.2. Text Changes to the Document

Old text: (Section 5.1.2)

The sender of INIT may include a 'Supported Address Types' parameter in the INIT to indicate what types of address are acceptable. When this parameter is present, the receiver of INIT (initiate) MUST either use one of the address types indicated in the Supported Address Types parameter when responding to the INIT, or abort the association with an "Unresolvable Address" error cause if it is unwilling or incapable of using any of the address types indicated by its peer.

New text: (Section 5.1.2)

The sender of INIT chunks MAY include a 'Supported Address Types' parameter in the INIT to indicate what types of addresses are acceptable.

This text is in final form, and is not further updated in this document.

3.42.3. Solution Description

The conflicting text has been removed.

3.43. Integration of RFC 6096

3.43.1. Description of the Problem

[RFC6096] updates [RFC4960] by adding a Chunk Flags Registry. This should be integrated into the base specification.

3.43.2. Text Changes to the Document

Old text: (Section 14.1)

14.1. IETF-Defined Chunk Extension

The assignment of new chunk parameter type codes is done through an IETF Consensus action, as defined in [RFC2434]. Documentation of the chunk parameter MUST contain the following information:

- a) A long and short name for the new chunk type.
- b) A detailed description of the structure of the chunk, which MUST conform to the basic structure defined in Section 3.2.
- c) A detailed definition and description of the intended use of each field within the chunk, including the chunk flags if any.
- d) A detailed procedural description of the use of the new chunk type within the operation of the protocol.

The last chunk type (255) is reserved for future extension if necessary.

New text: (Section 14.1)

14.1. IETF-Defined Chunk Extension

The assignment of new chunk type codes is done through an IETF Review action, as defined in [RFC8126]. Documentation of a new chunk MUST contain the following information:

- a) A long and short name for the new chunk type;
- b) A detailed description of the structure of the chunk, which MUST conform to the basic structure defined in Section 3.2 of [RFC4960];
- c) A detailed definition and description of the intended use of each field within the chunk, including the chunk flags if any. Defined chunk flags will be used as initial entries in the chunk flags table for the new chunk type;
- d) A detailed procedural description of the use of the new chunk type within the operation of the protocol.

The last chunk type (255) is reserved for future extension if necessary.

For each new chunk type, IANA creates a registration table for the chunk flags of that type. The procedure for registering particular chunk flags is described in the following Section 14.2.

This text has been modified by multiple errata. It includes modifications from Section 3.3. It is in final form, and is not further updated in this document.

New text: (Section 14.2)

14.2. New IETF Chunk Flags Registration

The assignment of new chunk flags is done through an RFC required action, as defined in [RFC8126]. Documentation of the chunk flags MUST contain the following information:

- a) A name for the new chunk flag;
- b) A detailed procedural description of the use of the new chunk flag within the operation of the protocol. It MUST be considered that implementations not supporting the flag will send '0' on transmit and just ignore it on receipt.

IANA selects a chunk flags value. This MUST be one of 0x01, 0x02, 0x04, 0x08, 0x10, 0x20, 0x40, or 0x80, which MUST be unique within the chunk flag values for the specific chunk type.

This text is in final form, and is not further updated in this document.

Please note that Sections 14.2, 14.3, 14.4, and 14.5 need to be renumbered.

3.43.3. Solution Description

[RFC6096] was integrated and the reference updated to [RFC8126].

3.44. Integration of RFC 6335

3.44.1. Description of the Problem

[RFC6335] updates [RFC4960] by updating Procedures for the Port Numbers Registry. This should be integrated into the base specification. While there, update the reference to the RFC giving guidelines for writing IANA sections to [RFC8126].

3.44.2. Text Changes to the Document

Old text: (Section 14.5)

SCTP services may use contact port numbers to provide service to unknown callers, as in TCP and UDP. IANA is therefore requested to

open the existing Port Numbers registry for SCTP using the following rules, which we intend to mesh well with existing Port Numbers registration procedures. An IESG-appointed Expert Reviewer supports IANA in evaluating SCTP port allocation requests, according to the procedure defined in [RFC2434].

Port numbers are divided into three ranges. The Well Known Ports are those from 0 through 1023, the Registered Ports are those from 1024 through 49151, and the Dynamic and/or Private Ports are those from 49152 through 65535. Well Known and Registered Ports are intended for use by server applications that desire a default contact point on a system. On most systems, Well Known Ports can only be used by system (or root) processes or by programs executed by privileged users, while Registered Ports can be used by ordinary user processes or programs executed by ordinary users. Dynamic and/or Private Ports are intended for temporary use, including client-side ports, out-of-band negotiated ports, and application testing prior to registration of a dedicated port; they MUST NOT be registered.

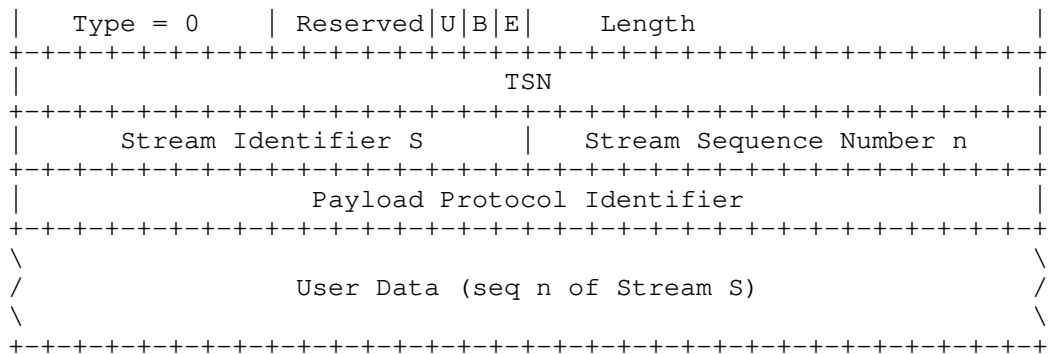
The Port Numbers registry should accept registrations for SCTP ports in the Well Known Ports and Registered Ports ranges. Well Known and Registered Ports SHOULD NOT be used without registration. Although in some cases -- such as porting an application from TCP to SCTP -- it may seem natural to use an SCTP port before registration completes, we emphasize that IANA will not guarantee registration of particular Well Known and Registered Ports. Registrations should be requested as early as possible.

Each port registration SHALL include the following information:

- o A short port name, consisting entirely of letters (A-Z and a-z), digits (0-9), and punctuation characters from "-_+./*" (not including the quotes).
- o The port number that is requested for registration.
- o A short English phrase describing the port's purpose.
- o Name and contact information for the person or entity performing the registration, and possibly a reference to a document defining the port's use. Registrations coming from IETF working groups need only name the working group, but indicating a contact person is recommended.

Registrants are encouraged to follow these guidelines when submitting a registration.

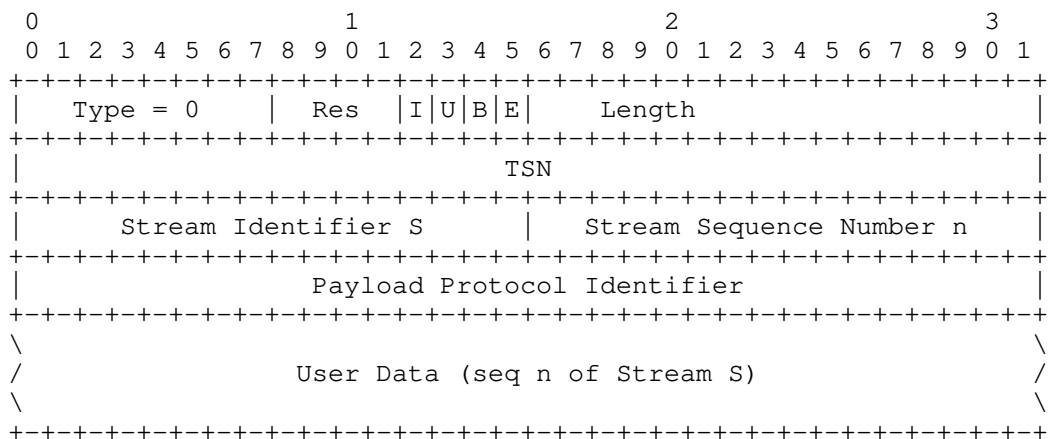
- o A port name SHOULD NOT be registered for more than one SCTP port



Reserved: 5 bits

Should be set to all '0's and ignored by the receiver.

 New text: (Section 3.3.1)



Res: 4 bits

SHOULD be set to all '0's and ignored by the receiver.

I bit: 1 bit

The (I)mmmediate Bit MAY be set by the sender, whenever the sender of a DATA chunk can benefit from the corresponding SACK chunk being sent back without delay. See [RFC7053] for a discussion about

This text is in final form, and is not further updated in this document.

New text: (Append to Section 6.1)

Whenever the sender of a DATA chunk can benefit from the corresponding SACK chunk being sent back without delay, the sender MAY set the I bit in the DATA chunk header. Please note that why the sender has set the I bit is irrelevant to the receiver.

Reasons for setting the I bit include, but are not limited to (see Section 4 of [RFC7053] for the benefits):

- o The application requests to set the I bit of the last DATA chunk of a user message when providing the user message to the SCTP implementation (see Section 7).
- o The sender is in the SHUTDOWN-PENDING state.
- o The sending of a DATA chunk fills the congestion or receiver window.

This text is in final form, and is not further updated in this document.

Old text: (Section 6.2)

Note: The SHUTDOWN chunk does not contain Gap Ack Block fields. Therefore, the endpoint should use a SACK instead of the SHUTDOWN chunk to acknowledge DATA chunks received out of order.

New text: (Section 6.2)

Note: The SHUTDOWN chunk does not contain Gap Ack Block fields. Therefore, the endpoint SHOULD use a SACK instead of the SHUTDOWN chunk to acknowledge DATA chunks received out of order.

Upon receipt of an SCTP packet containing a DATA chunk with the I bit set, the receiver SHOULD NOT delay the sending of the corresponding SACK chunk, i.e., the receiver SHOULD immediately respond with the corresponding SACK chunk.

Please note that this change is only about adding a paragraph.

This text is in final form, and is not further updated in this document.

Old text: (Section 10.1 E))

E) Send

Format: SEND(association id, buffer address, byte count [,context]
[,stream id] [,life time] [,destination transport address]
[,unordered flag] [,no-bundle flag] [,payload protocol-id])
-> result

New text: (Section 10.1 E))

E) Send

Format: SEND(association id, buffer address, byte count [,context]
[,stream id] [,life time] [,destination transport address]
[,unordered flag] [,no-bundle flag] [,payload protocol-id]
[,sack immediately])
-> result

This text is in final form, and is not further updated in this document.

New text: (Append optional parameter in Subsection E of Section 10.1)

- o sack immediately - set the I bit on the last DATA chunk used for sending buffer.

This text is in final form, and is not further updated in this document.

3.45.3. Solution Description

[RFC7053] was integrated.

3.46. CRC32c Code Improvements

3.46.1. Description of the Problem

The code given for the CRC32c computations uses types like long which may have different length on different operating systems or processors. Therefore, the code is changed to use specific types like uint32_t.

While there, fix also some syntax errors and a comment.

3.46.2. Text Changes to the Document

```

-----
Old text: (Appendix C)
-----
/*****
/* Note Definition for Ross Williams table generator would */
/* be: TB_WIDTH=4, TB_POLLY=0x1EDC6F41, TB_REVER=TRUE */
/* For Mr. Williams direct calculation code use the settings */
/* cm_width=32, cm_poly=0x1EDC6F41, cm_init=0xFFFFFFFF, */
/* cm_refin=TRUE, cm_refot=TRUE, cm_xorort=0x00000000 */
*****/

/* Example of the crc table file */
#ifndef __crc32cr_table_h__
#define __crc32cr_table_h__

#define CRC32C_POLY 0x1EDC6F41
#define CRC32C(c,d) (c=(c>>8)^crc_c[(c^(d))&0xFF])

unsigned long crc_c[256] =
{
0x00000000L, 0xF26B8303L, 0xE13B70F7L, 0x1350F3F4L,
0xC79A971FL, 0x35F1141CL, 0x26A1E7E8L, 0xD4CA64EBL,
0x8AD958CFL, 0x78B2DBCCL, 0x6BE22838L, 0x9989AB3BL,
0x4D43CFD0L, 0xBF284CD3L, 0xAC78BF27L, 0x5E133C24L,
0x105EC76FL, 0xE235446CL, 0xF165B798L, 0x030E349BL,
0xD7C45070L, 0x25AFD373L, 0x36FF2087L, 0xC494A384L,
0x9A879FA0L, 0x68EC1CA3L, 0x7BBCEF57L, 0x89D76C54L,
0x5D1D08BFL, 0xAF768BBCL, 0xBC267848L, 0x4E4DFB4BL,
0x20BD8EDEL, 0xD2D60DDDL, 0xC186FE29L, 0x33ED7D2AL,
0xE72719C1L, 0x154C9AC2L, 0x061C6936L, 0xF477EA35L,
0xAA64D611L, 0x580F5512L, 0x4B5FA6E6L, 0xB93425E5L,
0x6DFE410EL, 0x9F95C20DL, 0x8CC531F9L, 0x7EAE2FAL,
0x30E349B1L, 0xC288CAB2L, 0xD1D83946L, 0x23B3BA45L,

```

0xF779DEAEL, 0x05125DADL, 0x1642AE59L, 0xE4292D5AL,
0xBA3A117EL, 0x4851927DL, 0x5B016189L, 0xA96AE28AL,
0x7DA08661L, 0x8FCB0562L, 0x9C9BF696L, 0x6EF07595L,
0x417B1DBCL, 0xB3109EBFL, 0xA0406D4BL, 0x522BEE48L,
0x86E18AA3L, 0x748A09A0L, 0x67DAFA54L, 0x95B17957L,
0xCBA24573L, 0x39C9C670L, 0x2A993584L, 0xD8F2B687L,
0x0C38D26CL, 0xFE53516FL, 0xED03A29BL, 0x1F682198L,
0x5125DAD3L, 0xA34E59D0L, 0xB01EAA24L, 0x42752927L,
0x96BF4DCCL, 0x64D4CECFL, 0x77843D3BL, 0x85EFBE38L,
0xDBFC821CL, 0x2997011FL, 0x3AC7F2EBL, 0xC8AC71E8L,
0x1C661503L, 0xEE0D9600L, 0xFD5D65F4L, 0x0F36E6F7L,
0x61C69362L, 0x93AD1061L, 0x80FDE395L, 0x72966096L,
0xA65C047DL, 0x5437877EL, 0x4767748AL, 0xB50CF789L,
0xEB1FCBADL, 0x197448AEL, 0x0A24BB5AL, 0xF84F3859L,
0x2C855CB2L, 0xDEEEDFB1L, 0xCDBE2C45L, 0x3FD5AF46L,
0x7198540DL, 0x83F3D70EL, 0x90A324FAL, 0x62C8A7F9L,
0xB602C312L, 0x44694011L, 0x5739B3E5L, 0xA55230E6L,
0xFB410CC2L, 0x092A8FC1L, 0x1A7A7C35L, 0xE811FF36L,
0x3CDB9BDDL, 0xCEB018DEL, 0xDDE0EB2AL, 0x2F8B6829L,
0x82F63B78L, 0x709DB87BL, 0x63CD4B8FL, 0x91A6C88CL,
0x456CAC67L, 0xB7072F64L, 0xA457DC90L, 0x563C5F93L,
0x082F63B7L, 0xFA44E0B4L, 0xE9141340L, 0x1B7F9043L,
0xCFB5F4A8L, 0x3DDE77ABL, 0x2E8E845FL, 0xDCE5075CL,
0x92A8FC17L, 0x60C37F14L, 0x73938CE0L, 0x81F80FE3L,
0x55326B08L, 0xA759E80BL, 0xB4091BFFL, 0x466298FCL,
0x1871A4D8L, 0xEA1A27DBL, 0xF94AD42FL, 0x0B21572CL,
0xDFEB33C7L, 0x2D80B0C4L, 0x3ED04330L, 0xCCBBC033L,
0xA24BB5A6L, 0x502036A5L, 0x4370C551L, 0xB11B4652L,
0x65D122B9L, 0x97BAA1BAL, 0x84EA524EL, 0x7681D14DL,
0x2892ED69L, 0xDAF96E6AL, 0xC9A99D9EL, 0x3BC21E9DL,
0xEF087A76L, 0x1D63F975L, 0x0E330A81L, 0xFC588982L,
0xB21572C9L, 0x407EF1CAL, 0x532E023EL, 0xA145813DL,
0x758FE5D6L, 0x87E466D5L, 0x94B49521L, 0x66DF1622L,
0x38CC2A06L, 0xCAA7A905L, 0xD9F75AF1L, 0x2B9CD9F2L,
0xFF56BD19L, 0x0D3D3E1AL, 0x1E6DCDEEL, 0xEC064EEDL,
0xC38D26C4L, 0x31E6A5C7L, 0x22B65633L, 0xD0DDD530L,
0x0417B1DBL, 0xF67C32D8L, 0xE52CC12CL, 0x1747422FL,
0x49547E0BL, 0xBB3FFD08L, 0xA86F0EFCL, 0x5A048DFFL,
0x8ECEE914L, 0x7CA56A17L, 0x6FF599E3L, 0x9D9E1AE0L,
0xD3D3E1ABL, 0x21B862A8L, 0x32E8915CL, 0xC083125FL,
0x144976B4L, 0xE622F5B7L, 0xF5720643L, 0x07198540L,
0x590AB964L, 0xAB613A67L, 0xB831C993L, 0x4A5A4A90L,
0x9E902E7BL, 0x6CFBAD78L, 0x7FAB5E8CL, 0x8DC0DD8FL,
0xE330A81AL, 0x115B2B19L, 0x020BD8EDL, 0xF0605BEEL,
0x24AA3F05L, 0xD6C1BC06L, 0xC5914FF2L, 0x37FACCF1L,
0x69E9F0D5L, 0x9B8273D6L, 0x88D28022L, 0x7AB90321L,
0xAE7367CAL, 0x5C18E4C9L, 0x4F48173DL, 0xBD23943EL,
0xF36E6F75L, 0x0105EC76L, 0x12551F82L, 0xE03E9C81L,

```

0x34F4F86AL, 0xC69F7B69L, 0xD5CF889DL, 0x27A40B9EL,
0x79B737BAL, 0x8BDCB4B9L, 0x988C474DL, 0x6AE7C44EL,
0xBE2DA0A5L, 0x4C4623A6L, 0x5F16D052L, 0xAD7D5351L,
};

```

```

#endif

```

```

-----
New text: (Appendix B)
-----

```

```

<CODE BEGINS>
/*****
/* Note Definition for Ross Williams table generator would */
/* be: TB_WIDTH=4, TB_POLLY=0x1EDC6F41, TB_REVER=TRUE */
/* For Mr. Williams direct calculation code use the settings */
/* cm_width=32, cm_poly=0x1EDC6F41, cm_init=0xFFFFFFFF, */
/* cm_refin=TRUE, cm_refot=TRUE, cm_xorort=0x00000000 */
*****/

/* Example of the crc table file */
#ifndef __crc32cr_h__
#define __crc32cr_h__

#define CRC32C_POLY 0x1EDC6F41UL
#define CRC32C(c,d) (c=(c>>8)^crc_c[(c^(d))&0xFF])

uint32_t crc_c[256] =
{
0x00000000UL, 0xF26B8303UL, 0xE13B70F7UL, 0x1350F3F4UL,
0xC79A971FUL, 0x35F1141CUL, 0x26A1E7E8UL, 0xD4CA64EBUL,
0x8AD958CFUL, 0x78B2DBCCUL, 0x6BE22838UL, 0x9989AB3BUL,
0x4D43CFD0UL, 0xBF284CD3UL, 0xAC78BF27UL, 0x5E133C24UL,
0x105EC76FUL, 0xE235446CUL, 0xF165B798UL, 0x030E349BUL,
0xD7C45070UL, 0x25AFD373UL, 0x36FF2087UL, 0xC494A384UL,
0x9A879FA0UL, 0x68EC1CA3UL, 0x7BBCEF57UL, 0x89D76C54UL,
0x5D1D08BFUL, 0xAF768BBCUL, 0xBC267848UL, 0x4E4DFB4BUL,
0x20BD8EDEUL, 0xD2D60DDDUL, 0xC186FE29UL, 0x33ED7D2AUL,
0xE72719C1UL, 0x154C9AC2UL, 0x061C6936UL, 0xF477EA35UL,
0xAA64D611UL, 0x580F5512UL, 0x4B5FA6E6UL, 0xB93425E5UL,
0x6DFE410EUL, 0x9F95C20DUL, 0x8CC531F9UL, 0x7EAE2FAUL,
0x30E349B1UL, 0xC288CAB2UL, 0xD1D83946UL, 0x23B3BA45UL,
0xF779DEAEUL, 0x05125DADUL, 0x1642AE59UL, 0xE4292D5AUL,
0xBA3A117EUL, 0x4851927DUL, 0x5B016189UL, 0xA96AE28AUL,
0x7DA08661UL, 0x8FCB0562UL, 0x9C9BF696UL, 0x6EF07595UL,
0x417B1DBCUL, 0xB3109EBFUL, 0xA0406D4BUL, 0x522BEE48UL,
0x86E18AA3UL, 0x748A09A0UL, 0x67DAFA54UL, 0x95B17957UL,
0xCBA24573UL, 0x39C9C670UL, 0x2A993584UL, 0xD8F2B687UL,

```

```
0x0C38D26CUL, 0xFE53516FUL, 0xED03A29BUL, 0x1F682198UL,
0x5125DAD3UL, 0xA34E59D0UL, 0xB01EAA24UL, 0x42752927UL,
0x96BF4DCCUL, 0x64D4CECFUL, 0x77843D3BUL, 0x85EFBE38UL,
0xDBFC821CUL, 0x2997011FUL, 0x3AC7F2EBUL, 0xC8AC71E8UL,
0x1C661503UL, 0xEE0D9600UL, 0xFD5D65F4UL, 0x0F36E6F7UL,
0x61C69362UL, 0x93AD1061UL, 0x80FDE395UL, 0x72966096UL,
0xA65C047DUL, 0x5437877EUL, 0x4767748AUL, 0xB50CF789UL,
0xEB1FCBADUL, 0x197448AEUL, 0x0A24BB5AUL, 0xF84F3859UL,
0x2C855CB2UL, 0xDEEEDFB1UL, 0xCDBE2C45UL, 0x3FD5AF46UL,
0x7198540DUL, 0x83F3D70EUL, 0x90A324FAUL, 0x62C8A7F9UL,
0xB602C312UL, 0x44694011UL, 0x5739B3E5UL, 0xA55230E6UL,
0xFB410CC2UL, 0x092A8FC1UL, 0x1A7A7C35UL, 0xE811FF36UL,
0x3CDB9BDDUL, 0xCEB018DEUL, 0xDDE0EB2AUL, 0x2F8B6829UL,
0x82F63B78UL, 0x709DB87BUL, 0x63CD4B8FUL, 0x91A6C88CUL,
0x456CAC67UL, 0xB7072F64UL, 0xA457DC90UL, 0x563C5F93UL,
0x082F63B7UL, 0xFA44E0B4UL, 0xE9141340UL, 0x1B7F9043UL,
0xCFB5F4A8UL, 0x3DDE77ABUL, 0x2E8E845FUL, 0xDCE5075CUL,
0x92A8FC17UL, 0x60C37F14UL, 0x73938CE0UL, 0x81F80FE3UL,
0x55326B08UL, 0xA759E80BUL, 0xB4091BFFUL, 0x466298FCUL,
0x1871A4D8UL, 0xEA1A27DBUL, 0xF94AD42FUL, 0x0B21572CUL,
0xDFEB33C7UL, 0x2D80B0C4UL, 0x3ED04330UL, 0xCCBBC033UL,
0xA24BB5A6UL, 0x502036A5UL, 0x4370C551UL, 0xB11B4652UL,
0x65D122B9UL, 0x97BAA1BAUL, 0x84EA524EUL, 0x7681D14DUL,
0x2892ED69UL, 0xDAF96E6AUL, 0xC9A99D9EUL, 0x3BC21E9DUL,
0xEF087A76UL, 0x1D63F975UL, 0x0E330A81UL, 0xFC588982UL,
0xB21572C9UL, 0x407EF1CAUL, 0x532E023EUL, 0xA145813DUL,
0x758FE5D6UL, 0x87E466D5UL, 0x94B49521UL, 0x66DF1622UL,
0x38CC2A06UL, 0xCA7A905UL, 0xD9F75AF1UL, 0x2B9CD9F2UL,
0xFF56BD19UL, 0x0D3D3E1AUL, 0x1E6DCDEEUL, 0xEC064EEDUL,
0xC38D26C4UL, 0x31E6A5C7UL, 0x22B65633UL, 0xD0DDD530UL,
0x0417B1DBUL, 0xF67C32D8UL, 0xE52CC12CUL, 0x1747422FUL,
0x49547E0BUL, 0xBB3FFD08UL, 0xA86F0EFCUL, 0x5A048DFFUL,
0x8ECEE914UL, 0x7CA56A17UL, 0x6FF599E3UL, 0x9D9E1AE0UL,
0xD3D3E1ABUL, 0x21B862A8UL, 0x32E8915CUL, 0xC083125FUL,
0x144976B4UL, 0xE622F5B7UL, 0xF5720643UL, 0x07198540UL,
0x590AB964UL, 0xAB613A67UL, 0xB831C993UL, 0x4A5A4A90UL,
0x9E902E7BUL, 0x6CFBAD78UL, 0x7FAB5E8CUL, 0x8DC0DD8FUL,
0xE330A81AUL, 0x115B2B19UL, 0x020BD8EDUL, 0xF0605BEEUL,
0x24AA3F05UL, 0xD6C1BC06UL, 0xC5914FF2UL, 0x37FACCF1UL,
0x69E9F0D5UL, 0x9B8273D6UL, 0x88D28022UL, 0x7AB90321UL,
0xAE7367CAUL, 0x5C18E4C9UL, 0x4F48173DUL, 0xBD23943EUL,
0xF36E6F75UL, 0x0105EC76UL, 0x12551F82UL, 0xE03E9C81UL,
0x34F4F86AUL, 0xC69F7B69UL, 0xD5CF889DUL, 0x27A40B9EUL,
0x79B737BAUL, 0x8BDCB4B9UL, 0x988C474DUL, 0x6AE7C44EUL,
0xBE2DA0A5UL, 0x4C4623A6UL, 0x5F16D052UL, 0xAD7D5351UL,
};
```

```
#endif
```

This text has been modified by multiple errata. It includes modifications from Section 3.10. It is in final form, and is not further updated in this document.

Old text: (Appendix C)

```
/* Example of table build routine */
```

```
#include <stdio.h>
```

```
#include <stdlib.h>
```

```
#define OUTPUT_FILE    "crc32cr.h"
```

```
#define CRC32C_POLY    0x1EDC6F41L
```

```
FILE *tf;
```

```
unsigned long
```

```
reflect_32 (unsigned long b)
```

```
{
```

```
    int i;
```

```
    unsigned long rw = 0L;
```

```
    for (i = 0; i < 32; i++){
```

```
        if (b & 1)
```

```
            rw |= 1 << (31 - i);
```

```
        b >>= 1;
```

```
    }
```

```
    return (rw);
```

```
}
```

```
unsigned long
```

```
build_crc_table (int index)
```

```
{
```

```
    int i;
```

```
    unsigned long rb;
```

```
    rb = reflect_32 (index);
```

```
    for (i = 0; i < 8; i++){
```

```
        if (rb & 0x80000000L)
```

```
            rb = (rb << 1) ^ CRC32C_POLY;
```

```
        else
```

```
            rb <<= 1;
```

```
    }
```

```
    return (reflect_32 (rb));
```

```
}
```

```

main ()
{
    int i;

    printf ("\nGenerating CRC-32c table file <%=s>\n",
        OUTPUT_FILE);
    if ((tf = fopen (OUTPUT_FILE, "w")) == NULL){
        printf ("Unable to open %s\n", OUTPUT_FILE);
        exit (1);
    }
    fprintf (tf, "#ifndef __crc32cr_table_h__\n");
    fprintf (tf, "#define __crc32cr_table_h__\n\n");
    fprintf (tf, "#define CRC32C_POLY 0x%08lX\n",
        CRC32C_POLY);
    fprintf (tf,
        "#define CRC32C(c,d) (c=(c>>8)^crc_c[(c^(d))&0xFF])\n");
    fprintf (tf, "\nunsigned long  crc_c[256] =\n{\n");
    for (i = 0; i < 256; i++){
        fprintf (tf, "0x%08lXL, ", build_crc_table (i));
        if ((i & 3) == 3)
            fprintf (tf, "\n");
    }
    fprintf (tf, "};\n\n#endif\n");

    if (fclose (tf) != 0)
        printf ("Unable to close <%=s>." OUTPUT_FILE);
    else
        printf ("\nThe CRC-32c table has been written to <%=s>.\n",
            OUTPUT_FILE);
}

```

```

-----
New text: (Appendix B)
-----

```

```

/* Example of table build routine */

#include <stdio.h>
#include <stdlib.h>

#define OUTPUT_FILE    "crc32cr.h"
#define CRC32C_POLY    0x1EDC6F41UL

static FILE *tf;

static uint32_t
reflect_32(uint32_t b)
{

```

```

    int i;
    uint32_t rw = 0UL;

    for (i = 0; i < 32; i++) {
        if (b & 1)
            rw |= 1 << (31 - i);
        b >>= 1;
    }
    return (rw);
}

static uint32_t
build_crc_table(int index)
{
    int i;
    uint32_t rb;

    rb = reflect_32(index);

    for (i = 0; i < 8; i++) {
        if (rb & 0x80000000UL)
            rb = (rb << 1) ^ (uint32_t)CRC32C_POLY;
        else
            rb <<= 1;
    }
    return (reflect_32(rb));
}

int
main (void)
{
    int i;

    printf("\nGenerating CRC-32c table file <%=s>\n",
        OUTPUT_FILE);
    if ((tf = fopen(OUTPUT_FILE, "w")) == NULL) {
        printf ("Unable to open %s\n", OUTPUT_FILE);
        exit (1);
    }
    fprintf(tf, "#ifndef __crc32cr_h__\n");
    fprintf(tf, "#define __crc32cr_h__\n\n");
    fprintf(tf, "#define CRC32C_POLY 0x%08XUL\n",
        (uint32_t)CRC32C_POLY);
    fprintf(tf,
        "#define CRC32C(c,d) (c=(c>>8)^crc_c[(c^(d))&0xFF])\n");
    fprintf(tf, "\nuint32_t crc_c[256] =\n{\n");
    for (i = 0; i < 256; i++) {
        fprintf(tf, "0x%08XUL,", build_crc_table (i));

```

```

        if ((i & 3) == 3)
            fprintf(tf, "\n");
        else
            fprintf(tf, " ");
    }
    fprintf(tf, "};\n\n#endif\n");

    if (fclose (tf) != 0)
        printf("Unable to close <%s>.", OUTPUT_FILE);
    else
        printf("\nThe CRC-32c table has been written to <%s>.\n",
            OUTPUT_FILE);
}

```

This text has been modified by multiple errata. It includes modifications from Section 3.10. It is in final form, and is not further updated in this document.

 Old text: (Appendix C)

```

/* Example of crc insertion */

#include "crc32cr.h"

unsigned long
generate_crc32c(unsigned char *buffer, unsigned int length)
{
    unsigned int i;
    unsigned long crc32 = ~0L;
    unsigned long result;
    unsigned char byte0,byte1,byte2,byte3;

    for (i = 0; i < length; i++){
        CRC32C(crc32, buffer[i]);
    }

    result = ~crc32;

    /* result now holds the negated polynomial remainder;
     * since the table and algorithm is "reflected" [williams95].
     * That is, result has the same value as if we mapped the message
     * to a polynomial, computed the host-bit-order polynomial
     * remainder, performed final negation, then did an end-for-end
     * bit-reversal.
    */
}

```

```

    * Note that a 32-bit bit-reversal is identical to four inplace
    * 8-bit reversals followed by an end-for-end byteswap.
    * In other words, the bytes of each bit are in the right order,
    * but the bytes have been byteswapped. So we now do an explicit
    * byteswap. On a little-endian machine, this byteswap and
    * the final ntohl cancel out and could be elided.
    */

    byte0 = result & 0xff;
    byte1 = (result>>8) & 0xff;
    byte2 = (result>>16) & 0xff;
    byte3 = (result>>24) & 0xff;
    crc32 = ((byte0 << 24) |
              (byte1 << 16) |
              (byte2 << 8) |
              byte3);
    return ( crc32 );
}

int
insert_crc32(unsigned char *buffer, unsigned int length)
{
    SCTP_message *message;
    unsigned long crc32;
    message = (SCTP_message *) buffer;
    message->common_header.checksum = 0L;
    crc32 = generate_crc32c(buffer,length);
    /* and insert it into the message */
    message->common_header.checksum = htonl(crc32);
    return 1;
}

int
validate_crc32(unsigned char *buffer, unsigned int length)
{
    SCTP_message *message;
    unsigned int i;
    unsigned long original_crc32;
    unsigned long crc32 = ~0L;

    /* save and zero checksum */
    message = (SCTP_message *) buffer;
    original_crc32 = ntohl(message->common_header.checksum);
    message->common_header.checksum = 0L;
    crc32 = generate_crc32c(buffer,length);
    return ((original_crc32 == crc32)? 1 : -1);
}
```

 New text: (Appendix B)

```
/* Example of crc insertion */

#include "crc32cr.h"

uint32_t
generate_crc32c(unsigned char *buffer, unsigned int length)
{
    unsigned int i;
    uint32_t crc32 = 0xffffffffUL;
    uint32_t result;
    uint8_t byte0, byte1, byte2, byte3;

    for (i = 0; i < length; i++) {
        CRC32C(crc32, buffer[i]);
    }

    result = ~crc32;

    /* result now holds the negated polynomial remainder;
     * since the table and algorithm is "reflected" [williams95].
     * That is, result has the same value as if we mapped the message
     * to a polynomial, computed the host-bit-order polynomial
     * remainder, performed final negation, then did an end-for-end
     * bit-reversal.
     * Note that a 32-bit bit-reversal is identical to four inplace
     * 8-bit reversals followed by an end-for-end byteswap.
     * In other words, the bits of each byte are in the right order,
     * but the bytes have been byteswapped. So we now do an explicit
     * byteswap. On a little-endian machine, this byteswap and
     * the final ntohl cancel out and could be elided.
     */

    byte0 = result & 0xff;
    byte1 = (result>>8) & 0xff;
    byte2 = (result>>16) & 0xff;
    byte3 = (result>>24) & 0xff;
    crc32 = ((byte0 << 24) |
              (byte1 << 16) |
              (byte2 << 8) |
              byte3);
    return (crc32);
}

int
```

```
insert_crc32(unsigned char *buffer, unsigned int length)
{
    SCTP_message *message;
    uint32_t crc32;
    message = (SCTP_message *) buffer;
    message->common_header.checksum = 0UL;
    crc32 = generate_crc32c(buffer, length);
    /* and insert it into the message */
    message->common_header.checksum = htonl(crc32);
    return 1;
}

int
validate_crc32(unsigned char *buffer, unsigned int length)
{
    SCTP_message *message;
    unsigned int i;
    uint32_t original_crc32;
    uint32_t crc32;

    /* save and zero checksum */
    message = (SCTP_message *)buffer;
    original_crc32 = ntohl(message->common_header.checksum);
    message->common_header.checksum = 0L;
    crc32 = generate_crc32c(buffer, length);
    return ((original_crc32 == crc32)? 1 : -1);
}
<CODE ENDS>
```

This text has been modified by multiple errata. It includes modifications from Section 3.5 and Section 3.10. It is in final form, and is not further updated in this document.

3.46.3. Solution Description

The code was changed to use platform independent types.

3.47. Clarification of Gap Ack Blocks in SACK Chunks

3.47.1. Description of the Problem

The Gap Ack Blocks in the SACK chunk are intended to be isolated. However, this is not mentioned with normative text.

This issue was reported as part of an Errata for [RFC4960] with Errata ID 5202.

3.47.2. Text Changes to the Document

Old text: (Section 3.3.4)

The SACK also contains zero or more Gap Ack Blocks. Each Gap Ack Block acknowledges a subsequence of TSNs received following a break in the sequence of received TSNs. By definition, all TSNs acknowledged by Gap Ack Blocks are greater than the value of the Cumulative TSN Ack.

New text: (Section 3.3.4)

The SACK also contains zero or more Gap Ack Blocks. Each Gap Ack Block acknowledges a subsequence of TSNs received following a break in the sequence of received TSNs. The Gap Ack Blocks SHOULD be isolated. This means that the TSN just before each Gap Ack Block and the TSN just after each Gap Ack Block has not been received. By definition, all TSNs acknowledged by Gap Ack Blocks are greater than the value of the Cumulative TSN Ack.

This text is in final form, and is not further updated in this document.

Old text: (Section 3.3.4)

Gap Ack Blocks:

These fields contain the Gap Ack Blocks. They are repeated for each Gap Ack Block up to the number of Gap Ack Blocks defined in the Number of Gap Ack Blocks field. All DATA chunks with TSNs greater than or equal to (Cumulative TSN Ack + Gap Ack Block Start) and less than or equal to (Cumulative TSN Ack + Gap Ack Block End) of each Gap Ack Block are assumed to have been received correctly.

New text: (Section 3.3.4)

Gap Ack Blocks:

These fields contain the Gap Ack Blocks. They are repeated for each Gap Ack Block up to the number of Gap Ack Blocks defined in the Number of Gap Ack Blocks field. All DATA chunks with TSNs greater than or equal to (Cumulative TSN Ack + Gap Ack Block Start) and less than or equal to (Cumulative TSN Ack + Gap Ack Block End) of each Gap Ack Block are assumed to have been received correctly. Gap Ack Blocks SHOULD be isolated. That means that the DATA chunks with TSN equal to (Cumulative TSN Ack + Gap Ack Block Start - 1) and (Cumulative TSN Ack + Gap Ack Block End + 1) have not been received.

This text is in final form, and is not further updated in this document.

3.47.3. Solution Description

Normative text describing the intended usage of Gap Ack Blocks has been added.

3.48. Handling of SSN Wrap Arounds

3.48.1. Description of the Problem

The Stream Sequence Number (SSN) is used for preserving the ordering of user messages within each SCTP stream. The SSN is limited to 16 bits. Therefore, multiple wrap arounds of the SSN might happen within the current send window. To allow the receiver to deliver

ordered user messages in the correct sequence, the sender should limit the number of user messages per stream.

3.48.2. Text Changes to the Document

Old text: (Section 6.1)

Note: The data sender SHOULD NOT use a TSN that is more than $2^{31} - 1$ above the beginning TSN of the current send window.

New text: (Section 6.1)

Note: The data sender SHOULD NOT use a TSN that is more than $2^{31} - 1$ above the beginning TSN of the current send window.

Note: For each stream, the data sender SHOULD NOT have more than $2^{16} - 1$ ordered user messages in the current send window.

This text is in final form, and is not further updated in this document.

3.48.3. Solution Description

The data sender is required to limit the number of ordered user messages within the current send window.

3.49. Update RFC 2119 Boilerplate

3.49.1. Description of the Problem

The text to be used to refer to the [RFC2119] terms has been updated by [RFC8174].

3.49.2. Text Changes to the Document

Old text: (Section 2)

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119 [RFC2119].

New text: (Section 2)

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

This text is in final form, and is not further updated in this document.

3.49.3. Solution Description

The text has been updated to the one specified in [RFC8174].

3.50. Missed Text Removal

3.50.1. Description of the Problem

When integrating the changes to Section 7.2.4 of [RFC2960] as described in Section 2.8.2 of [RFC4460] some text was not removed and is therefore still in [RFC4960].

3.50.2. Text Changes to the Document

Old text: (Section 7.2.4)

A straightforward implementation of the above keeps a counter for each TSN hole reported by a SACK. The counter increments for each consecutive SACK reporting the TSN hole. After reaching 3 and starting the Fast-Retransmit procedure, the counter resets to 0. Because cwnd in SCTP indirectly bounds the number of outstanding TSN's, the effect of TCP Fast Recovery is achieved automatically with no adjustment to the congestion control window size.

New text: (Section 7.2.4)

This text is in final form, and is not further updated in this document.

3.50.3. Solution Description

The text has finally been removed.

4. IANA Considerations

Section 3.44 of this document updates the port number registry for SCTP to be consistent with [RFC6335]. IANA is requested to review Section 3.44.

IANA is only requested to check if it is OK to make the proposed text change in an upcoming standards track document that updates [RFC4960]. IANA is not asked to perform any other action and this document does not request IANA to make a change to any registry.

5. Security Considerations

This document does not add any security considerations to those given in [RFC4960].

6. Acknowledgments

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May 24, 2021

Propagating Explicit Congestion Notification Across IP Tunnel Headers
Separated by a Shim
draft-ietf-tsvwg-rfc6040update-shim-14

Abstract

RFC 6040 on "Tunnelling of Explicit Congestion Notification" made the rules for propagation of ECN consistent for all forms of IP in IP tunnel. This specification updates RFC 6040 to clarify that its scope includes tunnels where two IP headers are separated by at least one shim header that is not sufficient on its own for wide area packet forwarding. It surveys widely deployed IP tunnelling protocols that use such shim header(s) and updates the specifications of those that do not mention ECN propagation (L2TPv2, L2TPv3, GRE, Teredo and AMT). This specification also updates RFC 6040 with configuration requirements needed to make any legacy tunnel ingress safe.

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Table of Contents

1. Introduction	2
2. Terminology	3
3. Scope of RFC 6040	3
3.1. Feasibility of ECN Propagation between Tunnel Headers . .	4
3.2. Desirability of ECN Propagation between Tunnel Headers .	5
4. Making a non-ECN Tunnel Ingress Safe by Configuration	5
5. ECN Propagation and Fragmentation/Reassembly	7
6. IP-in-IP Tunnels with Tightly Coupled Shim Headers	7
6.1. Specific Updates to Protocols under IETF Change Control .	10
6.1.1. L2TP (v2 and v3) ECN Extension	10
6.1.2. GRE	13
6.1.3. Teredo	14
6.1.4. AMT	15
7. IANA Considerations	17
8. Security Considerations	17
9. Comments Solicited	17
10. Acknowledgements	17
11. References	18
11.1. Normative References	18
11.2. Informative References	19
Author's Address	22

1. Introduction

RFC 6040 on "Tunnelling of Explicit Congestion Notification" [RFC6040] made the rules for propagation of Explicit Congestion Notification (ECN [RFC3168]) consistent for all forms of IP in IP tunnel.

A common pattern for many tunnelling protocols is to encapsulate an inner IP header (v4 or v6) with shim header(s) then an outer IP header (v4 or v6). Some of these shim headers are designed as generic encapsulations, so they do not necessarily directly encapsulate an inner IP header. Instead they can encapsulate headers such as link-layer (L2) protocols that in turn often encapsulate IP.

To clear up confusion, this specification clarifies that the scope of RFC 6040 includes any IP-in-IP tunnel, including those with shim header(s) and other encapsulations between the IP headers. Where necessary, it updates the specifications of the relevant encapsulation protocols with the specific text necessary to comply with RFC 6040.

This specification also updates RFC 6040 to state how operators ought to configure a legacy tunnel ingress to avoid unsafe system configurations.

2. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119 [RFC2119] when, and only when, they appear in all capitals, as shown here.

This specification uses the terminology defined in RFC 6040 [RFC6040].

3. Scope of RFC 6040

In section 1.1 of RFC 6040, its scope is defined as:

"...ECN field processing at encapsulation and decapsulation for any IP-in-IP tunnelling, whether IPsec or non-IPsec tunnels. It applies irrespective of whether IPv4 or IPv6 is used for either the inner or outer headers. ..."

This was intended to include cases where shim header(s) sit between the IP headers. Many tunnelling implementers have interpreted the scope of RFC 6040 as it was intended, but it is ambiguous. Therefore, this specification updates RFC 6040 by adding the following scoping text after the sentences quoted above:

It applies in cases where an outer IP header encapsulates an inner IP header either directly or indirectly by encapsulating other headers that in turn encapsulate (or might encapsulate) an inner IP header.

There is another problem with the scope of RFC 6040. Like many IETF specifications, RFC 6040 is written as a specification that implementations can choose to claim compliance with. This means it does not cover two important cases:

1. those cases where it is infeasible for an implementation to access an inner IP header when adding or removing an outer IP header;
2. those implementations that choose not to propagate ECN between IP headers.

However, the ECN field is a non-optional part of the IP header (v4 and v6). So any implementation that creates an outer IP header has to give the ECN field some value. There is only one safe value a tunnel ingress can use if it does not know whether the egress supports propagation of the ECN field; it has to clear the ECN field in any outer IP header to 0b00.

However, an RFC has no jurisdiction over implementations that choose not to comply with it or cannot comply with it, including all those implementations that pre-dated the RFC. Therefore it would have been unreasonable to add such a requirement to RFC 6040. Nonetheless, to ensure safe propagation of the ECN field over tunnels, it is reasonable to add requirements on operators, to ensure they configure their tunnels safely (where possible). Before stating these configuration requirements in Section 4, the factors that determine whether propagating ECN is feasible or desirable will be briefly introduced.

3.1. Feasibility of ECN Propagation between Tunnel Headers

In many cases shim header(s) and an outer IP header are always added to (or removed from) an inner IP packet as part of the same procedure. We call this a tightly coupled shim header. Processing the shim and outer together is often necessary because the shim(s) are not sufficient for packet forwarding in their own right; not unless complemented by an outer header. In these cases it will often be feasible for an implementation to propagate the ECN field between the IP headers.

In some cases a tunnel adds an outer IP header and a tightly coupled shim header to an inner header that is not an IP header, but that in turn encapsulates an IP header (or might encapsulate an IP header). For instance an inner Ethernet (or other link layer) header might encapsulate an inner IP header as its payload. We call this a tightly coupled shim over an encapsulating header.

Digging to arbitrary depths to find an inner IP header within an encapsulation is strictly a layering violation so it cannot be a required behaviour. Nonetheless, some tunnel endpoints already look within a L2 header for an IP header, for instance to map the Diffserv codepoint between an encapsulated IP header and an outer IP header

[RFC2983]. In such cases at least, it should be feasible to also (independently) propagate the ECN field between the same IP headers. Thus, access to the ECN field within an encapsulating header can be a useful and benign optimization. The guidelines in section 5 of [I-D.ietf-tsvwg-ecn-encap-guidelines] give the conditions for this layering violation to be benign.

3.2. Desirability of ECN Propagation between Tunnel Headers

Developers and network operators are encouraged to implement and deploy tunnel endpoints compliant with RFC 6040 (as updated by the present specification) in order to provide the benefits of wider ECN deployment [RFC8087]. Nonetheless, propagation of ECN between IP headers, whether separated by shim headers or not, has to be optional to implement and to use, because:

- o Legacy implementations of tunnels without any ECN support already exist
- o A network might be designed so that there is usually no bottleneck within the tunnel
- o If the tunnel endpoints would have to search within an L2 header to find an encapsulated IP header, it might not be worth the potential performance hit

4. Making a non-ECN Tunnel Ingress Safe by Configuration

Even when no specific attempt has been made to implement propagation of the ECN field at a tunnel ingress, it ought to be possible for the operator to render a tunnel ingress safe by configuration. The main safety concern is to disable (clear to zero) the ECN capability in the outer IP header at the ingress if the egress of the tunnel does not implement ECN logic to propagate any ECN markings into the packet forwarded beyond the tunnel. Otherwise the non-ECN egress could discard any ECN marking introduced within the tunnel, which would break all the ECN-based control loops that regulate the traffic load over the tunnel.

Therefore this specification updates RFC 6040 by inserting the following text at the end of section 4.3:

"

Whether or not an ingress implementation claims compliance with RFC 6040, RFC 4301 or RFC3168, when the outer tunnel header is IP (v4 or v6), if possible, the operator MUST configure the ingress to zero the outer ECN field in any of the following cases:

- * if it is known that the tunnel egress does not support any of the RFCs that define propagation of the ECN field (RFC 6040, RFC 4301 or the full functionality mode of RFC 3168)
- * or if the behaviour of the egress is not known or an egress with unknown behaviour might be dynamically paired with the ingress.
- * or if an IP header might be encapsulated within a non-IP header that the tunnel ingress is encapsulating, but the ingress does not inspect within the encapsulation.

For the avoidance of doubt, the above only concerns the outer IP header. The ingress MUST NOT alter the ECN field of the arriving IP header that will become the inner IP header.

In order that the network operator can comply with the above safety rules, even if an implementation of a tunnel ingress does not claim to support RFC 6040, RFC 4301 or the full functionality mode of RFC 3168:

- * it MUST NOT treat the former ToS octet (IPv4) or the former Traffic Class octet (IPv6) as a single 8-bit field, as the resulting linkage of ECN and Diffserv field propagation between inner and outer is not consistent with the definition of the 6-bit Diffserv field in [RFC2474] and [RFC3260];
- * it SHOULD be able to be configured to zero the ECN field of the outer header.

"

For instance, if a tunnel ingress with no ECN-specific logic had a configuration capability to refer to the last 2 bits of the old ToS Byte of the outer (e.g. with a 0x3 mask) and set them to zero, while also being able to allow the DSCP to be re-mapped independently, that would be sufficient to satisfy both the above implementation requirements.

There might be concern that the above "MUST NOT" makes compliant implementations non-compliant at a stroke. However, by definition it solely applies to equipment that provides Diffserv configuration. Any such Diffserv equipment that is configuring treatment of the former ToS octet (IPv4) or the former Traffic Class octet (IPv6) as a single 8-bit field must have always been non-compliant with the definition of the 6-bit Diffserv field in [RFC2474] and [RFC3260]. If a tunnel ingress does not have any ECN logic, copying the ECN field as a side-effect of copying the DSCP is a seriously unsafe bug

that risks breaking the feedback loops that regulate load on a tunnel.

Zeroing the outer ECN field of all packets in all circumstances would be safe, but it would not be sufficient to claim compliance with RFC 6040 because it would not meet the aim of introducing ECN support to tunnels (see Section 4.3 of [RFC6040]).

5. ECN Propagation and Fragmentation/Reassembly

The following requirements update RFC6040, which omitted handling of the ECN field during fragmentation or reassembly. These changes might alter how many ECN-marked packets are propagated by a tunnel that fragments packets, but this would not raise any backward compatibility issues:

If a tunnel ingress fragments a packet, it MUST set the outer ECN field of all the fragments to the same value as it would have set if it had not fragmented the packet.

Section 5.3 of [RFC3168] specifies ECN requirements for reassembly of sets of outer fragments [I-D.ietf-intarea-tunnels] into packets. The following two additional requirements apply at a tunnel egress:

- o During reassembly of outer fragments [I-D.ietf-intarea-tunnels], if the ECN fields of the outer headers being reassembled into a single packet consist of a mixture of Not-ECT and other ECN codepoints, the packet MUST be discarded.
- o If there is mix of ECT(0) and ECT(1) fragments, then the reassembled packet MUST be set to either ECT(0) or ECT(1). In this case, reassembly SHOULD take into account that the RFC series has so far ensured that ECT(0) and ECT(1) can either be considered equivalent, or they can provide 2 levels of congestion severity, where the ranking of severity from highest to lowest is CE, ECT(1), ECT(0) [RFC6040].

6. IP-in-IP Tunnels with Tightly Coupled Shim Headers

There follows a list of specifications of encapsulations with tightly coupled shim header(s), in rough chronological order. The list is confined to standards track or widely deployed protocols. The list is not necessarily exhaustive so, for the avoidance of doubt, the scope of RFC 6040 is defined in Section 3 and is not limited to this list.

- o PPTP (Point-to-Point Tunneling Protocol) [RFC2637];

- o L2TP (Layer 2 Tunneling Protocol), specifically L2TPv2 [RFC2661] and L2TPv3 [RFC3931], which not only includes all the L2-specific specializations of L2TP, but also derivatives such as the Keyed IPv6 Tunnel [RFC8159];
- o GRE (Generic Routing Encapsulation) [RFC2784] and NVGRE (Network Virtualization using GRE) [RFC7637];
- o GTP (GPRS Tunneling Protocol), specifically GTPv1 [GTPv1], GTP v1 User Plane [GTPv1-U], GTP v2 Control Plane [GTPv2-C];
- o Teredo [RFC4380];
- o CAPWAP (Control And Provisioning of Wireless Access Points) [RFC5415];
- o LISP (Locator/Identifier Separation Protocol) [RFC6830];
- o AMT (Automatic Multicast Tunneling) [RFC7450];
- o VXLAN (Virtual eXtensible Local Area Network) [RFC7348] and VXLAN-GPE [I-D.ietf-nvo3-vxlan-gpe];
- o The Network Service Header (NSH [RFC8300]) for Service Function Chaining (SFC);
- o Geneve [RFC8926];
- o GUE (Generic UDP Encapsulation) [I-D.ietf-intarea-gue];
- o Direct tunnelling of an IP packet within a UDP/IP datagram (see Section 3.1.11 of [RFC8085]);
- o TCP Encapsulation of IKE and IPsec Packets (see Section 12.5 of [RFC8229]).

Some of the listed protocols enable encapsulation of a variety of network layer protocols as inner and/or outer. This specification applies in the cases where there is an inner and outer IP header as described in Section 3. Otherwise [I-D.ietf-tsvwg-ecn-encap-guidelines] gives guidance on how to design propagation of ECN into other protocols that might encapsulate IP.

Where protocols in the above list need to be updated to specify ECN propagation and they are under IETF change control, update text is given in the following subsections. For those not under IETF control, it is RECOMMENDED that implementations of encapsulation and decapsulation comply with RFC 6040. It is also RECOMMENDED that

their specifications are updated to add a requirement to comply with RFC 6040 (as updated by the present document).

PPTP is not under the change control of the IETF, but it has been documented in an informational RFC [RFC2637]. However, there is no need for the present specification to update PPTP because L2TP has been developed as a standardized replacement.

NVGRE is not under the change control of the IETF, but it has been documented in an informational RFC [RFC7637]. NVGRE is a specific use-case of GRE (it re-purposes the key field from the initial specification of GRE [RFC1701] as a Virtual Subnet ID). Therefore the text that updates GRE in Section 6.1.2 below is also intended to update NVGRE.

Although the definition of the various GTP shim headers is under the control of the 3GPP, it is hard to determine whether the 3GPP or the IETF controls standardization of the `_process_` of adding both a GTP and an IP header to an inner IP header. Nonetheless, the present specification is provided so that the 3GPP can refer to it from any of its own specifications of GTP and IP header processing.

The specification of CAPWAP already specifies RFC 3168 ECN propagation and ECN capability negotiation. Without modification the CAPWAP specification already interworks with the backward compatible updates to RFC 3168 in RFC 6040.

LISP made the ECN propagation procedures in RFC 3168 mandatory from the start. RFC 3168 has since been updated by RFC 6040, but the changes are backwards compatible so there is still no need for LISP tunnel endpoints to negotiate their ECN capabilities.

VXLAN is not under the change control of the IETF but it has been documented in an informational RFC. In contrast, VXLAN-GPE (Generic Protocol Extension) is being documented under IETF change control. It is RECOMMENDED that VXLAN and VXLAN-GPE implementations comply with RFC 6040 when the VXLAN header is inserted between (or removed from between) IP headers. The authors of any future update to these specifications are encouraged to add a requirement to comply with RFC 6040 as updated by the present specification.

The Network Service Header (NSH [RFC8300]) has been defined as a shim-based encapsulation to identify the Service Function Path (SFP) in the Service Function Chaining (SFC) architecture [RFC7665]. A proposal has been made for the processing of ECN when handling transport encapsulation [I-D.ietf-sfc-nsh-ecn-support].

The specifications of Geneve and GUE already refer to RFC 6040 for ECN encapsulation.

Section 3.1.11 of RFC 8085 already explains that a tunnel that encapsulates an IP header within a UDP/IP datagram needs to follow RFC 6040 when propagating the ECN field between inner and outer IP headers. The requirements in Section 4 update RFC 6040, and hence implicitly update the UDP usage guidelines in RFC 8085 to add the important but previously unstated requirement that, if the UDP tunnel egress does not, or might not, support ECN propagation, a UDP tunnel ingress has to clear the outer IP ECN field to 0b00, e.g. by configuration.

Section 12.5 of TCP Encapsulation of IKE and IPsec Packets [RFC8229] already recommends the compatibility mode of RFC 6040 in this case, because there is not a one-to-one mapping between inner and outer packets.

6.1. Specific Updates to Protocols under IETF Change Control

6.1.1. L2TP (v2 and v3) ECN Extension

The L2TP terminology used here is defined in [RFC2661] and [RFC3931].

L2TPv3 [RFC3931] is used as a shim header between any packet-switched network (PSN) header (e.g. IPv4, IPv6, MPLS) and many types of layer 2 (L2) header. The L2TPv3 shim header encapsulates an L2-specific sub-layer then an L2 header that is likely to contain an inner IP header (v4 or v6). Then this whole stack of headers can be encapsulated optionally within an outer UDP header then an outer PSN header that is typically IP (v4 or v6).

L2TPv2 is used as a shim header between any PSN header and a PPP header, which is in turn likely to encapsulate an IP header.

Even though these shims are rather fat (particularly in the case of L2TPv3), they still fit the definition of a tightly coupled shim header over an encapsulating header (Section 3.1), because all the headers encapsulating the L2 header are added (or removed) together. L2TPv2 and L2TPv3 are therefore within the scope of RFC 6040, as updated by Section 3 above.

L2TP maintainers are RECOMMENDED to implement the ECN extension to L2TPv2 and L2TPv3 defined in Section 6.1.1.2 below, in order to provide the benefits of ECN [RFC8087], whenever a node within an L2TP tunnel becomes the bottleneck for an end-to-end traffic flow.

6.1.1.1. Safe Configuration of a 'Non-ECN' Ingress LCCE

The following text is appended to both Section 5.3 of [RFC2661] and Section 4.5 of [RFC3931] as an update to the base L2TPv2 and L2TPv3 specifications:

The operator of an LCCE that does not support the ECN Extension in Section 6.1.1.2 of RFCXXXX MUST follow the configuration requirements in Section 4 of RFCXXXX to ensure it clears the outer IP ECN field to 0b00 when the outer PSN header is IP (v4 or v6). {RFCXXXX refers to the present document so it will need to be inserted by the RFC Editor}

In particular, for an LCCE implementation that does not support the ECN Extension, this means that configuration of how it propagates the ECN field between inner and outer IP headers MUST be independent of any configuration of the Diffserv extension of L2TP [RFC3308].

6.1.1.2. ECN Extension for L2TP (v2 or v3)

When the outer PSN header and the payload inside the L2 header are both IP (v4 or v6), to comply with RFC 6040, an LCCE will follow the rules for propagation of the ECN field at ingress and egress in Section 4 of RFC 6040 [RFC6040].

Before encapsulating any data packets, RFC 6040 requires an ingress LCCE to check that the egress LCCE supports ECN propagation as defined in RFC 6040 or one of its compatible predecessors ([RFC4301] or the full functionality mode of [RFC3168]). If the egress supports ECN propagation, the ingress LCCE can use the normal mode of encapsulation (copying the ECN field from inner to outer). Otherwise, the ingress LCCE has to use compatibility mode [RFC6040] (clearing the outer IP ECN field to 0b00).

An LCCE can determine the remote LCCE's support for ECN either statically (by configuration) or by dynamic discovery during setup of each control connection between the LCCEs, using the Capability AVP defined in Section 6.1.1.2.1 below.

Where the outer PSN header is some protocol other than IP that supports ECN, the appropriate ECN propagation specification will need to be followed, e.g. "Explicit Congestion Marking in MPLS" [RFC5129]. Where no specification exists for ECN propagation by a particular PSN, [I-D.ietf-tsvwg-ecn-encap-guidelines] gives general guidance on how to design ECN propagation into a protocol that encapsulates IP.

6.1.1.2.1. LCCE Capability AVP for ECN Capability Negotiation

The LCCE Capability Attribute-Value Pair (AVP) defined here has Attribute Type ZZ. The Attribute Value field for this AVP is a bit-mask with the following 16-bit format:

```

      0                               1
    0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5
+---+---+---+---+---+---+---+---+
|X X X X X X X X X X X X X X E|
+---+---+---+---+---+---+---+---+

```

Figure 1: Value Field for the LCCE Capability Attribute

This AVP MAY be present in the following message types: SCCRQ and SCCRP (Start-Control-Connection-Request and Start-Control-Connection-Reply). This AVP MAY be hidden (the H-bit set to 0 or 1) and is optional (M-bit not set). The length (before hiding) of this AVP MUST be 8 octets. The Vendor ID is the IETF Vendor ID of 0.

Bit 15 of the Value field of the LCCE Capability AVP is defined as the ECN Capability flag (E). When the ECN Capability flag is set to 1, it indicates that the sender supports ECN propagation. When the ECN Capability flag is cleared to zero, or when no LCCE Capability AVP is present, it indicates that the sender does not support ECN propagation. All the other bits are reserved. They MUST be cleared to zero when sent and ignored when received or forwarded.

An LCCE initiating a control connection will send a Start-Control-Connection-Request (SCCRQ) containing an LCCE Capability AVP with the ECN Capability flag set to 1. If the tunnel terminator supports ECN, it will return a Start-Control-Connection-Reply (SCCRP) that also includes an LCCE Capability AVP with the ECN Capability flag set to 1. Then, for any sessions created by that control connection, both ends of the tunnel can use the normal mode of RFC 6040, i.e. it can copy the IP ECN field from inner to outer when encapsulating data packets.

If, on the other hand, the tunnel terminator does not support ECN it will ignore the ECN flag in the LCCE Capability AVP and send an SCCRP to the tunnel initiator without a Capability AVP (or with a Capability AVP but with the ECN Capability flag cleared to zero). The tunnel initiator interprets the absence of the ECN Capability flag in the SCCRP as an indication that the tunnel terminator is incapable of supporting ECN. When encapsulating data packets for any sessions created by that control connection, the tunnel initiator will then use the compatibility mode of RFC 6040 to clear the ECN field of the outer IP header to 0b00.

If the tunnel terminator does not support this ECN extension, the network operator is still expected to configure it to comply with the safety provisions set out in Section 6.1.1.1 above, when it acts as an ingress LCCE.

6.1.2. GRE

The GRE terminology used here is defined in [RFC2784]. GRE is often used as a tightly coupled shim header between IP headers. Sometimes the GRE shim header encapsulates an L2 header, which might in turn encapsulate an IP header. Therefore GRE is within the scope of RFC 6040 as updated by Section 3 above.

GRE tunnel endpoint maintainers are RECOMMENDED to support [RFC6040] as updated by the present specification, in order to provide the benefits of ECN [RFC8087] whenever a node within a GRE tunnel becomes the bottleneck for an end-to-end IP traffic flow tunnelled over GRE using IP as the delivery protocol (outer header).

GRE itself does not support dynamic set-up and configuration of tunnels. However, control plane protocols such as Mobile IPv4 (MIP4) [RFC5944], Mobile IPv6 (MIP6) [RFC6275], Proxy Mobile IP (PMIP) [RFC5845] and IKEv2 [RFC7296] are sometimes used to set up GRE tunnels dynamically.

When these control protocols set up IP-in-IP or IPSec tunnels, it is likely that they propagate the ECN field as defined in RFC 6040 or one of its compatible predecessors (RFC 4301 or the full functionality mode of RFC 3168). However, if they use a GRE encapsulation, this presumption is less sound.

Therefore, If the outer delivery protocol is IP (v4 or v6) the operator is obliged to follow the safe configuration requirements in Section 4 above. Section 6.1.2.1 below updates the base GRE specification with this requirement, to emphasize its importance.

Where the delivery protocol is some protocol other than IP that supports ECN, the appropriate ECN propagation specification will need to be followed, e.g Explicit Congestion Marking in MPLS [RFC5129]. Where no specification exists for ECN propagation by a particular PSN, [I-D.ietf-tsvwg-ecn-encap-guidelines] gives more general guidance on how to propagate ECN to and from protocols that encapsulate IP.

6.1.2.1. Safe Configuration of a 'Non-ECN' GRE Ingress

The following text is appended to Section 3 of [RFC2784] as an update to the base GRE specification:

The operator of a GRE tunnel ingress MUST follow the configuration requirements in Section 4 of RFCXXXX when the outer delivery protocol is IP (v4 or v6). {RFCXXXX refers to the present document so it will need to be inserted by the RFC Editor}

6.1.3. Teredo

Teredo [RFC4380] provides a way to tunnel IPv6 over an IPv4 network, with a UDP-based shim header between the two.

For Teredo tunnel endpoints to provide the benefits of ECN, the Teredo specification would have to be updated to include negotiation of the ECN capability between Teredo tunnel endpoints. Otherwise it would be unsafe for a Teredo tunnel ingress to copy the ECN field to the IPv6 outer.

It is believed that current implementations do not support propagation of ECN, but that they do safely zero the ECN field in the outer IPv6 header. However the specification does not mention anything about this.

To make existing Teredo deployments safe, it would be possible to add ECN capability negotiation to those that are subject to remote OS update. However, for those implementations not subject to remote OS update, it will not be feasible to require them to be configured correctly, because Teredo tunnel endpoints are generally deployed on hosts.

Therefore, until ECN support is added to the specification of Teredo, the only feasible further safety precaution available here is to update the specification of Teredo implementations with the following text, as a new section 5.1.3:

"5.1.3 Safe 'Non-ECN' Teredo Encapsulation

A Teredo tunnel ingress implementation that does not support ECN propagation as defined in RFC 6040 or one of its compatible predecessors (RFC 4301 or the full functionality mode of RFC 3168) MUST zero the ECN field in the outer IPv6 header."

6.1.4. AMT

Automatic Multicast Tunneling (AMT [RFC7450]) is a tightly coupled shim header that encapsulates an IP packet and is itself encapsulated within a UDP/IP datagram. Therefore AMT is within the scope of RFC 6040 as updated by Section 3 above.

AMT tunnel endpoint maintainers are RECOMMENDED to support [RFC6040] as updated by the present specification, in order to provide the benefits of ECN [RFC8087] whenever a node within an AMT tunnel becomes the bottleneck for an IP traffic flow tunnelled over AMT.

To comply with RFC 6040, an AMT relay and gateway will follow the rules for propagation of the ECN field at ingress and egress respectively, as described in Section 4 of RFC 6040 [RFC6040].

Before encapsulating any data packets, RFC 6040 requires an ingress AMT relay to check that the egress AMT gateway supports ECN propagation as defined in RFC 6040 or one of its compatible predecessors (RFC 4301 or the full functionality mode of RFC 3168). If the egress gateway supports ECN, the ingress relay can use the normal mode of encapsulation (copying the IP ECN field from inner to outer). Otherwise, the ingress relay has to use compatibility mode, which means it has to clear the outer ECN field to zero [RFC6040].

An AMT tunnel is created dynamically (not manually), so the relay will need to determine the remote gateway's support for ECN using the ECN capability declaration defined in Section 6.1.4.2 below.

6.1.4.1. Safe Configuration of a 'Non-ECN' Ingress AMT Relay

The following text is appended to Section 4.2.2 of [RFC7450] as an update to the AMT specification:

The operator of an AMT relay that does not support RFC 6040 or one of its compatible predecessors (RFC 4301 or the full functionality mode of RFC 3168) MUST follow the configuration requirements in Section 4 of RFCXXXX to ensure it clears the outer IP ECN field to zero. {RFCXXXX refers to the present document so it will need to be inserted by the RFC Editor}

6.1.4.2. ECN Capability Declaration of an AMT Gateway

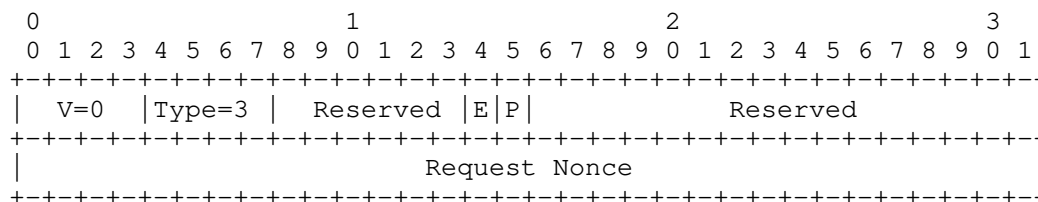


Figure 2: Updated AMT Request Message Format

Bit 14 of the AMT Request Message counting from 0 (or bit 7 of the Reserved field counting from 1) is defined here as the AMT Gateway ECN Capability flag (E), as shown in Figure 2. The definitions of all other fields in the AMT Request Message are unchanged from RFC 7450.

When the E flag is set to 1, it indicates that the sender of the message supports RFC 6040 ECN propagation. When it is cleared to zero, it indicates the sender of the message does not support RFC 6040 ECN propagation. An AMT gateway "that supports RFC 6040 ECN propagation" means one that propagates the ECN field to the forwarded data packet based on the combination of arriving inner and outer ECN fields, as defined in Section 4 of RFC 6040.

The other bits of the Reserved field remain reserved. They will continue to be cleared to zero when sent and ignored when either received or forwarded, as specified in Section 5.1.3.3. of RFC 7450.

An AMT gateway that does not support RFC 6040 MUST NOT set the E flag of its Request Message to 1.

An AMT gateway that supports RFC 6040 ECN propagation MUST set the E flag of its Relay Discovery Message to 1.

The action of the corresponding AMT relay that receives a Request message with the E flag set to 1 depends on whether the relay itself supports RFC 6040 ECN propagation:

- o If the relay supports RFC 6040 ECN propagation, it will store the ECN capability of the gateway along with its address. Then whenever it tunnels datagrams towards this gateway, it MUST use the normal mode of RFC 6040 to propagate the ECN field when encapsulating datagrams (i.e. it copies the IP ECN field from inner to outer).

- o If the discovered AMT relay does not support RFC 6040 ECN propagation, it will ignore the E flag in the Reserved field, as per section 5.1.3.3. of RFC 7450.

If the AMT relay does not support RFC 6040 ECN propagation, the network operator is still expected to configure it to comply with the safety provisions set out in Section 6.1.4.1 above.

7. IANA Considerations

IANA is requested to assign the following L2TP Control Message Attribute Value Pair:

Attribute Type	Description	Reference
ZZ	ECN Capability	RFCXXXX

[TO BE REMOVED: This registration should take place at the following location: <https://www.iana.org/assignments/l2tp-parameters/l2tp-parameters.xhtml>]

8. Security Considerations

The Security Considerations in [RFC6040] and [I-D.ietf-tsvwg-ecn-encap-guidelines] apply equally to the scope defined for the present specification.

9. Comments Solicited

Comments and questions are encouraged and very welcome. They can be addressed to the IETF Transport Area working group mailing list <tsvwg@ietf.org>, and/or to the authors.

10. Acknowledgements

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Stream Schedulers and User Message Interleaving for the Stream Control
Transmission Protocol
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Abstract

The Stream Control Transmission Protocol (SCTP) is a message oriented transport protocol supporting arbitrarily large user messages. This document adds a new chunk to SCTP for carrying payload data. This allows a sender to interleave different user messages that would otherwise result in head of line blocking at the sender. The interleaving of user messages is required for WebRTC Datachannels.

Whenever an SCTP sender is allowed to send user data, it may choose from multiple outgoing SCTP streams. Multiple ways for performing this selection, called stream schedulers, are defined in this document. A stream scheduler can choose to either implement, or not implement, user message interleaving.

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Table of Contents

1. Introduction	3
1.1. Overview	3
1.2. Conventions	5
2. User Message Interleaving	5
2.1. The I-DATA Chunk Supporting User Message Interleaving . .	6
2.2. Procedures	8
2.2.1. Negotiation	9
2.2.2. Sender Side Considerations	9
2.2.3. Receiver Side Considerations	10
2.3. Interaction with other SCTP Extensions	10
2.3.1. SCTP Partial Reliability Extension	10
2.3.2. SCTP Stream Reconfiguration Extension	12
3. Stream Schedulers	12
3.1. First Come First Served Scheduler (SCTP_SS_FCFS)	13
3.2. Round Robin Scheduler (SCTP_SS_RR)	13
3.3. Round Robin Scheduler per Packet (SCTP_SS_RR_PKT)	13
3.4. Priority Based Scheduler (SCTP_SS_PRIO)	13
3.5. Fair Capacity Scheduler (SCTP_SS_FC)	14
3.6. Weighted Fair Queueing Scheduler (SCTP_SS_WFQ)	14
4. Socket API Considerations	14
4.1. Exposure of the Stream Sequence Number (SSN)	14
4.2. SCTP_ASSOC_CHANGE Notification	15
4.3. Socket Options	15
4.3.1. Enable or Disable the Support of User Message Interleaving (SCTP_INTERLEAVING_SUPPORTED)	15
4.3.2. Get or Set the Stream Scheduler (SCTP_STREAM_SCHEDULER)	16
4.3.3. Get or Set the Stream Scheduler Parameter (SCTP_STREAM_SCHEDULER_VALUE)	17
4.4. Explicit EOR Marking	18
5. IANA Considerations	18

5.1. I-DATA Chunk	18
5.2. I-FORWARD-TSN Chunk	19
6. Security Considerations	19
7. Acknowledgments	20
8. References	20
8.1. Normative References	20
8.2. Informative References	21
Authors' Addresses	21

1. Introduction

1.1. Overview

When SCTP [RFC4960] was initially designed it was mainly envisioned for the transport of small signaling messages. Late in the design stage it was decided to add support for fragmentation and reassembly of larger messages with the thought that someday Session Initiation Protocol (SIP) [RFC3261] style signaling messages may also need to use SCTP and a single Maximum Transmission Unit (MTU) sized message would be too small. Unfortunately this design decision, though valid at the time, did not account for other applications that might send large messages over SCTP. The sending of such large messages over SCTP as specified in [RFC4960] can result in a form of sender side head of line blocking (e.g., when the transmission of a message is blocked from transmission because the sender has started the transmission of another, possibly large, message). This head of line blocking is caused by the use of the Transmission Sequence Number (TSN) for three different purposes:

1. As an identifier for DATA chunks to provide a reliable transfer.
2. As an identifier for the sequence of fragments to allow reassembly.
3. As a sequence number allowing up to $2^{16} - 1$ Stream Sequence Numbers (SSNs) outstanding.

The protocol requires all fragments of a user message to have consecutive TSNs. This document allows an SCTP sender to interleave different user messages.

This document also defines several stream schedulers for general SCTP associations allowing different relative stream treatments. The stream schedulers may behave differently depending on whether user message interleaving has been negotiated for the association or not.

Figure 1 illustrates the behaviour of a round robin stream scheduler using DATA chunks when three streams with the Stream Identifiers

(SIDs) 0, 1, and 2 are used. Each queue for SID 0 and SID 2 contains a single user message requiring three chunks, the queue for SID 1 contains three user messages each requiring a single chunk. It is shown how these user messages are encapsulated in chunk using TSN 0 to TSN 8. Please note that the use of such a scheduler implies late TSN assignment but it can be used with an [RFC4960] compliant implementation that does not support user message interleaving. Late TSN assignment means that the sender generates chunks from user messages and assigns the TSN as late as possible in the process of sending the user messages.

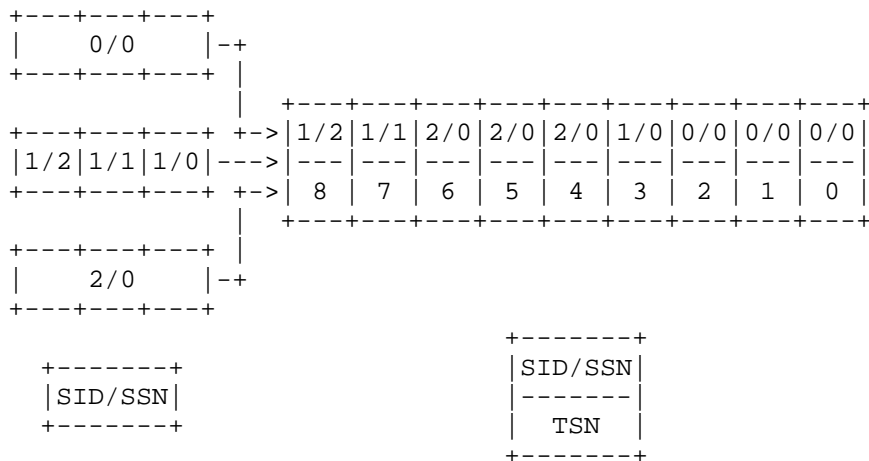


Figure 1: Round Robin Scheduler without User Message Interleaving

This document describes a new chunk carrying payload data called I-DATA. This chunk incorporates the properties of the current SCTP DATA chunk, all the flags and fields except the Stream Sequence Number (SSN), but also adds two new fields in its chunk header, the Fragment Sequence Number (FSN) and the Message Identifier (MID). The FSN is only used for reassembling all fragments having the same MID and ordering property. The TSN is only used for the reliable transfer in combination with Selective Acknowledgment (SACK) chunks.

In addition, the MID is also used for ensuring ordered delivery instead of using the stream sequence number (The I-DATA chunk omits a SSN.).

Figure 2 illustrates the behaviour of an interleaving round robin stream scheduler using I-DATA chunks.

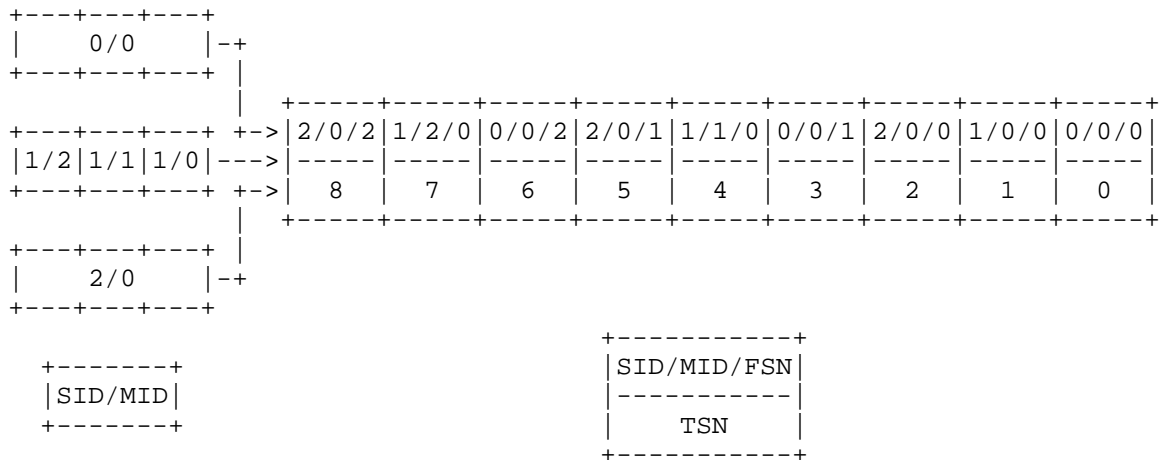


Figure 2: Round Robin Scheduler with User Message Interleaving

The support of the I-DATA chunk is negotiated during the association setup using the Supported Extensions Parameter as defined in [RFC5061]. If I-DATA support has been negotiated for an association, I-DATA chunks are used for all user-messages. DATA chunks are not permitted when I-DATA support has been negotiated. It should be noted that an SCTP implementation supporting I-DATA chunks needs to allow the coexistence of associations using DATA chunks and associations using I-DATA chunks.

In Section 2 this document specifies the user message interleaving by defining the I-DATA chunk, the procedures to use it and its interactions with other SCTP extensions. Multiple stream schedulers are defined in Section 3 followed in Section 4 by describing an extension to the socket API for using what is specified in this document.

1.2. Conventions

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

2. User Message Interleaving

The protocol mechanisms described in this document allow the interleaving of user messages sent on different streams. They do not support the interleaving of multiple messages (ordered or unordered) sent on the same stream.

The interleaving of user messages is required for WebRTC Datachannels as specified in [I-D.ietf-rtcweb-data-channel].

An SCTP implementation supporting user message interleaving is REQUIRED to support the coexistence of associations using DATA chunks and associations using I-DATA chunks. If an SCTP implementation supports user message interleaving and the Partial Reliability extension described in [RFC3758] or the Stream Reconfiguration Extension described in [RFC6525], it is REQUIRED to implement the corresponding changes specified in Section 2.3.

2.1. The I-DATA Chunk Supporting User Message Interleaving

The following Figure 3 shows the new I-DATA chunk allowing user message interleaving.

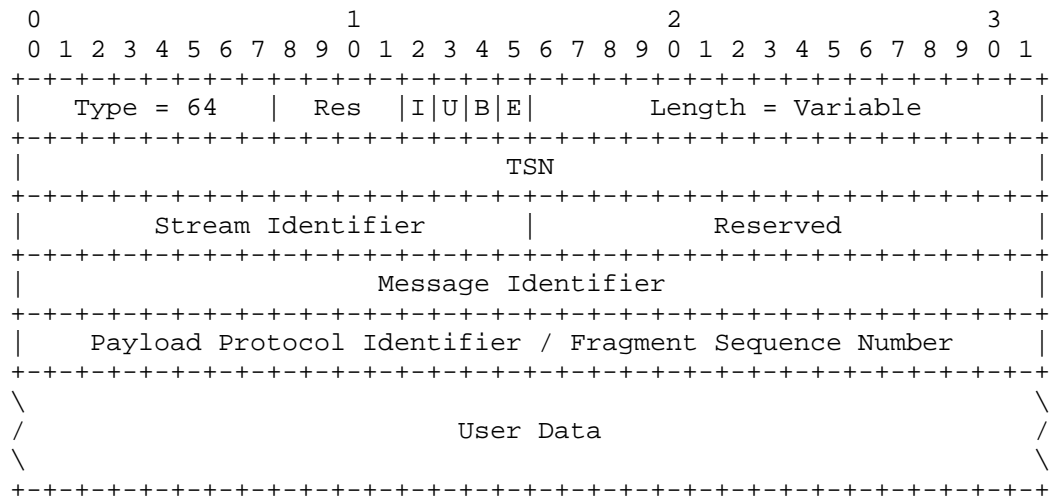


Figure 3: I-DATA chunk format

The only differences between the I-DATA chunk in Figure 3 and the DATA chunk defined in [RFC4960] and [RFC7053] are the addition of the new Message Identifier (MID) and the new Fragment Sequence Number (FSN) and the removal of the Stream Sequence Number (SSN). The Payload Protocol Identifier (PPID) already defined for DATA chunks in [RFC4960] and the new FSN are stored at the same location of the packet using the B bit to determine which value is stored at the location. The length of the I-DATA chunk header is 20 bytes, which is 4 bytes more than the length of the DATA chunk header defined in [RFC4960] and [RFC7053].

The old fields are:

Res: 4 bits

These bits are reserved. They MUST be set to 0 by the sender and MUST be ignored by the receiver.

I bit: 1 bit

The (I)mmmediate Bit, if set, indicates that the receiver SHOULD NOT delay the sending of the corresponding SACK chunk. Same as the I bit for DATA chunks as specified in [RFC7053].

U bit: 1 bit

The (U)nordered bit, if set, indicates the user message is unordered. Same as the U bit for DATA chunks as specified in [RFC4960].

B bit: 1 bit

The (B)eginning fragment bit, if set, indicates the first fragment of a user message. Same as the B bit for DATA chunks as specified in [RFC4960].

E bit: 1 bit

The (E)nding fragment bit, if set, indicates the last fragment of a user message. Same as the E bit for DATA chunks as specified in [RFC4960].

Length: 16 bits (unsigned integer)

This field indicates the length of the DATA chunk in bytes from the beginning of the type field to the end of the User Data field excluding any padding. Similar to the Length for DATA chunks as specified in [RFC4960].

TSN: 32 bits (unsigned integer)

This value represents the TSN for this I-DATA chunk. Same as the TSN for DATA chunks as specified in [RFC4960].

Stream Identifier: 16 bits (unsigned integer)

Identifies the stream to which the user data belongs. Same as the Stream Identifier for DATA chunks as specified in [RFC4960].

The new fields are:

Reserved: 16 bits (unsigned integer)

This field is reserved. It MUST be set to 0 by the sender and MUST be ignored by the receiver.

Message Identifier (MID): 32 bits (unsigned integer)

The MID is the same for all fragments of a user message, it is used to determine which fragments (enumerated by the FSN) belong to the same user message. For ordered user messages, the MID is

also used by the SCTP receiver to deliver the user messages in the correct order to the upper layer (similar to the SSN of the DATA chunk defined in [RFC4960]). The sender uses for each outgoing stream two counters, one for ordered messages, one for unordered messages. All of these counters are independent and initially 0. They are incremented by 1 for each user message. Please note that the serial number arithmetic defined in [RFC1982] using `SERIAL_BITS = 32` applies. Therefore, the sender MUST NOT have more than $2^{31} - 1$ ordered messages for each outgoing stream in flight and MUST NOT have more than $2^{31} - 1$ unordered messages for each outgoing stream in flight. A message is considered in flight, if at least one of its I-DATA chunks is not acknowledged in a non-renegable way (i.e. not acknowledged by the cumulative TSN Ack). Please note that the MID is in "network byte order", a.k.a. Big Endian.

Payload Protocol Identifier (PPID) / Fragment Sequence Number (FSN):
32 bits (unsigned integer)

If the B bit is set, this field contains the PPID of the user message. Note that in this case, this field is not touched by an SCTP implementation; therefore, its byte order is not necessarily in network byte order. The upper layer is responsible for any byte order conversions to this field, similar to the PPID of DATA chunks. In this case the FSN is implicitly considered to be 0. If the B bit is not set, this field contains the FSN. The FSN is used to enumerate all fragments of a single user message, starting from 0 and incremented by 1. The last fragment of a message MUST have the E bit set. Note that the FSN MAY wrap completely multiple times allowing arbitrarily large user messages. For the FSN the serial number arithmetic defined in [RFC1982] applies with `SERIAL_BITS = 32`. Therefore, a sender MUST NOT have more than $2^{31} - 1$ fragments of a single user message in flight. A fragment is considered in flight, if it is not acknowledged in a non-renegable way. Please note that the FSN is in "network byte order", a.k.a. Big Endian.

2.2. Procedures

This subsection describes how the support of the I-DATA chunk is negotiated and how the I-DATA chunk is used by the sender and receiver.

The handling of the I bit for the I-DATA chunk corresponds to the handling of the I bit for the DATA chunk described in [RFC7053].

2.2.1. Negotiation

An SCTP end point indicates user message interleaving support by listing the I-DATA Chunk within the Supported Extensions Parameter as defined in [RFC5061]. User message interleaving has been negotiated for an association if both end points have indicated I-DATA support.

If user message interleaving support has been negotiated for an association, I-DATA chunks MUST be used for all user messages and DATA-chunks MUST NOT be used. If user message interleaving support has not been negotiated for an association, DATA chunks MUST be used for all user messages and I-DATA chunks MUST NOT be used.

An end point implementing the socket API specified in [RFC6458] MUST NOT indicate user message interleaving support unless the user has requested its use (e.g. via the socket API, see Section 4.3). This constraint is made since the usage of this chunk requires that the application is capable of handling interleaved messages upon reception within an association. This is not the default choice within the socket API (see the `SCTP_FRAGMENT_INTERLEAVE` socket option in Section 8.1.20 of [RFC6458]) thus the user MUST indicate to the SCTP implementation its support for receiving completely interleaved messages.

Note that stacks that do not implement [RFC6458] may use other methods to indicate interleaved message support and thus indicate the support of user message interleaving. The crucial point is that the SCTP stack MUST know that the application can handle interleaved messages before indicating the I-DATA support.

2.2.2. Sender Side Considerations

The sender side usage of the I-DATA chunk is quite simple. Instead of using the TSN for fragmentation purposes, the sender uses the new FSN field to indicate which fragment number is being sent. The first fragment MUST have the B bit set. The last fragment MUST have the E bit set. All other fragments MUST NOT have the B bit or E bit set. All other properties of the existing SCTP DATA chunk also apply to the I-DATA chunk, i.e. congestion control as well as receiver window conditions MUST be observed as defined in [RFC4960].

Note that the usage of this chunk implies the late assignment of the actual TSN to any chunk being sent. Each I-DATA chunk uses a single TSN. This way messages from other streams may be interleaved with the fragmented message. Please note that this is the only form of interleaving support. For example, it is not possible to interleave multiple ordered or unordered user messages from the same stream.

The sender MUST NOT process (move user data into I-DATA chunks and assign a TSN to it) more than one user message in any given stream at any time. At any time, a sender MAY process multiple user messages, each of them on different streams.

The sender MUST assign TSNs to I-DATA chunks in a way that the receiver can make progress. One way to achieve this is to assign a higher TSN to the later fragments of a user message and send out the I-DATA chunks such that the TSNs are in sequence.

2.2.3. Receiver Side Considerations

Upon reception of an SCTP packet containing an I-DATA chunk whose user message needs to be reassembled, the receiver MUST first use the SID to identify the stream, consider the U bit to determine if it is part of an ordered or unordered message, find the user message identified by the MID and finally use the FSN for reassembly of the message and not the TSN. The receiver MUST NOT make any assumption about the TSN assignments of the sender. Note that a non-fragmented message is indicated by the fact that both the E and B bits are set. A message (either ordered or unordered) may be identified as being fragmented whose E and B bits are not both set.

If I-DATA support has been negotiated for an association, the reception of a DATA chunk is a violation of the above rules and therefore the receiver of the DATA chunk MUST abort the association by sending an ABORT chunk. The ABORT chunk MAY include the 'Protocol Violation' error cause. The same applies if I-DATA support has not been negotiated for an association and an I-DATA chunk is received.

2.3. Interaction with other SCTP Extensions

The usage of the I-DATA chunk might interfere with other SCTP extensions. Future SCTP extensions MUST describe if and how they interfere with the usage of I-DATA chunks. For the SCTP extensions already defined when this document was published, the details are given in the following subsections.

2.3.1. SCTP Partial Reliability Extension

When the SCTP extension defined in [RFC3758] is used in combination with the user message interleaving extension, the new I-FORWARD-TSN chunk MUST be used instead of the FORWARD-TSN chunk. The difference between the FORWARD-TSN and the I-FORWARD-TSN chunk is that the 16-bit Stream Sequence Number (SSN) has been replaced by the 32-bit Message Identifier (MID) and the largest skipped MID can also be provided for unordered messages. Therefore, the principle applied to

ordered message when using FORWARD-TSN chunks is applied to ordered and unordered messages when using I-FORWARD-TSN chunks.

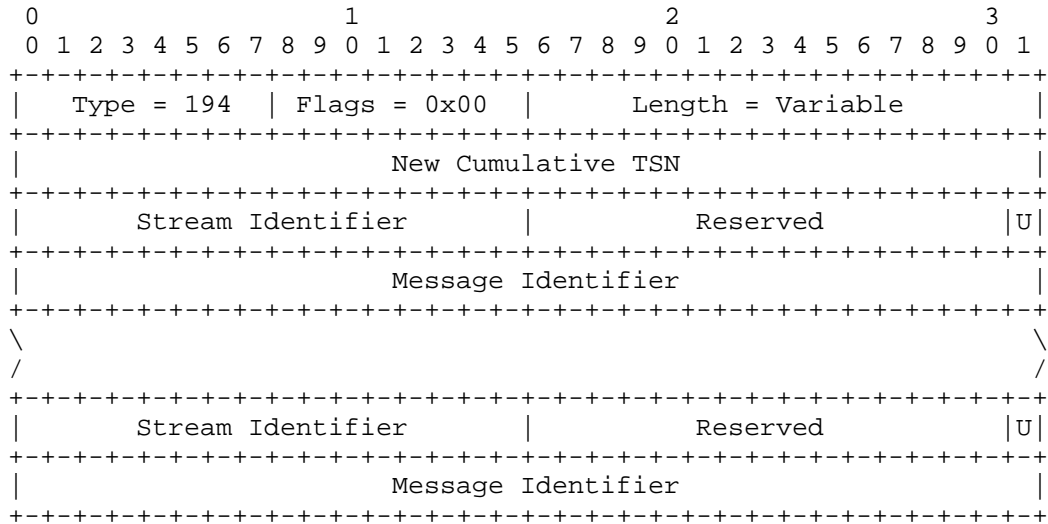


Figure 4: I-FORWARD-TSN chunk format

The old fields are:

Flags: 8-bits (unsigned integer)

These bits are reserved. They MUST be set to 0 by the sender and MUST be ignored by the receiver. Same as the Flags for FORWARD TSN chunks as specified in [RFC3758].

Length: 16-bits (unsigned integer)

This field holds the length of the chunk. Similar to the Length for FORWARD TSN chunks as specified in [RFC3758].

New Cumulative TSN: 32-bits (unsigned integer)

This indicates the new cumulative TSN to the data receiver. Same as the New Cumulative TSN for FORWARD TSN chunks as specified in [RFC3758].

The new fields are:

Stream Identifier (SID): 16-bits (unsigned integer)

This field holds the stream number this entry refers to.

Reserved: 15 bits

This field is reserved. It MUST be set to 0 by the sender and MUST be ignored by the receiver.

U bit: 1 bit

The U bit specifies if the Message Identifier of this entry refers to unordered messages (U bit is set) or ordered messages (U bit is not set).

Message Identifier (MID): 32 bits (unsigned integer)

This field holds the largest Message Identifier for ordered or unordered messages indicated by the U bit that was skipped for the stream specified by the Stream Identifier. For ordered messages this is similar to the FORWARD-TSN chunk, just replacing the 16-bit SSN by the 32-bit MID.

Support for the I-FORWARD-TSN chunk is negotiated during the SCTP association setup via the Supported Extensions Parameter as defined in [RFC5061]. Only if both end points indicated their support of user message interleaving and the I-FORWARD-TSN chunk, the partial reliability extension is negotiated and can be used in combination with user message interleaving.

The FORWARD-TSN chunk MUST be used in combination with the DATA chunk and MUST NOT be used in combination with the I-DATA chunk. The I-FORWARD-TSN chunk MUST be used in combination with the I-DATA chunk and MUST NOT be used in combination with the DATA chunk.

If I-FORWARD-TSN support has been negotiated for an association, the reception of a FORWARD-TSN chunk is a violation of the above rules and therefore the receiver of the FORWARD-TSN chunk MUST abort the association by sending an ABORT chunk. The ABORT chunk MAY include the 'Protocol Violation' error cause. The same applies if I-FORWARD-TSN support has not been negotiated for an association and a FORWARD-TSN chunk is received.

2.3.2. SCTP Stream Reconfiguration Extension

When an association resets the SSN using the SCTP extension defined in [RFC6525], the two counters (one for the ordered messages, one for the unordered messages) used for the MIDs MUST be reset to 0.

Since most schedulers, especially all schedulers supporting user message interleaving, require late TSN assignment, it should be noted that the implementation of [RFC6525] needs to handle this.

3. Stream Schedulers

This section defines several stream schedulers. The stream schedulers may behave differently depending on whether user message interleaving has been negotiated for the association or not. An implementation MAY implement any subset of them. If the

implementation is used for WebRTC Datachannels as specified in [I-D.ietf-rtcweb-data-channel] it MUST implement the Weighted Fair Queueing Scheduler defined in Section 3.6.

The selection of the stream scheduler is done at the sender side. There is no mechanism provided for signalling the stream scheduler being used to the receiver side or even let the receiver side influence the selection of the stream scheduler used at the sender side.

3.1. First Come First Served Scheduler (SCTP_SS_FCFS)

The simple first-come, first-served scheduler of user messages is used. It just passes through the messages in the order in which they have been delivered by the application. No modification of the order is done at all. The usage of user message interleaving does not affect the sending of the chunks, except that I-DATA chunks are used instead of DATA chunks.

3.2. Round Robin Scheduler (SCTP_SS_RR)

When not using user message interleaving, this scheduler provides a fair scheduling based on the number of user messages by cycling around non-empty stream queues. When using user message interleaving, this scheduler provides a fair scheduling based on the number of I-DATA chunks by cycling around non-empty stream queues.

3.3. Round Robin Scheduler per Packet (SCTP_SS_RR_PKT)

This is a round-robin scheduler, which only switches streams when starting to fill a new packet. It bundles only DATA or I-DATA chunks referring to the same stream in a packet. This scheduler minimizes head-of-line blocking when a packet is lost because only a single stream is affected.

3.4. Priority Based Scheduler (SCTP_SS_PRIO)

Scheduling of user messages with strict priorities is used. The priority is configurable per outgoing SCTP stream. Streams having a higher priority will be scheduled first and when multiple streams have the same priority, the scheduling between them is implementation dependent. When using user message interleaving, the sending of large lower priority user messages will not delay the sending of higher priority user messages.

3.5. Fair Capacity Scheduler (SCTP_SS_FC)

A fair capacity distribution between the streams is used. This scheduler considers the lengths of the messages of each stream and schedules them in a specific way to maintain an equal capacity for all streams. The details are implementation dependent. Using user message interleaving allows for a better realization of the fair capacity usage.

3.6. Weighted Fair Queueing Scheduler (SCTP_SS_WFQ)

A weighted fair queueing scheduler between the streams is used. The weight is configurable per outgoing SCTP stream. This scheduler considers the lengths of the messages of each stream and schedules them in a specific way to use the capacity according to the given weights. If the weight of stream S1 is n times the weight of stream S2, the scheduler should assign to stream S1 n times the capacity it assigns to stream S2. The details are implementation dependent. Using user message interleaving allows for a better realization of the capacity usage according to the given weights.

This scheduler in combination with user message interleaving is used for WebRTC Datachannels as specified in [I-D.ietf-rtcweb-data-channel].

4. Socket API Considerations

This section describes how the socket API defined in [RFC6458] is extended to allow applications to use the extension described in this document.

Please note that this section is informational only.

4.1. Exposure of the Stream Sequence Number (SSN)

The socket API defined in [RFC6458] defines several structures in which the SSN of a received user message is exposed to the application. The list of these structures includes:

```
struct sctp_sndrcvinfo
    Specified in Section 5.3.2 SCTP Header Information Structure
    (SCTP_SNDRCV) of [RFC6458] and marked as deprecated.

struct sctp_extrcvinfo
    Specified in Section 5.3.3 Extended SCTP Header Information
    Structure (SCTP_EXTRCV) of [RFC6458] and marked as deprecated.

struct sctp_rcvinfo
```

Specified in Section 5.3.5 SCTP Receive Information Structure (SCTP_RCVINFO) of [RFC6458].

If user message interleaving is used, the lower order 16 bits of the MID are used as the SSN when filling out these structures.

4.2. SCTP_ASSOC_CHANGE Notification

When an SCTP_ASSOC_CHANGE notification (specified in Section 6.1.1 of [RFC6458]) is delivered indicating a sac_state of SCTP_COMM_UP or SCTP_RESTART for an SCTP association where both peers support the I-DATA chunk, SCTP_ASSOC_SUPPORTS_INTERLEAVING should be listed in the sac_info field.

4.3. Socket Options

option name	data type	get	set
SCTP_INTERLEAVING_SUPPORTED	struct sctp_assoc_value	X	X
SCTP_STREAM_SCHEDULER	struct sctp_assoc_value	X	X
SCTP_STREAM_SCHEDULER_VALUE	struct sctp_stream_value	X	X

4.3.1. Enable or Disable the Support of User Message Interleaving (SCTP_INTERLEAVING_SUPPORTED)

This socket option allows the enabling or disabling of the negotiation of user message interleaving support for future associations. For existing associations it allows to query whether user message interleaving support was negotiated or not on a particular association.

This socket option uses IPPROTO_SCTP as its level and SCTP_INTERLEAVING_SUPPORTED as its name. It can be used with getsockopt() and setsockopt(). The socket option value uses the following structure defined in [RFC6458]:

```
struct sctp_assoc_value {
    sctp_assoc_t assoc_id;
    uint32_t assoc_value;
};
```

assoc_id: This parameter is ignored for one-to-one style sockets. For one-to-many style sockets, this parameter indicates upon which association the user is performing an action. The special

sctp_assoc_t Sctp_FUTURE_ASSOC can also be used, it is an error to use Sctp_{CURRENT|ALL}_ASSOC in assoc_id.

assoc_value: A non-zero value encodes the enabling of user message interleaving whereas a value of 0 encodes the disabling of user message interleaving.

sctp_opt_info() needs to be extended to support Sctp_INTERLEAVING_SUPPORTED.

An application using user message interleaving should also set the fragment interleave level to 2 by using the Sctp_FRAGMENT_INTERLEAVE socket option specified in Section 8.1.20 of [RFC6458]. This allows the interleaving of user messages from different streams. Please note that it does not allow the interleaving of user messages (ordered or unordered) on the same stream. Failure to set this option can possibly lead to application deadlock. Some implementations might therefore put some restrictions on setting combinations of these values. Setting the interleaving level to at least 2 before enabling the negotiation of user message interleaving should work on all platforms. Since the default fragment interleave level is not 2, user message interleaving is disabled per default.

4.3.2. Get or Set the Stream Scheduler (Sctp_STREAM_SCHEDULER)

A stream scheduler can be selected with the Sctp_STREAM_SCHEDULER option for setsockopt(). The struct sctp_assoc_value is used to specify the association for which the scheduler should be changed and the value of the desired algorithm.

The definition of struct sctp_assoc_value is the same as in [RFC6458]:

```
struct sctp_assoc_value {
    sctp_assoc_t assoc_id;
    uint32_t assoc_value;
};
```

assoc_id: Holds the identifier for the association of which the scheduler should be changed. The special Sctp_{FUTURE|CURRENT|ALL}_ASSOC can also be used. This parameter is ignored for one-to-one style sockets.

assoc_value: This specifies which scheduler is used. The following constants can be used:

Sctp_SS_DEFAULT: The default scheduler used by the Sctp implementation. Typical values are Sctp_SS_FCFS or Sctp_SS_RR.

SCTP_SS_FCFS: Use the scheduler specified in Section 3.1.

SCTP_SS_RR: Use the scheduler specified in Section 3.2.

SCTP_SS_RR_PKT: Use the scheduler specified in Section 3.3.

SCTP_SS_PRIO: Use the scheduler specified in Section 3.4. The priority can be assigned with the `sctp_stream_value` struct. The higher the assigned value, the lower the priority, that is the default value 0 is the highest priority and therefore the default scheduling will be used if no priorities have been assigned.

SCTP_SS_FB: Use the scheduler specified in Section 3.5.

SCTP_SS_WFQ: Use the scheduler specified in Section 3.6. The weight can be assigned with the `sctp_stream_value` struct.

`sctp_opt_info()` needs to be extended to support `SCTP_STREAM_SCHEDULER`.

4.3.3. Get or Set the Stream Scheduler Parameter (`SCTP_STREAM_SCHEDULER_VALUE`)

Some schedulers require additional information to be set for individual streams as shown in the following table:

name	per stream info
SCTP_SS_DEFAULT	n/a
SCTP_SS_FCFS	no
SCTP_SS_RR	no
SCTP_SS_RR_PKT	no
SCTP_SS_PRIO	yes
SCTP_SS_FB	no
SCTP_SS_WFQ	yes

This is achieved with the `SCTP_STREAM_SCHEDULER_VALUE` option and the corresponding struct `sctp_stream_value`. The definition of struct `sctp_stream_value` is as follows:

```
struct sctp_stream_value {
    sctp_assoc_t assoc_id;
    uint16_t stream_id;
    uint16_t stream_value;
};
```

assoc_id: Holds the identifier for the association of which the scheduler should be changed. The special SCTP_{FUTURE|CURRENT|ALL}_ASSOC can also be used. This parameter is ignored for one-to-one style sockets.

stream_id: Holds the stream id of the stream for which additional information has to be provided.

stream_value: The meaning of this field depends on the scheduler specified. It is ignored when the scheduler does not need additional information.

sctp_opt_info() needs to be extended to support SCTP_STREAM_SCHEDULER_VALUE.

4.4. Explicit EOR Marking

Using explicit End of Record (EOR) marking for an SCTP association supporting user message interleaving allows the user to interleave the sending of user messages on different streams.

5. IANA Considerations

[NOTE to RFC-Editor:

"RFCXXXX" is to be replaced by the RFC number you assign this document.

]

[NOTE to RFC-Editor:

The suggested values for the chunk types and the chunk flags are tentative and to be confirmed by IANA.

]

This document (RFCXXXX) is the reference for all registrations described in this section.

Two new chunk types have to be assigned by IANA.

5.1. I-DATA Chunk

IANA should assign the chunk type for this chunk from the pool of chunks with the upper two bits set to '01'. This requires an additional line in the "Chunk Types" registry for SCTP:

ID Value	Chunk Type	Reference
64	Payload Data supporting Interleaving (I-DATA)	[RFCXXXX]

The registration table as defined in [RFC6096] for the chunk flags of this chunk type is initially given by the following table:

Chunk Flag Value	Chunk Flag Name	Reference
0x01	E bit	[RFCXXXX]
0x02	B bit	[RFCXXXX]
0x04	U bit	[RFCXXXX]
0x08	I bit	[RFCXXXX]
0x10	Unassigned	
0x20	Unassigned	
0x40	Unassigned	
0x80	Unassigned	

5.2. I-FORWARD-TSN Chunk

IANA should assign the chunk type for this chunk from the pool of chunks with the upper two bits set to '11'. This requires an additional line in the "Chunk Types" registry for SCTP:

ID Value	Chunk Type	Reference
194	I-FORWARD-TSN	[RFCXXXX]

The registration table as defined in [RFC6096] for the chunk flags of this chunk type is initially empty.

6. Security Considerations

This document does not add any additional security considerations in addition to the ones given in [RFC4960] and [RFC6458].

It should be noted that the application has to consent that it is willing to do the more complex reassembly support required for user message interleaving. When doing so, an application has to provide a reassembly buffer for each incoming stream. It has to protect itself against these buffers taking too many resources. If user message

interleaving is not used, only a single reassembly buffer needs to be provided for each association. But the application has to protect itself for excessive resource usages there too.

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Tunnel Congestion Feedback
draft-ietf-tsvwg-tunnel-congestion-feedback-07

Abstract

This document describes a method to measure congestion on a tunnel segment based on recommendations from RFC 6040, "Tunneling of Explicit Congestion Notification", and to use IPFIX to communicate the congestion measurements from the tunnel's egress to a controller which can respond by modifying the traffic control policies at the tunnel's ingress.

Status of this Memo

This Internet-Draft is submitted to IETF in full conformance with the provisions of BCP 78 and BCP 79.

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<http://www.ietf.org/lid-abstracts.html>

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<http://www.ietf.org/shadow.html>

1. Introduction

In IP networks, persistent congestion[RFC2914] lowers transport throughput, leading to waste of network resource. Appropriate congestion control mechanisms are therefore critical to prevent the network from falling into the persistent congestion state. Currently, transport protocols such as TCP[RFC793], SCTP[RFC4960], DCCP[RFC4340], have their built-in congestion control mechanisms, and even for certain single transport protocol like TCP there can be a couple of different congestion control mechanisms to choose from. All these congestion control mechanisms are implemented on host side, and there are reasons that only host side congestion control is not sufficient for the whole network to keep away from persistent congestion. For example, (1) some protocol's congestion control scheme may have internal design flaws; (2) improper software implementation of protocol; (3) some transport protocols, e.g. RTP[RFC3550] do not even provide congestion control at all; (4) a heavy load from a much larger than expected number of responsive flows could also lead to persistent congestion.

Tunnels are widely deployed in various networks including public Internet, data center network, and enterprise network etc. A tunnel consists of ingress, egress and a set of intermediate routers. For the tunnel scenario, a tunnel-based mechanism is introduced for network traffic control to keep the network from persistent congestion. Here, tunnel ingress will implement congestion management function to control the traffic entering the tunnel.

This document provides a mechanism of feeding back inner tunnel congestion level to the ingress. Using this mechanism the egress can feed the tunnel congestion level information it collects back to the ingress. After receiving this information the ingress will be able to perform congestion management according to network management policy.

The following subjects are out of scope of current document: it gives no advice on how to select which tunnel endpoints should be used in order to manage traffic over a network criss-crossed by multiple tunnels; if a congested node is part of multiple tunnels, and it causes congestion feedback to multiple traffic management functions at the ingresses of all the tunnels, the draft gives no advice on how all the traffic management functions should respond.

2. Conventions And Terminologies

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119 [RFC2119]

DP: Decision Point, an logical entity that makes congestion management decision based on the received congestion feedback information.

EP: Enforcement Point, an logical entity that implements congestion management action according to the decision made by Decision Point.

ECT: ECN-Capable Transport code point defined in RFC3168.

3. Congestion Information Feedback Models

The feedback model mainly consists of tunnel egress and tunnel ingress. The tunnel egress composes of meter function and exporter function; tunnel ingress composes EP (Enforcement Point) function, collector function and DP (Decision Point) function.

The Meter function collects network congestion level information, and conveys the information to Exporter which feeds back the information to the collector function.

The feedback message contains CE-marked packet ratio, the traffic volumes of all kinds of ECN marking packets.

The collector collects congestion level information from exporter, after that congestion management Decision Point (DP) function will make congestion management decision based on the information from collector.

The Enforcement Point controls the traffic entering tunnel, and it implements traffic control decision of DP.

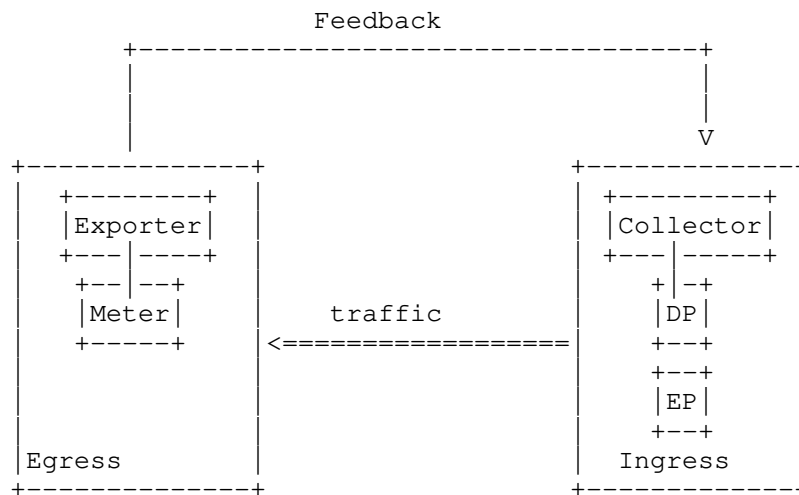


Figure 1: Feedback Model.

4. Congestion Level Measurement

The congestion level measurement is based on ECN (Explicit Congestion Notification) [RFC3168] and packet drop. The network congestion level could be indicated through the ratio of CE-marked packet and the volumes of packet drop, the relationship between these two kinds of indicator is complementary. If the congestion level in tunnel is not high enough, the packets would be marked as CE instead of being dropped, and then it is easy to calculate congestion level according to the ratio of CE-marked packets. If the congestion level is so high that ECT packet will be dropped, then the packet loss ratio could be calculated by comparing total packets entering ingress and total packets arriving at egress over the same span of packets, if packet loss is detected, it could be assumed that severe congestion has occurred in the tunnel.

Egress calculates CE-marked packet ratio by counting different kinds of ECN-marked packet, the CE-marked packet ratio will be used as an indication of tunnel load level. It's assumed that routers in the tunnel will not drop packets biased towards certain ECN codepoint, so calculating of CE-marked packet ratio is not affect by packet drop.

The calculation of volumes of packet drop is by comparing the traffic volumes between ingress and egress.

Faked ECN-capable transport (ECT) is used at ingress to defer

packet loss to egress. The basic idea of faked ECT is that, when encapsulating packets, ingress first marks tunnel outer header according to RFC6040, and then remarks outer header of Not-ECT packet as ECT, there will be three kinds of combination of outer header ECN field and inner header ECN field: CE|CE, ECT|N-ECT, ECT|ECT (in the form of outer ECN| inner ECN); when decapsulating packets at egress, RFC6040 defined decapsulation behavior is used, and according to RFC6040, the packets marked as CE|N-ECT will be dropped by egress. Faked-ECT is used to shift some drops to the egress in order to calculate CE-marked packet ratio more precisely by egress.

To calculate congestion level, for the same span of packets, the ratio of CE-marked packets will be calculated by egress, and the total bytes count of packets at ingress and egress will be compared to detect the traffic volume loss in tunnel.

The basic procedure of packets loss measurement is as follows:

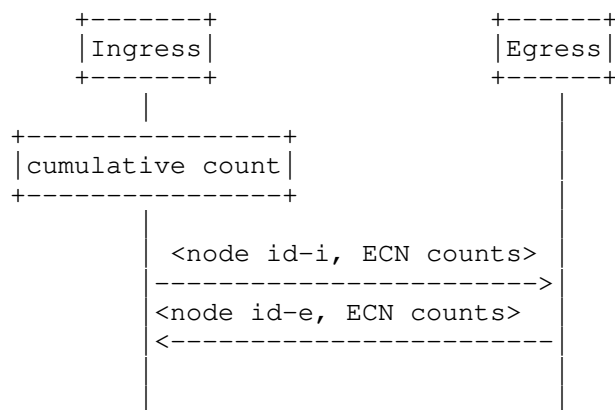


Figure 2: Procedure of Packet Loss Measurement

Ingress encapsulates packets and marks outer header according to faked ECT as described above. Ingress cumulatively counts packet bytes for three types of ECN combination (CE|CE, ECT|N-ECT, ECT|ECT) and then the ingress regularly sends cumulative bytes counts message of each type of ECN combination to the egress.

When each message arrives at egress, (1) egress calculates the ratio of CE-marked packet; (2) the egress cumulatively counts packet bytes coming from the ingress and adds its own bytes counts of each type of ECN combination (CE|CE, ECT|N-ECT, CE|N-ECT, CE|ECT, ECT|ECT) to the

message for ingress to calculate packet loss. Egress feeds back CE-marked packet ratio and bytes counts information to the ingress for evaluating congestion level in the tunnel.

The counting of bytes can be at the granularity of the all traffic from the ingress to the egress to learn about the overall congestion status of the path between the ingress and the egress. The counting can also be at the granularity of individual customer's traffic or a specific set of flows to learn about their congestion contribution.

5. Congestion Information Delivery

As described above, the tunnel ingress needs to convey a message containing cumulative bytes counts of packets of each type of ECN combination to tunnel egress, and the tunnel egress also needs to feed back the message of cumulative bytes counts of packets of each type of ECN combination and CE-marked packet ratio to the ingress. This section describes how the messages should be conveyed.

The message travels along the same path with network data traffic, referred as in-band signal. Because the message is transmitted in band, so the message packet may get lost in case of network congestion. To cope with the situation that the message packet gets lost, the bytes counts values are sent as cumulative counters. Then if a message is lost the next message will recover the missing information. Even though the missing information could be recovered, the message should be transmitted in a much higher priority than users' traffic flows.

IPFIX [RFC7011] is selected as a candidate information feedback protocol. IPFIX uses preferably SCTP as transport. SCTP allows partially reliable delivery [RFC3758], which ensures the feedback message will not be blocked in case of packet loss due to network congestion.

Ingress can do congestion management at different granularity which means both the overall aggregated inner tunnel congestion level and congestion level contributed by certain traffic(s) could be measured for different congestion management purpose. For example, if the ingress only wants to limit congestion volume caused by certain traffic(s), e.g. UDP-based traffic, then congestion volume for the traffic will be fed back; or if the ingress do overall congestion management, the aggregated congestion volume will be fed back.

When sending message from ingress to egress, the ingress acts as IPFIX exporter and egress acts as IPFIX collector; When feedback congestion level information from egress to ingress, then the egress acts as IPFIX exporter and ingress acts as IPFIX collector.

The combination of congestion level measurement and congestion information delivery procedure should be as following:

The ingress determines IPFIX template record to be used. The template record can be pre-configured or determined at runtime, the content of template record will be determined according to the granularity of congestion management, if the ingress wants to limit congestion volume contributed by specific traffic flow then the elements such as source IP address, destination IP address, flow id and CE-marked packet volume of the flow etc will be included in the template record.

Meter on ingress measures traffic volume according to template record chosen and then the measurement records are sent to egress in band.

Meter on egress measures congestion level information according to template record, the content of template record should be the same as template record of ingress.

Exporter of egress sends measurement record together with the measurement record of ingress back to the ingress.

5.1 IPFIX Extensions

This sub-section defines a list of new IPFIX Information Elements according to RFC7013 [RFC7013].

5.1.1 tunnelEcnCeCeByteTotalCount

Description: The total number of bytes of incoming packets with CE|CE ECN marking combination at the Observation Point since the Metering Process (re-)initialization for this Observation Point.

Abstract Data Type: unsigned64

Data Type Semantics: totalCounter

ElementId: TBD1

Statuses: current

Units: bytes

5.1.2 tunnelEcnEct0NectBytetTotalCount

Description: The total number of bytes of incoming packets with ECT(0)|N-ECT ECN marking combination at the Observation Point since

the Metering Process (re-)initialization for this Observation Point.

Abstract Data Type: unsigned64

Data Type Semantics: totalCounter

ElementId: TBD2

Statuses: current

Units: bytes

5.1.3 tunnelEcnEct1NectByteTotalCount

Description: The total number of bytes of incoming packets with ECT(1)|N-ECT ECN marking combination at the Observation Point since the Metering Process (re-)initialization for this Observation Point.

Abstract Data Type: unsigned64

Data Type Semantics: totalCounter

ElementId: TBD3

Statuses: current

Units: bytes

5.1.4 tunnelEcnCeNectByteTotalCount

Description: The total number of bytes of incoming packets with CE|N-ECT ECN marking combination at the Observation Point since the Metering Process (re-)initialization for this Observation Point.

Abstract Data Type: unsigned64

Data Type Semantics: totalCounter

ElementId: TBD4

Statuses: current

Units: bytes

5.1.5 tunnelEcnCeEct0ByteTotalCount

Description: The total number of bytes of incoming packets with CE|ECT(0) ECN marking combination at the Observation Point since the

Metering Process (re-)initialization for this Observation Point.

Abstract Data Type: unsigned64

Data Type Semantics: totalCounter

ElementId: TBD5

Statues: current

Units: bytes

5.1.6 tunnelEcnCeEct1ByteTotalCount

Description: The total number of bytes of incoming packets with CE|ECT(1) ECN marking combination at the Observation Point since the Metering Process (re-)initialization for this Observation Point.

Abstract Data Type: unsigned64

Data Type Semantics: totalCounter

ElementId: TBD6

Statues: current

Units: bytes

5.1.7 tunnelEcnEct0Ect0ByteTotalCount

Description: The total number of bytes of incoming packets with ECT(0)|ECT(0) ECN marking combination at the Observation Point since the Metering Process (re-)initialization for this Observation Point.

Abstract Data Type: unsigned64

Data Type Semantics: totalCounter

ElementId: TBD7

Statues: current

Units: bytes

5.1.8 tunnelEcnEct1Ect1PacketTotalCount

Description: The total number of bytes of incoming packets with ECT(1)|ECT(1) ECN marking combination at the Observation Point since

the Metering Process (re-)initialization for this Observation Point.

Abstract Data Type: unsigned64

Data Type Semantics: totalCounter

ElementId: TBD8

Statuses: current

Units: bytes

5.1.9 tunnelEcnCEMarkedRatio

Description: The ratio of CE-marked Packet at the Observation Point.

Abstract Data Type: float32

ElementId: TBD8

Statuses: current

6. Congestion Management

After tunnel ingress receives congestion level information, then congestion management actions could be taken based on the information, e.g. if the congestion level is higher than a predefined threshold, then action could be taken to reduce the congestion level.

The design of network side congestion management SHOULD take host side e2e congestion control mechanism into consideration, which means the congestion management needs to avoid the impacts on e2e congestion control. For instance, congestion management action must be delayed by more than a worst-case global RTT (e.g. 100ms), otherwise tunnel traffic management will not give normal e2e congestion control enough time to do its job, and the system could go unstable.

The detailed description of congestion management is out of scope of this document, as examples, congestion management such as circuit breaker [RFC8084] could be applied. Circuit breaker is an automatic mechanism to estimate congestion, and to terminate flow(s) when persistent congestion is detected to prevent network congestion collapse.

6.1 Example

This subsection provides an example of how the solution described in this document could work.

First of all, IPFIX template records are exchanged between ingress and egress to negotiate the format of data record, the example here is to measure the congestion level for the overall tunnel (caused by all the traffic in tunnel). After the negotiation is finished, ingress sends in-band message to egress, the message contains the number of each kind of ECN-marked packets (i.e. CE|CE, ECT|N-ECT and ECT|ECT) received until the sending of message.

After egress receives the message, the egress calculates CE-marked packet ratio and counts number of different kinds of ECN-marking packets received until receiving the message, then the egress sends a feedback message containing the counts together with the information in ingress's message to ingress.

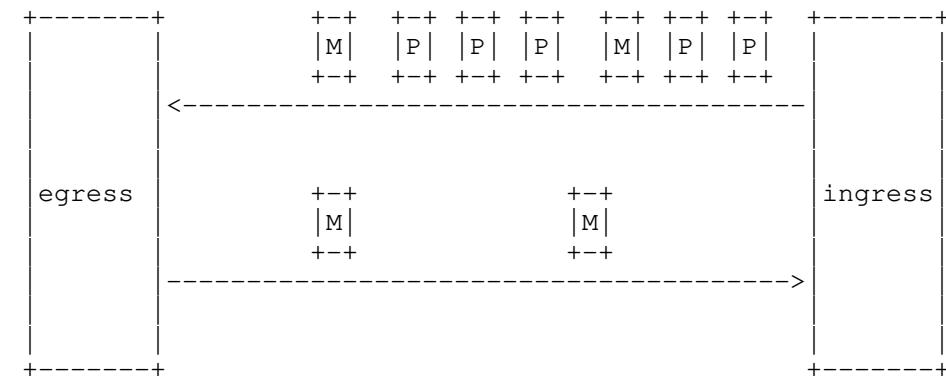
Figure 3 to Figure 6 below show the example procedure between ingress and egress.

Set ID=2	Length=40
Template ID=256	Field Count =8
tunnelEcnCeCeByteTotalCount	Field Length=8
tunnelEcnEctNectByteTotalCount	Field Length=8
tunnelEcnEctEctByteTotalCount	Field Length=8
tunnelEcnCeCeByteTotalCount	Field Length=8
tunnelEcnEctNectByteTotalCount	Field Length=8
tunnelEcnEctEctByteTotalCount	Field Length=8
tunnelEcnCeNectByteTotalCount	Field Length=8
tunnelEcnCeEctByteTotalCount	Field Length=8
tunnelEcnCEMarkedRatio	Field Length=4

Figure 3: Template Record Sent From Egress to Ingress

Set ID=2	Length=28
Template ID=257	Field Count =3
tunnelEcnCeCeByteTotalCount	Field Length=8
tunnelEcnEctNectByteTotalCount	Field Length=8
tunnelEcnEctEctByteTotalCount	Field Length=8

Figure 4: Template Record Sent From Ingress to Egress



++
 |M| : Message Packet
 +-+

++
 |P| : User Packet
 +-+

Figure 5 Traffic flow Between Ingress and Egress

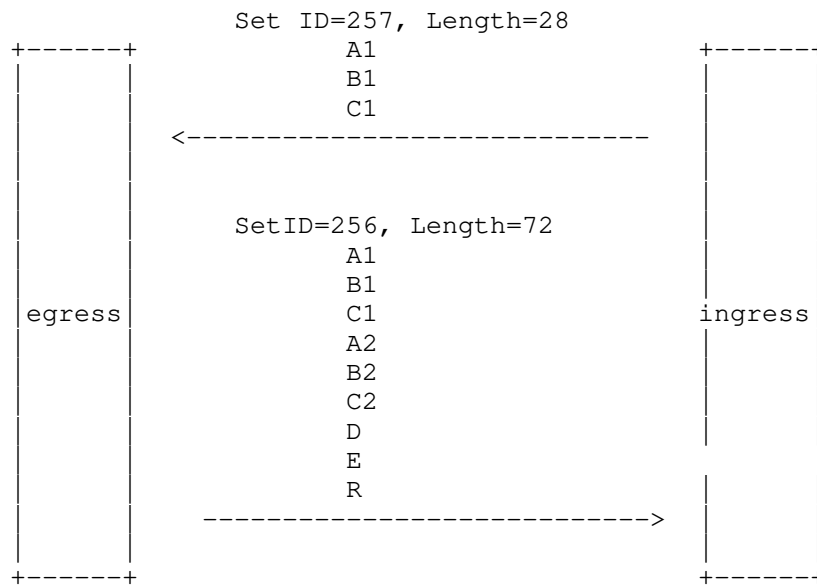


Figure 6: Message Between Ingress and Egress

The following provides an example of how tunnel congestion level could be calculated:

Congestion Level could be divided into two categories: (1) slight congestion (no packets dropped); (2) serious congestion (packet dropping happen).

For slight congestion, the congestion level is indicated as the ratio of CE-marked packet:

$ce_marked = R;$

For serious congestion, the congestion level is indicated as the number of volume loss:

$total_ingress = (A1 + B1 + C1)$

$total_egress = (A2 + B2 + C2 + D + E)$

$volume_loss = (total_ingress - total_egress)$

7. Security Considerations

This document describes the tunnel congestion calculation and feedback.

The tunnel endpoints are assumed to be deployed in the same administrative domain, so the ingress and egress will trust each other, the signaling traffic between ingress and egress will be protected utilizing security mechanism provided IPFIX (see section 11 in RFC7011).

From the consideration of privacy point of view, in case of fine grained congestion management, ingress is aware of the amount of traffic for specific application flows inside the tunnel which seems to be an invasion of privacy. But in any way, the ingress could The solution doesn't introduce more privacy problem.

8. IANA Considerations

This document defines a set of new IPFIX Information Elements (IE), which need to be registered at IANA IPFIX Information Element Registry.

ElementID: TBD1

Name: tunnelEcnCeCePacketTotalCount

Data Type: unsigned64

Data Type Semantics: totalCounter

Status: current

Description: The total number of bytes of incoming packets with CE|CE ECN marking combination at the Observation Point since the Metering Process (re-)initialization for this Observation Point.

Units: octets

ElementID: TBD2

Name: tunnelEcnEct0NectPacketTotalCount

Data Type: unsigned64

Data Type Semantics: totalCounter

Status: current

Description: The total number of bytes of incoming packets with ECT(0)|N-ECT ECN marking combination at the Observation Point since the Metering Process (re-)initialization for this Observation Point.

Units: octets

ElementID: TBD3

Name: tunnelEcnEct1NectPacketTotalCount

Data Type: unsigned64

Data Type Semantics: totalCounter

Status: current

Description: The total number of bytes of incoming packets with

ECT(1)|N-ECT ECN marking combination at the Observation Point since the Metering Process (re-)initialization for this Observation Point.
Units: octets

ElementID: TBD4
Name:tunnelEcnCeNectPacketTotalCount
Data Type: unsigned64
Data Type Semantics: totalCounter
Status: current
Description:The total number of bytes of incoming packets with CE|N-ECT ECN marking combination at the Observation Point since the Metering Process (re-)initialization for this Observation Point.
Units: octets

ElementID: TBD5
Name:tunnelEcnCeEct0PacketTotalCount
Data Type: unsigned64
Data Type Semantics: totalCounter
Status: current
Description:The total number of bytes of incoming packets with CE|ECT(0) ECN marking combination at the Observation Point since the Metering Process (re-)initialization for this Observation Point.
Units: octets

ElementID: TBD6
Name:tunnelEcnCeEct1PacketTotalCount
Data Type: unsigned64
Data Type Semantics: totalCounter
Status: current
Description:The total number of bytes of incoming packets with CE|ECT(1) ECN marking combination at the Observation Point since the Metering Process (re-)initialization for this Observation Point.
Units: octets

ElementID: TBD7
Name:tunnelEcnEct0Ect0PacketTotalCount
Data Type: unsigned64
Data Type Semantics: totalCounter
Status: current
Description:The total number of bytes of incoming packets with ECT(0)|ECT(0) ECN marking combination at the Observation Point since the Metering Process (re-)initialization for this Observation Point.
Units: octets

ElementID: TBD8
Name:tunnelEcnEct1Ect1PacketTotalCount
Data Type: unsigned64
Data Type Semantics: totalCounter

Status: current

Description: The total number of bytes of incoming packets with ECT(1) | ECT(1)ECN marking combination at the Observation Point since the Metering Process (re-)initialization for this Observation Point.
Units: octets

ElementID: TBD9

Name: tunnelEcnCEMarkedRatio

Data Type: float32

Status: current

Description: The ratio of CE-marked Packet at the Observation Point.

[TO BE REMOVED: This registration should take place at the following location: <http://www.iana.org/assignments/ipfix/ipfix.xhtml#ipfix-information-elements>]

9. References

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Forward Error Correction (FEC) Framework Extension to Sliding Window
Codes
draft-roca-tsvwg-fecframev2-04

Abstract

RFC 6363 describes a framework for using Forward Error Correction (FEC) codes with applications in public and private IP networks to provide protection against packet loss. The framework supports applying FEC to arbitrary packet flows over unreliable transport and is primarily intended for real-time, or streaming, media. However FECFRAME as per RFC 6363 is restricted to block FEC codes. The present document extends FECFRAME to support FEC Codes based on a sliding encoding window, in addition to Block FEC Codes, in a backward compatible way. During multicast/broadcast real-time content delivery, the use of sliding window codes significantly improves robustness in harsh environments, with less repair traffic and lower FEC-related added latency.

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Table of Contents

1. Introduction	2
2. Definitions and Abbreviations	4
3. Architecture Overview	7
4. Procedural Overview	9
4.1. General	9
4.2. Sender Operation with Sliding Window FEC Codes	9
4.3. Receiver Operation with Sliding Window FEC Codes	12
5. Protocol Specification	14
5.1. General	14
5.2. FEC Framework Configuration Information	15
5.3. FEC Scheme Requirements	15
6. Feedback	15
7. Transport Protocols	16
8. Congestion Control	16
9. Implementation Status	16
10. Security Considerations	16
11. Operations and Management Considerations	17
12. IANA Considerations	17
13. Acknowledgments	17
14. References	17
14.1. Normative References	17
14.2. Informative References	17
Appendix A. About Sliding Encoding Window Management (non Normative)	19

1. Introduction

Many applications need to transport a continuous stream of packetized data from a source (sender) to one or more destinations (receivers) over networks that do not provide guaranteed packet delivery. In particular packets may be lost, which is strictly the focus of this document: we assume that transmitted packets are either received without any corruption or totally lost (e.g., because of a congested router, of a poor signal-to-noise ratio in a wireless network, or because the number of bit errors exceeds the correction capabilities of a low-layer error correcting code).

For these use-cases, Forward Error Correction (FEC) applied within the transport or application layer, is an efficient technique to improve packet transmission robustness in presence of packet losses (or "erasures"), without going through packet retransmissions that create a delay often incompatible with real-time constraints. The FEC Building Block defined in [RFC5052] provides a framework for the definition of Content Delivery Protocols (CDPs) that make use of separately defined FEC schemes. Any CDP defined according to the requirements of the FEC Building Block can then easily be used with any FEC scheme that is also defined according to the requirements of the FEC Building Block.

Then FECFRAME [RFC6363] provides a framework to define Content Delivery Protocols (CDPs) that provide FEC protection for arbitrary packet flows over unreliable transports such as UDP. It is primarily intended for real-time or streaming media applications, using broadcast, multicast, or on-demand delivery.

However [RFC6363] only considers block FEC schemes defined in accordance with the FEC Building Block [RFC5052] (e.g., [RFC6681], [RFC6816] or [RFC6865]). These codes require the input flow(s) to be segmented into a sequence of blocks. Then FEC encoding (at a sender or an encoding middlebox) and decoding (at a receiver or a decoding middlebox) are both performed on a per-block basis. This approach has major impacts on FEC encoding and decoding delays. The data packets of continuous media flow(s) can be sent immediately, without delay. But the block creation time, that depends on the number k of source symbols in this block, impacts the FEC encoding delay since encoding requires that all source symbols be known. This block creation time also impacts the decoding delay a receiver will experience in case of erasures, since no repair symbol for the current block can be received before. Therefore a good value for the block size is necessarily a balance between the maximum decoding latency at the receivers (which must be in line with the most stringent real-time requirement of the protected flow(s), hence an incentive to reduce the block size), and the desired robustness against long loss bursts (which increases with the block size, hence an incentive to increase this size).

This document extends [RFC6363] in order to also support FEC codes based on a sliding encoding window (A.K.A. convolutional codes). This encoding window, either of fixed or variable size, slides over the set of source symbols. FEC encoding is launched whenever needed, from the set of source symbols present in the sliding encoding window at that time. This approach significantly reduces FEC-related latency, since repair symbols can be generated and sent on-the-fly, at any time, and can be regularly received by receivers to quickly recover packet losses. Using sliding window FEC codes is therefore

highly beneficial to real-time flows, one of the primary targets of FECFRAME. [RLC-ID] provides an example of such FEC Scheme for FECFRAME, built upon the simple sliding window Random Linear Codes (RLC).

This document is fully backward compatible with [RFC6363] that it extends but does not replace. Indeed:

- o this extension does not prevent nor compromise in any way the support of block FEC codes. Both types of codes can nicely co-exist, just like different block FEC schemes can co-exist;
- o any receiver, for instance a legacy receiver that only supports block FEC schemes, can easily identify the FEC scheme used in a FECFRAME session thanks to the associated SDP file and its FEC Encoding ID information (i.e., the "encoding-id=" parameter of a "fec-repair-flow" attribute, [RFC6364]). This mechanism is not specific to this extension but is the basic approach for a FECFRAME receiver to determine whether or not it supports the FEC scheme used in a given FECFRAME session;

This document leverages on [RFC6363] and re-uses its structure. It proposes new sections specific to sliding window FEC codes whenever required. The only exception is Section 3 that provides a quick summary of FECFRAME in order to facilitate the understanding of this document to readers not familiar with the concepts and terminology.

2. Definitions and Abbreviations

The following list of definitions and abbreviations is copied from [RFC6363], adding only the Block/sliding window FEC Code and Encoding/Decoding Window definitions:

Application Data Unit (ADU): The unit of source data provided as payload to the transport layer.

ADU Flow: A sequence of ADUs associated with a transport-layer flow identifier (such as the standard 5-tuple {source IP address, source port, destination IP address, destination port, transport protocol}).

AL-FEC: Application-layer Forward Error Correction.

Application Protocol: Control protocol used to establish and control the source flow being protected, e.g., the Real-Time Streaming Protocol (RTSP).

Content Delivery Protocol (CDP): A complete application protocol specification that, through the use of the framework defined in this document, is able to make use of FEC schemes to provide FEC capabilities.

FEC Code: An algorithm for encoding data such that the encoded data flow is resilient to data loss. Note that, in general, FEC codes may also be used to make a data flow resilient to corruption, but that is not considered in this document.

Block FEC Code: An FEC Code that operates in a block manner, i.e., for which the input flow MUST be segmented into a sequence of blocks, FEC encoding and decoding being performed independently on a per-block basis.

Sliding Window (or Convolutional) FEC Code: An FEC Code that can generate repair symbols on-the-fly, at any time, from the set of source symbols present in the sliding encoding window at that time.

FEC Framework: A protocol framework for the definition of Content Delivery Protocols using FEC, such as the framework defined in this document.

FEC Framework Configuration Information: Information that controls the operation of the FEC Framework.

FEC Payload ID: Information that identifies the contents of a packet with respect to the FEC scheme.

FEC Repair Packet: At a sender (respectively, at a receiver), a payload submitted to (respectively, received from) the transport protocol containing one or more repair symbols along with a Repair FEC Payload ID and possibly an RTP header.

FEC Scheme: A specification that defines the additional protocol aspects required to use a particular FEC code with the FEC Framework.

FEC Source Packet: At a sender (respectively, at a receiver), a payload submitted to (respectively, received from) the transport protocol containing an ADU along with an optional Explicit Source FEC Payload ID.

Protection Amount: The relative increase in data sent due to the use of FEC.

Repair Flow: The packet flow carrying FEC data.

Repair FEC Payload ID: A FEC Payload ID specifically for use with repair packets.

Source Flow: The packet flow to which FEC protection is to be applied. A source flow consists of ADUs.

Source FEC Payload ID: A FEC Payload ID specifically for use with source packets.

Source Protocol: A protocol used for the source flow being protected, e.g., RTP.

Transport Protocol: The protocol used for the transport of the source and repair flows, e.g., UDP and the Datagram Congestion Control Protocol (DCCP).

Encoding Window: Set of Source Symbols available at the sender/coding node that are used to generate a repair symbol, with a Sliding Window FEC Code.

Decoding Window: Set of received or decoded source and repair symbols available at a receiver that are used to decode erased source symbols, with a Sliding Window FEC Code.

Code Rate: The ratio between the number of source symbols and the number of encoding symbols. By definition, the code rate is such that $0 < \text{code rate} \leq 1$. A code rate close to 1 indicates that a small number of repair symbols have been produced during the encoding process.

Encoding Symbol: Unit of data generated by the encoding process. With systematic codes, source symbols are part of the encoding symbols.

Packet Erasure Channel: A communication path where packets are either lost (e.g., by a congested router, or because the number of transmission errors exceeds the correction capabilities of the physical-layer codes) or received. When a packet is received, it is assumed that this packet is not corrupted.

Repair Symbol: Encoding symbol that is not a source symbol.

Source Block: Group of ADUs that are to be FEC protected as a single block. This notion is restricted to Block FEC Codes.

Source Symbol: Unit of data used during the encoding process.

Systematic Code: FEC code in which the source symbols are part of the encoding symbols.

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

3. Architecture Overview

The architecture of [RFC6363], Section 3, equally applies to this FECFRAME extension and is not repeated here. However we provide hereafter a quick summary to facilitate the understanding of this document to readers not familiar with the concepts and terminology.

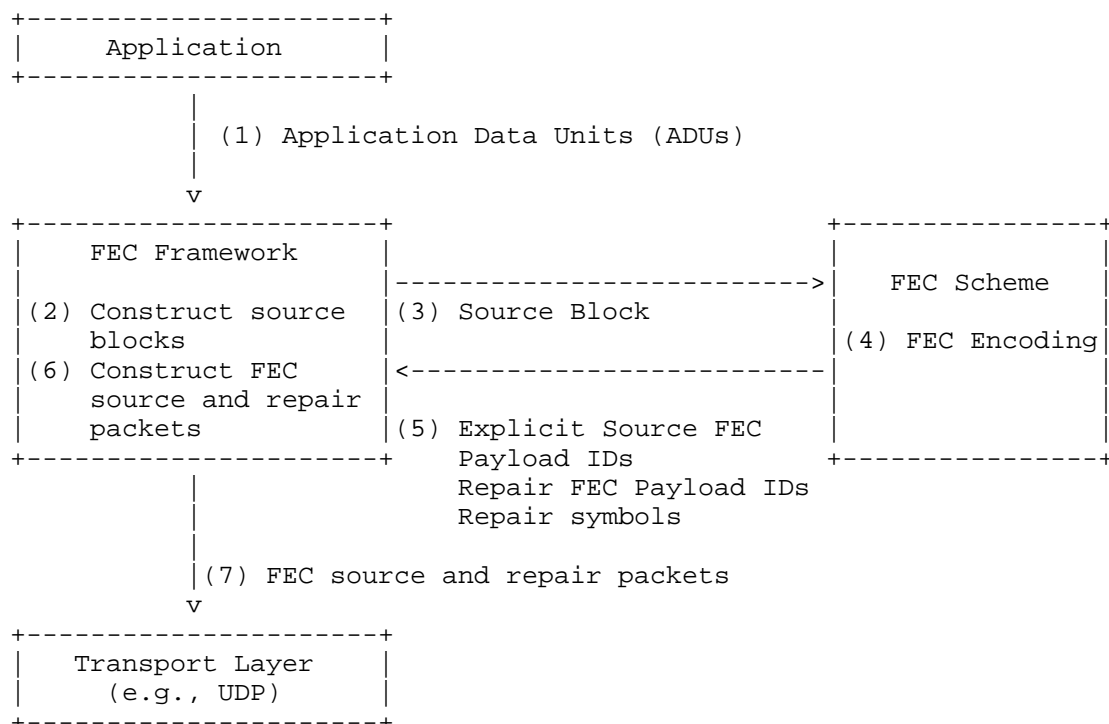


Figure 1: FECFRAME architecture at a sender.

The FECFRAME architecture is illustrated in Figure 1 from the sender's point of view, in case of a block FEC Scheme. It shows an application generating an ADU flow (other flows, from other applications, may co-exist). These ADUs, of variable size, must be somehow mapped to source symbols of fixed size. This is the goal of an ADU to symbols mapping process that is FEC Scheme specific (see

below). Once the source block is built, taking into account both the FEC Scheme constraints (e.g., in terms of maximum source block size) and the application's flow constraints (e.g., real-time constraints), the associated source symbols are handed to the FEC Scheme in order to produce an appropriate number of repair symbols. FEC Source Packets (containing ADUs) and FEC Repair Packets (containing one or more repair symbols each) are then generated and sent using UDP (more precisely [RFC6363], Section 7, requires a transport protocol providing an unreliable datagram service, like UDP or DCCP). In practice FEC Source Packets can be sent as soon as available, without having to wait for FEC encoding to take place. In that case a copy of the associated source symbols need to be kept within FECFRAME for future FEC encoding purposes.

At a receiver (not shown), FECFRAME processing operates in a similar way, taking as input the incoming FEC source and repair packets received. In case of FEC source packet losses, when the FEC decoding of the associated block recovers all the missing source symbols, the lost ADUs are recovered and assigned to their respective flow (see below). ADUs are then returned to the application(s), either in order or not depending on the application requirements.

FECFRAME features two subtle mechanisms:

- o ADUs to source symbols mapping: in order to manage variable size ADUs, FECFRAME and FEC Schemes can use small, fixed size, symbols and create a mapping between ADUs and symbols. To each ADU this mechanism prepends a length field (plus a flow identifier, see below) and pads the result to a multiple of the symbol size. A small ADU may be mapped to a single source symbol while a large one may be mapped to multiple symbols. The mapping details are FEC Scheme dependant and must be defined there.
- o Assignment of decoded ADUs to flows in multi-flow configurations: when multiple flows are multiplexed over the same FECFRAME instance, a problem is to assign a decoded ADU to the right flow (UDP port numbers/IP addresses traditionally used to map incoming ADUs to flows are not recovered during FEC decoding). To make it possible, at the FECFRAME sending instance, each ADU is prepended with a flow identifier (1 byte) before doing the mapping to source symbols (see above). This (flow ID + length + application payload + padding), called ADUI, is then FEC protected. Therefore a decoded ADUI contains enough information to assign the ADU to the right flow.

A few aspects are not considered by FECFRAME, namely:

- o congestion control (see [RFC6363], section 8 for a more detailed discussion);
- o feedbacks from receiver(s) (although they may exist within the application, e.g., through RCTP control messages);
- o flow adaptation at a FECFRAME sender (e.g., by adjusting the FEC code rate based on channel conditions, since there is no feedback mechanism within FECFRAME);

4. Procedural Overview

4.1. General

The general considerations of [RFC6363], Section 4.1, that are specific to block FEC codes are not repeated here.

With a Sliding Window FEC Code, the FEC source packet MUST contain information to identify the position occupied by the ADU within the source flow, in terms specific to the FEC scheme. This information is known as the Source FEC Payload ID, and the FEC scheme is responsible for defining and interpreting it.

With a Sliding Window FEC Code, the FEC repair packets MUST contain information that identifies the relationship between the contained repair payloads and the original source symbols used during encoding. This information is known as the Repair FEC Payload ID, and the FEC scheme is responsible for defining and interpreting it.

The Sender Operation ([RFC6363], Section 4.2.) and Receiver Operation ([RFC6363], Section 4.3) are both specific to block FEC codes and therefore omitted below. The following two sections detail similar operations for Sliding Window FEC codes.

4.2. Sender Operation with Sliding Window FEC Codes

With a Sliding Window FEC scheme, the following operations, illustrated in Figure 2 for the case of UDP repair flows, and in Figure 3 for the case of RTP repair flows, describe a possible way to generate compliant source and repair flows:

1. A new ADU is provided by the application.
2. The FEC Framework communicates this ADU to the FEC scheme.
3. The sliding encoding window is updated by the FEC scheme. The ADU to source symbols mapping as well as the encoding window management details are both the responsibility of the FEC scheme

and MUST be detailed there. Appendix A provides some hints on the way it might be performed.

4. The Source FEC Payload ID information of the source packet is determined by the FEC scheme. If required by the FEC scheme, the Source FEC Payload ID is encoded into the Explicit Source FEC Payload ID field and returned to the FEC Framework.
5. The FEC Framework constructs the FEC source packet according to [RFC6363] Figure 6, using the Explicit Source FEC Payload ID provided by the FEC scheme if applicable.
6. The FEC source packet is sent using normal transport-layer procedures. This packet is sent using the same ADU flow identification information as would have been used for the original source packet if the FEC Framework were not present (for example, in the UDP case, the UDP source and destination addresses and ports on the IP datagram carrying the source packet will be the same whether or not the FEC Framework is applied).
7. When the FEC Framework needs to send one or several FEC repair packets (e.g., according to the target Code Rate), it asks the FEC scheme to create one or several repair packet payloads from the current sliding encoding window along with their Repair FEC Payload ID.
8. The Repair FEC Payload IDs and repair packet payloads are provided back by the FEC scheme to the FEC Framework.
9. The FEC Framework constructs FEC repair packets according to [RFC6363] Figure 7, using the FEC Payload IDs and repair packet payloads provided by the FEC scheme.
10. The FEC repair packets are sent using normal transport-layer procedures. The port(s) and multicast group(s) to be used for FEC repair packets are defined in the FEC Framework Configuration Information.

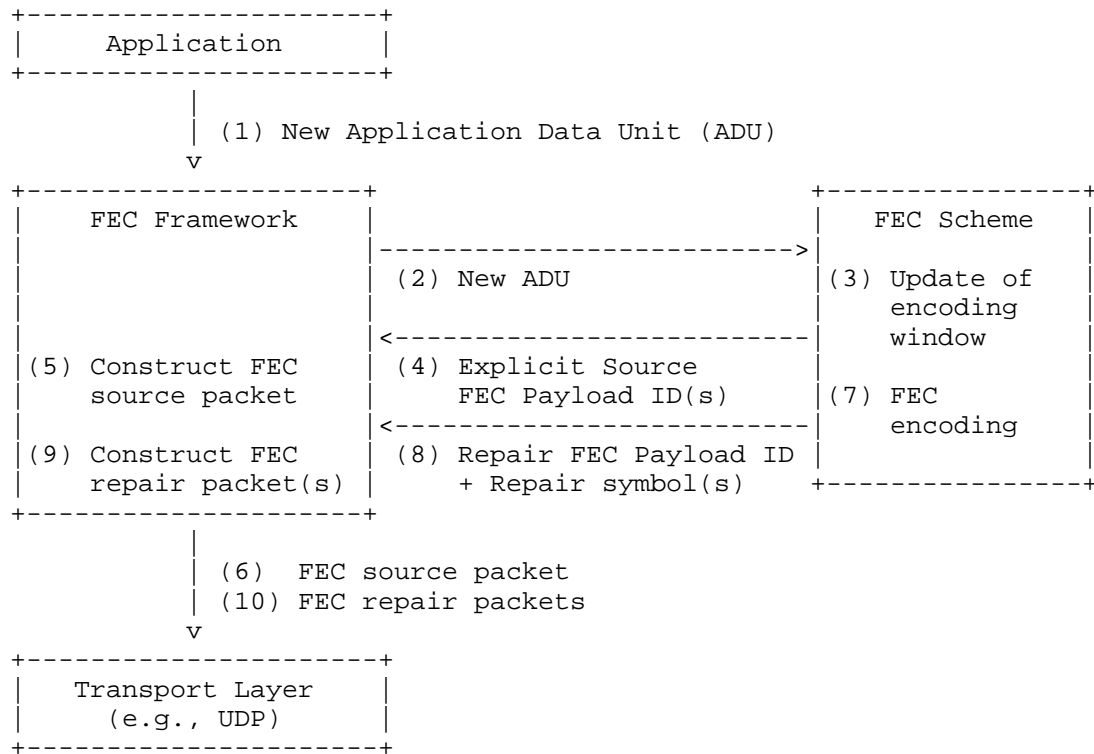


Figure 2: Sender Operation with Convolutional FEC Codes

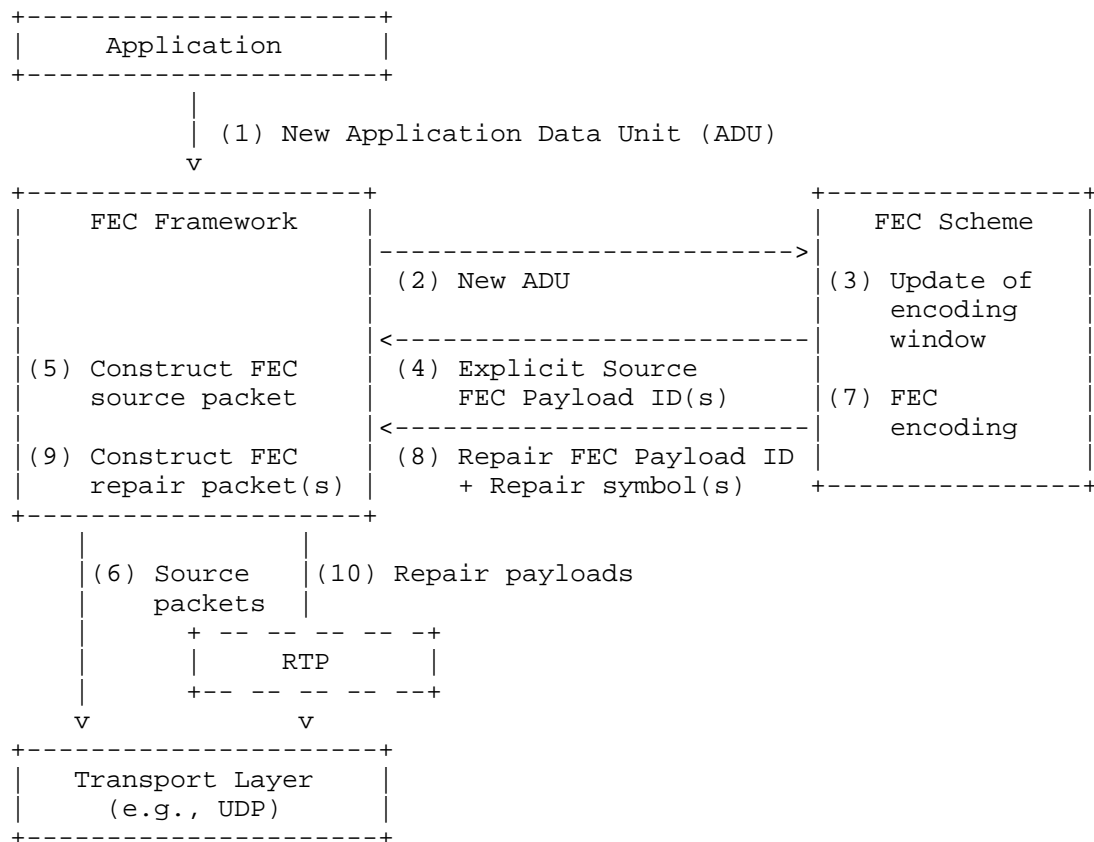


Figure 3: Sender Operation with RTP Repair Flows

4.3. Receiver Operation with Sliding Window FEC Codes

With a Sliding Window FEC scheme, the following operations, illustrated in Figure 4 for the case of UDP repair flows, and in Figure 5 for the case of RTP repair flows. The only differences with respect to block FEC codes lie in steps (4) and (5). Therefore this section does not repeat the other steps of [RFC6363], Section 4.3, "Receiver Operation". The new steps (4) and (5) are:

4. The FEC scheme uses the received FEC Payload IDs (and derived FEC Source Payload IDs when the Explicit Source FEC Payload ID field is not used) to insert source and repair packets into the decoding window in the right way. If at least one source packet is missing and at least one repair packet has been received and the rank of the associated linear system permits it, then FEC decoding can be performed in order to recover missing source

payloads. The FEC scheme determines whether source packets have been lost and whether enough repair packets have been received to decode any or all of the missing source payloads.

5. The FEC scheme returns the received and decoded ADUs to the FEC Framework, along with indications of any ADUs that were missing and could not be decoded.

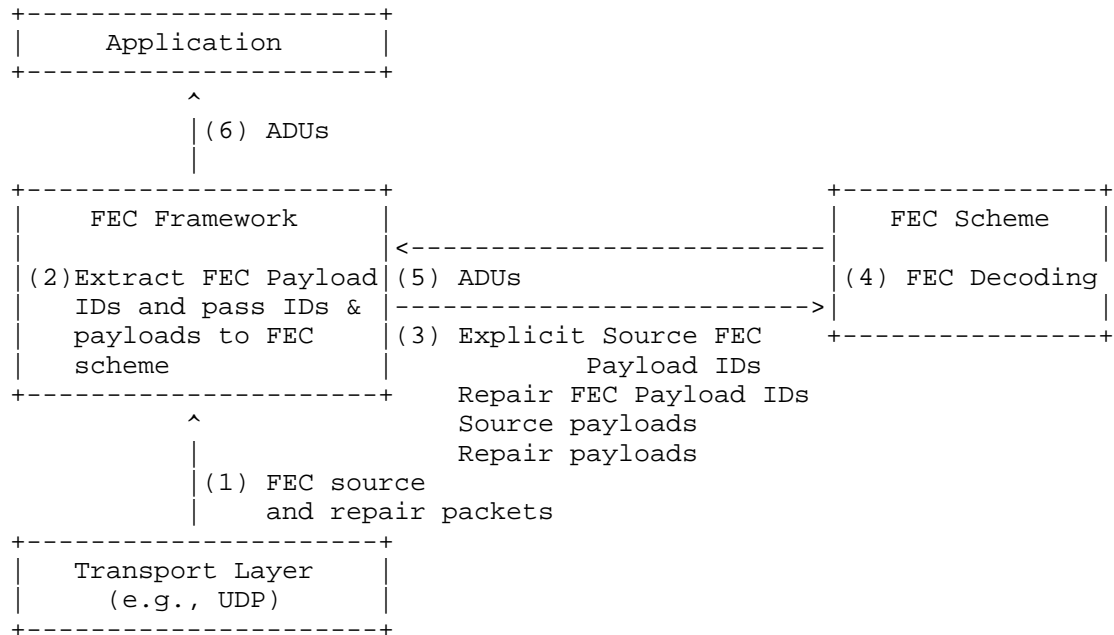


Figure 4: Receiver Operation with Sliding Window FEC Codes

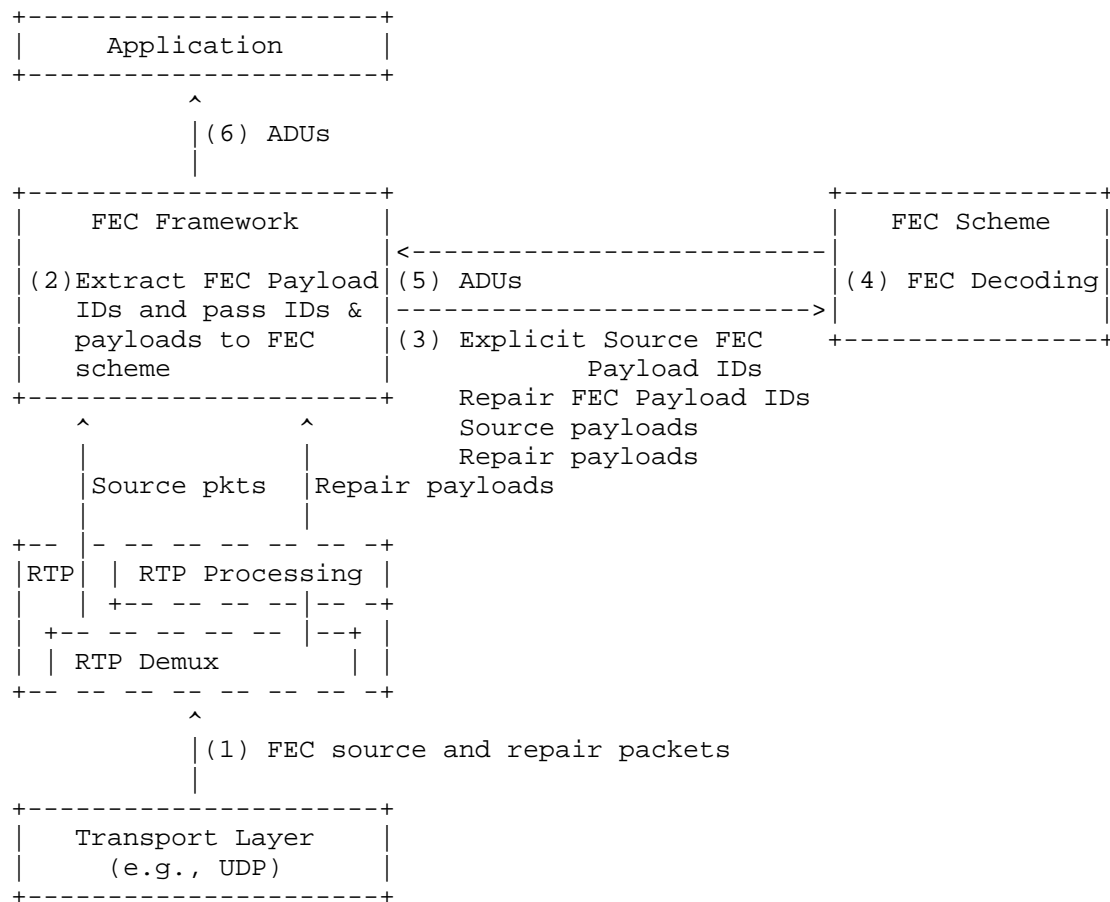


Figure 5: Receiver Operation with RTP Repair Flows

5. Protocol Specification

5.1. General

This section discusses the protocol elements for the FEC Framework specific to Sliding Window FEC schemes. The global formats of source data packets (i.e., [RFC6363], Figure 6) and repair data packets (i.e., [RFC6363], Figures 7 and 8) remain the same with Sliding Window FEC codes. They are not repeated here.

5.2. FEC Framework Configuration Information

The FEC Framework Configuration Information considerations of [RFC6363], Section 5.5, equally applies to this FECFRAME extension and is not repeated here.

5.3. FEC Scheme Requirements

The FEC scheme requirements of [RFC6363], Section 5.6, mostly apply to this FECFRAME extension and are not repeated here. An exception though is the "full specification of the FEC code", item (4), that is specific to block FEC codes. The following item (4) applies instead:

4. A full specification of the Sliding Window FEC code

This specification MUST precisely define the valid FEC-Scheme-Specific Information values, the valid FEC Payload ID values, and the valid packet payload sizes (where packet payload refers to the space within a packet dedicated to carrying encoding symbols).

Furthermore, given valid values of the FEC-Scheme-Specific Information, a valid Repair FEC Payload ID value, a valid packet payload size, and a valid encoding window (i.e., a set of source symbols), the specification MUST uniquely define the values of the encoding symbols to be included in the repair packet payload with the given Repair FEC Payload ID value.

Additionally, the FEC scheme associated to a Sliding Window FEC Code:

- o MUST define the relationships between ADUs and the associated source symbols (mapping);
- o MUST define the management of the encoding window that slides over the set of ADUs. Appendix A provides a non normative example;
- o MUST define the management of the decoding window, consisting of a system of linear equations (in case of a linear FEC code);

6. Feedback

The discussion of [RFC6363], Section 6, equally applies to this FECFRAME extension and is not repeated here.

7. Transport Protocols

The discussion of [RFC6363], Section 7, equally applies to this FECFRAME extension and is not repeated here.

8. Congestion Control

The discussion of [RFC6363], Section 8, equally applies to this FECFRAME extension and is not repeated here.

9. Implementation Status

Editor's notes: RFC Editor, please remove this section motivated by RFC 7942 before publishing the RFC. Thanks!

An implementation of FECFRAME extended to Sliding Window codes exists:

- o Organisation: Inria
- o Description: This is an implementation of FECFRAME extended to Sliding Window codes and supporting the RLC FEC Scheme [RLC-ID]. It is based on: (1) a proprietary implementation of FECFRAME, made by Inria and Expway for which interoperability tests have been conducted; and (2) a proprietary implementation of RLC Sliding Window FEC Codes.
- o Maturity: the basic FECFRAME maturity is "production", the FECFRAME extension maturity is "under progress".
- o Coverage: the software implements a subset of [RFC6363], as specialized by the 3GPP eMBMS standard [MBMSTS]. This software also covers the additional features of FECFRAME extended to Sliding Window codes, in particular the RLC FEC Scheme.
- o Lincensing: proprietary.
- o Implementation experience: maximum.
- o Information update date: March 2017.
- o Contact: vincent.roca@inria.fr

10. Security Considerations

This FECFRAME extension does not add any new security consideration. All the considerations of [RFC6363], Section 9, apply to this document as well.

11. Operations and Management Considerations

This FECFRAME extension does not add any new Operations and Management Consideration. All the considerations of [RFC6363], Section 10, apply to this document as well.

12. IANA Considerations

A FEC scheme for use with this FEC Framework is identified via its FEC Encoding ID. It is subject to IANA registration in the "FEC Framework (FECFRAME) FEC Encoding IDs" registry. All the rules of [RFC6363], Section 11, apply and are not repeated here.

13. Acknowledgments

TBD

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Appendix A. About Sliding Encoding Window Management (non Normative)

The FEC Framework does not specify the management of the sliding encoding window which is the responsibility of the FEC Scheme. This annex provides a few hints with respect to the management of this encoding window.

Source symbols are added to the sliding encoding window each time a new ADU arrives, where the following information is provided for this ADU by the FEC Framework: a description of the source flow with which the ADU is associated, the ADU itself, and the length of the ADU. This information is sufficient for the FEC scheme to map the ADU to the corresponding source symbols.

Source symbols and the corresponding ADUs are removed from the sliding encoding window, for instance:

- o after a certain delay, when an "old" ADU of a real-time flow times out. The source symbol retention delay in the sliding encoding window should therefore be initialized according to the real-time features of incoming flow(s).
- o once the sliding encoding window has reached its maximum size (there is usually an upper limit to the sliding encoding window size). In that case the oldest symbol is removed each time a new source symbol is added.

Several aspects exist that can impact the sliding encoding window management:

- o at the source flows level: real-time constraints can limit the total time source symbols can remain in the encoding window;
- o at the FEC code level: there may be theoretical or practical limitations (e.g., because of computational complexity) that limit the number of source symbols in the encoding window.
- o at the FEC scheme level: signaling and window management are intrinsically related. For instance, an encoding window composed of a non sequential set of source symbols requires an appropriate signaling to inform a receiver of the composition of the encoding window. On the opposite, an encoding window always composed of a sequential set of source symbols simplifies signaling: providing the identity of the first source symbol plus their number is sufficient.

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The Sliding Window Random Linear Code (RLC) Forward Erasure Correction
(FEC) Scheme for FECFRAME
draft-roca-tsvwg-rlc-fec-scheme-01

Abstract

This document describes a fully-specified FEC scheme for the Sliding Window Random Linear Codes (RLC) over $GF(2^m)$, where m equals 1 (binary case), 4 or 8, that can be used to protect arbitrary media streams along the lines defined by FECFRAME extended to sliding window codes. These sliding window FEC codes rely on an encoding window that slides over the source symbols, generating new repair symbols whenever needed. Compared to block FEC codes, these sliding window FEC codes offer key advantages with real-time flows in terms of reduced FEC-related latency while often providing improved erasure recovery capabilities.

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Table of Contents

1. Introduction	3
1.1. Limits of Block Codes with Real-Time Flows	3
1.2. Lower Latency and Better Protection of Real-Time Flows with the Sliding Window RLC Codes	3
1.3. Small Transmission Overheads with the Sliding Window RLC FEC Scheme	4
1.4. Document Organization	5
2. Definitions and Abbreviations	5
3. Procedures	6
3.1. Parameters Derivation	6
3.2. ADU, ADUI and Source Symbols Mappings	7
3.3. Encoding Window Management	9
3.4. Pseudo-Random Number Generator	9
3.5. Coding Coefficients Generation Function	10
4. Sliding Window RLC FEC Scheme for Arbitrary ADU Flows	12
4.1. Formats and Codes	12
4.1.1. FEC Framework Configuration Information	12
4.1.2. Explicit Source FEC Payload ID	13
4.1.3. Repair FEC Payload ID	13
4.1.4. Additional Procedures	15
5. FEC Code Specification	15
5.1. Encoding Side	15
5.2. Decoding Side	15
6. Implementation Status	16
7. Security Considerations	16
7.1. Attacks Against the Data Flow	17
7.1.1. Access to Confidential Content	17
7.1.2. Content Corruption	17
7.2. Attacks Against the FEC Parameters	17
7.3. When Several Source Flows are to be Protected Together	18
7.4. Baseline Secure FEC Framework Operation	18
8. Operations and Management Considerations	18
8.1. Operational Recommendations: Finite Field Element Size (m Parameter)	18
9. IANA Considerations	19
10. Acknowledgments	19
11. References	19
11.1. Normative References	19
11.2. Informative References	20

Appendix A. Decoding Beyond Maximum Latency Optimization	22
Author's Address	22

1. Introduction

Application-Level Forward Erasure Correction (AL-FEC) codes are a key element of communication systems. They are used to recover from packet losses (or erasures) during content delivery sessions to a large number of receivers (multicast/broadcast transmissions). This is the case with the FLUTE/ALC protocol [RFC6726] in case of reliable file transfers over lossy networks, and the FECFRAME protocol for reliable continuous media transfers over lossy networks.

The present document only focusses on the FECFRAME protocol, used in multicast/broadcast delivery mode, with contents that feature stringent real-time constraints: each source packet has a maximum validity period after which it will not be considered by the destination application.

1.1. Limits of Block Codes with Real-Time Flows

With FECFRAME, there is a single FEC encoding point (either a end-host/server (source) or a middlebox) and a single FEC decoding point (either a end-host (receiver) or middlebox). In this context, currently standardized AL-FEC codes for FECFRAME like Reed-Solomon [RFC6865], LDPC-Staircase [RFC6816], or Raptor/RaptorQ, are all linear block codes: they require the data flow to be segmented into blocks of a predefined maximum size. The block size is a balance between robustness (in particular in front of long erasure bursts for which there is an incentive to increase the block size) and maximum decoding latency (for which there is an incentive to decrease the block size). Therefore, with a multicast/broadcast session, the block code is dimensioned by considering the worst communication channel one wants to support, and this choice impacts all receivers, no matter their individual channel quality.

1.2. Lower Latency and Better Protection of Real-Time Flows with the Sliding Window RLC Codes

This document introduces a fully-specified FEC scheme that follows a totally different approach: the Sliding Window Random Linear Codes (RLC) over $GF(2^m)$, where m equals 1, 4 or 8. This FEC scheme is used to protect arbitrary media streams along the lines defined by FECFRAME extended to sliding window codes [fecframe-ext]. This FEC scheme is extremely efficient for instance with media that feature real-time constraints sent within a multicast/broadcast session.

The RLC codes belong to the broad class of sliding window AL-FEC codes (A.K.A. convolutional codes). The encoding process is based on an encoding window that slides over the set of source packets (in fact source symbols as we will see in Section 3.2), and which is either of fixed or variable size (elastic window). Repair packets (symbols) are generated and sent on-the-fly, after computing a random linear combination of the source symbols present in the current encoding window.

At the receiver, a linear system is managed from the set of received source and repair packets. New variables (representing source symbols) and equations (representing the linear combination of each repair symbol received) are added upon receiving new packets. Variables are removed when they are too old with respect to their validity period (real-time constraints), as well as the associated equations they are involved in (Appendix A introduces an optimisation that extends the time a variable is considered in the system). Erased source symbols are then recovered thanks this linear system whenever its rank permits it.

With RLC codes (more generally with sliding window codes), the protection of a multicast/broadcast session also needs to be dimensioned by considering the worst communication channel one wants to support. However the receivers experiencing a good to medium channel quality observe a FEC-related latency close to zero [Roca16] since an isolated erased source packet is quickly recovered by the following repair packet. On the opposite, with a block code, recovering an isolated erased source packet always requires waiting the end of the block for the first repair packet to arrive. Additionally, under certain situations (e.g., with a limited FEC-related latency budget and with constant bit rate transmissions after FECFRAME encoding), sliding window codes achieve more easily a target transmission quality (e.g., measured by the residual loss after FEC decoding) by sending fewer repair packets (i.e., higher code rate) than block codes.

1.3. Small Transmission Overheads with the Sliding Window RLC FEC Scheme

The Sliding Window RLC FEC scheme is designed so as to reduce the transmission overhead. The main requirement is that each repair packet header must enable a receiver to reconstruct the list of source symbols and the associated random coefficients used during the encoding process. In order to minimize packet overhead, the set of symbols in the encoding window as well as the set of coefficients over $GF(2^m)$ used in the linear combination are not individually listed in the repair packet header. Instead, each FEC repair packet header contains:

- o the Encoding Symbol Identifier (ESI) of the first source symbol in the encoding window as well as the number of symbols (since this number may vary with a variable size, elastic window). These two pieces of information enable each receiver to easily reconstruct the set of source symbols considered during encoding, the only constraint being that there cannot be any gap;
- o the seed used by a coding coefficients generation function (Section 3.5). This information enables each receiver to generate the same set of coding coefficients over $GF(2^m)$ as the sender;

Therefore, no matter the number of source symbols present in the encoding window, each FEC repair packet features a fixed 64-bit long header, called Repair FEC Payload ID (Figure 7). Similarly, each FEC source packet features a fixed 32-bit long trailer, called Explicit Source FEC Payload ID (Figure 5), that contains the ESI of the first source symbol (see the ADUI and source symbol mapping, Section 3.2).

1.4. Document Organization

This fully-specified FEC scheme follows the structure required by [RFC6363], section 5.6. "FEC Scheme Requirements", namely:

3. Procedures: This section describes procedures specific to this FEC scheme, namely: RLC parameters derivation, ADUI and source symbols mapping, pseudo-random number generator, and coding coefficients generation function;
4. Formats and Codes: This section defines the Source FEC Payload ID and Repair FEC Payload ID formats, carrying the signalling information associated to each source or repair symbol. It also defines the FEC Framework Configuration Information (FFCI) carrying signalling information for the session;
5. FEC Code Specification: Finally this section provides the code specification.

2. Definitions and Abbreviations

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

This document uses the following definitions and abbreviations:

$GF(q)$ denotes a finite field (also known as the Galois Field) with q elements. We assume that $q = 2^m$ in this document

m defines the length of the elements in the finite field, in bits.

In this document, m is equal to 1, 4 or 8

ADU: Application Data Unit

ADUI: Application Data Unit Information (includes the F, L and padding fields in addition to the ADU)
E: encoding symbol size (i.e., source or repair symbol), assumed fixed (in bytes)
br_out: transmission bitrate at the output of the FECFRAME sender, assumed fixed (in bits/s)
max_lat: maximum FEC-related latency within FECFRAME (in seconds)
cr: AL-FEC coding rate
plr: packet loss rate on the erasure channel
ew_size: encoding window current size at a sender (in symbols)
ew_max_size: encoding window maximum size at a sender (in symbols)
dw_size: decoding window current size at a receiver (in symbols)
dw_max_size: decoding window maximum size at a receiver (in symbols)
ls_max_size: linear system maximum size (or width) at a receiver (in symbols)
ls_size: linear system current size (or width) at a receiver (in symbols)
PRNG: pseudo-random number generator
pmms_rand(maxv): PRNG defined in Section 3.4 and used in this specification, that returns a new random integer in [0; maxv-1]

3. Procedures

This section introduces the procedures that are used by this FEC scheme.

3.1. Parameters Derivation

The Sliding Window RLC FEC Scheme relies on several key internal parameters:

Maximum FEC-related latency budget, max_lat (in seconds) A source ADU flow can have real-time constraints, and therefore any FECFRAME related operation must take place within the validity period of each ADU. When there are multiple flows with different real-time constraints, we consider the most stringent constraints (see [RFC6363], Section 10.2, item 6, for recommendations when several flows are globally protected). This maximum FEC-related latency accounts for all sources of latency added by FEC encoding (sender) and FEC decoding (receiver). Other sources of latency (e.g., added by network communications) are out of scope and must be considered separately (e.g., they have already been deducted). It can be regarded as the latency budget permitted for all FEC-related operations. This is also an input parameter that enables to derive other internal parameters;
Encoding window current (resp. maximum) size, ew_size (resp. ew_max_size) (in symbols):

these parameters are used by a sender during FEC encoding. More precisely, each repair symbol is a linear combination of the `ew_size` source symbols present in the encoding window when RLC encoding took place. In all situations, we MUST have `ew_size <= ew_max_size`;

Decoding window current (resp. maximum) size, `dw_size` (resp. `dw_max_size`) (in symbols):

these parameters are used by a receiver when managing the linear system used for decoding. `dw_size` is the current size of the decoding window, i.e., the set of received or erased source symbols that are currently part of the linear system. In all situations, we MUST have `dw_size <= dw_max_size`;

In order to comply with the maximum FEC-related latency budget, assuming a constant transmission bitrate at the output of the FECFRAME sender (`br_out`), encoding symbol size (`E`), and code rate (`cr`), we have:

$$\text{dw_max_size} = (\text{max_lat} * \text{br_out} * \text{cr}) / (8 * E)$$

This `dw_max_size` defines the maximum delay after which an old source symbol may be recovered: after this delay, this old source symbol will be removed from the decoding window.

It is often good practice to choose:

$$\text{ew_max_size} = \text{dw_max_size} / 2$$

However any value `ew_max_size < dw_max_size` can be used without impact on the FEC-related latency budget. Finding the optimal value can depend on the erasure channel one wants to support and should be determined after simulations or field trials.

Note that the decoding beyond maximum latency optimisation (Appendix A) enables an old source symbol to be kept in the linear system beyond the FEC-related latency budget, but not delivered to the receiving application. Here we have: `ls_size >= dw_max_size`

3.2. ADU, ADUI and Source Symbols Mappings

An ADU, coming from the application, cannot be mapped to source symbols directly. Indeed, an erased ADU recovered at a receiver must contain enough information to be assigned to the right application flow (UDP port numbers and IP addresses cannot be used to that purpose as they are not protected by FEC encoding). This requires adding the flow identifier to each ADU before doing FEC encoding.

Additionally, since ADUs are of variable size, padding is needed so that each ADU (with its flow identifier) contribute to an integral number of source symbols. This requires adding the original ADU length to each ADU before doing FEC encoding. Because of these requirements, an intermediate format, the ADUI, or ADU Information, is considered [RFC6363].

For each incoming ADU, an ADUI is created as follows. First of all, 3 bytes are prepended: (Figure 1):

Flow ID (F) (8-bit field): this unsigned byte contains the integer identifier associated to the source ADU flow to which this ADU belongs. It is assumed that a single byte is sufficient, which implies that no more than 256 flows will be protected by a single FECFRAME instance.

Length (L) (16-bit field): this unsigned integer contains the length of this ADU, in network byte order (i.e., big endian). This length is for the ADU itself and does not include the F, L, or Pad fields.

Then, zero padding is added to the ADU if needed:

Padding (Pad) (variable size field): this field contains zero padding to align the F, L, ADU and padding up to a size that is multiple of E bytes (i.e., the source and repair symbol length).

Each ADUI contributes to an integral number of source symbols. The data unit resulting from the ADU and the F, L, and Pad fields is called ADU Information (or ADUI). Since ADUs can be of different size, this is also the case for ADUIs.

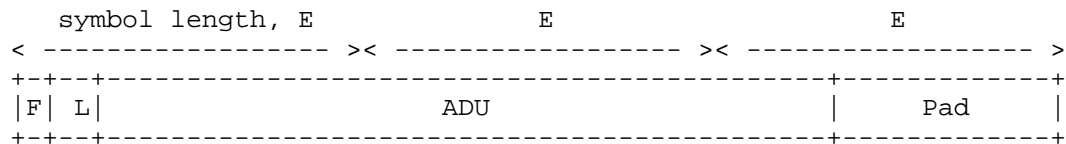


Figure 1: ADUI Creation example (here 3 source symbols are created for this ADUI).

Note that neither the initial 3 bytes nor the optional padding are sent over the network. However, they are considered during FEC encoding. It means that a receiver who lost a certain FEC source packet (e.g., the UDP datagram containing this FEC source packet) will be able to recover the ADUI if FEC decoding succeeds. Thanks to the initial 3 bytes, this receiver will get rid of the padding (if any) and identify the corresponding ADU flow.

3.3. Encoding Window Management

Source symbols and the corresponding ADUs are removed from the encoding window:

- o when the sliding encoding window has reached its maximum size, `ew_max_size`. In that case the oldest symbol **MUST** be removed before adding a new symbol, so that the current encoding window size always remains inferior or equal to the maximum size: `ew_size <= ew_max_size`;
- o when an ADU has reached its maximum validity duration in case of a real-time flow. When this happens, all source symbols corresponding to the ADUI that expired **SHOULD** be removed from the encoding window;

Source symbols are added to the sliding encoding window each time a new ADU arrives, once the ADU to ADUI and then to source symbols mapping has been performed (Section 3.2). The current size of the encoding window, `ew_size`, is updated after adding new source symbols. This process may require to remove old source symbols so that: `ew_size <= ew_max_size`.

Note that a FEC codec may feature practical limits in the number of source symbols in the encoding window (e.g., for computational complexity reasons). This factor may further limit the `ew_max_lat` value, in addition to the maximum FEC-related latency budget (Section 3.1).

3.4. Pseudo-Random Number Generator

The RLC codes rely on the following Pseudo-Random Number Generator (PRNG), identical to the PRNG used with LDPC-Staircase codes ([RFC5170], section 5.7).

The Park-Miller "minimal standard" PRNG [PM88] **MUST** be used. It defines a simple multiplicative congruential algorithm: $I_{j+1} = A * I_j \pmod{M}$, with the following choices: $A = 7^5 = 16807$ and $M = 2^{31} - 1 = 2147483647$. A validation criteria of such a PRNG is the following: if seed = 1, then the 10,000th value returned **MUST** be equal to 1043618065.

Several implementations of this PRNG are known and discussed in the literature. An optimized implementation of this algorithm, using only 32-bit mathematics, and which does not require any division, can be found in [rand3lpmc]. It uses the Park and Miller algorithm [PM88] with the optimization suggested by D. Carta in [CA90]. The history behind this algorithm is detailed in [WI08]. Yet, any other implementation of the PRNG algorithm that matches the above

validation criteria, like the ones detailed in [PM88], is appropriate.

This PRNG produces, natively, a 31-bit value between 1 and 0x7FFFFFFE ($2^{31}-2$) inclusive. Since it is desired to scale the pseudo-random number between 0 and maxv-1 inclusive, one must keep the most significant bits of the value returned by the PRNG (the least significant bits are known to be less random, and modulo-based solutions should be avoided [PTVF92]). The following algorithm MUST be used:

Input:

raw_value: random integer generated by the inner PRNG algorithm, between 1 and 0x7FFFFFFE ($2^{31}-2$) inclusive.
maxv: upper bound used during the scaling operation.

Output:

scaled_value: random integer between 0 and maxv-1 inclusive.

Algorithm:

```
scaled_value = (unsigned long) ((double)maxv * (double)raw_value /  
(double)0x7FFFFFFF);  
(NB: the above C type casting to unsigned long is equivalent to  
using floor() with positive floating point values.)
```

In this document, pmms_rand(maxv) denotes the PRNG function that implements the Park-Miller "minimal standard" algorithm, defined above, and that scales the raw value between 0 and maxv-1 inclusive, using the above scaling algorithm.

Additionally, the pmms_srand(seed) function must be provided to enable the initialization of the PRNG with a seed before calling pmms_rand(maxv) the first time. The seed is a 31-bit integer between 1 and 0x7FFFFFFE inclusive. In this specification, the seed is restricted to a value between 1 and 0xFFFF inclusive, as this is the Repair_Key 16-bit field value of the Repair FEC Payload ID (Section 4.1.3).

3.5. Coding Coefficients Generation Function

The coding coefficients, used during the encoding process, are generated at the RLC encoder by the following function each time a new repair symbol needs to be produced:

```

<CODE BEGINS>
/*
 * Fills in the table of coding coefficients (of the right size)
 * provided with the appropriate number of coding coefficients to
 * use for the repair symbol key provided.
 *
 * (in) repair_key    key associated to this repair symbol
 * (in) cc_tab[]      pointer to a table of the right size to store
 *                   coding coefficients. All coefficients are
 *                   stored as bytes, regardless of the m parameter,
 *                   upon return of this function.
 * (in) cc_nb[]       number of entries in the table. This value is
 *                   equal to the current encoding window size.
 * (in) m             Finite Field GF(2^m) parameter.
 * (out)              returns an error code
 */
int generate_coding_coefficients (UINT16    repair_key,
                                UINT8      cc_tab[],
                                UINT16     cc_nb,
                                UINT8      m)
{
    UINT32    i;

    if (repair_key == 0) {
        return SOMETHING_WENT_WRONG;
    }
    pmms_srand(repair_key);
    if (m == 1) {
        /* 0 is a valid coefficient value in binary GF */
        for (i = 0 ; i < cc_nb ; i ++ ) {
            cc_tab[i] = (UINT8) pmms_rand(2);
        }
    } else {
        /* coefficient 0 is avoided in non-binary GF to consider each
         * source symbol */
        UINT32    maxv;
        maxv = get_gf_size(); /* i.e., 16 if m=4 or 256 if m=8 */
        for (i = 0 ; i < cc_nb ; i ++ ) {
            do {
                cc_tab[i] = (UINT8) pmms_rand(maxv);
            } while (cc_tab[i] == 0)
        }
    }
    return EVERYTHING_IS_OKAY;
}
<CODE ENDS>

```

Figure 2: Coding Coefficients Generation Function pseudo-code

4. Sliding Window RLC FEC Scheme for Arbitrary ADU Flows

4.1. Formats and Codes

4.1.1. FEC Framework Configuration Information

The FEC Framework Configuration Information (or FFCI) includes information that **MUST** be communicated between the sender and receiver(s). More specifically, it enables the synchronization of the FECFRAME sender and receiver instances. It includes both mandatory elements and scheme-specific elements, as detailed below.

4.1.1.1. Mandatory Information

- o FEC Encoding ID: the value assigned to this fully specified FEC scheme **MUST** be XXXX, as assigned by IANA (Section 9).

When SDP is used to communicate the FFCI, this FEC Encoding ID is carried in the 'encoding-id' parameter.

4.1.1.2. FEC Scheme-Specific Information

The FEC Scheme-Specific Information (FSSI) includes elements that are specific to the present FEC scheme. More precisely:

Encoding symbol size (E): a non-negative integer that indicates the size of each encoding symbol in bytes;

m parameter (m): the length of the elements in the finite field, in bits, where m is equal to 1, 4 or 8;

These elements are required both by the sender (RLC encoder) and the receiver(s) (RLC decoder).

When SDP is used to communicate the FFCI, this FEC scheme-specific information is carried in the 'fssi' parameter in textual representation as specified in [RFC6364]. For instance:

fssi=E:1400,m:8

If another mechanism requires the FSSI to be carried as an opaque octet string (for instance, after a Base64 encoding), the encoding format consists of the following 2 octets:

Encoding symbol length (E): 16-bit field.

m parameter (m): 8-bit field.

case, the number of repair symbols within this FEC repair packet is easily deduced by comparing the known received FEC repair packet size (equal to the UDP payload size when UDP is the underlying transport protocol) and the symbol size, E , communicated in the FFCI.

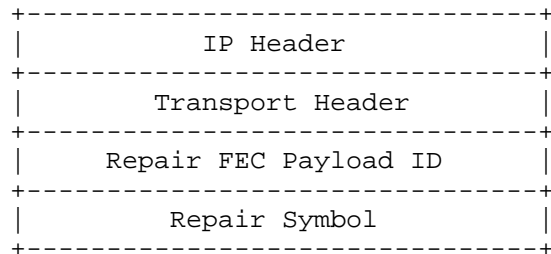


Figure 6: Structure of an FEC Repair Packet with the Repair FEC Payload ID

More precisely, the Repair FEC Payload ID is composed of the following fields (Figure 7):

Repair_Key (16-bit field): this unsigned integer is used as a seed by the coefficient generation function (Section 3.5) in order to generate the desired number of coding coefficients. Value 0 MUST NOT be used. When a FEC repair packet contains several repair packets, this repair key value is that of the first repair symbol. The remaining repair keys can be deduced by incrementing by 1 this value, up to a maximum value of 65535 after which it loops back to 1.

Number of Source Symbols in the Encoding Window, NSS (16-bit field):

this unsigned integer indicates the number of source symbols in the encoding window when this repair symbol was generated.

ESI of first source symbol in encoding window, FSS_ESI (32-bit field):

this unsigned integer indicates the ESI of the first source symbol in the encoding window when this repair symbol was generated.

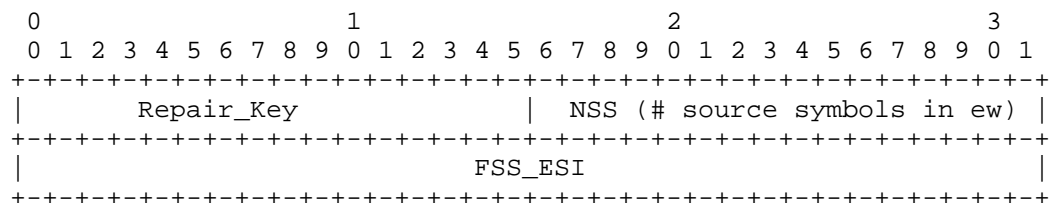


Figure 7: Repair FEC Payload ID Encoding Format

4.1.4. Additional Procedures

The following procedure applies:

- o The ESI of source symbols MUST start with value 0 for the first source symbol and MUST be managed sequentially. Wrapping to zero will happen after reaching the maximum 32-bit value.

5. FEC Code Specification

5.1. Encoding Side

This section provides a high level description of a Sliding Window RLC encoder.

Whenever a new FEC repair packet is needed, the RLC encoder instance first gathers the `ew_size` source symbols currently in the sliding encoding window. Then it chooses a repair key, which can be a non zero monotonically increasing integer value, incremented for each repair symbol up to a maximum value of 65535 (as it is carried within a 16-bit field) after which it loops back to 1 (indeed, being used as a PRNG seed, value 0 is prohibited). This repair key is communicated to the coefficient generation function (Section Section 3.5) in order to generate `ew_size` coding coefficients. Finally, the FECFRAME sender computes the repair symbol as a linear combination of the `ew_size` source symbols using the `ew_size` coding coefficients. When `E` is small and when there is an incentive to pack several repair symbols within the same FEC Repair Packet, the appropriate number of repair symbols are computed. The only constraint is to increment by 1 the repair key for each of them, keeping the same `ew_size` source symbols, since only the first repair key will be carried in the Repair FEC Payload ID. The FEC repair packet can then be sent. The source versus repair FEC packet transmission order is out of scope of this document and several approaches exist that are implementation specific.

5.2. Decoding Side

This section provides a high level description of a Sliding Window RLC decoder.

A FECFRAME receiver needs to maintain a linear system whose variables are the received and lost source symbols. Upon receiving a FEC repair packet, a receiver first extracts all the repair symbols it contains (in case several repair symbols are packed together). For each repair symbol, when at least one of the corresponding source symbols it protects has been lost, the receiver adds an equation to the linear system (or no equation if this repair packet does not

change the linear system rank). This equation of course re-uses the `ew_size` coding coefficients that are computed by the same coefficient generation function (Section Section 3.5), using the repair key and encoding window descriptions carried in the Repair FEC Payload ID. Whenever possible (i.e., when a sub-system covering one or more lost source symbols is of full rank), decoding is performed in order to recover lost source symbols. Each time an ADUI can be totally recovered, it is assigned to the corresponding application flow (thanks to the Flow ID (F) field of the ADUI) and padding (if any) removed (thanks to the Length (L) field of the ADUI). This ADU is finally passed to the corresponding upper application. Received FEC source packets, containing an ADU, can be passed to the application either immediately or after some time to guaranty an ordered delivery to the application(s). This document does not mandate any approach as this is an operational and management decision.

With real-time flows, a lost ADU that is decoded after the maximum latency (or an ADU received far too late) should not be considered by the application. Instead the associated source symbols should be removed from the linear system maintained by the receiver(s). Appendix A discusses a backward compatible optimization whereby those late source symbols may still be useful to improve the global loss recovery performance.

6. Implementation Status

Editor's notes: RFC Editor, please remove this section motivated by RFC 6982 before publishing the RFC. Thanks.

An implementation of the Sliding Window RLC FEC Scheme for FECFRAME exists:

- o Organisation: Inria
- o Description: This is an implementation of the Sliding Window RLC FEC Scheme. It relies on a modified version of our OpenFEC (<http://openfec.org>) FEC code library. It is integrated in our FECFRAME software (see [fecframe-ext]).
- o Maturity: prototype.
- o Coverage: this software complies with the Sliding Window RLC FEC Scheme (limited to $m=8$ as of June, 2017).
- o Lincensing: proprietary.
- o Contact: vincent.roca@inria.fr

7. Security Considerations

The FEC Framework document [RFC6363] provides a comprehensive analysis of security considerations applicable to FEC schemes.

Therefore, the present section follows the security considerations section of [RFC6363] and only discusses specific topics.

7.1. Attacks Against the Data Flow

7.1.1. Access to Confidential Content

The Sliding Window RLC FEC Scheme specified in this document does not change the recommendations of [RFC6363]. To summarize, if confidentiality is a concern, it is RECOMMENDED that one of the solutions mentioned in [RFC6363] is used with special considerations to the way this solution is applied (e.g., is encryption applied before or after FEC protection, within the end-system or in a middlebox) to the operational constraints (e.g., performing FEC decoding in a protected environment may be complicated or even impossible) and to the threat model.

7.1.2. Content Corruption

The Sliding Window RLC FEC Scheme specified in this document does not change the recommendations of [RFC6363]. To summarize, it is RECOMMENDED that one of the solutions mentioned in [RFC6363] is used on both the FEC Source and Repair Packets.

7.2. Attacks Against the FEC Parameters

The FEC Scheme specified in this document defines parameters that can be the basis of attacks. More specifically, the following parameters of the FFCI may be modified by an attacker who only targets receivers (Section 4.1.1.2):

- o FEC Encoding ID: changing this parameter leads the receivers to consider a different FEC Scheme, which enables an attacker to create a Denial of Service (DoS);
- o Encoding symbol length (E): setting this E parameter to a different value will confuse the receivers and create a DoS. More precisely, the FEC Repair Packets received will probably no longer be multiple of E, leading receivers to reject them;
- o m parameter: changing this parameter triggers a DoS since the receivers will generate a different set of coding coefficients. The recovered source symbols (and thereafter ADUs) will be corrupted.

An attacker who only targets a sender will achieve the same results. However if the attacker targets both sender and receivers at the same time (the same wrong piece of information is communicated to everybody), the results will be suboptimal but less severe.

It is therefore RECOMMENDED that security measures are taken to guarantee the FFCI integrity, as specified in [RFC6363]. How to achieve this depends on the way the FFCI is communicated from the sender to the receiver, which is not specified in this document.

Similarly, attacks are possible against the Explicit Source FEC Payload ID and Repair FEC Payload ID: by modifying the Encoding Symbol ID (ESI), or the repair key, NSS or FSS_ESI. It is therefore RECOMMENDED that security measures are taken to guarantee the FEC Source and Repair Packets as stated in [RFC6363].

7.3. When Several Source Flows are to be Protected Together

The Sliding Window RLC FEC Scheme specified in this document does not change the recommendations of [RFC6363].

7.4. Baseline Secure FEC Framework Operation

The Sliding Window RLC FEC Scheme specified in this document does not change the recommendations of [RFC6363] concerning the use of the IPsec/ESP security protocol as a mandatory to implement (but not mandatory to use) security scheme. This is well suited to situations where the only insecure domain is the one over which the FEC Framework operates.

8. Operations and Management Considerations

The FEC Framework document [RFC6363] provides a comprehensive analysis of operations and management considerations applicable to FEC schemes. Therefore, the present section only discusses specific topics.

8.1. Operational Recommendations: Finite Field Element Size (m Parameter)

The present document requires that m equals 1 (binary case), 4 or 8. It is expected that $m = 8$ will be mostly used since it warrants a high loss protection. Additionally, elements in the finite field are 8 bits long, which makes read/write memory operations aligned on bytes during encoding and decoding.

An alternative when one can accommodate a lower loss protection is $m = 4$. Elements in the finite field are 4 bits long, so if 2 elements are accessed at a time, read/write memory operations are aligned on bytes during encoding and decoding.

Finally, in particular when dealing with large encoding windows, an alternative is $m = 1$. In that case operations symbols can be

directly XORed together which warrants high bitrate encoding and decoding operations.

Since several values for the *m* parameter are possible, the use case SHOULD define which value or values need to be supported. In any case, any compliant implementation MUST support at least the default *m* = 8 value.

9. IANA Considerations

This document registers one value in the "FEC Framework (FECFRAME) FEC Encoding IDs" registry [RFC6363] as follows:

- o XXX refers to the Sliding Window Random Linear Codes (RLC) FEC Scheme for Arbitrary Packet Flows, as defined in Section XXX of this document.

10. Acknowledgments

The authors would like to thank Belkacem Teibi (Inria) who in particular implemented the RLC codec. The author would also like to thank Marie-Jose Montpetit for her valuable feedbacks on this document.

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Appendix A. Decoding Beyond Maximum Latency Optimization

This annex introduces non normative considerations. They are provided as suggestions, without any impact on interoperability. For more information see [Roca16].

It is possible to improve the decoding performance of sliding window codes without impacting maximum latency, at the cost of extra CPU overhead. The optimization consists, for a receiver, to extend the linear system beyond the decoding window:

$$ls_max_size > dw_max_size$$

Usually the following choice is a good trade-off between decoding performance and extra CPU overhead:

$$ls_max_size = 2 * dw_max_size$$

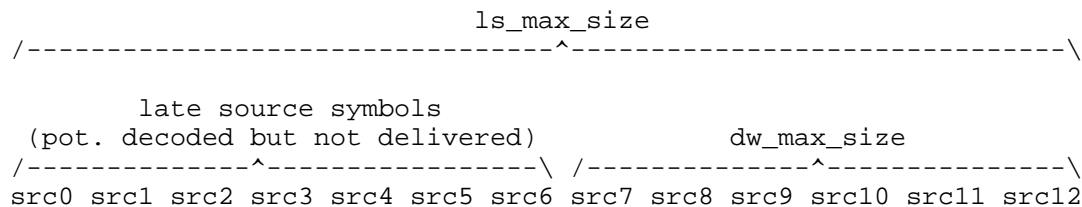


Figure 8: Relationship between parameters to decode beyond maximum latency.

It means that source symbols (and therefore ADUs) may be decoded even if their transport protocol added latency exceeds the maximum value permitted by the application. It follows that these source symbols SHOULD NOT be delivered to the application and SHOULD be dropped once they are no longer needed. However, decoding these late symbols significantly improves the global robustness in bad reception conditions and is therefore recommended for receivers experiencing bad channels[Roca16]. In any case whether or not to use this facility and what exact value to use for the `ls_max_size` parameter are decisions made by each receiver independently, without any impact on others, neither the other receivers nor the source.

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TSVWG
Internet Draft
Intended status: Standards Track
Intended updates: 768
Expires: November 2017

J. Touch
USC/ISI
May 16, 2017

Transport Options for UDP
draft-touch-tsvwg-udp-options-09.txt

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Abstract

Transport protocols are extended through the use of transport header options. This document experimentally extends UDP by indicating the location, syntax, and semantics for UDP transport layer options.

Table of Contents

1. Introduction.....	2
2. Conventions used in this document.....	3
3. Background.....	3
4. The UDP Option Area.....	4
5. UDP Options.....	7
5.1. End of Options List (EOL).....	8
5.2. No Operation (NOP).....	8
5.3. Option Checksum (OCS).....	9
5.4. Alternate Checksum (ACS).....	10
5.5. Lite (LITE).....	10
5.6. Maximum Segment Size (MSS).....	12
5.7. Timestamps (TIME).....	13
5.8. Fragmentation (FRAG).....	13
5.8.1. Coupling FRAG with LITE.....	16
5.9. Authentication and Encryption (AE).....	16
5.10. Experimental (EXP).....	17
6. UDP API Extensions.....	17
7. Whose options are these?.....	18
8. UDP options vs. UDP-Lite.....	18
9. Interactions with Legacy Devices.....	19
10. Options in a Stateless, Unreliable Transport Protocol.....	20
11. UDP Option State Caching.....	20
12. Security Considerations.....	21
13. IANA Considerations.....	22
14. References.....	22
14.1. Normative References.....	22
14.2. Informative References.....	22
15. Acknowledgments.....	24
Appendix A. Implementation Information.....	26

1. Introduction

Transport protocols use options as a way to extend their capabilities. TCP [RFC793], SCTP [RFC4960], and DCCP [RFC4340] include space for these options but UDP [RFC768] currently does not. This document defines an experimental extension to UDP that provides space for transport options including their generic syntax and

semantics for their use in UDP's stateless, unreliable message protocol.

2. Conventions used in this document

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119 [RFC2119].

In this document, these words will appear with that interpretation only when in ALL CAPS. Lowercase uses of these words are not to be interpreted as carrying significance described in RFC 2119.

In this document, the characters ">>" preceding an indented line(s) indicates a statement using the key words listed above. This convention aids reviewers in quickly identifying or finding the portions of this RFC covered by these key words.

3. Background

Many protocols include a default header and an area for header options. These options enable the protocol to be extended for use in particular environments or in ways unforeseen by the original designers. Examples include TCP's Maximum Segment Size, Window Scale, Timestamp, and Authentication Options [RFC793][RFC5925][RFC7323].

These options are used both in stateful (connection-oriented, e.g., TCP [RFC793], SCTP [RFC4960], DCCP [RFC4340]) and stateless (connectionless, e.g., IPv4 [RFC791], IPv6 [RFC2460] protocols. In stateful protocols they can help extend the way in which state is managed. In stateless protocols their effect is often limited to individual packets, but they can have an aggregate effect on a sequence as well. One example of such uses is Substrate Protocol for User Datagram (SPUD) [Tr15], and this document is intended to provide an out-of-band option area as an alternative to the in-band mechanism currently proposed [Hi15].

UDP is one of the most popular protocols that lacks space for options [RFC768]. The UDP header was intended to be a minimal addition to IP, providing only ports and a data checksum for protection. This document experimentally extends UDP to provide a trailer area for options located after the UDP data payload.

4. The UDP Option Area

The UDP transport header includes demultiplexing and service identification (port numbers), a checksum, and a field that indicates the UDP datagram length (including UDP header). The UDP Length length field is typically redundant with the size of the maximum space available as a transport protocol payload (see also discussion in Section 9).

For IPv4, IP Total Length field indicates the total IP datagram length (including IP header), and the size of the IP options is indicated in the IP header (in 4-byte words) as the "Internet Header Length" (IHL), as shown in Figure 1 [RFC791]. As a result, the typical (and largest valid) value for UDP Length is:

$$\text{UDP_Length} = \text{IPv4_Total_Length} - \text{IPv4_IHL} * 4$$

For IPv6, the IP Payload Length field indicates the datagram after the base IPv6 header, which includes the IPv6 extension headers and space available for the transport protocol, as shown in Figure 2 [RFC2460]. Note that the Next HDR field in IPv6 might not indicate UDP (i.e., 17), e.g., when intervening IP extension headers are present. For IPv6, the lengths of any additional IP extensions are indicated within each extension [RFC2460], so the typical (and largest valid) value for UDP Length is:

$$\text{UDP_Length} = \text{IPv6_Payload_Length} - \text{sum}(\text{extension header lengths})$$

In both cases, the space available for the UDP transport protocol data unit is indicated by IP, either completely in the base header (for IPv4) or adding information in the extensions (for IPv6). In either case, this document will refer to this available space as the "IP transport payload".

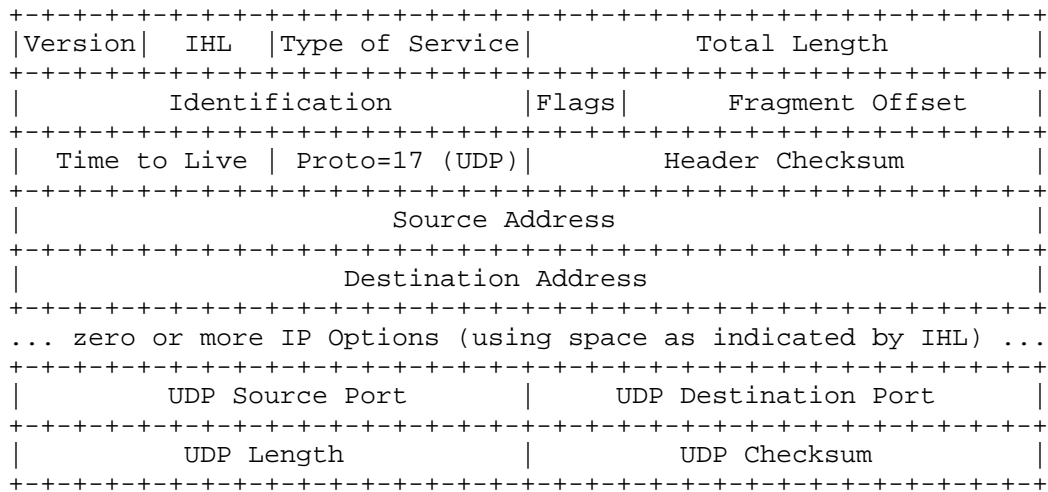


Figure 1 IPv4 datagram with UDP transport payload

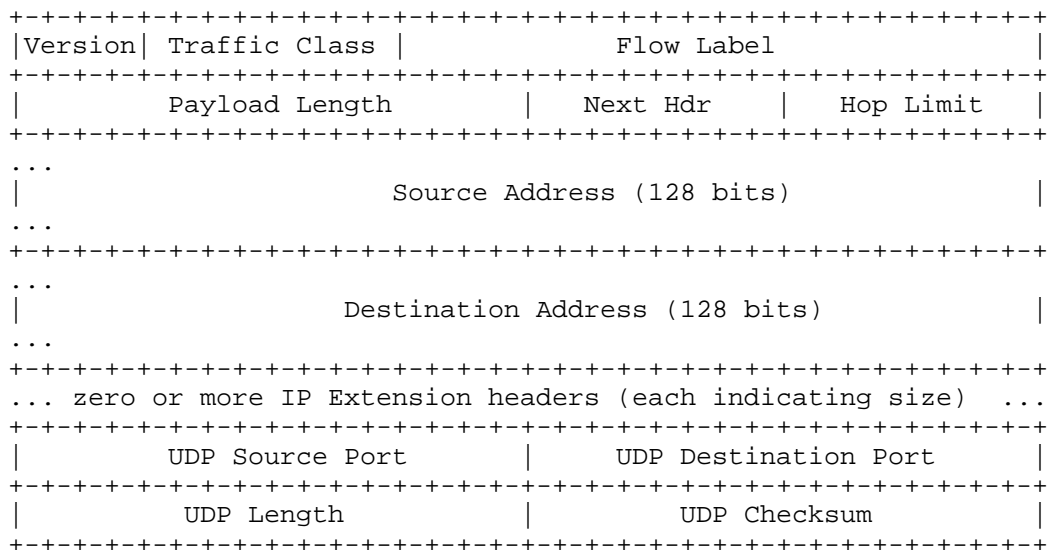


Figure 2 IPv6 datagram with UDP transport payload

As a result of this redundancy, there is an opportunity to use the UDP Length field as a way to break up the IP transport payload into two areas - that intended as UDP user data and an additional "surplus area" (as shown in Figure 3).

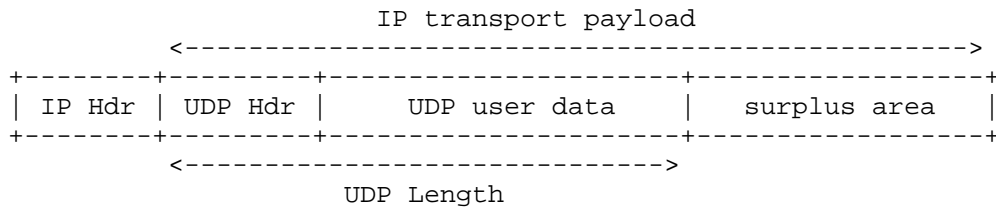


Figure 3 IP transport payload vs. UDP Length

In most cases, the IP transport payload and UDP Length point to the same location, indicating that there is no surplus area. It is important to note that this is not a requirement of UDP [RFC768] (discussed further in Section 9). UDP-Lite used the difference in these pointers to indicate the partial coverage of the UDP Checksum, such that the UDP user data, UDP header, and UDP pseudoheader (a subset of the IP header) are covered by the UDP checksum but additional user data in the surplus area is not covered [RFC3828]. This document uses the surplus area for UDP transport options.

The UDP option area is thus defined as the location between the end of the UDP payload and the end of the IP datagram as a trailing options area. This area can occur at any valid byte offset, i.e., it need not be 16-bit or 32-bit aligned. In effect, this document redefines the UDP "Length" field as a "trailer offset".

UDP options are defined using a TLV (type, length, and optional value) syntax similar to that of TCP [RFC793]. They are typically a minimum of two bytes in length as shown in Figure 4, excepting only the one byte options "No Operation" (NOP) and "End of Options List" (EOL) described below.

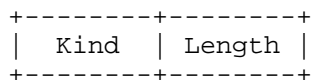


Figure 4 UDP option default format

>> UDP options MAY occur at any UDP length offset.

>> The UDP length MUST be at least as large as the UDP header (8) and no larger than the IP transport payload. Values outside this range MUST be silently discarded as invalid and logged where rate-limiting permits.

Others have considered using values of the UDP Length that is larger than the IP transport payload as an additional type of signal. Using

a value smaller than the IP transport payload is expected to be backward compatible with existing UDP implementations, i.e., to deliver the UDP Length of user data to the application and silently ignore the additional surplus area data. Using a value larger than the IP transport payload would either be considered malformed (and be silently dropped) or could cause buffer overruns, and so is not considered silently and safely backward compatible. Its use is thus out of scope for the extension described in this document.

>> UDP options MUST be interpreted in the order in which they occur in the UDP option area.

5. UDP Options

The following UDP options are currently defined:

Kind	Length	Meaning

0*	-	End of Options List (EOL)
1*	-	No operation (NOP)
2*	2	Option checksum (OCS)
3	4	Alternate checksum (ACS)
4	4	Lite (LITE)
5	4	Maximum segment size (MSS)
6	10	Timestamps (TIME)
7	12	Fragmentation (FRAG)
8	(varies)	Authentication and Encryption (AE)
9-126	(varies)	UNASSIGNED (assignable by IANA)
127-253		RESERVED
254	N(>=4)	RFC 3692-style experiments (EXP)
255		RESERVED

These options are defined in the following subsections.

>> An endpoint supporting UDP options MUST support those marked with a "*" above: EOL, NOP, and OCS.

[QUESTION: Should we extend these, e.g., through #7?]

>> All other options (without a "*") MAY be implemented, and their use SHOULD be determined either out-of-band or negotiated.

>> Receivers MUST silently ignore unknown options. That includes options whose length does not indicate the specified value.

Receivers cannot treat unexpected option lengths as invalid, as this would unnecessarily limit future revision of options (e.g., defining a new ACS that is defined by having a different length).

>> Option lengths MUST NOT exceed the IP length of the packet. If this occurs, the packet MUST be treated as malformed and dropped, and the event MAY be logged for diagnostics (logging SHOULD be rate limited).

>> Required options MUST come before other options. Each required option MUST NOT occur more than once (if they are repeated in a received segment, all except the first MUST be silently ignored).

The requirement that required options come before others is intended to allow for endpoints to implement DOS protection, as discussed further in Section 12.

5.1. End of Options List (EOL)

The End of Options List (EOL) option indicates that there are no more options. It is used to indicate the end of the list of options without needing to pad the options to fill all available option space.

```
+-----+
| Kind=0 |
+-----+
```

Figure 5 UDP EOL option format

>> When the UDP options do not consume the entire option area, the last non-NOP option SHOULD be EOL (vs. filling the entire option area with NOP values).

>> All bytes after EOL MUST be ignored by UDP option processing. As a result, there can only ever be one EOL option (even if other bytes were zero, they are ignored).

5.2. No Operation (NOP)

The No Operation (NOP) option is a one byte placeholder, intended to be used as padding, e.g., to align multi-byte options along 16-bit or 32-bit boundaries.

```

+-----+
| Kind=1 |
+-----+

```

Figure 6 UDP NOP option format

>> If options longer than one byte are used, NOP options SHOULD be used at the beginning of the UDP options area to achieve alignment as would be more efficient for active (i.e., non-NOP) options.

>> Segments SHOULD NOT use more than three consecutive NOPs. NOPs are intended to assign with alignment, not other padding or fill.

[NOTE: Tom Herbert suggested we declare "more than 3 consecutive NOPs" a fatal error to reduce the potential of using NOPs as a DOS attack, but IMO there are other equivalent ways (e.g., using RESERVED or other UNASSIGNED values) and the "no more than 3" creates its own DOS vulnerability)

5.3. Option Checksum (OCS)

The Option Checksum (OCS) is an 8-bit ones-complement sum (Ones8) that covers all of the UDP options. OCS is 8-bits to allow the entire option to occupy a total of 16 bits.

OCS can be calculated by computing the 16-bit ones-complement sum and "folding over" the result (using carry wraparound). Note that OCS is direct, i.e., it is not negated or adjusted if zero (unlike the Internet checksum as used in IPv4, TCP, and UDP headers). OCS protects the option area from errors in a similar way that the UDP checksum protects the UDP user data.

```

+-----+-----+
| Kind=2 | Ones8  |
+-----+-----+

```

Figure 7 UDP OCS option format

>> When present, the option checksum SHOULD occur as early as possible, preferably preceded by only NOP options for alignment and the LITE option if present.

OCS covers the entire UDP option, including the Lite option as formatted before swapping for transmission (or, equivalently, after the swap after reception).

>> If the option checksum fails, all options MUST be ignored and any trailing surplus data (and Lite data, if used) silently discarded.

>> UDP data that is validated by a correct UDP checksum MUST be delivered to the application layer, even if the UDP option checksum fails, unless the endpoints have negotiated otherwise for this segment's socket pair.

5.4. Alternate Checksum (ACS)

The Alternate Checksum (ACS) is a 16-bit CRC of the UDP payload only (excluding the IP pseudoheader, UDP header, and UDP options). It does not include the IP pseudoheader or UDP header, and so need not be updated by NATs when IP addresses or UDP ports are rewritten. Its purpose is to detect errors that the UDP checksum might not detect. CRC-CCITT (polynomial $x^{16} + x^{12} + x^5 + x$ or polynomial 0x1021) has been chosen because of its ubiquity and use in other packet protocols, such as X.25, HDLC, and Bluetooth.

```

+-----+-----+-----+-----+
| Kind=3 | Len=4  |      CRC16sum      |
+-----+-----+-----+-----+

```

Figure 8 UDP ACS option format

5.5. Lite (LITE)

The Lite option (LITE) is intended to provide equivalent capability to the UDP Lite transport protocol [RFC3828]. UDP Lite allows the UDP checksum to cover only a prefix of the UDP data payload, to protect critical information (e.g., application headers) but allow potentially erroneous data to be passed to the user. This feature helps protect application headers but allows for application data errors. Some applications are impacted more by a lack of data than errors in data, e.g., voice and video.

>> When LITE is active, it MUST come first in the UDP options list.

LITE is intended to support the same API as for UDP Lite to allow applications to send and receive data that has a marker indicating the portion protected by the UDP checksum and the portion not protected by the UDP checksum.

LITE includes a 2-byte offset that indicates the length of the portion of the UDP data that is not covered by the UDP checksum.

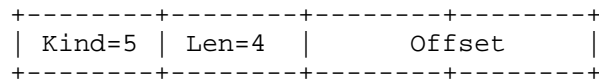


Figure 9 UDP LITE option format

At the sender, the option is formed using the following steps:

1. Create a LITE option, ordered as the first UDP option (Figure 10).
2. Calculate the location of the start of the options as an absolute offset from the start of the UDP header and place that length in the last two bytes of the LITE option.
3. Swap all four bytes of the LITE option with the first 4 bytes of the LITE data area (Figure 11).

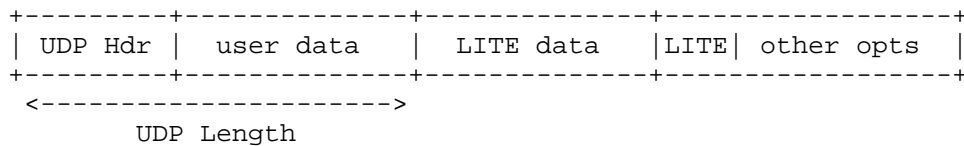


Figure 10 LITE option formation - LITE goes first

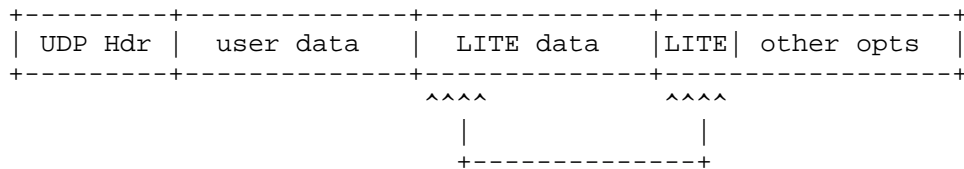


Figure 11 Before sending swap LITE option and front of LITE data

The resulting packet has the format shown in Figure 12. Note that the UDP length now points to the LITE option, and the LITE option points to the start of the option area.

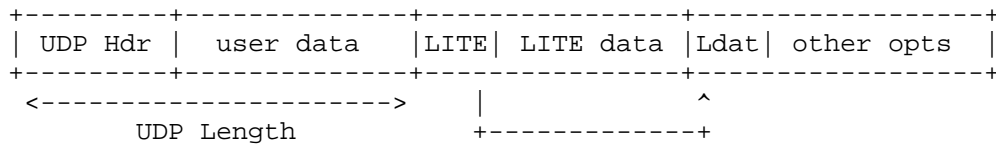


Figure 12 Lite option as sent

A legacy endpoint receiving this packet will discard the LITE option and everything that follows, including the lite data and remainder of the UDP options. The UDP checksum will protect only the user data, not the LITE option or lite data.

Receiving endpoints capable of processing UDP options will do the following:

1. Process options as usual. This will start at the LITE option.
2. When the LITE option is encountered, record its location as the start of the LITE data area and swap the four bytes there with the four bytes at the location indicated inside the LITE option, which indicates the start of all of the options, including the LITE one (one past the end of the lite data area). This restores the format of the option as per Figure 10.
3. Continue processing the remainder of the options, which are now in the format shown in Figure 11.

The purpose of this swap is to support the equivalent of UDP Lite operation together with other UDP options without requiring the entire LITE data area to be moved after the UDP option area.

5.6. Maximum Segment Size (MSS)

The Maximum Segment Size (MSS, Kind = 3) is a 16-bit indicator of the largest UDP segment that can be received. As with the TCP MSS option [RFC793], the size indicated is the IP layer MTU decreased by the fixed IP and UDP headers only [RFC6691]. The space needed for IP and UDP options need to be adjusted by the sender when using the value indicated. The value transmitted is based on EMTU_R, the largest IP datagram that can be received (i.e., reassembled at the receiver) [RFC1122].

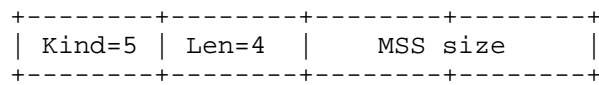


Figure 13 UDP MSS option format

The UDP MSS option MAY be used for path MTU discovery [RFC1191][RFC1981], but this may be difficult because of known issues with ICMP blocking [RFC2923] as well as UDP lacking automatic retransmission. It is more likely to be useful when coupled with IP source fragmentation to limit the largest reassembled UDP message, e.g., when EMTU_R is larger than the required minimums (576 for IPv4 [RFC791] and 1500 for IPv6 [RFC2460]).

5.7. Timestamps (TIME)

The UDP Timestamp option (TIME) exchanges two four-byte timestamp fields. It serves a similar purpose to TCP's TS option [RFC7323], enabling UDP to estimate the round trip time (RTT) between hosts. For UDP, this RTT can be useful for establishing UDP fragment reassembly timeouts or transport-layer rate-limiting [RFC8085].

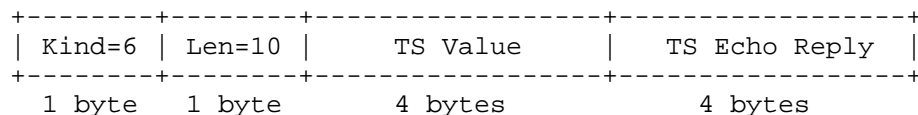


Figure 14 UDP TIME option format

TS Value (TSval) and TS Echo (TSecr) are used in a similar manner to the TCP TS option [RFC7323]. A host using the Timestamp option sets TS Value on all UDP segments issued. Received TSval values are provided to the application, which passes this value as TSecr on UDP messages sent in response to such a message.

>> UDP MAY use an RTT estimate based on nonzero Timestamp values as a hint for fragmentation reassembly, rate limiting, or other mechanisms that benefit from such an estimate.

>> UDP SHOULD make this RTT estimate available to the user application.

5.8. Fragmentation (FRAG)

The Fragmentation option (FRAG) supports UDP fragmentation and reassembly, which can be used to transfer UDP messages larger than limited by the IP receive MTU (EMTU_R [RFC1122]). It is typically

used with the UDP MSS option to enable more efficient use of large messages, both at the UDP and IP layers. FRAG is designed similar to the IPv6 Fragmentation Header [RFC2460], except that the UDP variant uses a 16-bit Offset measured in bytes, rather than IPv6's 13-bit Fragment Offset measured in 8-byte units. This UDP variant avoids creating reserved fields.

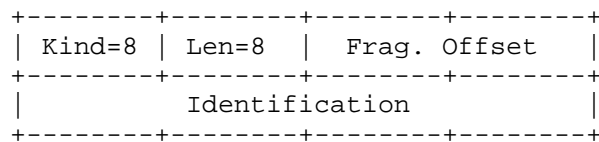


Figure 15 UDP non-terminal FRAG option format

The FRAG option also lacks a "more" bit, zeroed for the terminal fragment of a set. This is possible because the terminal FRAG option is indicated as a longer, 12-byte variant, which includes an Internet checksum over the reassembled payload (omitting the IP pseudoheader and UDP header, as well as UDP options), as shown in Figure 16.

>> The reassembly checksum SHOULD be used, but MAY be unused in the same situations when the UDP checksum is unused (e.g., for transit tunnels or applications that have their own integrity checks [RFC2460]), and by the same mechanism (set the field to 0x0000).

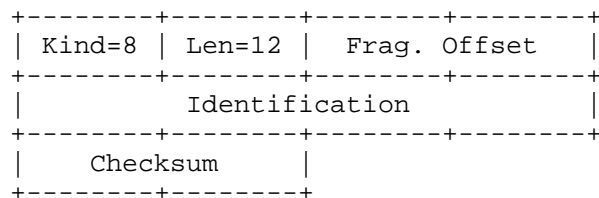


Figure 16 UDP terminal FRAG option format

The Fragment Offset is 16 bits and indicates the location of the UDP payload fragment in bytes from the beginning of the original unfragmented payload. The Len field indicates whether there are more fragments (Len=8) or no more fragments (Len=12).

>> The Identification field is a 32-bit value that MUST be unique over the expected fragment reassembly timeout.

>> The Identification field SHOULD be generated in a manner similar to that of the IPv6 Fragment ID [RFC2460].

>> UDP fragments MUST NOT overlap.

FRAG needs to be used with extreme care because it will present incorrect datagram boundaries to a legacy receiver, unless encoded as LITE data (see Section 5.8.1).

>> A host SHOULD indicate FRAG support by transmitting an unfragmented datagram using the Fragmentation option (e.g., with Offset zero and length 12, i.e., including the checksum area), except when encoded as LITE.

>> A host MUST NOT transmit a UDP fragment before receiving recent confirmation from the remote host, except when FRAG is encoded as LITE.

UDP fragmentation relies on a fragment expiration timer, which can be preset or could use a value computed using the UDP Timestamp option.

>> The default UDP reassembly SHOULD be no more than 2 minutes.

Implementers are advised to limit the space available for UDP reassembly.

>> UDP reassembly space SHOULD be limited to reduce the impact of DOS attacks on resource use.

>> UDP reassembly space limits SHOULD NOT be implemented as an aggregate, to avoid cross-socketpair DOS attacks.

>> Individual UDP fragments MUST NOT be forwarded to the user. The reassembled datagram is received only after complete reassembly, checksum validation, and continued processing of the remaining options.

Any additional UDP options would follow the FRAG option in the final fragment, and would be included in the reassembled packet. Processing of those options would commence after reassembly.

>> UDP options MUST NOT follow the FRAG header in non-terminal fragments. Any data following the FRAG header in non-terminal fragments MUST be silently dropped. All other options that apply to a reassembled packet MUST follow the FRAG header in the terminal fragment.

5.8.1. Coupling FRAG with LITE

FRAG can be coupled with LITE to avoid impacting legacy receivers. Each fragment is sent as LITE un-checksummed data, where each UDP packet contains no legacy-compatible data. Legacy receivers interpret these as zero-payload packets, which would not affect the receiver unless the presence of the packet itself were a signal. The header of such a packet would appear as shown in Figure 17 and Figure 18.

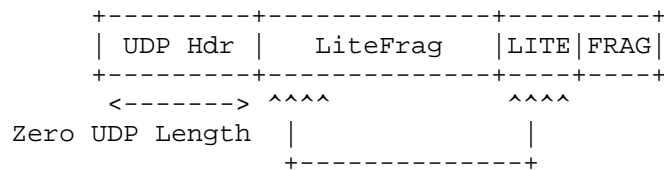


Figure 17 Preparing FRAG as Lite data

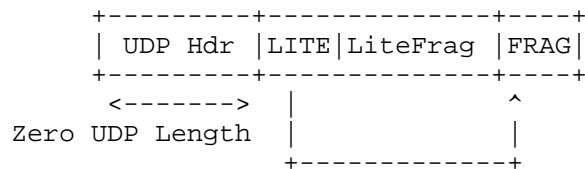


Figure 18 Lite option before transmission

When a packet is reassembled, it appears as a complete LITE data region. The UDP header of the reassembled packet is adjusted accordingly, so that the reassembled region now appears as conventional UDP user data, and processing of the UDP options continues, as with the non-LITE FRAG variant.

5.9. Authentication and Encryption (AE)

The Authentication and Encryption option (AE) is intended to allow UDP to provide a similar type of authentication as the TCP Authentication Option (TCP-AO) [RFC5925]. It uses the same format as specified for TCP-AO, except that it uses a Kind of 8. UDP-AO supports NAT traversal in a similar manner as TCP-AO [RFC6978]. UDP-AO can also be extended to provide a similar encryption capability as TCP-AO-ENC, in a similar manner [To17ao]. For these reasons, the option is known as UDP-AE.

Like TCP-AO, UDP-AE is not negotiated in-band. Its use assumes both endpoints have populated Master Key Tuples (MKTs), used to exclude non-protected traffic.

TCP-AO generates unique traffic keys from a hash of TCP connection parameters. UDP lacks a three-way handshake to coordinate connection-specific values, such as TCP's Initial Sequence Numbers (ISNs) [RFC793], thus UDP-AE's Key Derivation Function (KDF) uses zeroes as the value for both ISNs. This means that the UDP-AE reuses keys when socket pairs are reused, unlike TCP-AO.

5.10. Experimental (EXP)

The Experimental option (EXP) is reserved for experiments [RFC3692]. Only one such value is reserved because experiments are expected to use an Experimental ID (ExIDs) to differentiate concurrent use for different purposes, using UDP ExIDs registered with IANA according to the approach developed for TCP experimental options [RFC6994].

>> The length of the experimental option MUST be at least 4 to account for the Kind, Length, and the minimum 16-bit UDP ExID identifier (similar to TCP ExIDs [RFC6994]).

6. UDP API Extensions

UDP currently specifies an application programmer interface (API), summarized as follows (with Unix-style command as an example) [RFC768]:

- o Method to create new receive ports
 - o E.g., `bind(handle, recvaddr(optional), recvport)`
- o Receive, which returns data octets, source port, and source address
 - o E.g., `recvfrom(handle, srcaddr, srcport, data)`
- o Send, which specifies data, source and destination addresses, and source and destination ports
 - o E.g., `sendto(handle, destaddr, destport, data)`

This API is extended to support options as follows:

- o Extend the method to create receive ports to include receive options that are required. Datagrams not containing these required options MUST be silently dropped and MAY be logged.
- o Extend the receive function to indicate the options and their parameters as received with the corresponding received datagram.
- o Extend the send function to indicate the options to be added to the corresponding sent datagram.

Examples of API instances for Linux and FreeBSD are provided in Appendix A, to encourage uniform cross-platform implementations.

7. Whose options are these?

UDP options are indicated in an area of the IP payload that is not used by UDP. That area is really part of the IP payload, not the UDP payload, and as such, it might be tempting to consider whether this is a generally useful approach to extending IP.

Unfortunately, the surplus area exists only for transports that include their own transport layer payload length indicator. TCP and SCTP include header length fields that already provide space for transport options by indicating the total length of the header area, such that the entire remaining area indicated in the network layer (IP) is transport payload. UDP-Lite already uses the UDP Length field to indicate the boundary between data covered by the transport checksum and data not covered, and so there is no remaining area where the length of the UDP-Lite payload as a whole can be indicated [RFC3828].

UDP options are intended for use only by the transport endpoints. They are no more (or less) appropriate to be modified in-transit than any other portion of the transport datagram.

UDP options are transport options. Generally, transport datagrams are not intended to be modified in-transit. However, the UDP option mechanism provides no specific protection against in-transit modification of the UDP header, UDP payload, or UDP option area, except as provided by the options selected (e.g., OCS, ACS, or AE).

8. UDP options vs. UDP-Lite

UDP-Lite provides partial checksum coverage, so that packets with errors in some locations can be delivered to the user [RFC3828]. It uses a different transport protocol number (136) than UDP (17) to

interpret the UDP Length field as the prefix covered by the UDP checksum.

UDP (protocol 17) already defines the UDP Length field as the limit of the UDP checksum, but by default also limits the data provided to the application as that which precedes the UDP Length. A goal of UDP-Lite is to deliver data beyond UDP Length as a default, which is why a separate transport protocol number was required.

UDP options do not need a separate transport protocol number because the data beyond the UDP Length offset (surplus data) is not provided to the application by default. That data is interpreted exclusively within the UDP transport layer.

UDP options support a similar service to UDP-Lite by terminating the UDP options with an EOL option. The additional data not covered by the UDP checksum follows that EOL option, and is passed to the user separately. The difference is that UDP-Lite provides the un-checksummed user data to the application by default, whereas UDP options can provide the same capability only for endpoints that are negotiated in advance (i.e., by default, UDP options would silently discard this non-checksummed data). Additionally, in UDP-Lite the checksummed and non-checksummed payload components are adjacent, whereas in UDP options they are separated by the option area - which, minimally, must consist of at least one EOL option.

UDP-Lite cannot support UDP options, either as proposed here or in any other form, because the entire payload of the UDP packet is already defined as user data and there is no additional field in which to indicate a separate area for options. The UDP Length field in UDP-Lite is already used to indicate the boundary between user data covered by the checksum and user data not covered.

9. Interactions with Legacy Devices

It has always been permissible for the UDP Length to be inconsistent with the IP transport payload length [RFC768]. Such inconsistency has been utilized in UDP-Lite using a different transport number. There are no known systems that use this inconsistency for UDP [RFC3828]. It is possible that such use might interact with UDP options, i.e., where legacy systems might generate UDP datagrams that appear to have UDP options. The UDP OCS provides protection against such events and is stronger than a static "magic number".

UDP options have been tested as interoperable with Linux, Max OS-X, and Windows Cygwin, and worked through NAT devices. These systems

successfully delivered only the user data indicated by the UDP Length field and silently discarded the surplus area.

One reported embedded device passes the entire IP datagram to the UDP application layer. Although this feature could enable application-layer UDP option processing, it would require that conventional UDP user applications examine only the UDP payload. This feature is also inconsistent with the UDP application interface [RFC768] [RFC1122].

It has been reported that Alcatel-Lucent's "Brick" Intrusion Detection System has a default configuration that interprets inconsistencies between UDP Length and IP Length as an attack to be reported. Note that other firewall systems, e.g., CheckPoint, use a default "relaxed UDP length verification" to avoid falsely interpreting this inconsistency as an attack.

(TBD: test with UDP checksum offload and UDP fragmentation offload)

10. Options in a Stateless, Unreliable Transport Protocol

There are two ways to interpret options for a stateless, unreliable protocol -- an option is either local to the message or intended to affect a stream of messages in a soft-state manner. Either interpretation is valid for defined UDP options.

It is impossible to know in advance whether an endpoint supports a UDP option.

>> UDP options MUST allow for silent failure on first receipt.

>> UDP options that rely on soft-state exchange MUST allow for message reordering and loss.

>> A UDP option MUST be silently optional until confirmed by exchange with an endpoint.

The above requirements prevent using any option that cannot be safely ignored unless that capability has been negotiated with an endpoint in advance for a socket pair. Legacy systems would need to be able to interpret the transport payload fragments as individual transport datagrams.

11. UDP Option State Caching

Some TCP connection parameters, stored in the TCP Control Block, can be usefully shared either among concurrent connections or between

connections in sequence, known as TCP Sharing [RFC2140][To17cb]. Although UDP is stateless, some of the options proposed herein may have similar benefit in being shared or cached. We call this UCB Sharing, or UDP Control Block Sharing, by analogy.

[TBD: extend this section to indicate which options MAY vs. MUST NOT be shared and how, e.g., along the lines of To17cb]

Updates to RFC 768

This document updates RFC 768 as follows:

- o This document defines the meaning of the IP payload area beyond the UDP length but within the IP length.
- o This document extends the UDP API to support the use of options.

12. Security Considerations

The use of UDP packets with inconsistent IP and UDP Length fields has the potential to trigger a buffer overflow error if not properly handled, e.g., if space is allocated based on the smaller field and copying is based on the larger. However, there have been no reports of such vulnerability and it would rely on inconsistent use of the two fields for memory allocation and copying.

UDP options are not covered by DTLS (datagram transport-layer security). Despite the name, neither TLS [RFC5246] (transport layer security, for TCP) nor DTLS [RFC6347] (TLS for UDP) protect the transport layer. Both operate as a shim layer solely on the payload of transport packets, protecting only their contents. Just as TLS does not protect the TCP header or its options, DTLS does not protect the UDP header or the new options introduced by this document. Transport security is provided in TCP by the TCP Authentication Option (TCP-AO [RFC5925]) or in UDP by the Authentication Extension option (Section 5.9). Transport headers are also protected as payload when using IP security (IPsec) [RFC4301].

UDP options use the TLV syntax similar to that of TCP. This syntax is known to require serial processing and may pose a DOS risk, e.g., if an attacker adds large numbers of unknown options that must be parsed in their entirety. Implementations concerned with the potential for this vulnerability MAY implement only the required options and MAY also limit NOPs (e.g., no more than three consecutive NOPs or some total number that might occur between the required options, if all are present). Because the required options

come first and at most once each (and all later duplicates silently ignored), this limits the DOS impact.

13. IANA Considerations

Upon publication, IANA is hereby requested to create a new registry for UDP Option Kind numbers, similar to that for TCP Option Kinds. Initial values of this registry are as listed in Section 5. Additional values in this registry are to be assigned by IESG Approval or Standards Action [RFC5226].

Upon publication, IANA is hereby requested to create a new registry for UDP Experimental Option Experiment Identifiers (UDP ExIDs) for use in a similar manner as TCP ExIDs [RFC6994]. This registry is initially empty. Values in this registry are to be assigned by IANA using first-come, first-served (FCFS) rules [RFC5226].

14. References

14.1. Normative References

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Appendix A. Implementation Information

The following information is provided to encourage interoperable API implementations.

System-level variables (sysctl):

Name	default	meaning
net.ipv4.udp_opt	0	UDP options available
net.ipv4.udp_opt_ocs	1	Default include OCS
net.ipv4.udp_opt_acs	0	Default include ACS
net.ipv4.udp_opt_lite	0	Default include LITE
net.ipv4.udp_opt_mss	0	Default include MSS
net.ipv4.udp_opt_time	0	Default include TIME
net.ipv4.udp_opt_frag	0	Default include FRAG
net.ipv4.udp_opt_ae	0	Default include AE

Socket options (sockopt), cached for outgoing datagrams:

Name	meaning
UDP_OPT	Enable UDP options (at all)
UDP_OPT_OCS	Enable UDP OCS option
UDP_OPT_ACS	Enable UDP ACS option
UDP_OPT_LITE	Enable UDP LITE option
UDP_OPT_MSS	Enable UDP MSS option
UDP_OPT_TIME	Enable UDP TIME option
UDP_OPT_FRAG	Enable UDP FRAG option
UDP_OPT_AE	Enable UDP AE option

Send/sendto parameters:

(TBD - currently using cached parameters)

Connection parameters (per-socketpair cached state, part UCB):

Name	Initial value
opts_enabled	net.ipv4.udp_opt
ocs_enabled	net.ipv4.udp_opt_ocs

The following option is included for debugging purposes, and MUST NOT be enabled otherwise.

System variables

```
net.ipv4.udp_opt_junk    0
```

System-level variables (sysctl):

Name	default	meaning

net.ipv4.udp_opt_junk	0	Default use of junk

Socket options (sockopt):

Name	params	meaning

UDP_JUNK	-	Enable UDP junk option
UDP_JUNK_VAL	fillval	Value to use as junk fill
UDP_JUNK_LEN	length	Length of junk payload in bytes

Connection parameters (per-socketpair cached state, part UCB):

Name	Initial value

junk_enabled	net.ipv4.udp_opt_junk
junk_value	0xABCD
junk_len	4

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A Lower Effort Per-Hop Behavior (LE PHB)
draft-tsvwg-le-phb-00

Abstract

This document specifies properties and characteristics of a Lower Effort (LE) per-hop behavior (PHB). The primary objective of this LE PHB is to protect best-effort (BE) traffic (packets forwarded with the default PHB) from LE traffic in congestion situations, i.e., when resources become scarce, best-effort traffic has precedence over LE traffic and may preempt it. There are numerous uses for this PHB, e.g., for background traffic of low precedence, such as bulk data transfers with low priority in time, non time-critical backups, larger software updates, web search engines while gathering information from web servers and so on. This document recommends a standard DSCP value for the LE PHB.

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Table of Contents

1. Introduction	2
1.1. Applicability	3
1.2. Deployment Considerations	4
1.3. Requirements Language	4
2. PHB Description	4
3. Traffic Conditioning Actions	5
4. Recommended DS Codepoint	5
5. Remarking to other DSCPs/PHBs	5
6. IANA Considerations	6
7. Security Considerations	6
8. References	6
8.1. Normative References	6
8.2. Informative References	6
Appendix A. History of the LE PHB	7
Appendix B. Acknowledgments	7
Author's Address	7

1. Introduction

This document defines a Differentiated Services per-hop behavior RFC 2474 [RFC2474] called "Lower Effort" (LE) which is intended for traffic of sufficiently low urgency, in which all other traffic takes precedence over LE traffic in consumption of network link bandwidth. Low urgency traffic has got a low priority in time, which does not necessarily imply that it is generally of minor importance. From this viewpoint, it can be considered as a network equivalent to a background priority for processes in an operating system. There may or may not be memory (buffer) resources allocated for this type of traffic.

Some networks carry traffic for which delivery is considered optional; that is, packets of this type of traffic ought to consume network resources only when no other traffic is present. Alternatively, the effect of this type of traffic on all other network traffic is strictly limited. This is distinct from "best-effort" (BE) traffic since the network makes no commitment to deliver LE packets. In contrast, BE traffic receives an implied "good faith" commitment of at least some available network resources. This

document proposes a Lower Effort Differentiated Services per-hop behavior (LE PHB) for handling this "optional" traffic in a differentiated services node.

1.1. Applicability

A Lower Effort PHB is for sending extremely non-critical traffic across a Differentiated Services (DS) domain or DS region. There should be an expectation that packets of the LE PHB may be delayed or dropped when any other traffic is present. Use of the LE PHB might assist a network operator in moving certain kinds of traffic or users to off-peak times. Alternatively, or in addition, packets can be designated for the LE PHB when the goal is to protect all other packet traffic from competition with the LE aggregate while not completely banning LE traffic from the network. An LE PHB should not be used for a customer's "normal internet" traffic nor should packets be "downgraded" to the LE PHB used as a substitute for dropping packets that ought simply to be dropped as unauthorized. The LE PHB is expected to have applicability in networks that have at least some unused capacity at some times of day.

This is a PHB that allows networks to protect themselves from selected types of traffic rather than giving a selected traffic aggregate preferential treatment. Moreover, it may also exploit all unused resources from other PHBs.

There is no intrinsic reason to limit the applicability of the LE PHB to any particular application or type of traffic. It is intended as an additional tool for administrators in engineering networks. For instance, it can be used for filling up protection capacity of transmission links which is otherwise unused. Some network providers keep link utilization below 50% in order to being able carrying all traffic without loss in case of rerouting due to a link failure. LE marked traffic can utilize the normally unused capacity and will be preempted automatically in case of link failure when 100% of the link capacity is required for all other traffic. Ideally, applications mark their packets as LE traffic, since they know the urgency of flows.

Example uses for the LE PHB comprise:

- o For traffic caused by world-wide web search engines while they gather information from web servers.
- o For software updates or dissemination of new releases of operating systems.

- o For backup traffic or non-time critical sychronization or mirroring traffic.
- o For content distribution transfers between caches.
- o For Netnews and other "bulk mail" of the Internet.
- o For "downgraded" traffic from some other PHB when this does not violate the operational objectives of the other PHB or the overall network. LE should not be used for the general case of downgraded traffic, but may be used by design, e.g., to protect an internal network from untrusted external traffic sources. In this case there is no way for attackers to preempt internal (non LE) traffic by flooding. Another use case is mentioned in [RFC3754]: non-admitted multicast traffic.

1.2. Deployment Considerations

Internet-wide deployment of the LE PHB is eased by the following properties:

- o No harm to other traffic: since the LE PHB has got the lowest priority it does not take resources from other PHBs. Deployment across different provider domains causes no trust issues or attack vectors to existing traffic.
- o No parameters or configuration: the LE PHB requires no parameters and no configuration of traffic profiles and so on.
- o No traffic conditioning mechanisms: the LE PHB requires only a queue and a scheduling mechanism, but no traffic meters, droppers or shapers.

Since LE traffic may be starved completely for a longer period of time, transport protocols or applications should be able to detect such a situation and should resume the transfer as soon as possible.

1.3. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119 [RFC2119].

2. PHB Description

This PHB is defined in relation to the default PHB (best-effort). A packet forwarded with this PHB SHOULD have lower precedence than packets forwarded with the default PHB. Ideally, LE packets should

be forwarded only if no best-effort packet is waiting for its transmission. A straightforward implementation could be a simple priority scheduler serving the default PHB queue with higher priority than the lower-effort PHB queue. Alternative implementations may use scheduling algorithms that assign a very small weight to the LE class. This, however, may sometimes cause better service for LE packets compared to BE packets in cases when the BE share is fully utilized and the LE share not.

3. Traffic Conditioning Actions

As for most other PHBs an initial classification and marking would usually be performed at the first DS boundary node. In many cases, packets may also be pre-marked in DS aware end systems by applications due to their specific knowledge about the particular precedence of packets. There is no incentive for DS domains to distrust this initial marking, because letting LE traffic enter a DS domain causes no harm. In the worst case it evokes the same effect as it would have been marked with the default PHB, i.e., as best-effort traffic. Thus, any policing such as limiting the traffic rate is not necessary at the DS boundary.

Usually, the amount of LE traffic is implicitly limited by queueing mechanisms and related discard actions of the PHB. Therefore, there is normally no need to meter and police LE traffic explicitly.

4. Recommended DS Codepoint

The recommended codepoint for the LE PHB is 000010.

RFC 4594 [RFC4594] recommended to use CS1 as codepoint (as mentioned in [RFC3662]). This is problematic since it may cause a priority inversion resulting in treating LE packets with higher precedence than BE packets. Existing implementations SHOULD therefore use the unambiguous LE codepoint 000010 whenever possible.

5. Remarking to other DSCPs/PHBs

"DSCP bleaching", i.e., setting the DSCP to 000000 (default PHB) is not recommended for this PHB. This may cause effects that are in contrast to the original intent in protecting BE traffic from LE traffic. In case DS domains do not support the LE PHB, they may treat LE marked packets with the default PHB instead, but they should do so without remarking to the DSCP 000000. The reason for this is that later traversed DS domains may then have still the possibility to treat such packets according the LE PHB.

6. IANA Considerations

This memo includes a request to assign a Differentiated Services Field Codepoint (DSCP) 000010 from the Differentiated Services Field Codepoints (DSCP) registry <https://www.iana.org/assignments/dscp-registry/dscp-registry.xml>

7. Security Considerations

There are no specific security exposures for this PHB. Since it defines a new class of low forwarding priority, other traffic may be downgraded to this LE PHB in case it is remarked as LE traffic. See the general security considerations in RFC 2474 [RFC2474] and RFC 2475 [RFC2475].

8. References

8.1. Normative References

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Appendix A. History of the LE PHB

A first version of this PHB was suggested by Roland Bless and Klaus Wehrle in 1999 [draft-bless-diffserv-lbe-phb-00]. After some discussion in the DiffServ Working Group Brian Carpenter and Kathie Nichols proposed a bulk handling per-domain behavior and believed a PHB was not necessary. Eventually, Lower Effort was specified as per-domain behavior and finally became [RFC3662]. More detailed information about its history can be found in Section 10 of [RFC3662].

Appendix B. Acknowledgments

Since text is borrowed from earlier Internet-Drafts and RFCs the co-authors of previous specifications are acknowledged here: Kathie Nichols and Klaus Wehrle.

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Additional Considerations for UDP Encapsulation of Stream Control
Transmission Protocol (SCTP) Packets
draft-tuexen-tsvwg-sctp-udp-encaps-cons-05

Abstract

RFC 6951 specifies the UDP encapsulation of SCTP packets. The described handling of received packets requires the check of the verification tag. However, RFC 6951 misses a specification of the handling of received packets for which this check is not possible.

This document updates RFC 6951 by specifying the handling of received packets for which the verification tag can not be checked.

Status of This Memo

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Table of Contents

1. Introduction	2
2. Conventions	2
3. Handling of Out of the Blue Packets	3
4. Handling of SCTP Packets Containing an INIT Chunk Matching an Existing Associations	3
5. Middlebox Considerations	5
6. IANA Considerations	5
7. Security Considerations	6
8. Acknowledgments	6
9. Normative References	6
Authors' Addresses	7

1. Introduction

[RFC6951] specifies the UDP encapsulation of SCTP packets. To be able to adopt automatically to changes of the remote UDP encapsulation port number, it is updated when processing received packets. This includes automatic enabling and disabling of UDP encapsulation.

Section 5.4 of [RFC6951] describes the processing of received packets and requires the check of the verification tag before updating the remote UDP encapsulation port and the possible enabling or disabling of UDP encapsulation.

[RFC6951] basically misses a description of the handling of received packets where checking the verification tag is not possible. This includes packets for which no association can be found and packets containing an INIT chunk, since the verification tag of these packets is 0.

2. Conventions

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

3. Handling of Out of the Blue Packets

If the processing of an out of the blue packet requires the sending of a packet in response according to the rules specified in Section 8.4 of [RFC4960], the following rules apply:

1. If the received packet was encapsulated in UDP, the response packets MUST also be encapsulated in UDP. The UDP source port and UDP destination port used for sending the response packet are the UDP destination port and UDP source port of the received packet.
2. If the received packet was not encapsulated in UDP, the response packet MUST NOT be encapsulated in UDP.

Please note that in these cases a check of the verification tag is not possible.

4. Handling of SCTP Packets Containing an INIT Chunk Matching an Existing Associations

SCTP packets containing an INIT chunk have the verification tag 0 in the common header. Therefore the verification tag can't be checked.

The following rules apply when processing the received packet:

1. The remote UDP encapsulation port for the source address of the received SCTP packet MUST NOT be updated if the encapsulation of outgoing packets is enabled and the received SCTP packet is encapsulated.
2. The UDP encapsulation for outgoing packets towards the source address of the received SCTP packet MUST NOT be enabled, if it is disabled and the received SCTP packet is encapsulated.
3. The UDP encapsulation for outgoing packets towards the source address of the received SCTP packet MUST NOT be disabled, if it is enabled and the received SCTP packet is not encapsulated.

4. If the UDP encapsulation for outgoing packets towards the source address of the received SCTP packet is disabled and the received SCTP packet is encapsulated, an SCTP packet containing an ABORT chunk MUST be sent. The ABORT chunk MAY include the error cause defined below indicating an "Restart of an Association with New Encapsulation Port". This packet containing the ABORT chunk MUST be encapsulated in UDP. The UDP source port and UDP destination port used for sending the packet containing the ABORT chunk are the UDP destination port and UDP source port of the received packet containing the INIT chunk.
5. If the UDP encapsulation for outgoing packets towards the source address of the received SCTP packet is disabled and the received SCTP packet is not encapsulated, the processing defined in [RFC4960] MUST be performed. If a packet is sent in response, it MUST NOT be encapsulated.
6. If the UDP encapsulation for outgoing packets towards the source address of the received SCTP packet is enabled and the received SCTP packet is not encapsulated, an SCTP packet containing an ABORT chunk MUST be sent. The ABORT chunk MAY include the error cause defined below indicating an "Restart of an Association with New Encapsulation Port". This packet containing the ABORT chunk MUST NOT be encapsulated in UDP.
7. If the UDP encapsulation for outgoing packets towards the source address of the received SCTP packet is enabled and the received SCTP packet is encapsulated, but the UDP source port of the received SCTP packet is not equal to the remote UDP encapsulation port for the source address of the received SCTP packet, an SCTP packet containing an ABORT chunk MUST be sent. The ABORT chunk MAY include the error cause defined below indicating an "Restart of an Association with New Encapsulation Port". This packet containing the ABORT chunk MUST be encapsulated in UDP. The UDP source port and UDP destination port used for sending the packet containing the ABORT chunk are the UDP destination port and UDP source port of the received packet containing the INIT chunk.
8. If the UDP encapsulation for outgoing packets towards the source address of the received SCTP packet is enabled and the received SCTP packet is encapsulated and the UDP source port of the received SCTP packet is equal to the remote UDP encapsulation port for the source address of the received SCTP packet, the processing defined in [RFC4960] MUST be performed. If a packet is sent in response, it MUST be encapsulated. The UDP source port and UDP destination port used for sending the packet containing the ABORT chunk are the UDP destination port and UDP source port of the received packet containing the INIT chunk.

The error cause indicating an "Restart of an Association with New Encapsulation Port" is defined by the following figure.

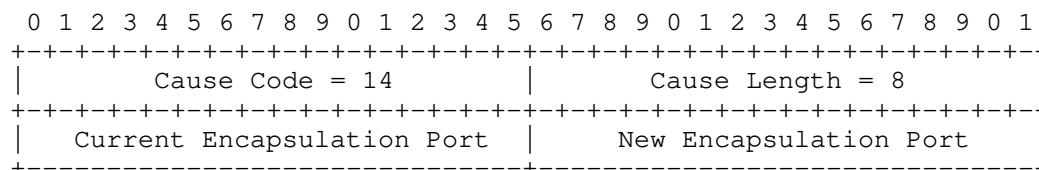


Figure 1: Restart of an Association with New Encapsulation Port error cause

Cause Code: 2 bytes (unsigned integer)

This field holds the IANA defined cause code for the "Restart of an Association with New Encapsulation Port" error cause. IANA is requested to assign the value 14 for this cause code.

Cause Length: 2 bytes (unsigned integer)

This field holds the length in bytes of the error cause; the value MUST be 8.

Current Encapsulation Port: 2 bytes (unsigned integer)

This field holds the remote encapsulation port currently being used for the destination address the received packet containing the INIT chunk was sent from. If the UDP encapsulation for destination address is currently disabled, 0 is used.

New Encapsulation Port: 2 bytes (unsigned integer)

If the received SCTP packet containing the INIT chunk is encapsulated in UDP, this field holds the UDP source port number of the UDP packet. If the received SCTP packet is not encapsulated in UDP, this field is 0.

All transported integer numbers are in "network byte order" a.k.a., Big Endian.

5. Middlebox Considerations

Middleboxes often use different timeouts for UDP based flows than for other flows. Therefore the HEARTBEAT.Interval parameter SHOULD be lowered to 15 seconds when UDP encapsulation is used.

6. IANA Considerations

[NOTE to RFC-Editor: "RFCXXXX" is to be replaced by the RFC number you assign this document.]

[NOTE to RFC-Editor: The requested values for the cause code are tentative and to be confirmed by IANA.]

This document (RFCXXXX) is the reference for the registration described in this section.

A new error cause code has to be assigned by IANA. This requires an additional line in the "Error Cause Codes" registry for SCTP:

Value	Cause Code	Reference
14	Restart of an Association with New Encapsulation Port	[RFCXXXX]

Table 1: New entry in Error Cause Codes registry

7. Security Considerations

This document does not change the considerations given in [RFC6951].

However, not following the procedures given in this document might allow an attacker to take over SCTP associations. The attacker needs only to share the IP address of an existing SCTP association.

It should also be noted that if firewalls will be applied at the SCTP association level they have to take the UDP encapsulation into account.

8. Acknowledgments

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