TCP Maintenance & Minor Extensions (tcpm)
Internet-Draft
Updates: 3168 (if approved)
Intended status: Standards Track
Expires: May 1, 2021

B. Briscoe
Independent
M. Kuehlewind
Ericsson
R. Scheffenegger
NetApp

October 28, 2020

More Accurate ECN Feedback in TCP
draft-ietf-tcpm-accurate-ecn-12

Abstract

Explicit Congestion Notification (ECN) is a mechanism where network nodes can mark IP packets instead of dropping them to indicate incipient congestion to the end-points. Receivers with an ECN-capable transport protocol feed back this information to the sender. ECN is specified for TCP in such a way that only one feedback signal can be transmitted per Round-Trip Time (RTT). Recent new TCP mechanisms like Congestion Exposure (ConEx), Data Center TCP (DCTCP) or Low Latency Low Loss Scalable Throughput (L4S) need more accurate ECN feedback information whenever more than one marking is received in one RTT. This document specifies a scheme to provide more than one feedback signal per RTT in the TCP header. Given TCP header space is scarce, it allocates a reserved header bit, that was previously used for the ECN-Nonce which has now been declared historic. It also overloads the two existing ECN flags in the TCP header. The resulting extra space is exploited to feed back the IP-ECN field received during the 3-way handshake as well. Supplementary feedback information can optionally be provided in a new TCP option, which is never used on the TCP SYN.

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1. Introduction

Explicit Congestion Notification (ECN) [RFC3168] is a mechanism where network nodes can mark IP packets instead of dropping them to indicate incipient congestion to the end-points. Receivers with an ECN-capable transport protocol feed back this information to the sender. In RFC 3168, ECN was specified for TCP in such a way that only one feedback signal could be transmitted per Round-Trip Time (RTT). Recently, proposed mechanisms like Congestion Exposure (ConEx [RFC7713]), DCTCP [RFC8257] or L4S [I-D.ietf-tsvwg-l4s-arch] need to know when more than one marking is received in one RTT which is information that cannot be provided by the feedback scheme as

specified in [RFC3168]. This document specifies an update to the ECN feedback scheme of RFC 3168 that provides more accurate information and could be used by these and potentially other future TCP extensions. A fuller treatment of the motivation for this specification is given in the associated requirements document [RFC7560].

This documents specifies a standards track scheme for ECN feedback in the TCP header to provide more than one feedback signal per RTT. It will be called the more accurate ECN feedback scheme, or AccECN for short. This document updates RFC 3168 with respect to negotiation and use of the feedback scheme for TCP. All aspects of RFC 3168

other than the TCP feedback scheme, in particular the definition of ECN at the IP layer, remain unchanged by this specification. Section 4 gives a more detailed specification of exactly which aspects of RFC 3168 this document updates.

AccECN is intended to be a complete replacement for classic TCP/ECN feedback, not a fork in the design of TCP. AccECN feedback complements TCP's loss feedback and it can coexist alongside 'classic' [RFC3168] TCP/ECN feedback. So its applicability is intended to include all public and private IP networks (and even any non-IP networks over which TCP is used today), whether or not any nodes on the path support ECN, of whatever flavour. This document uses the term Classic ECN when it needs to distinguish the RFC 3168 ECN TCP feedback scheme from the AccECN TCP feedback scheme.

AccECN feedback overloads the two existing ECN flags in the TCP header and allocates the currently reserved flag (previously called NS) in the TCP header, to be used as one three-bit counter field indicating the number of congestion experienced marked packets. Given the new definitions of these three bits, both ends have to support the new wire protocol before it can be used. Therefore during the TCP handshake the two ends use these three bits in the TCP header to negotiate the most advanced feedback protocol that they can both support, in a way that is backward compatible with [RFC3168].

AccECN is solely a change to the TCP wire protocol; it covers the negotiation and signaling of more accurate ECN feedback from a TCP Data Receiver to a Data Sender. It is completely independent of how TCP might respond to congestion feedback, which is out of scope, but

ultimately the motivation for accurate ECN feedback. Like Classic ECN feedback, AccECN can be used by standard Reno congestion control [RFC5681] to respond to the existence of at least one congestion notification within a round trip. Or, unlike Reno, AccECN can be used to respond to the extent of congestion notification over a round trip, as for example DCTCP does in controlled environments [RFC8257]. For congestion response, this specification refers to RFC 3168, or ECN experiments such as those referred to in [RFC8311], namely: a TCP-based Low Latency Low Loss Scalable (L4S) congestion control [I-D.ietf-tsvwg-l4s-arch]; or Alternative Backoff with ECN (ABE) [RFC8511].

It is recommended that the AccECN protocol is implemented alongside SACK [RFC2018] and the experimental ECN++ protocol [I-D.ietf-tcpm-generalized-ecn], which allows the ECN capability to be used on TCP control packets. Therefore, this specification does not discuss implementing AccECN alongside [RFC5562], which was an earlier experimental protocol with narrower scope than ECN++.

1.1. Document Roadmap

The following introductory section outlines the goals of AccECN (Section 1.2). Then terminology is defined (Section 1.3) and a recap of existing prerequisite technology is given (Section 1.4).

Section 2 gives an informative overview of the AccECN protocol. Then Section 3 gives the normative protocol specification, and Section 4 clarifies which aspects of RFC 3168 are updated by this specification. Section 5 assesses the interaction of AccECN with commonly used variants of TCP, whether standardized or not. Section 6 summarizes the features and properties of AccECN.

Section 7 summarizes the protocol fields and numbers that IANA will need to assign and Section 8 points to the aspects of the protocol that will be of interest to the security community.

Appendix A gives pseudocode examples for the various algorithms that AccECN uses and Appendix B explains why AccECN uses flags in the main TCP header and quantifies the space left for future use.

1.2. Goals

[RFC7560] enumerates requirements that a candidate feedback scheme will need to satisfy, under the headings: resilience, timeliness, integrity, accuracy (including ordering and lack of bias), complexity, overhead and compatibility (both backward and forward). It recognizes that a perfect scheme that fully satisfies all the requirements is unlikely and trade-offs between requirements are likely. Section 6 presents the properties of AccECN against these requirements and discusses the trade-offs made.

The requirements document recognizes that a protocol as ubiquitous as TCP needs to be able to serve as-yet-unspecified requirements. Therefore an AccECN receiver aims to act as a generic (dumb) reflector of congestion information so that in future new sender behaviours can be deployed unilaterally.

1.3. Terminology

AccECN: The more accurate ECN feedback scheme will be called AccECN for short.

Classic ECN: the ECN protocol specified in [RFC3168].

Classic ECN feedback: the feedback aspect of the ECN protocol specified in [RFC3168], including generation, encoding,

transmission and decoding of feedback, but not the Data Sender's subsequent response to that feedback.

ACK: A TCP acknowledgement, with or without a data payload (ACK=1).

Pure ACK: A TCP acknowledgement without a data payload.

Acceptable packet / segment: A packet or segment that passes the acceptability tests in [RFC0793] and [RFC5961].

TCP client: The TCP stack that originates a connection.

TCP server: The TCP stack that responds to a connection request.

Data Receiver: The endpoint of a TCP half-connection that receives

data and sends AccECN feedback.

Data Sender: The endpoint of a TCP half-connection that sends data and receives AccECN feedback.

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 BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

1.4. Recap of Existing ECN feedback in IP/TCP

ECN [RFC3168] uses two bits in the IP header. Once ECN has been negotiated with the receiver at the transport layer, an ECN sender can set two possible codepoints (ECT(0) or ECT(1)) in the IP header to indicate an ECN-capable transport (ECT). If both ECN bits are zero, the packet is considered to have been sent by a Not-ECN-capable Transport (Not-ECT). When a network node experiences congestion, it will occasionally either drop or mark a packet, with the choice depending on the packet's ECN codepoint. If the codepoint is Not-ECT, only drop is appropriate. If the codepoint is ECT(0) or ECT(1), the node can mark the packet by setting both ECN bits, which is termed 'Congestion Experienced' (CE), or loosely a 'congestion mark'. Table 1 summarises these codepoints.

IP-ECN codepoint	Codepoint name	Description
0b00	Not-ECT	Not ECN-Capable Transport
0b01	ECT(1)	ECN-Capable Transport (1)
0b10	ECT(0)	ECN-Capable Transport (0)
0b11	CE	Congestion Experienced

Table 1: The ECN Field in the IP Header

In the TCP header the first two bits in byte 14 are defined as flags for the use of ECN (CWR and ECE in Figure 1 [RFC3168]). A TCP client indicates it supports ECN by setting ECE=CWR=1 in the SYN, and an ECN-enabled server confirms ECN support by setting ECE=1 and CWR=0 in the SYN/ACK. On reception of a CE-marked packet at the IP layer, the Data Receiver starts to set the Echo Congestion Experienced (ECE) flag continuously in the TCP header of ACKs, which ensures the signal is received reliably even if ACKs are lost. The TCP sender confirms that it has received at least one ECE signal by responding with the congestion window reduced (CWR) flag, which allows the TCP receiver to stop repeating the ECN-Echo flag. This always leads to a full RTT of ACKs with ECE set. Thus any additional CE markings arriving within this RTT cannot be fed back.

The last bit in byte 13 of the TCP header was defined as the Nonce Sum (NS) for the ECN Nonce [RFC3540]. In the absence of widespread deployment RFC 3540 has been reclassified as historic [RFC8311] and the respective flag has been marked as "reserved", making this TCP flag available for use by the AccECN experiment instead.

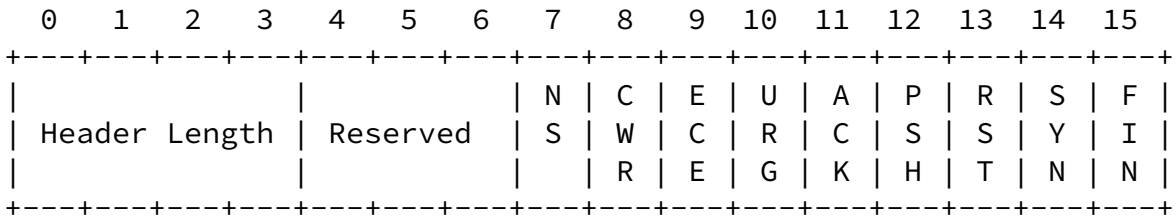

Figure 1: The (post-ECN Nonce) definition of the TCP header flags

2. AccECN Protocol Overview and Rationale

This section provides an informative overview of the AccECN protocol that will be normatively specified in Section 3

Like the original TCP approach, the Data Receiver of each TCP half-connection sends AccECN feedback to the Data Sender on TCP

acknowledgements, reusing data packets of the other half-connection

whenever possible.

The AccECN protocol has had to be designed in two parts:

- an essential part that re-uses ECN TCP header bits to feed back the number of arriving CE marked packets. This provides more accuracy than classic ECN feedback, but limited resilience against ACK loss;

- a supplementary part using a new AccECN TCP Option that provides additional feedback on the number of bytes that arrive marked with each of the three ECN codepoints (not just CE marks). This provides greater resilience against ACK loss than the essential feedback, but it is more likely to suffer from middlebox interference.

The two part design was necessary, given limitations on the space available for TCP options and given the possibility that certain incorrectly designed middleboxes prevent TCP using any new options.

The essential part overloads the previous definition of the three flags in the TCP header that had been assigned for use by ECN. This design choice deliberately replaces the classic ECN feedback protocol, rather than leaving classic ECN feedback intact and adding more accurate feedback separately because:

- this efficiently reuses scarce TCP header space, given TCP option space is approaching saturation;

- a single upgrade path for the TCP protocol is preferable to a fork in the design;

- otherwise classic and accurate ECN feedback could give conflicting feedback on the same segment, which could open up new security concerns and make implementations unnecessarily complex;

- middleboxes are more likely to faithfully forward the TCP ECN flags than newly defined areas of the TCP header.

AccECN is designed to work even if the supplementary part is removed or zeroed out, as long as the essential part gets through.

2.1. Capability Negotiation

AccECN is a change to the wire protocol of the main TCP header, therefore it can only be used if both endpoints have been upgraded to understand it. The TCP client signals support for AccECN on the

initial SYN of a connection and the TCP server signals whether it supports AccECN on the SYN/ACK. The TCP flags on the SYN that the client uses to signal AccECN support have been carefully chosen so that a TCP server will interpret them as a request to support the most recent variant of ECN feedback that it supports. Then the client falls back to the same variant of ECN feedback.

An AccECN TCP client does not send the new AccECN Option on the SYN as SYN option space is limited. The TCP server sends the AccECN Option on the SYN/ACK and the client sends it on the first ACK to test whether the network path forwards the option correctly.

2.2. Feedback Mechanism

A Data Receiver maintains four counters initialized at the start of the half-connection. Three count the number of arriving payload bytes marked CE, ECT(1) and ECT(0) respectively. The fourth counts the number of packets arriving marked with a CE codepoint (including control packets without payload if they are CE-marked).

The Data Sender maintains four equivalent counters for the half connection, and the AccECN protocol is designed to ensure they will match the values in the Data Receiver's counters, albeit after a little delay.

Each ACK carries the three least significant bits (LSBs) of the packet-based CE counter using the ECN bits in the TCP header, now renamed the Accurate ECN (ACE) field (see Figure 3 later). The 24 LSBs of each byte counter are carried in the AccECN Option.

2.3. Delayed ACKs and Resilience Against ACK Loss

With both the ACE and the AccECN Option mechanisms, the Data Receiver continually repeats the current LSBs of each of its respective counters. There is no need to acknowledge these continually repeated counters, so the congestion window reduced (CWR) mechanism is no longer used. Even if some ACKs are lost, the Data Sender should be able to infer how much to increment its own counters, even if the protocol field has wrapped.

The 3-bit ACE field can wrap fairly frequently. Therefore, even if it appears to have incremented by one (say), the field might have actually cycled completely then incremented by one. The Data Receiver is not allowed to delay sending an ACK to such an extent that the ACE field would cycle. However cycling is still a possibility at the Data Sender because a whole sequence of ACKs

carrying intervening values of the field might all be lost or delayed in transit.

The fields in the AccECN Option are larger, but they will increment in larger steps because they count bytes not packets. Nonetheless, their size has been chosen such that a whole cycle of the field would never occur between ACKs unless there had been an infeasibly long sequence of ACK losses. Therefore, as long as the AccECN Option is available, it can be treated as a dependable feedback channel.

If the AccECN Option is not available, e.g. it is being stripped by a middlebox, the AccECN protocol will only feed back information on CE markings (using the ACE field). Although not ideal, this will be sufficient, because it is envisaged that neither ECT(0) nor ECT(1) will ever indicate more severe congestion than CE, even though future uses for ECT(0) or ECT(1) are still unclear [RFC8311]. Because the 3-bit ACE field is so small, when it is the only field available the Data Sender has to interpret it assuming the most likely wrap, but with a degree of conservatism.

Certain specified events trigger the Data Receiver to include an AccECN Option on an ACK. The rules are designed to ensure that the order in which different markings arrive at the receiver is communicated to the sender (as long as options are reaching the sender and as long as there is no ACK loss). Implementations are encouraged to send an AccECN Option more frequently, but this is left up to the implementer.

2.4. Feedback Metrics

The CE packet counter in the ACE field and the CE byte counter in the AccECN Option both provide feedback on received CE-marks. The CE packet counter includes control packets that do not have payload data, while the CE byte counter solely includes marked payload bytes. If both are present, the byte counter in the option will provide the more accurate information needed for modern congestion control and policing schemes, such as L4S, DCTCP or ConEx. If the option is stripped, a simple algorithm to estimate the number of marked bytes from the ACE field is given in Appendix A.3.

Feedback in bytes is recommended in order to protect against the receiver using attacks similar to 'ACK-Division' to artificially

inflate the congestion window, which is why [RFC5681] now recommends that TCP counts acknowledged bytes not packets.

2.5. Generic (Dumb) Reflector

The ACE field provides information about CE markings on both data and control packets. According to [RFC3168] the Data Sender is meant to set control packets to Not-ECT. However, mechanisms in certain private networks (e.g. data centres) set control packets to be ECN

capable because they are precisely the packets that performance depends on most.

For this reason, AccECN is designed to be a generic reflector of whatever ECN markings it sees, whether or not they are compliant with a current standard. Then as standards evolve, Data Senders can upgrade unilaterally without any need for receivers to upgrade too. It is also useful to be able to rely on generic reflection behaviour when senders need to test for unexpected interference with markings (for instance Section 3.2.2.3, Section 3.2.2.4 and Section 3.2.3.2 of the present document and para 2 of Section 20.2 of [RFC3168]).

The initial SYN is the most critical control packet, so AccECN provides feedback on its ECN marking. Although RFC 3168 prohibits an ECN-capable SYN, providing feedback of ECN marking on the SYN supports future scenarios in which SYNs might be ECN-enabled (without prejudging whether they ought to be). For instance, [RFC8311] updates this aspect of RFC 3168 to allow experimentation with ECN-capable TCP control packets.

Even if the TCP client (or server) has set the SYN (or SYN/ACK) to not-ECT in compliance with RFC 3168, feedback on the state of the ECN field when it arrives at the receiver could still be useful, because middleboxes have been known to overwrite the ECN IP field as if it is still part of the old Type of Service (ToS) field [Mandalari18]. If a TCP client has set the SYN to Not-ECT, but receives feedback that the ECN field on the SYN arrived with a different codepoint, it can detect such middlebox interference and send Not-ECT for the rest of the connection. Today, if a TCP server receives ECT or CE on a SYN, it cannot know whether it is invalid (or valid) because only the TCP client knows whether it originally marked the SYN as Not-ECT (or ECT). Therefore, prior to AccECN, the server's only safe course of

action was to disable ECN for the connection. Instead, the AccECN protocol allows the server to feed back the received ECN field to the client, which then has all the information to decide whether the connection has to fall-back from supporting ECN (or not).

3. AccECN Protocol Specification

3.1. Negotiating to use AccECN

3.1.1. Negotiation during the TCP handshake

Given the ECN Nonce [RFC3540] has been reclassified as historic [RFC8311], the present specification re-allocates the TCP flag at bit 7 of the TCP header, which was previously called NS (Nonce Sum), as the AE (Accurate ECN) flag (see IANA Considerations in Section 7) as shown below.

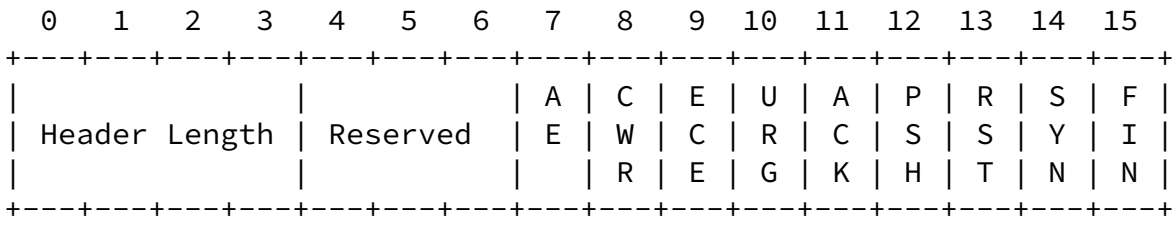

Figure 2: The (post-AccECN) definition of the TCP header flags during the TCP handshake

During the TCP handshake at the start of a connection, to request more accurate ECN feedback the TCP client (host A) MUST set the TCP flags AE=1, CWR=1 and ECE=1 in the initial SYN segment.

If a TCP server (B) that is AccECN-enabled receives a SYN with the above three flags set, it MUST set both its half connections into AccECN mode. Then it MUST set the TCP flags on the SYN/ACK to one of the 4 values shown in the top block of Table 2 to confirm that it supports AccECN. The TCP server MUST NOT set one of these 4 combination of flags on the SYN/ACK unless the preceding SYN requested support for AccECN as above.

A TCP server in AccECN mode MUST set the AE, CWR and ECE TCP flags on the SYN/ACK to the value in Table 2 that feeds back the IP-ECN field that arrived on the SYN. This applies whether or not the server

itself supports setting the IP-ECN field on a SYN or SYN/ACK (see Section 2.5 for rationale).

Once a TCP client (A) has sent the above SYN to declare that it supports AccECN, and once it has received the above SYN/ACK segment that confirms that the TCP server supports AccECN, the TCP client MUST set both its half connections into AccECN mode.

Once in AccECN mode, a TCP client or server has the rights and obligations to participate in the ECN protocol defined in Section 3.1.5.

The procedure for the client to follow if a SYN/ACK does not arrive before its retransmission timer expires is given in Section 3.1.4.

3.1.2. Backward Compatibility

The three flags set to 1 to indicate AccECN support on the SYN have been carefully chosen to enable natural fall-back to prior stages in the evolution of ECN, as above. Table 2 tabulates all the negotiation possibilities for ECN-related capabilities that involve at least one AccECN-capable host. The entries in the first two columns have been abbreviated, as follows:

AccECN: More Accurate ECN Feedback (the present specification)

Nonce: ECN Nonce feedback [RFC3540]

ECN: 'Classic' ECN feedback [RFC3168]

No ECN: Not-ECN-capable. Implicit congestion notification using packet drop.

A	B	SYN A->B	SYN/ACK B->A	Feedback Mode
		AE CWR ECE	AE CWR ECE	
AccECN	AccECN	1 1 1	0 1 0	AccECN (no ECT on SYN)
AccECN	AccECN	1 1 1	0 1 1	AccECN (ECT1 on SYN)
AccECN	AccECN	1 1 1	1 0 0	AccECN (ECT0 on SYN)

AccECN	AccECN	1	1	1	1	1	0	AccECN (CE on SYN)
AccECN	Nonce	1	1	1	1	0	1	(Reserved)
AccECN	ECN	1	1	1	0	0	1	classic ECN
AccECN	No ECN	1	1	1	0	0	0	Not ECN
Nonce	AccECN	0	1	1	0	0	1	classic ECN
ECN	AccECN	0	1	1	0	0	1	classic ECN
No ECN	AccECN	0	0	0	0	0	0	Not ECN
AccECN	Broken	1	1	1	1	1	1	Not ECN

Table 2: ECN capability negotiation between Client (A) and Server (B)

Table 2 is divided into blocks each separated by an empty row.

1. The top block shows the case already described in Section 3.1 where both endpoints support AccECN and how the TCP server (B) indicates congestion feedback.

2. The second block shows the cases where the TCP client (A) supports AccECN but the TCP server (B) supports some earlier variant of TCP feedback, indicated in its SYN/ACK. Therefore, as soon as an AccECN-capable TCP client (A) receives the SYN/ACK shown it MUST set both its half connections into the feedback mode shown in the rightmost column. If it has set itself into classic ECN feedback mode it MUST then comply with [RFC3168].

The server response called 'Nonce' in the table is now historic. For an AccECN implementation, there is no need to recognize or support ECN Nonce feedback [RFC3540], which has been reclassified as historic [RFC8311]. AccECN is compatible with alternative ECN feedback integrity approaches (see Section 5.3).

3. The third block shows the cases where the TCP server (B) supports AccECN but the TCP client (A) supports some earlier variant of TCP feedback, indicated in its SYN.

   When an AccECN-enabled TCP server (B) receives a SYN with

AE,CWR,ECE = 0,1,1 it MUST do one of the following:

* set both its half connections into the classic ECN feedback mode and return a SYN/ACK with AE, CWR, ECE = 0,0,1 as shown. Then it MUST comply with [RFC3168].

* set both its half-connections into No ECN mode and return a SYN/ACK with AE,CWR,ECE = 0,0,0, then continue with ECN disabled. This latter case is unlikely to be desirable, but it is allowed as a possibility, e.g. for minimal TCP implementations.

When an AccECN-enabled TCP server (B) receives a SYN with AE,CWR,ECE = 0,0,0 it MUST set both its half connections into the Not ECN feedback mode, return a SYN/ACK with AE,CWR,ECE = 0,0,0 as shown and continue with ECN disabled.

4. The fourth block displays a combination labelled `Broken'. Some older TCP server implementations incorrectly set the reserved flags in the SYN/ACK by reflecting those in the SYN. Such broken TCP servers (B) cannot support ECN, so as soon as an AccECN-capable TCP client (A) receives such a broken SYN/ACK it MUST fall back to Not ECN mode for both its half connections and continue with ECN disabled.

The following additional rules do not fit the structure of the table, but they complement it:

Simultaneous Open: An originating AccECN Host (A), having sent a SYN with AE=1, CWR=1 and ECE=1, might receive another SYN from host B. Host A MUST then enter the same feedback mode as it would have entered had it been a responding host and received the same SYN. Then host A MUST send the same SYN/ACK as it would have sent had it been a responding host.

In-window SYN during TIME-WAIT: Many TCP implementations create a new TCP connection if they receive an in-window SYN packet during

TIME-WAIT state. When a TCP host enters TIME-WAIT or CLOSED state, it should ignore any previous state about the negotiation of AccECN for that connection and renegotiate the feedback mode according to Table 2.

3.1.3. Forward Compatibility

If a TCP server that implements AccECN receives a SYN with the three TCP header flags (AE, CWR and ECE) set to any combination other than 000, 011 or 111, it MUST negotiate the use of AccECN as if they had been set to 111. This ensures that future uses of the other combinations on a SYN can rely on consistent behaviour from the installed base of AccECN servers.

For the avoidance of doubt, the behaviour described in the present specification applies whether or not the three remaining reserved TCP header flags are zero.

3.1.4. Retransmission of the SYN

If the sender of an AccECN SYN times out before receiving the SYN/ACK, the sender SHOULD attempt to negotiate the use of AccECN at least one more time by continuing to set all three TCP ECN flags on the first retransmitted SYN (using the usual retransmission time-outs). If this first retransmission also fails to be acknowledged, the sender SHOULD send subsequent retransmissions of the SYN with the three TCP-ECN flags cleared (AE=CWR=ECE=0). A retransmitted SYN MUST use the same ISN as the original SYN.

Retrying once before fall-back adds delay in the case where a middlebox drops an AccECN (or ECN) SYN deliberately. However, current measurements imply that a drop is less likely to be due to middlebox interference than other intermittent causes of loss, e.g. congestion, wireless interference, etc.

Implementers MAY use other fall-back strategies if they are found to be more effective (e.g. attempting to negotiate AccECN on the SYN only once or more than twice (most appropriate during high levels of congestion). However, other fall-back strategies will need to follow all the rules in Section 3.1.5, which concern behaviour when SYNs or SYN/ACKs negotiating different types of feedback have been sent within the same connection.

Further it may make sense to also remove any other new or experimental fields or options on the SYN in case a middlebox might be blocking them, although the required behaviour will depend on the specification of the other option(s) and any attempt to co-ordinate fall-back between different modules of the stack.

Whichever fall-back strategy is used, the TCP initiator SHOULD cache failed connection attempts. If it does, it SHOULD NOT give up attempting to negotiate AccECN on the SYN of subsequent connection attempts until it is clear that the blockage is persistently and specifically due to AccECN. The cache should be arranged to expire so that the initiator will infrequently attempt to check whether the problem has been resolved.

The fall-back procedure if the TCP server receives no ACK to acknowledge a SYN/ACK that tried to negotiate AccECN is specified in Section 3.2.3.2.

3.1.5. Implications of AccECN Mode

Section 3.1.1 describes the only ways that a host can enter AccECN mode, whether as a client or as a server.

As a Data Sender, a host in AccECN mode has the rights and obligations concerning the use of ECN defined below, which build on those in [RFC3168] as updated by [RFC8311]:

- Using ECT:
  - It can set an ECT codepoint in the IP header of packets to indicate to the network that the transport is capable and willing to participate in ECN for this packet.
  - It does not have to set ECT on any packet (for instance if it has reason to believe such a packet would be blocked).
- Switching feedback negotiation (e.g. fall-back):
  - It SHOULD NOT set ECT on any packet if it has received at least one valid SYN or Acceptable SYN/ACK with AE=CWR=ECE=0. A "valid SYN" has the same port numbers and the same ISN as the SYN that caused the server to enter AccECN mode.
  - It MUST NOT send an ECN-setup SYN [RFC3168] within the same connection as it has sent a SYN requesting AccECN feedback.
  - It MUST NOT send an ECN-setup SYN/ACK [RFC3168] within the same connection as it has sent a SYN/ACK agreeing to use AccECN feedback.

The above rules are necessary because, when one peer negotiates the feedback mode in two different types of handshake, it is not possible for the other peer to know for certain which handshake

packet(s) the other end eventually receives or in which order it

receives them. So the two peers can end up using difference feedback modes without knowing it.

- Congestion response:
  - It is still obliged to respond appropriately to AccECN feedback with congestion indications on packets it had previously sent, as defined in Section 6.1 of [RFC3168] and updated by Sections 2.1 and 4.1 of [RFC8311].
  - The commitment to respond appropriately to incoming indications of congestion remains even if it sends a SYN packet with AE=CWR=ECE=0, in a later transmission within the same TCP connection.
  - Unlike an RFC 3168 data sender, it MUST NOT set CWR to indicate it has received and responded to indications of congestion (for the avoidance of doubt, this does not preclude it from setting the bits of the ACE counter field, which includes an overloaded use of the same bit).

As a Data Receiver:

- a host in AccECN mode MUST feed back the information in the IP-ECN field on incoming packets using Accurate ECN feedback, as specified in Section 3.2 below.
- if it receives an ECN-setup SYN or ECN-setup SYN/ACK [RFC3168] during the same connection as it receives a SYN requesting AccECN feedback or a SYN/ACK agreeing to use AccECN feedback, it MUST reset the connection with a RST packet.
- If for any reason it is not willing to provide ECN feedback on a particular TCP connection, to indicate this unwillingness it SHOULD clear the AE, CWR and ECE flags in all SYN and/or SYN/ACK packets that it sends.
- it MUST NOT use reception of packets with ECT set in the IP-ECN field as an implicit signal that the peer is ECN-capable. Reason: ECT at the IP layer does not explicitly confirm the peer has the

correct ECN feedback logic, and the packets could have been mangled at the IP layer.

3.2. AccECN Feedback

Each Data Receiver of each half connection maintains four counters, r.cep, r.ceb, r.e0b and r.e1b:

- The Data Receiver MUST increment the CE packet counter (r.cep), for every Acceptable packet that it receives with the CE code point in the IP ECN field, including CE marked control packets but excluding CE on SYN packets (SYN=1; ACK=0).

- The Data Receiver MUST increment the r.ceb, r.e0b or r.e1b byte counters by the number of TCP payload octets in Acceptable packets marked respectively with the CE, ECT(0) and ECT(1) codepoint in their IP-ECN field, including any payload octets on control packets, but not including any payload octets on SYN packets (SYN=1; ACK=0).

Each Data Sender of each half connection maintains four counters, s.cep, s.ceb, s.e0b and s.e1b intended to track the equivalent counters at the Data Receiver.

A Data Receiver feeds back the CE packet counter using the Accurate ECN (ACE) field, as explained in Section 3.2.2. And it feeds back all the byte counters using the AccECN TCP Option, as specified in Section 3.2.3.

Whenever a host feeds back the value of any counter, it MUST report the most recent value, no matter whether it is in a pure ACK, an ACK with new payload data or a retransmission. Therefore the feedback carried on a retransmitted packet is unlikely to be the same as the feedback on the original packet.

3.2.1. Initialization of Feedback Counters

When a host first enters AccECN mode, in its role as a Data Receiver it initializes its counters to r.cep = 5 and r.ceb = 0, The initial values of the other two byte counters depend on the Data Receiver's choice of the order of fields it will use in the AccECN TCP Option

(see Section 3.2.3). If field order 0, it will initialize the remaining counters to r.e0b = 1; r.e1b.= 0. If field order 1, it will initialize them to r.e0b = 0 and r.e1b.= 0x800001.

Non-zero initial values are used to support a stateless handshake (see Section 5.1) and to be distinct from cases where the fields are incorrectly zeroed (e.g. by middleboxes - see Section 3.2.3.2.4).

When a host enters AccECN mode, in its role as a Data Sender it initializes its counters to s.cep = 5 and s.ceb = 0. The initial values of the other two byte counters depend on the peer's choice of the order of fields it will use in the AccECN TCP Option (see Section 3.2.3). If field order 0, it will initialize the remaining counters to s.e0b = 1; s.e1b.= 0. If field order 1, it will initialize them to s.e0b = 0 and s.e1b.= 0x800001.

3.2.2. The ACE Field

After AccECN has been negotiated on the SYN and SYN/ACK, both hosts overload the three TCP flags (AE, CWR and ECE) in the main TCP header as one 3-bit field. Then the field is given a new name, ACE, as shown in Figure 3.

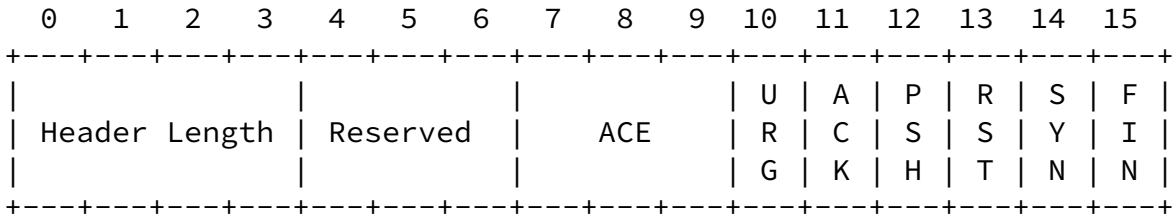

Figure 3: Definition of the ACE field within bytes 13 and 14 of the TCP Header (when AccECN has been negotiated and SYN=0).

The original definition of these three flags in the TCP header, including the addition of support for the ECN Nonce, is shown for comparison in Figure 1. This specification does not rename these three TCP flags to ACE unconditionally; it merely overloads them with another name and definition once an AccECN connection has been established.

With one exception (Section 3.2.2.1), a host with both of its half-connections in AccECN mode MUST interpret the AE, CWR and ECE flags

as the 3-bit ACE counter on a segment with the SYN flag cleared (SYN=0). On such a packet, a Data Receiver MUST encode the three least significant bits of its r.cep counter into the ACE field that it feeds back to the Data Sender. A host MUST NOT interpret the 3 flags as a 3-bit ACE field on any segment with SYN=1 (whether ACK is 0 or 1), or if AccECN negotiation is incomplete or has not succeeded.

Both parts of each of these conditions are equally important. For instance, even if AccECN negotiation has been successful, the ACE field is not defined on any segments with SYN=1 (e.g. a retransmission of an unacknowledged SYN/ACK, or when both ends send SYN/ACKs after AccECN support has been successfully negotiated during a simultaneous open).

3.2.2.1. ACE Field on the ACK of the SYN/ACK

A TCP client (A) in AccECN mode MUST feed back which of the 4 possible values of the IP-ECN field was on the SYN/ACK by writing it into the ACE field of a pure ACK with no SACK blocks using the binary encoding in Table 3 (which is the same as that used on the SYN/ACK in Table 2). This shall be called the handshake encoding of the ACE field, and it is the only exception to the rule that the ACE field

carries the 3 least significant bits of the r.cep counter on packets with SYN=0.

Normally, a TCP client acknowledges a SYN/ACK with an ACK that satisfies the above conditions anyway (SYN=0, no data, no SACK blocks). If an AccECN TCP client intends to acknowledge the SYN/ACK with a packet that does not satisfy these conditions (e.g. it has data to include on the ACK), it SHOULD first send a pure ACK that does satisfy these conditions (see Section 5.2), so that it can feed back which of the four values of the IP-ECN field arrived on the SYN/ACK. A valid exception to this "SHOULD" would be where the implementation will only be used in an environment where mangling of the ECN field is unlikely.

IP-ECN codepoint on SYN/ACK	ACE on pure ACK of SYN/ACK	r.cep of client in AccECN mode
Not-ECT	0b010	5

ECT(1)	0b011	5
ECT(0)	0b100	5
CE	0b110	6

Table 3: The encoding of the ACE field in the ACK of the SYN-ACK to reflect the SYN-ACK's IP-ECN field

When an AccECN server in SYN-RCVD state receives a pure ACK with SYN=0 and no SACK blocks, instead of treating the ACE field as a counter, it MUST infer the meaning of each possible value of the ACE field from Table 4, which also shows the value that an AccECN server MUST set s.cep to as a result.

Given this encoding of the ACE field on the ACK of a SYN/ACK is exceptional, an AccECN server using large receive offload (LRO) might prefer to disable LRO until such an ACK has transitioned it out of SYN-RCVD state.

ACE on ACK of SYN/ACK	IP-ECN codepoint on SYN/ACK inferred by server	s.cep of server in AccECN mode
0b000	{Notes 1, 3}	Disable ECN
0b001	{Notes 2, 3}	5
0b010	Not-ECT	5
0b011	ECT(1)	5
0b100	ECT(0)	5
0b101	Currently Unused {Note 2}	5
0b110	CE	6
0b111	Currently Unused {Note 2}	5

+--------------+-----------------------------+--------------------+

Table 4: Meaning of the ACE field on the ACK of the SYN/ACK

{Note 1}: If the server is in AccECN mode, the value of zero raises suspicion of zeroing of the ACE field on the path (see Section 3.2.2.3).

{Note 2}: If the server is in AccECN mode, these values are Currently Unused but the AccECN server's behaviour is still defined for forward compatibility. Then the designer of a future protocol can know for certain what AccECN servers will do with these codepoints.

{Note 3}: In the case where a server that implements AccECN is also using a stateless handshake (termed a SYN cookie) it will not remember whether it entered AccECN mode. The values 0b000 or 0b001 will remind it that it did not enter AccECN mode, because AccECN does not use them (see Section 5.1 for details). If a stateless server that implements AccECN receives either of these two values in the ACK, its action is implementation-dependent and outside the scope of this spec, It will certainly not take the action in the third column because, after it receives either of these values, it is not in AccECN mode. I.e., it will not disable ECN (at least not just because ACE is 0b000) and it will not set s.cep.

3.2.2.2. Encoding and Decoding Feedback in the ACE Field

Whenever the Data Receiver sends an ACK with SYN=0 (with or without data), unless the handshake encoding in Section 3.2.2.1 applies, the Data Receiver MUST encode the least significant 3 bits of its r.cep counter into the ACE field (see Appendix A.2).

Whenever the Data Sender receives an ACK with SYN=0 (with or without data), it first checks whether it has already been superseded by another ACK in which case it ignores the ECN feedback. If the ACK has not been superseded, and if the special handshake encoding in

Section 3.2.2.1 does not apply, the Data Sender decodes the ACE field as follows (see Appendix A.2 for examples).

- It takes the least significant 3 bits of its local s.cep counter and subtracts them from the incoming ACE counter to work out the

minimum positive increment it could apply to s.cep (assuming the ACE field only wrapped at most once).

- It then follows the safety procedures in Section 3.2.2.5.2 to calculate or estimate how many packets the ACK could have acknowledged under the prevailing conditions to determine whether the ACE field might have wrapped more than once.

The encode/decode procedures during the three-way handshake are exceptions to the general rules given so far, so they are spelled out step by step below for clarity:

- If a TCP server in AccECN mode receives a CE mark in the IP-ECN field of a SYN (SYN=1, ACK=0), it MUST NOT increment r.cep (it remains at its initial value of 5).

  Reason: It would be redundant for the server to include CE-marked SYNs in its r.cep counter, because it already reliably delivers feedback of any CE marking on the SYN/ACK using the encoding in Table 2. This also ensures that, when the server starts using the ACE field, it has not unnecessarily consumed more than one initial value, given they can be used to negotiate variants of the AccECN protocol (see Appendix B.3).

- If a TCP client in AccECN mode receives CE feedback in the TCP flags of a SYN/ACK, it MUST NOT increment s.cep (it remains at its initial value of 5), so that it stays in step with r.cep on the server. Nonetheless, the TCP client still triggers the congestion control actions necessary to respond to the CE feedback.

- If a TCP client in AccECN mode receives a CE mark in the IP-ECN field of a SYN/ACK, it MUST increment r.cep, but no more than once no matter how many CE-marked SYN/ACKs it receives (i.e. incremented from 5 to 6, but no further).

  Reason: Incrementing r.cep ensures the client will eventually deliver any CE marking to the server reliably when it starts using the ACE field. Even though the client also feeds back any CE marking on the ACK of the SYN/ACK using the encoding in Table 3, this ACK is not delivered reliably, so it can be considered as a timely notification that is redundant but unreliable. The client does not increment r.cep more than once, because the server can

only increment s.cep once (see next bullet). Also, this limits the unnecessarily consumed initial values of the ACE field to two.

- If a TCP server in AccECN mode and in SYN-RCVD state receives CE feedback in the TCP flags of a pure ACK with no SACK blocks, it MUST increment s.cep (from 5 to 6). The TCP server then triggers the congestion control actions necessary to respond to the CE feedback.

  Reasoning: The TCP server can only increment s.cep once, because the first ACK it receives will cause it to transition out of SYN-RCVD state. The server's congestion response would be no different even if it could receive feedback of more than one CE-marked SYN/ACK.

  Once the TCP server transitions to ESTABLISHED state, it might later receive other pure ACK(s) with the handshake encoding in the ACE field. The conditions for this to occur are quite unusual, but not impossible, e.g. a SYN/ACK (or ACK of the SYN/ACK) that is delayed for longer than the server's retransmission timeout; or packet duplication by the network. Nonetheless, once in the ESTABLISHED state, the server will consider the ACE field to be encoded as the normal ACE counter on all packets with SYN=0 (given it will be following the above rule in this bullet). The server MAY include a test to avoid this case.

3.2.2.3. Testing for Zeroing of the ACE Field

Section 3.2.2 required the Data Receiver to initialize the r.cep counter to a non-zero value. Therefore, in either direction the initial value of the ACE counter ought to be non-zero.

If AccECN has been successfully negotiated, the Data Sender SHOULD check the value of the ACE counter in the first packet (with or without data) that arrives with SYN=0. If the value of this ACE field is zero (0b000), the Data Sender disables sending ECN-capable packets for the remainder of the half-connection by setting the IP/ECN field in all subsequent packets to Not-ECT.

Usually, the server checks the ACK of the SYN/ACK from the client, while the client checks the first data segment from the server. However, if reordering occurs, "the first packet ... that arrives" will not necessarily be the same as the first packet in sequence order. The test has been specified loosely like this to simplify implementation, and because it would not have been any more precise to have specified the first packet in sequence order, which would not necessarily be the first ACE counter that the Data Receiver fed back anyway, given it might have been a retransmission.

The possibility of re-ordering means that there is a small chance that the ACE field on the first packet to arrive is genuinely zero (without middlebox interference). This would cause a host to unnecessarily disable ECN for a half connection. Therefore, in environments where there is no evidence of the ACE field being zeroed, implementations can skip this test.

Note that the Data Sender MUST NOT test whether the arriving counter in the initial ACE field has been initialized to a specific valid value - the above check solely tests whether the ACE fields have been incorrectly zeroed. This allows hosts to use different initial values as an additional signalling channel in future.

3.2.2.4. Testing for Mangling of the IP/ECN Field

The value of the ACE field on the SYN/ACK indicates the value of the IP/ECN field when the SYN arrived at the server. The client can compare this with how it originally set the IP/ECN field on the SYN. If this comparison implies an unsafe transition (see below) of the IP/ECN field, for the remainder of the connection the client MUST NOT send ECN-capable packets, but it MUST continue to feed back any ECN markings on arriving packets.

The value of the ACE field on the last ACK of the 3WHS indicates the value of the IP/ECN field when the SYN/ACK arrived at the client. The server can compare this with how it originally set the IP/ECN field on the SYN/ACK. If this comparison implies an unsafe transition of the IP/ECN field, for the remainder of the connection the server MUST NOT send ECN-capable packets, but it MUST continue to feedback any ECN markings on arriving packets.

The ACK of the SYN/ACK is not reliably delivered (nonetheless, the count of CE marks is still eventually delivered reliably). If this ACK does not arrive, the server can continue to send ECN-capable packets without having tested for mangling of the IP/ECN field on the SYN/ACK.

Invalid transitions of the IP/ECN field are defined in [RFC3168] and repeated here for convenience:

- the not-ECT codepoint changes;

- either ECT codepoint transitions to not-ECT;

- the CE codepoint changes.

RFC 3168 says that a router that changes ECT to not-ECT is invalid but safe. However, from a host's viewpoint, this transition is

unsafe because it could be the result of two transitions at different routers on the path: ECT to CE (safe) then CE to not-ECT (unsafe). This scenario could well happen where an ECN-enabled home router congests its upstream mobile broadband bottleneck link, then the ingress to the mobile network clears the ECN field [Mandalari18].

The above fall-back behaviours are necessary in case mangling of the IP/ECN field is asymmetric, which is currently common over some mobile networks [Mandalari18]. Then one end might see no unsafe transition and continue sending ECN-capable packets, while the other end sees an unsafe transition and stops sending ECN-capable packets.

3.2.2.5. Safety against Ambiguity of the ACE Field

If too many CE-marked segments are acknowledged at once, or if a long run of ACKs is lost or thinned out, the 3-bit counter in the ACE field might have cycled between two ACKs arriving at the Data Sender. The following safety procedures minimize this ambiguity.

3.2.2.5.1. Data Receiver Safety Procedures

An AccECN Data Receiver:

- SHOULD immediately send an ACK whenever a data packet marked CE arrives after the previous data packet was not CE.

- MUST immediately send an ACK once 'n' CE marks have arrived since the previous ACK, where 'n' SHOULD be 2 and MUST be no greater than 6.

These rules for when to send an ACK are designed to be complemented by those in Section 3.2.3.3, which concern whether the AccECN TCP Option ought to be included on ACKs.

For the avoidance of doubt, the change-triggered ACK mechanism is

deliberately worded to solely apply to data packets, and to ignore the arrival of a control packet with no payload, because it is important that TCP does not acknowledge pure ACKs. The change-triggered ACK approach can lead to some additional ACKs but it feeds back the timing and the order in which ECN marks are received with minimal additional complexity. If only CE marks are infrequent, or there are multiple marks in a row, the additional load will be low. Other marking patterns could increase the load significantly.

Even though the first bullet is stated as a "SHOULD", it is important for a transition to immediately trigger an ACK if at all possible, so that the Data Sender can rely on change-triggered ACKs to detect queue growth as soon as possible, e.g. at the start of a flow. This

requirement can only be relaxed if certain offload hardware needed for high performance cannot support change-triggered ACKs (although high performance protocols such as DCTCP already successfully use change-triggered ACKs). One possible compromise would be for the receiver to heuristically detect whether the sender is in slow-start, then to implement change-triggered ACKs while the sender is in slow-start, and offload otherwise.

3.2.2.5.2. Data Sender Safety Procedures

If the Data Sender has not received AccECN TCP Options to give it more dependable information, and it detects that the ACE field could have cycled, it SHOULD deem whether it cycled by taking the safest likely case under the prevailing conditions. It can detect if the counter could have cycled by using the jump in the acknowledgement number since the last ACK to calculate or estimate how many segments could have been acknowledged. An example algorithm to implement this policy is given in Appendix A.2. An implementer MAY develop an alternative algorithm as long as it satisfies these requirements.

If missing acknowledgement numbers arrive later (reordering) and prove that the counter did not cycle, the Data Sender MAY attempt to neutralize the effect of any action it took based on a conservative assumption that it later found to be incorrect.

The Data Sender can estimate how many packets (of any marking) an ACK acknowledges. If the ACE counter on an ACK seems to imply that the minimum number of newly CE-marked packets is greater that the number

of newly acknowledged packets, the Data Sender SHOULD believe the ACE counter, unless it can be sure that it is counting all control packets correctly.

3.2.3. The AccECN Option

The AccECN Option is defined as shown in Figure 4. The initial 'E' of each field name stands for 'Echo'.

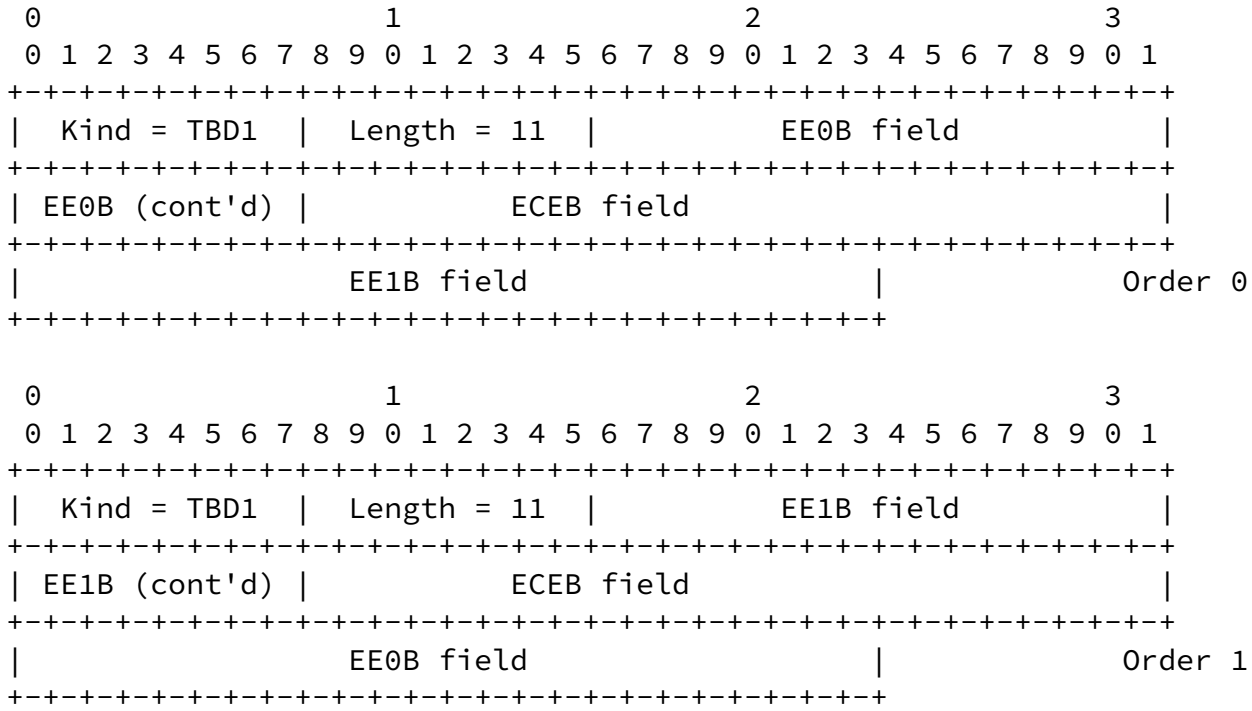

Figure 4: The AccECN TCP Option

When a Data Receiver sends an AccECN Option, it MUST set the Kind field to TBD1, which is registered in Section 7 as a new TCP option Kind called AccECN.

Figure 4 shows two option field orders; order 0 and order 1. They both consists of three 24-bit fields. Order 0 provides the 24 least significant bits of the r.e0b, r.ceb and r.e1b counters, respectively. Order 1 provides the same fields, but in the opposite order. Each half-connection can use a different field order, but a Data Receiver MUST consistently send the same field order within the same half-connection.

The field order to use for each half-connection is up to the Data Receiver implementation. It might use the same hard-coded order for all half-connections, or it might make a different choice for each half-connection. For instance, the implementation of a Data Receiver might default to using order 0, unless the ECN field in the IP header of the packet it received during the 3WHS is ECT(1). A Data Receiver just starts using its chosen field order and the field immediately after the length field in the first AccECN TCP Option of a half-connection will intrinsically indicate which order it is using, because the initial counter values that it is required to use depend on its chosen field order (see Section 3.2.1).

A Data Sender can know which field order the Data Receiver is using for a half-connection from the most significant bit (MSB) of the

counter in the field immediately after the length field in the first non-empty AccECN TCP Option to arrive. If this MSB = 0, field order 0 is being used, and if MSB = 1, field order 1 is being used. Note that the Data Sender only tests the most significant bit, not the value of the whole field, because the counters in the first packet to arrive might have started to increment (e.g. if the first packet to arrive is not the first packet sent due to loss or reordering).

Note that there is no field to feed back Not-ECT bytes. Nonetheless an algorithm for the Data Sender to calculate the number of payload bytes received as Not-ECT is given in Appendix A.5.

Whenever a Data Receiver sends an AccECN Option, the rules in Section 3.2.3.3 expect it to usually send a full-length option. To

cope with option space limitations, it can omit unchanged fields from the tail of the option, as long as it preserves the order of the remaining fields and includes any field that has changed. The length field MUST indicate which fields are present as follows:

Length	Type 0	Type 1
11	EE0B, ECEB, EE1B	EE1B, ECEB, EE0B
8	EE0B, ECEB	EE1B, ECEB
5	EE0B	EE1B
2	(empty)	(empty)

The empty option of Length=2 is provided to allow for a case where an AccECN Option has to be sent (e.g. on the SYN/ACK to test the path), but there is very limited space for the option.

All implementations of a Data Sender that read any AccECN Option MUST be able to read in AccECN Options of any of the above lengths. For forward compatibility, if the AccECN Option is of any other length, implementations MUST use those whole 3 octet fields that fit within the length and ignore the remainder of the option.

The AccECN Option has to be optional to implement, because both sender and receiver have to be able to cope without the option anyway - in cases where it does not traverse a network path. It is RECOMMENDED to implement both sending and receiving of the AccECN Option. If sending of the AccECN Option is implemented, the fall-backs described in this document will need to be implemented as well (unless solely for a controlled environment where path traversal is not considered a problem). Even if a developer does not implement sending of the AccECN Option, it is RECOMMENDED that they still

implement logic to receive and understand any AccECN Options sent by remote peers.

If a Data Receiver intends to send the AccECN Option at any time during the rest of the connection it is strongly recommended to also test path traversal of the AccECN Option as specified in Section 3.2.3.2.

3.2.3.1. Encoding and Decoding Feedback in the AccECN Option Fields

Whenever the Data Receiver includes any of the counter fields (ECEB, EE0B, EE1B) in an AccECN Option, it MUST encode the 24 least significant bits of the current value of the associated counter into the field (respectively r.ceb, r.e0b, r.e1b).

Whenever the Data Sender receives ACK carrying an AccECN Option, it first checks whether the ACK has already been superseded by another ACK in which case it ignores the ECN feedback. If the ACK has not been superseded, the Data Sender MUST decode the fields in the AccECN Option as follows. For each field, it takes the least significant 24 bits of its associated local counter (s.ceb, s.e0b or s.e1b) and subtracts them from the counter in the associated field of the incoming AccECN Option (respectively ECEB, EE0B, EE1B), to work out the minimum positive increment it could apply to s.ceb, s.e0b or s.e1b (assuming the field in the option only wrapped at most once).

Appendix A.1 gives an example algorithm for the Data Receiver to encode its byte counters into the AccECN Option, and for the Data Sender to decode the AccECN Option fields into its byte counters.

Note that, as specified in Section 3.2, any data on the SYN (SYN=1, ACK=0) is not included in any of the locally held octet counters nor in the AccECN Option on the wire.

3.2.3.2. Path Traversal of the AccECN Option

3.2.3.2.1. Testing the AccECN Option during the Handshake

The TCP client MUST NOT include the AccECN TCP Option on the SYN. (A fall-back strategy for the loss of the SYN (possibly due to middlebox interference) is specified in Section 3.1.4.)

A TCP server that confirms its support for AccECN (in response to an AccECN SYN from the client as described in Section 3.1) SHOULD include an AccECN TCP Option on the SYN/ACK.

A TCP client that has successfully negotiated AccECN SHOULD include an AccECN Option in the first ACK at the end of the 3WHS. However,

this first ACK is not delivered reliably, so the TCP client SHOULD also include an AccECN Option on the first data segment it sends (if it ever sends one).

A host MAY NOT include an AccECN Option in any of these three cases if it has cached knowledge that the packet would be likely to be blocked on the path to the other host if it included an AccECN Option.

3.2.3.2.2. Testing for Loss of Packets Carrying the AccECN Option

If after the normal TCP timeout the TCP server has not received an ACK to acknowledge its SYN/ACK, the SYN/ACK might just have been lost, e.g. due to congestion, or a middlebox might be blocking the AccECN Option. To expedite connection setup, the TCP server SHOULD retransmit the SYN/ACK repeating the same AE, CWR and ECE TCP flags as on the original SYN/ACK but with no AccECN Option. If this retransmission times out, to expedite connection setup, the TCP server SHOULD disable AccECN and ECN for this connection by retransmitting the SYN/ACK with AE=CWR=ECE=0 and no AccECN Option.

Implementers MAY use other fall-back strategies if they are found to be more effective (e.g. retrying the AccECN Option for a second time before fall-back - most appropriate during high levels of congestion). However, other fall-back strategies will need to follow all the rules in Section 3.1.5, which concern behaviour when SYNs or SYN/ACKs negotiating different types of feedback have been sent within the same connection.

If the TCP client detects that the first data segment it sent with the AccECN Option was lost, it SHOULD fall back to no AccECN Option on the retransmission. Again, implementers MAY use other fall-back strategies such as attempting to retransmit a second segment with the AccECN Option before fall-back, and/or caching whether the AccECN Option is blocked for subsequent connections. [I-D.ietf-tcpm-2140bis] further discusses caching of TCP parameters and status information.

If a host falls back to not sending the AccECN Option, it will continue to process any incoming AccECN Options as normal.

Either host MAY include the AccECN Option in a subsequent segment to retest whether the AccECN Option can traverse the path.

If the TCP server receives a second SYN with a request for AccECN support, it should resend the SYN/ACK, again confirming its support for AccECN, but this time without the AccECN Option. This approach rules out any interference by middleboxes that may drop packets with

unknown options, even though it is more likely that the SYN/ACK would have been lost due to congestion. The TCP server MAY try to send another packet with the AccECN Option at a later point during the connection but should monitor if that packet got lost as well, in which case it SHOULD disable the sending of the AccECN Option for this half-connection.

Similarly, an AccECN end-point MAY separately memorize which data packets carried an AccECN Option and disable the sending of AccECN Options if the loss probability of those packets is significantly higher than that of all other data packets in the same connection.

3.2.3.2.3. Testing for Absence of the AccECN Option

If the TCP client has successfully negotiated AccECN but does not receive an AccECN Option on the SYN/ACK (e.g. because is has been stripped by a middlebox or not sent by the server), the client switches into a mode that assumes that the AccECN Option is not available for this half connection.

Similarly, if the TCP server has successfully negotiated AccECN but does not receive an AccECN Option on the first segment that acknowledges sequence space at least covering the ISN, it switches into a mode that assumes that the AccECN Option is not available for this half connection.

While a host is in this mode that assumes incoming AccECN Options are not available, it MUST adopt the conservative interpretation of the ACE field discussed in Section 3.2.2.5. However, it cannot make any assumption about support of outgoing AccECN Options on the other half connection, so it SHOULD continue to send the AccECN Option itself (unless it has established that sending the AccECN Option is causing packets to be blocked as in Section 3.2.3.2.2).

If a host is in the mode that assumes incoming AccECN Options are not available, but it receives an AccECN Option at any later point during the connection, this clearly indicates that the AccECN Option is not blocked on the respective path, and the AccECN endpoint MAY switch out of the mode that assumes the AccECN Option is not available for this half connection.

3.2.3.2.4. Test for Zeroing of the AccECN Option

For a related test for invalid initialization of the ACE field, see Section 3.2.2.3

Section 3.2 required the Data Receiver to initialize the r.e0b counter to a non-zero value. Therefore, in either direction the

initial value of the EE0B field in the AccECN Option (if one exists) ought to be non-zero. If AccECN has been negotiated:

- the TCP server MAY check the initial value of the EE0B field in the first segment that acknowledges sequence space that at least covers the ISN plus 1. If the initial value of the EE0B field is zero, the server will switch into a mode that ignores the AccECN Option for this half connection.

- the TCP client MAY check the initial value of the EE0B field on the SYN/ACK. If the initial value of the EE0B field is zero, the client will switch into a mode that ignores the AccECN Option for this half connection.

While a host is in the mode that ignores the AccECN Option it MUST adopt the conservative interpretation of the ACE field discussed in Section 3.2.2.5.

Note that the Data Sender MUST NOT test whether the arriving byte counters in the initial AccECN Option have been initialized to specific valid values - the above checks solely test whether these fields have been incorrectly zeroed. This allows hosts to use different initial values as an additional signalling channel in future. Also note that the initial value of either field might be greater than its expected initial value, because the counters might already have been incremented. Nonetheless, the initial values of the counters have been chosen so that they cannot wrap to zero on these initial segments.

3.2.3.2.5. Consistency between AccECN Feedback Fields

When the AccECN Option is available it supplements but does not replace the ACE field. An endpoint using AccECN feedback MUST always consider the information provided in the ACE field whether or not the AccECN Option is also available.

If the AccECN option is present, the s.cep counter might increase while the s.ceb counter does not (e.g. due to a CE-marked control packet). The sender's response to such a situation is out of scope, and needs to be dealt with in a specification that uses ECN-capable control packets. Theoretically, this situation could also occur if a middlebox mangled the AccECN Option but not the ACE field. However, the Data Sender has to assume that the integrity of the AccECN Option is sound, based on the above test of the well-known initial values and optionally other integrity tests (Section 5.3).

If either end-point detects that the s.ceb counter has increased but the s.cep has not (and by testing ACK coverage it is certain how much

the ACE field has wrapped), this invalid protocol transition has to be due to some form of feedback mangling. So, the Data Sender MUST disable sending ECN-capable packets for the remainder of the half-connection by setting the IP/ECN field in all subsequent packets to Not-ECT.

3.2.3.3. Usage of the AccECN TCP Option

If the Data Receiver intends to use the AccECN TCP Option to provide feedback, the following rules determine when a Data Receiver in AccECN mode sends an ACK with the AccECN TCP Option, and which fields to include:

Change-Triggered ACKs: If an arriving packet increments a different byte counter to that incremented by the previous packet, the Data Receiver SHOULD immediately send an ACK with an AccECN Option, without waiting for the next delayed ACK (this is in addition to the safety recommendation in Section 3.2.2.5 against ambiguity of the ACE field).

Even though this bullet is stated as a "SHOULD", it is important for a transition to immediately trigger an ACK if at all possible, as already argued when specifying change-triggered ACKs for the ACE.

Continual Repetition: Otherwise, if arriving packets continue to increment the same byte counter, the Data Receiver can include an AccECN Option on most or all (delayed) ACKs, but it does not have to.

* It SHOULD include a counter that has continued to increment on the next scheduled ACK following a change-triggered ACK;

* while the same counter continues to increment, it SHOULD include the counter every n ACKs as consistently as possible, where n can be chosen by the implementer;

* It SHOULD always include an AccECN Option if the r.ceb counter is incrementing and it MAY include an AccECN Option if r.ec0b or r.ec1b is incrementing

* It SHOULD, include each counter at least once for every 2^22 bytes incremented to prevent overflow during continual repetition.

If the smallest allowed AccECN Option would leave insufficient space for two SACK blocks on a particular ACK, the Data Receiver

MUST give precedence to the SACK option (total 18 octets), because loss feedback is more critical.

Necessary Option Length: It MAY exclude counter(s) that have not changed for the whole connection (but beacons still include all fields - see below). It SHOULD include counter(s) that have incremented at some time during the connection. It MUST include the counter(s) that have incremented since the previous AccECN Option and it MUST only truncate fields from the right-hand tail of the option to preserve the order of the remaining fields (see Section 3.2.3);

Beaconing Full-Length Options: Nonetheless, it MUST include a full-length AccECN TCP Option on at least three ACKs per RTT, or on all ACKs if there are less than three per RTT (see Appendix A.4 for an example algorithm that satisfies this requirement).

The above rules complement those in Section 3.2.2.5, which determine when to generate an ACK irrespective of whether an AccECN TCP Option is to be included.

The following example series of arriving IP/ECN fields illustrates

when a Data Receiver will emit an ACK with an AccECN Option if it is using a delayed ACK factor of 2 segments and change-triggered ACKs: 01 -> ACK, 01, 01 -> ACK, 10 -> ACK, 10, 01 -> ACK, 01, 11 -> ACK, 01 -> ACK.

Even though first bullet is stated as a "SHOULD", it is important for a transition to immediately trigger an ACK if at all possible, so that the Data Sender can rely on change-triggered ACKs to detect queue growth as soon as possible, e.g. at the start of a flow. This requirement can only be relaxed if certain offload hardware needed for high performance cannot support change-triggered ACKs (although high performance protocols such as DCTCP already successfully use change-triggered ACKs). One possible experimental compromise would be for the receiver to heuristically detect whether the sender is in slow-start, then to implement change-triggered ACKs while the sender is in slow-start, and offload otherwise.

For the avoidance of doubt, this change-triggered ACK mechanism is deliberately worded to ignore the arrival of a control packet with no payload, which therefore does not alter any byte counters, because it is important that TCP does not acknowledge pure ACKs. The change-triggered ACK approach can lead to some additional ACKs but it feeds back the timing and the order in which ECN marks are received with minimal additional complexity. If only CE marks are infrequent, or there are multiple marks in a row, the additional load will be low. Other marking patterns could increase the load significantly,

Investigating the additional load is a goal of the proposed experiment.

Implementation note: sending an AccECN Option each time a different counter changes and including a full-length AccECN Option on every delayed ACK will satisfy the requirements described above and might be the easiest implementation, as long as sufficient space is available in each ACK (in total and in the option space).

Appendix A.3 gives an example algorithm to estimate the number of marked bytes from the ACE field alone, if the AccECN Option is not available.

If a host has determined that segments with the AccECN Option always seem to be discarded somewhere along the path, it is no longer

obliged to follow the above rules.

3.3. Requirements for TCP Proxies, Offload Engines and other Middleboxes on AccECN Compliance

A large class of middleboxes split TCP connections. Such a middlebox would be compliant with the AccECN protocol if the TCP implementation on each side complied with the present AccECN specification and each side negotiated AccECN independently of the other side.

Another large class of middleboxes intervenes to some degree at the transport layer, but attempts to be transparent (invisible) to the end-to-end connection. A subset of this class of middleboxes attempts to `normalize' the TCP wire protocol by checking that all values in header fields comply with a rather narrow interpretation of the TCP specifications. To comply with the present AccECN specification, such a middlebox MUST NOT change the ACE field or the AccECN Option and it SHOULD preserve the timing of each ACK (for example, if it coalesced ACKs it would not be AccECN-compliant) as these can be used by the Data Sender to infer further information about the path congestion level. A middlebox claiming to be transparent at the transport layer MUST forward the AccECN TCP Option unaltered, whether or not the length value matches one of those specified in Section 3.2.3, and whether or not the initial values of the byte-counter fields are correct. This is because blocking apparently invalid values does not improve security (because AccECN hosts are required to ignore invalid values anyway), while it prevents the standardized set of values being extended in future (because outdated normalizers would block updated hosts from using the extended AccECN standard).

Hardware to offload certain TCP processing represents another large class of middleboxes, even though it is often a function of a host's

network interface and rarely in its own 'box'. Leeway has been allowed in the present AccECN specification in the expectation that offload hardware could comply and still serve its function. Nonetheless, such hardware SHOULD also preserve the timing of each ACK (for example, if it coalesced ACKs it would not be AccECN-compliant).

The ACE field changes with every received CE marking, so today's

receive offloading could lead to many interrupts in high congestion situations. Although that would be useful (because congestion information is received sooner), it could also significantly increase processor load, particularly in scenarios such as DCTCP or L4S where the marking rate is generally higher.

In data centres it has been fortunate for offload hardware that DCTCP-style feedback changes less often when there are long sequences of CE marks, which is more common with a step marking threshold. In order to enable DCTCP to improve its responsiveness, DCs will need to move beyond step marking. Before this can happen, offload hardware will have to explicitly address the variability of ECN feedback.

ECN encodes a varying signal in the ACK stream, so it is inevitable that offload hardware will ultimately need to handle any form of ECN feedback exceptionally. The purpose of working towards standardized TCP ECN feedback is to reduce the risk for hardware developers, who would otherwise have to guess which scheme is likely to become dominant.

4. Updates to RFC 3168

Normative statements in the following sections of RFC3168 are updated by the present AccECN specification:

- The whole of "6.1.1 TCP Initialization" of [RFC3168] is updated by Section 3.1 of the present specification.

- In "6.1.2. The TCP Sender" of [RFC3168], all mentions of a congestion response to an ECN-Echo (ECE) ACK packet are updated by Section 3.2 of the present specification to mean an increment to the sender's count of CE-marked packets, s.cep. And the requirements to set the CWR flag no longer apply, as specified in Section 3.1.5 of the present specification. Otherwise, the remaining requirements in "6.1.2. The TCP Sender" still stand.

  It will be noted that RFC 8311 already updates, or potentially updates, a number of the requirements in "6.1.2. The TCP Sender". Section 6.1.2 of RFC 3168 extended standard TCP congestion control [RFC5681] to cover ECN marking as well as packet drop. Whereas,

RFC 8311 enables experimentation with alternative responses to ECN

marking, if specified for instance by an experimental RFC on the IETF document stream. RFC 8311 also strengthened the statement that "ECT(0) SHOULD be used" to a "MUST" (see [RFC8311] for the details).

- The whole of "6.1.3. The TCP Receiver" of [RFC3168] is updated by Section 3.2 of the present specification, with the exception of the last paragraph (about congestion response to drop and ECN in the same round trip), which still stands. Incidentally, this last paragraph is in the wrong section, because it relates to TCP sender behaviour.

- The following text within "6.1.5. Retransmitted TCP packets":

  > "the TCP data receiver SHOULD ignore the ECN field on arriving data packets that are outside of the receiver's current window."

  is updated by more stringent acceptability tests for any packet (not just data packets) in the present specification. Specifically, in the normative specification of AccECN (Section 3) only 'Acceptable' packets contribute to the ECN counters at the AccECN receiver and Section 1.3 defines an Acceptable packet as one that passes the acceptability tests in both [RFC0793] and [RFC5961].

- Sections 5.2, 6.1.1, 6.1.4, 6.1.5 and 6.1.6 of [RFC3168] prohibit use of ECN on TCP control packets and retransmissions. The present specification does not update that aspect of RFC 3168, but it does say what feedback an AccECN Data Receiver should provide if it receives an ECN-capable control packet or retransmission. This ensures AccECN is forward compatible with any future scheme that allows ECN on these packets, as provided for in section 4.3 of [RFC8311] and as proposed in [I-D.ietf-tcpm-generalized-ecn].

5. Interaction with TCP Variants

This section is informative, not normative.

5.1. Compatibility with SYN Cookies

A TCP server can use SYN Cookies (see Appendix A of [RFC4987]) to protect itself from SYN flooding attacks. It places minimal commonly used connection state in the SYN/ACK, and deliberately does not hold any state while waiting for the subsequent ACK (e.g. it closes the thread). Therefore it cannot record the fact that it entered AccECN

mode for both half-connections. Indeed, it cannot even remember whether it negotiated the use of classic ECN [RFC3168].

Nonetheless, such a server can determine that it negotiated AccECN as follows. If a TCP server using SYN Cookies supports AccECN and if it receives a pure ACK that acknowledges an ISN that is a valid SYN cookie, and if the ACK contains an ACE field with the value 0b010 to 0b111 (decimal 2 to 7), it can assume that:

- the TCP client must have requested AccECN support on the SYN
- it (the server) must have confirmed that it supported AccECN

Therefore the server can switch itself into AccECN mode, and continue as if it had never forgotten that it switched itself into AccECN mode earlier.

If the pure ACK that acknowledges a SYN cookie contains an ACE field with the value 0b000 or 0b001, these values indicate that the client did not request support for AccECN and therefore the server does not enter AccECN mode for this connection. Further, 0b001 on the ACK implies that the server sent an ECN-capable SYN/ACK, which was marked CE in the network, and the non-AccECN client fed this back by setting ECE on the ACK of the SYN/ACK.

5.2. Compatibility with TCP Experiments and Common TCP Options

AccECN is compatible (at least on paper) with the most commonly used TCP options: MSS, time-stamp, window scaling, SACK and TCP-AO. It is also compatible with the recent promising experimental TCP options TCP Fast Open (TFO [RFC7413]) and Multipath TCP (MPTCP [RFC6824]). AccECN is friendly to all these protocols, because space for TCP options is particularly scarce on the SYN, where AccECN consumes zero additional header space.

When option space is under pressure from other options, Section 3.2.3.3 provides guidance on how important it is to send an AccECN Option and whether it needs to be a full-length option.

Implementers of TFO need to take careful note of the recommendation in Section 3.2.2.1. That section recommends that, if the client has successfully negotiated AccECN, when acknowledging the SYN/ACK, even if it has data to send, it sends a pure ACK immediately before the data. Then it can reflect the IP-ECN field of the SYN/ACK on this pure ACK, which allows the server to detect ECN mangling.

5.3. Compatibility with Feedback Integrity Mechanisms

Three alternative mechanisms are available to assure the integrity of ECN and/or loss signals. AccECN is compatible with any of these approaches:

- The Data Sender can test the integrity of the receiver's ECN (or loss) feedback by occasionally setting the IP-ECN field to a value normally only set by the network (and/or deliberately leaving a sequence number gap). Then it can test whether the Data Receiver's feedback faithfully reports what it expects (similar to para 2 of Section 20.2 of [RFC3168]). Unlike the ECN Nonce [RFC3540], this approach does not waste the ECT(1) codepoint in the IP header, it does not require standardization and it does not rely on misbehaving receivers volunteering to reveal feedback information that allows them to be detected. However, setting the CE mark by the sender might conceal actual congestion feedback from the network and should therefore only be done sparingly.

- Networks generate congestion signals when they are becoming congested, so networks are more likely than Data Senders to be concerned about the integrity of the receiver's feedback of these signals. A network can enforce a congestion response to its ECN markings (or packet losses) using congestion exposure (ConEx) audit [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 neutralize any advantage that any of these three parties would otherwise gain.

  ConEx is a change to the Data Sender that is most useful when combined with AccECN. Without AccECN, the ConEx behaviour of a Data Sender would have to be more conservative than would be necessary if it had the accurate feedback of AccECN.

- The TCP authentication option (TCP-AO [RFC5925]) can be used to detect any tampering with AccECN feedback between the Data Receiver and the Data Sender (whether malicious or accidental). The AccECN fields are immutable end-to-end, so they are amenable to TCP-AO protection, which covers TCP options by default.

However, TCP-AO is often too brittle to use on many end-to-end paths, where middleboxes can make verification fail in their attempts to improve performance or security, e.g. by resegmentation or shifting the sequence space.

Originally the ECN Nonce [RFC3540] was proposed to ensure integrity of congestion feedback. With minor changes AccECN could be optimized for the possibility that the ECT(1) codepoint might be used as an ECN Nonce. However, given RFC 3540 has been reclassified as historic,

the AccECN design has been generalized so that it ought to be able to support other possible uses of the ECT(1) codepoint, such as a lower severity or a more instant congestion signal than CE.

6. Protocol Properties

This section is informative not normative. It describes how well the protocol satisfies the agreed requirements for a more accurate ECN feedback protocol [RFC7560].

Accuracy: From each ACK, the Data Sender can infer the number of new CE marked segments since the previous ACK. This provides better accuracy on CE feedback than classic ECN. In addition if the AccECN Option is present (not blocked by the network path) the number of bytes marked with CE, ECT(1) and ECT(0) are provided.

Overhead: The AccECN scheme is divided into two parts. The essential part reuses the 3 flags already assigned to ECN in the IP header. The supplementary part adds an additional TCP option consuming up to 11 bytes. However, no TCP option is consumed in the SYN.

Ordering: The order in which marks arrive at the Data Receiver is preserved in AccECN feedback, because the Data Receiver is expected to send an ACK immediately whenever a different mark arrives.

Timeliness: While the same ECN markings are arriving continually at the Data Receiver, it can defer ACKs as TCP does normally, but it will immediately send an ACK as soon as a different ECN marking arrives.

Timeliness vs Overhead: Change-Triggered ACKs are intended to enable latency-sensitive uses of ECN feedback by capturing the timing of transitions but not wasting resources while the state of the signalling system is stable. Within the constraints of the change-triggered ACK rules, the receiver can control how frequently it sends the AccECN TCP Option and therefore to some extent it can control the overhead induced by AccECN.

Resilience: All information is provided based on counters. Therefore if ACKs are lost, the counters on the first ACK following the losses allows the Data Sender to immediately recover the number of the ECN markings that it missed. And if data or ACKs are reordered, stale congestion information can be identified and ignored.

Resilience against Bias: Because feedback is based on repetition of counters, random losses do not remove any information, they only delay it. Therefore, even though some ACKs are change-triggered, random losses will not alter the proportions of the different ECN markings in the feedback.

Resilience vs Overhead: If space is limited in some segments (e.g. because more options are needed on some segments, such as the SACK option after loss), the Data Receiver can send AccECN Options less frequently or truncate fields that have not changed, usually down to as little as 5 bytes. However, it has to send a full-sized AccECN Option at least three times per RTT, which the Data Sender can rely on as a regular beacon or checkpoint.

Resilience vs Timeliness and Ordering: Ordering information and the timing of transitions cannot be communicated in three cases: i) during ACK loss; ii) if something on the path strips the AccECN Option; or iii) if the Data Receiver is unable to support Change-Triggered ACKs. Following ACK reordering, the Data Sender can reconstruct the order in which feedback was sent, but not until all the missing feedback has arrived.

Complexity: An AccECN implementation solely involves simple counter increments, some modulo arithmetic to communicate the least significant bits and allow for wrap, and some heuristics for

safety against fields cycling due to prolonged periods of ACK loss. Each host needs to maintain eight additional counters. The hosts have to apply some additional tests to detect tampering by middleboxes, but in general the protocol is simple to understand, simple to implement and requires few cycles per packet to execute.

Integrity: AccECN is compatible with at least three approaches that can assure the integrity of ECN feedback. If the AccECN Option is stripped the resolution of the feedback is degraded, but the integrity of this degraded feedback can still be assured.

Backward Compatibility: If only one endpoint supports the AccECN scheme, it will fall-back to the most advanced ECN feedback scheme supported by the other end.

Backward Compatibility: If the AccECN Option is stripped by a middlebox, AccECN still provides basic congestion feedback in the ACE field. Further, AccECN can be used to detect mangling of the IP ECN field; mangling of the TCP ECN flags; blocking of ECT-marked segments; and blocking of segments carrying the AccECN Option. It can detect these conditions during TCP's 3WHS so that it can fall back to operation without ECN and/or operation without the AccECN Option.

Forward Compatibility: The behaviour of endpoints and middleboxes is carefully defined for all reserved or currently unused codepoints in the scheme. Then, the designers of security devices can understand which currently unused values might appear in future. So, even if they choose to treat such values as anomalous while they are not widely used, any blocking will at least be under policy control not hard-coded. Then, if previously unused values start to appear on the Internet (or in standards), such policies could be quickly reversed.

7. IANA Considerations

This document reassigns bit 7 of the TCP header flags to the AccECN experiment. This bit was previously called the Nonce Sum (NS) flag [RFC3540], but RFC 3540 has been reclassified as historic [RFC8311]. The flag will now be defined as:

Bit	Name	Reference
7	AE (Accurate ECN)	RFC XXXX

[TO BE REMOVED: IANA is requested to update the existing entry in the Transmission Control Protocol (TCP) Header Flags registration (https://www.iana.org/assignments/tcp-header-flags/tcp-header-flags.xhtml#tcp-header-flags-1) for Bit 7 to "AE (Accurate ECN), previously used as NS (Nonce Sum) by [RFC3540], which is now Historic [RFC8311]" and change the reference to this RFC-to-be instead of RFC8311.]

This document also defines a new TCP option for AccECN, assigned a value of TBD1 (decimal) from the TCP option space. This value is defined as:

Kind	Length	Meaning	Reference
TBD1	N	Accurate ECN (AccECN)	RFC XXXX

[TO BE REMOVED: This registration should take place at the following location: http://www.iana.org/assignments/tcp-parameters/tcp-parameters.xhtml#tcp-parameters-1]

Early implementations using experimental option 254 per [RFC6994] with magic number 0xACCE (16 bits), as allocated in the IANA "TCP

Experimental Option Experiment Identifiers (TCP ExIDs)" registry, SHOULD migrate to use this new option kind (TBD1).

[TO BE REMOVED: The description of the 0xACCE value in the TCP ExIDs registry should be changed to "AccECN (current and new implementations SHOULD use option kind TBD1)" at the following location: https://www.iana.org/assignments/tcp-parameters/tcp-parameters.xhtml#tcp-exids]

8. Security Considerations

If ever the supplementary part of AccECN based on the new AccECN TCP Option is unusable (due for example to middlebox interference) the essential part of AccECN's congestion feedback offers only limited resilience to long runs of ACK loss (see Section 3.2.2.5). These problems are unlikely to be due to malicious intervention (because if an attacker could strip a TCP option or discard a long run of ACKs it could wreak other arbitrary havoc). However, it would be of concern if AccECN's resilience could be indirectly compromised during a flooding attack. AccECN is still considered safe though, because if the option is not presented, the AccECN Data Sender is then required to switch to more conservative assumptions about wrap of congestion indication counters (see Section 3.2.2.5 and Appendix A.2).

Section 5.1 describes how a TCP server can negotiate AccECN and use the SYN cookie method for mitigating SYN flooding attacks.

There is concern that ECN markings could be altered or suppressed, particularly because a misbehaving Data Receiver could increase its own throughput at the expense of others. AccECN is compatible with the three schemes known to assure the integrity of ECN feedback (see Section 5.3 for details). If the AccECN Option is stripped by an incorrectly implemented middlebox, the resolution of the feedback will be degraded, but the integrity of this degraded information can still be assured.

There is a potential concern that a receiver could deliberately omit the AccECN Option pretending that it had been stripped by a middlebox. No known way can yet be contrived to take advantage of this downgrade attack, but it is mentioned here in case someone else can contrive one.

The AccECN protocol is not believed to introduce any new privacy concerns, because it merely counts and feeds back signals at the transport layer that had already been visible at the IP layer.

9. Acknowledgements

We want to thank Koen De Schepper, Praveen Balasubramanian, Michael Welzl, Gorry Fairhurst, David Black, Spencer Dawkins, Michael Scharf,

Michael Tuexen, Yuchung Cheng, Kenjiro Cho, Olivier Tilmans and Ilpo Jaervinen for their input and discussion. The idea of using the three ECN-related TCP flags as one field for more accurate TCP-ECN feedback was first introduced in the re-ECN protocol that was the ancestor of ConEx.

Bob Briscoe was part-funded by the Comcast Innovation Fund, the European Community under its Seventh Framework Programme through the Reducing Internet Transport Latency (RITE) project (ICT-317700) and through the Trilogy 2 project (ICT-317756), and the Research Council of Norway through the TimeIn project. The views expressed here are solely those of the authors.

Mirja Kuehlewind was partly supported by the European Commission under Horizon 2020 grant agreement no. 688421 Measurement and Architecture for a Middleboxed Internet (MAMI), and by the Swiss State Secretariat for Education, Research, and Innovation under contract no. 15.0268. This support does not imply endorsement.

10. Comments Solicited

Comments and questions are encouraged and very welcome. They can be addressed to the IETF TCP maintenance and minor modifications working group mailing list <tcpm@ietf.org>, and/or to the authors.

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Appendix A. Example Algorithms

This appendix is informative, not normative. It gives example algorithms that would satisfy the normative requirements of the AccECN protocol. However, implementers are free to choose other ways to implement the requirements.

A.1. Example Algorithm to Encode/Decode the AccECN Option

The example algorithms below show how a Data Receiver in AccECN mode could encode its CE byte counter r.ceb into the ECEB field within the AccECN TCP Option, and how a Data Sender in AccECN mode could decode the ECEB field into its byte counter s.ceb. The other counters for bytes marked ECT(0) and ECT(1) in the AccECN Option would be similarly encoded and decoded.

It is assumed that each local byte counter is an unsigned integer greater than 24b (probably 32b), and that the following constant has been assigned:

DIVOPT = 2^24

Every time a CE marked data segment arrives, the Data Receiver increments its local value of r.ceb by the size of the TCP Data. Whenever it sends an ACK with the AccECN Option, the value it writes into the ECEB field is

```
   ECEB = r.ceb % DIVOPT
```

where '%' is the remainder operator.

On the arrival of an AccECN Option, the Data Sender first makes sure the ACK has not been superseded in order to avoid winding the s.ceb counter backwards. It uses the TCP acknowledgement number and any SACK options to calculate newlyAckedB, the amount of new data that the ACK acknowledges in bytes (newlyAckedB can be zero but not negative). If newlyAckedB is zero, either the ACK has been superseded or CE-marked packet(s) without data could have arrived. To break the tie for the latter case, the Data Sender could use timestamps (if present) to work out newlyAckedT, the amount of new time that the ACK acknowledges. If the Data Sender determines that the ACK has been superseded it ignores the AccECN Option. Otherwise, the Data Sender calculates the minimum non-negative difference d.ceb between the ECEB field and its local s.ceb counter, using modulo arithmetic as follows:


```
   if ((newlyAckedB > 0) || (newlyAckedT > 0)) {
       d.ceb = (ECEB + DIVOPT - (s.ceb % DIVOPT)) % DIVOPT
       s.ceb += d.ceb
   }
```

For example, if s.ceb is 33,554,433 and ECEB is 1461 (both decimal), then

```
   s.ceb % DIVOPT = 1
         d.ceb = (1461 + 2^24 - 1) % 2^24
               = 1460
         s.ceb = 33,554,433 + 1460
               = 33,555,893
```

A.2. Example Algorithm for Safety Against Long Sequences of ACK Loss

The example algorithms below show how a Data Receiver in AccECN mode could encode its CE packet counter r.cep into the ACE field, and how the Data Sender in AccECN mode could decode the ACE field into its

s.cep counter. The Data Sender's algorithm includes code to heuristically detect a long enough unbroken string of ACK losses that could have concealed a cycle of the congestion counter in the ACE field of the next ACK to arrive.

Two variants of the algorithm are given: i) a more conservative variant for a Data Sender to use if it detects that the AccECN Option is not available (see Section 3.2.2.5 and Section 3.2.3.2); and ii) a less conservative variant that is feasible when complementary information is available from the AccECN Option.

A.2.1. Safety Algorithm without the AccECN Option

It is assumed that each local packet counter is a sufficiently sized unsigned integer (probably 32b) and that the following constant has been assigned:

```
DIVACE = 2^3
```

Every time an Acceptable CE marked packet arrives (Section 3.2.2.2), the Data Receiver increments its local value of r.cep by 1. It repeats the same value of ACE in every subsequent ACK until the next CE marking arrives, where

```
ACE = r.cep % DIVACE.
```

If the Data Sender received an earlier value of the counter that had been delayed due to ACK reordering, it might incorrectly calculate that the ACE field had wrapped. Therefore, on the arrival of every

ACK, the Data Sender ensures the ACK has not been superseded using the TCP acknowledgement number, any SACK options and timestamps (if available) to calculate newlyAckedB, as in Appendix A.1. If the ACK has not been superseded, the Data Sender calculates the minimum difference d.cep between the ACE field and its local s.cep counter, using modulo arithmetic as follows:

```
if ((newlyAckedB > 0) || (newlyAckedT > 0))
    d.cep = (ACE + DIVACE - (s.cep % DIVACE)) % DIVACE
```

Section 3.2.2.5 expects the Data Sender to assume that the ACE field cycled if it is the safest likely case under prevailing conditions.

The 3-bit ACE field in an arriving ACK could have cycled and become ambiguous to the Data Sender if a row of ACKs goes missing that covers a stream of data long enough to contain 8 or more CE marks. We use the word `missing' rather than `lost', because some or all the missing ACKs might arrive eventually, but out of order. Even if some of the missing ACKs were piggy-backed on data (i.e. not pure ACKs) retransmissions will not repair the lost AccECN information, because AccECN requires retransmissions to carry the latest AccECN counters, not the original ones.

The phrase `under prevailing conditions' allows for implementation-dependent interpretation. A Data Sender might take account of the prevailing size of data segments and the prevailing CE marking rate just before the sequence of missing ACKs. However, we shall start with the simplest algorithm, which assumes segments are all full-sized and ultra-conservatively it assumes that ECN marking was 100% on the forward path when ACKs on the reverse path started to all be dropped. Specifically, if newlyAckedB is the amount of data that an ACK acknowledges since the previous ACK, then the Data Sender could assume that this acknowledges newlyAckedPkt full-sized segments, where newlyAckedPkt = newlyAckedB/MSS. Then it could assume that the ACE field incremented by

    dSafer.cep = newlyAckedPkt - ((newlyAckedPkt - d.cep) % DIVACE),

For example, imagine an ACK acknowledges newlyAckedPkt=9 more full-size segments than any previous ACK, and that ACE increments by a minimum of 2 CE marks (d.cep=2). The above formula works out that it would still be safe to assume 2 CE marks (because 9 - ((9-2) % 8) = 2). However, if ACE increases by a minimum of 2 but acknowledges 10 full-sized segments, then it would be necessary to assume that there could have been 10 CE marks (because 10 - ((10-2) % 8) = 10).

ACKs that acknowledge a large stretch of packets might be common in data centres to achieve a high packet rate or might be due to ACK thinning by a middlebox. In these cases, cycling of the ACE field

would often appear to have been possible, so the above algorithm would be over-conservative, leading to a false high marking rate and poor performance. Therefore it would be reasonable to only use dSafer.cep rather than d.cep if the moving average of newlyAckedPkt was well below 8.

Implementers could build in more heuristics to estimate prevailing average segment size and prevailing ECN marking. For instance, newlyAckedPkt in the above formula could be replaced with newlyAckedPktHeur = newlyAckedPkt*p*MSS/s, where s is the prevailing segment size and p is the prevailing ECN marking probability. However, ultimately, if TCP's ECN feedback becomes inaccurate it still has loss detection to fall back on. Therefore, it would seem safe to implement a simple algorithm, rather than a perfect one.

The simple algorithm for dSafer.cep above requires no monitoring of prevailing conditions and it would still be safe if, for example, segments were on average at least 5% of full-sized as long as ECN marking was 5% or less. Assuming it was used, the Data Sender would increment its packet counter as follows:

```
s.cep += dSafer.cep
```

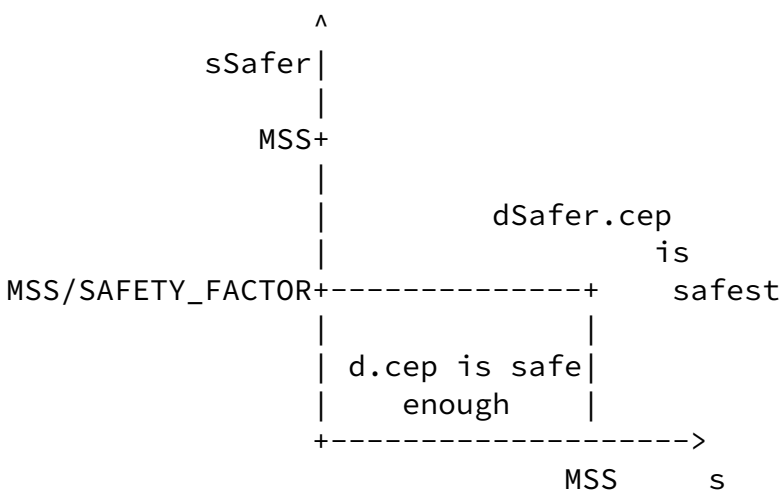
If missing acknowledgement numbers arrive later (due to reordering), Section 3.2.2.5 says "the Data Sender MAY attempt to neutralize the effect of any action it took based on a conservative assumption that it later found to be incorrect". To do this, the Data Sender would have to store the values of all the relevant variables whenever it made assumptions, so that it could re-evaluate them later. Given this could become complex and it is not required, we do not attempt to provide an example of how to do this.

A.2.2. Safety Algorithm with the AccECN Option

When the AccECN Option is available on the ACKs before and after the possible sequence of ACK losses, if the Data Sender only needs CE-marked bytes, it will have sufficient information in the AccECN Option without needing to process the ACE field. If for some reason it needs CE-marked packets, if dSafer.cep is different from d.cep, it can determine whether d.cep is likely to be a safe enough estimate by checking whether the average marked segment size (s = d.ceb/d.cep) is less than the MSS (where d.ceb is the amount of newly CE-marked bytes - see Appendix A.1). Specifically, it could use the following algorithm:

```
   SAFETY_FACTOR = 2
   if (dSafer.cep > d.cep) {
       if (d.ceb <= MSS * d.cep) {  % Same as (s <= MSS), but no DBZ
          sSafer = d.ceb/dSafer.cep
          if (sSafer < MSS/SAFETY_FACTOR)
              dSafer.cep = d.cep    % d.cep is a safe enough estimate
       } % else
           % No need for else; dSafer.cep is already correct,
           % because d.cep must have been too small
   }
```

The chart below shows when the above algorithm will consider d.cep can replace dSafer.cep as a safe enough estimate of the number of CE-marked packets:



The following examples give the reasoning behind the algorithm, assuming MSS=1460 [B]:

- if d.cep=0, dSafer.cep=8 and d.ceb=1460, then s=infinity and sSafer=182.5.
  Therefore even though the average size of 8 data segments is unlikely to have been as small as MSS/8, d.cep cannot have been correct, because it would imply an average segment size greater than the MSS.

- if d.cep=2, dSafer.cep=10 and d.ceb=1460, then s=730 and sSafer=146.
  Therefore d.cep is safe enough, because the average size of 10 data segments is unlikely to have been as small as MSS/10.

- if d.cep=7, dSafer.cep=15 and d.ceb=10200, then s=1457 and sSafer=680.

Therefore d.cep is safe enough, because the average data segment size is more likely to have been just less than one MSS, rather than below MSS/2.

If pure ACKs were allowed to be ECN-capable, missing ACKs would be far less likely. However, because [RFC3168] currently precludes this, the above algorithm assumes that pure ACKs are not ECN-capable.

A.3. Example Algorithm to Estimate Marked Bytes from Marked Packets

If the AccECN Option is not available, the Data Sender can only decode CE-marking from the ACE field in packets. Every time an ACK arrives, to convert this into an estimate of CE-marked bytes, it needs an average of the segment size, s_ave. Then it can add or subtract s_ave from the value of d.ceb as the value of d.cep increments or decrements. Some possible ways to calculate s_ave are outlined below. The precise details will depend on why an estimate of marked bytes is needed.

The implementation could keep a record of the byte numbers of all the boundaries between packets in flight (including control packets), and recalculate s_ave on every ACK. However it would be simpler to merely maintain a counter packets_in_flight for the number of packets in flight (including control packets), which is reset once per RTT. Either way, it would estimate s_ave as:

```
s_ave ~= flightsize / packets_in_flight,
```

where flightsize is the variable that TCP already maintains for the number of bytes in flight. To avoid floating point arithmetic, it could right-bit-shift by lg(packets_in_flight), where lg() means log base 2.

An alternative would be to maintain an exponentially weighted moving average (EWMA) of the segment size:

```
s_ave = a * s + (1-a) * s_ave,
```

where a is the decay constant for the EWMA. However, then it is necessary to choose a good value for this constant, which ought to depend on the number of packets in flight. Also the decay constant needs to be power of two to avoid floating point arithmetic.

A.4. Example Algorithm to Beacon AccECN Options

Section 3.2.3.3 requires a Data Receiver to beacon a full-length AccECN Option at least 3 times per RTT. This could be implemented by maintaining a variable to store the number of ACKs (pure and data

ACKs) since a full AccECN Option was last sent and another for the approximate number of ACKs sent in the last round trip time:

```
if (acks_since_full_last_sent > acks_in_round / BEACON_FREQ)
    send_full_AccECN_Option()
```

For optimized integer arithmetic, BEACON_FREQ = 4 could be used, rather than 3, so that the division could be implemented as an integer right bit-shift by lg(BEACON_FREQ).

In certain operating systems, it might be too complex to maintain acks_in_round. In others it might be possible by tagging each data segment in the retransmit buffer with the number of ACKs sent at the point that segment was sent. This would not work well if the Data Receiver was not sending data itself, in which case it might be necessary to beacon based on time instead, as follows:

```
if ( time_now > time_last_option_sent + (RTT / BEACON_FREQ) )
    send_full_AccECN_Option()
```

This time-based approach does not work well when all the ACKs are sent early in each round trip, as is the case during slow-start. In this case few options will be sent (evtl. even less than 3 per RTT). However, when continuously sending data, data packets as well as ACKs will spread out equally over the RTT and sufficient ACKs with the AccECN option will be sent.

A.5. Example Algorithm to Count Not-ECT Bytes

A Data Sender in AccECN mode can infer the amount of TCP payload data arriving at the receiver marked Not-ECT from the difference between the amount of newly ACKed data and the sum of the bytes with the other three markings, d.ceb, d.e0b and d.e1b. Note that, because r.e0b is initialized to 1 and the other two counters are initialized to 0, the initial sum will be 1, which matches the initial offset of

the TCP sequence number on completion of the 3WHS.

For this approach to be precise, it has to be assumed that spurious (unnecessary) retransmissions do not lead to double counting. This assumption is currently correct, given that RFC 3168 requires that the Data Sender marks retransmitted segments as Not-ECT. However, the converse is not true; necessary retransmissions will result in under-counting.

However, such precision is unlikely to be necessary. The only known use of a count of Not-ECT marked bytes is to test whether equipment on the path is clearing the ECN field (perhaps due to an out-dated attempt to clear, or bleach, what used to be the ToS field). To

detect bleaching it will be sufficient to detect whether nearly all bytes arrive marked as Not-ECT. Therefore there should be no need to keep track of the details of retransmissions.

Appendix B. Rationale for Usage of TCP Header Flags

B.1. Three TCP Header Flags in the SYN-SYN/ACK Handshake

AccECN uses a rather unorthodox approach to negotiate the highest version TCP ECN feedback scheme that both ends support, as justified below. It follows from the original TCP ECN capability negotiation [RFC3168], in which the client set the 2 least significant of the original reserved flags in the TCP header, and fell back to no ECN support if the server responded with the 2 flags cleared, which had previously been the default.

ECN originally used header flags rather than a TCP option because it was considered more efficient to use a header flag for 1 bit of feedback per ACK, and this bit could be overloaded to indicate support for ECN during the handshake. During the development of ECN, 1 bit crept up to 2, in order to deliver the feedback reliably and to work round some broken hosts that reflected the reserved flags during the handshake.

In order to be backward compatible with RFC 3168, AccECN continues this approach, using the 3rd least significant TCP header flag that had previously been allocated for the ECN nonce (now historic). Then, whatever form of server an AccECN client encounters, the

connection can fall back to the highest version of feedback protocol that both ends support, as explained in Section 3.1.

If AccECN had used the more orthodox approach of a TCP option, it would still have had to set the two ECN flags in the main TCP header, in order to be able to fall back to Classic RFC 3168 ECN, or to disable ECN support, without another round of negotiation. Then AccECN would also have had to handle all the different ways that servers currently respond to settings of the ECN flags in the main TCP header, including all the conflicting cases where a server might have said it supported one approach in the flags and another approach in the new TCP option. And AccECN would have had to deal with all the additional possibilities where a middlebox might have mangled the ECN flags, or removed the TCP option. Thus, usage of the 3rd reserved TCP header flag simplified the protocol.

The third flag was used in a way that could be distinguished from the ECN nonce, in case any nonce deployment was encountered. Previous usage of this flag for the ECN nonce was integrated into the original ECN negotiation. This further justified the 3rd flag's use for

AccECN, because a non-ECN usage of this flag would have had to use it as a separate single bit, rather than in combination with the other 2 ECN flags.

Indeed, having overloaded the original uses of these three flags for its handshake, AccECN overloads all three bits again as a 3-bit counter.

B.2. Four Codepoints in the SYN/ACK

Of the 8 possible codepoints that the 3 TCP header flags can indicate on the SYN/ACK, 4 already indicated earlier (or broken) versions of ECN support. In the early design of AccECN, an AccECN server could use only 2 of the 4 remaining codepoints. They both indicated AccECN support, but one fed back that the SYN had arrived marked as CE. Even though ECN support on a SYN is not yet on the standards track, the idea is for either end to act as a dumb reflector, so that future capabilities can be unilaterally deployed without requiring 2-ended deployment (justified in Section 2.5).

During traversal testing it was discovered that the ECN field in the

SYN was mangled on a non-negligible proportion of paths. Therefore it was necessary to allow the SYN/ACK to feed all four IP/ECN codepoints that the SYN could arrive with back to the client. Without this, the client could not know whether to disable ECN for the connection due to mangling of the IP/ECN field (also explained in Section 2.5). This development consumed the remaining 2 codepoints on the SYN/ACK that had been reserved for future use by AccECN in earlier versions.

B.3. Space for Future Evolution

Despite availability of usable TCP header space being extremely scarce, the AccECN protocol has taken all possible steps to ensure that there is space to negotiate possible future variants of the protocol, either if the experiment proves that a variant of AccECN is required, or if a completely different ECN feedback approach is needed:

Future AccECN variants: When the AccECN capability is negotiated during TCP's 3WHS, the rows in Table 2 tagged as 'Nonce' and 'Broken' in the column for the capability of node B are unused by any current protocol in the RFC series. These could be used by TCP servers in future to indicate a variant of the AccECN protocol. In recent measurement studies in which the response of large numbers of servers to an AccECN SYN has been tested, e.g. [Mandalari18], a very small number of SYN/ACKs arrive with the pattern tagged as 'Nonce', and a small but more significant number

arrive with the pattern tagged as 'Broken'. The 'Nonce' pattern could be a sign that a few servers have implemented the ECN Nonce [RFC3540], which has now been reclassified as historic [RFC8311], or it could be the random result of some unknown middlebox behaviour. The greater prevalence of the 'Broken' pattern suggests that some instances still exist of the broken code that reflects the reserved flags on the SYN.

The requirement not to reject unexpected initial values of the ACE counter (in the main TCP header) in the last para of Section 3.2.2.3 ensures that 3 unused codepoints on the ACK of the SYN/ACK, 6 unused values on the first SYN=0 data packet from the client and 7 unused values on the first SYN=0 data packet from the server could be used to declare future variants of the AccECN

protocol. The word 'declare' is used rather than 'negotiate' because, at this late stage in the 3WHS, it would be too late for a negotiation between the endpoints to be completed. A similar requirement not to reject unexpected initial values in the TCP option (Section 3.2.3.2.4) is for the same purpose. If traversal of the TCP option were reliable, this would have enabled a far wider range of future variation of the whole AccECN protocol. Nonetheless, it could be used to reliably negotiate a wide range of variation in the semantics of the AccECN Option.

Future non-AccECN variants: Five codepoints out of the 8 possible in the 3 TCP header flags used by AccECN are unused on the initial SYN (in the order AE,CWR,ECE): 001, 010, 100, 101, 110. Section 3.1.3 ensures that the installed base of AccECN servers will all assume these are equivalent to AccECN negotiation with 111 on the SYN. These codepoints would not allow fall-back to Classic ECN support for a server that did not understand them, but this approach ensures they are available in future, perhaps for uses other than ECN alongside the AccECN scheme. All possible combinations of SYN/ACK could be used in response except either 000 or reflection of the same values sent on the SYN.

Of course, other ways could be resorted to in order to extend AccECN or ECN in future, although their traversal properties are likely to be inferior. They include a new TCP option; using the remaining reserved flags in the main TCP header (preferably extending the 3-bit combinations used by AccECN to 4-bit combinations, rather than burning one bit for just one state); a non-zero urgent pointer in combination with the URG flag cleared; or some other unexpected combination of fields yet to be invented.

Authors' Addresses

Bob Briscoe
Independent
UK

EMail: ietf@bobbriscoe.net

URI: http://bobbriscoe.net/

Mirja Kuehlewind
Ericsson
Germany

EMail: ietf@kuehlewind.net

Richard Scheffenegger
NetApp
Vienna
Austria

EMail: Richard.Scheffenegger@netapp.com