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Network coding for satellite systems
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Abstract

This document is the product of the Coding for Efficient Network Communications Research Group (NWCRG). It conforms to the directions found in the NWCRG taxonomy [RFC8406]. Thus, the scope of the document is network coding as a linear combination of packets in and above the network layer. Physical and MAC layer coding are beyond the scope of the document. The draft focuses on a multi-gateway satellite system and identifies the use-cases where network coding provides significant performance improvements. The objective is to contribute to a larger deployment of network coding techniques in SATCOM to complement already implemented loss recovery mechanisms. The draft also identifies open research issues related to the deployment of network coding in SATCOM systems.

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1. Introduction

This document is the product of and represents the collaborative work and consensus of the Coding for Efficient Network Communications Research Group (NWCRG); while it is not an IETF product and not a standard it intends to inform the SATCOM and Internet research communities about recent developments in Network Coding. A glossary is proposed in Section 6 to clarify the terminology use throughout the document.

As will be shown in this draft, the implementation of network coding techniques above the network layer of the ISO model, at application or transport layers, offers an opportunity for improving the end-to-end performance of SATCOM systems. While physical- and link-layer coding error protection is usually enough to provide Quasi-Error Free transmission thus minimizing packet loss, when the physical and link layers coding fail or that residual errors create packet losses that greatly interfere with Internet protocols, retransmissions add significant delays because especially in geostationary system with over 0.7 second round-trip delays. Hence the use of network coding at the upper layers can improve the quality of service in SATCOM subnetworks and eventually favorably impact the experience of end users.

While there is an active research Community working on network coding techniques above the network layer in general and in SATCOM in particular, not much of this work made it to commercial systems in the satellite industry. In this context, this document aims at identifying opportunities for further usage of network coding in commercial SATCOM networks.

The notation used in this document is based on the NWCRG taxonomy [RFC8406]:

- Channel and link error correcting codes are considered part of the PHY layer error protection and are out of the scope of this document.

- FEC (also called Application-Level FEC) operates in and above the network layer and targets packet loss recovery.

- This document considers only coding (or coding techniques or coding schemes) that use a linear combination of packets and excludes for example content coding (e.g., to compress a video flow) or other non-linear operation.

2. A Note on Satellite Networks Topology

There are multiple SATCOM systems, for example broadcast TV, point to point communication or IoT and monitoring. Therefore, depending on the purpose of the system, the associated ground segments architecture will be different. This section focuses on a satellite system that follows the ETSI DVB standards to provide broadband Internet access via ground-based gateways. One must note that the overall data capacity of one satellite may be higher than the capacity that one single gateway support. Hence, there are usually multiple gateways for one unique satellite platform.

In this context, Figure 1 shows an example of a multi-gateway satellite system. More information on a generic SATCOM ground segment architecture for bidirectional Internet access can be found in [SAT2017].

```
+--------------------------+
| application servers      |
| (data, coding, multicast)|
+--------------------------+
       | ... |
       -----------------------------------
       |     |   |             |   |     |
+--------------------+     +--------------------+
| network function   |     | network function   |
|(firewall, PEP, etc)|     |(firewall, PEP, etc)|
+--------------------+     +--------------------+
    | ... | IP packets             |  ...   |
                                                ---
+------------------+         +------------------+ |
| access gateway   |         | access gateway   | |
+------------------+         +------------------+ |
       | BBFRAME                         |        | gateway
+------------------+         +------------------+ |
| physical gateway |         | physical gateway | |
+------------------+         +------------------+ |
                                                ---
       | PLFRAME                         |
+------------------+         +------------------+
| outdoor unit     |         | outdoor unit     |
+------------------+         +------------------+
       | satellite link                  |
+------------------+         +------------------+
| outdoor unit     |         | outdoor unit     |
+------------------+         +------------------+
       |                                 |
+------------------+         +------------------+
| sat terminals    |         | sat terminals    |
+------------------+         +------------------+
       |        |                  |        |
+----------+    |            +----------+   |
|end user 1|    |            |end user 3|   |
+----------+    |            +----------+   |
          +----------+               +----------+
          |end user 2|               |end user 4|
          +----------+               +----------+
```

Figure 1: Data plane functions in a generic satellite multi-gateway system. More details can be found in DVB standard documents.

3. Use-cases for Improving SATCOM System Performance Using Network Coding

This section details use-cases where network coding techniques could improve SATCOM system performance.

3.1. Two-way Relay Channel Mode

This use-case considers two-way communication between end-users, through a satellite link as seen in Figure 2.

Satellite terminal A sends a packet flow A and satellite terminal B sends a packet flow B to a coding server. The coding server then sends a combination of both flows instead of each individual flows. This results in non-negligible capacity savings that has been demonstrated in the past [ASMS2010]. In the example, a dedicated coding server is introduced (note that its location could be different based on deployment use-case). The network coding operations could also be done at the satellite level, although this would require a lot of computational resource on-board and may not be supported by today's satellites.

```
-X}-   : traffic from satellite terminal X to the server
={X+Y= : traffic from X and Y combined sent from
            the server to terminals X and Y

+-----------+        +-----+
|Sat term A |--A}-+  |     |
+-----------+     |  |     |      +---------+      +------+
    ^^            +--|     |--A}--|         |--A}--|Coding|
    ||               | SAT |--B}--| Gateway |--B}--|Server|
    ===={A+B=========|     |={A+B=|         |={A+B=|      |
    ||               |     |      +---------+      +------+
    vv            +--|     |
+-----------+     |  |     |
|Sat term B |--B}-+  |     |
+-----------+        +-----+
```

Figure 2: Network Architecture for Two-way Relay Channel using NC

3.2. Reliable Multicast

The use of multicast servers is one way to better utilize a satellite broadcast capabilities. Multicast is proposed in the SHINE ESA project [I-D.vazquez-nfvrg-netcod-function-virtualization] [SHINE]. This use-case considers adding redundancy to a multicast flow depending on what has been received by different end-users, resulting

in non-negligible savings of the scarce SATCOM resources. This scenario is shown in Figure 3.

```
-Li}- : packet indicating the loss of packet i of a multicast flow M
={M== : multicast flow including the missing packets

+-----------+       +-----+
|Sat term A |-Li}-+ |     |
+-----------+     | |     |      +---------+  +------+
    ^^            +-|     |-Li}--|         |  |Multi |
    ||              | SAT |-Lj}--| Gateway |--|Cast  |
    ===={M==========|     |={M===|         |  |Server|
    ||              |     |      +---------+  +------+
    vv            +-|     |
+-----------+     | |     |
|Sat term B |-Lj}-+ |     |
+-----------+       +-----+
```

Figure 3: Network Architecture for a Reliable Multicast using NC

A multicast flow (M) is forwarded to both satellite terminals A and B. However packet Ni (respectively Nj) gets lost at terminal A (respectively B), and terminal A (respectively B) returns a negative acknowledgment Li (respectively Lj), indicating that the packet is missing. Using NC, either the access gateway or the multicast server can include a repair packet (rather than the individual Ni and Nj packets) in the multicast flow to let both terminals recover from losses.

This could also be achieved by using other multicast or broadcast systems, such as NACK-Oriented Reliable Multicast (NORM) [RFC5740] or File Delivery over Unidirectional Transport (FLUTE) [RFC6726]. Both NORM and FLUTE are limited to block coding, none of them supporting more flexible sliding window encoding schemes that allow decoding before receiving the whole block an added delay benefit [RFC8406].

3.3. Hybrid Access

This use-case considers improving multiple path communications with network coding at the transport layer (see Figure 4). This use-case is inspired by the Broadband Access via Integrated Terrestrial Satellite Systems (BATS) project and has been published as an ETSI Technical Report [ETSITR2017].

To cope with packet loss (due to either end-user mobility or physical-layer residual errors), network coding can be introduced both at the CPE and at the concentrator. Apart from packet losses, other gains from this approach include a better tolerance to out-of-

order packet delivery which occur when exploited links exhibit high asymmetry in terms of RTT. Depending on the ground architecture [I-D.chin-nfvrg-cloud-5g-core-structure-yang] [SAT2017], some ground equipment might be hosting both SATCOM and cellular network functionality.

```
-{}- : bidirectional link

                        +---+    +---------------+
                   +-{}-|SAT|-{}-|BACKBONE       |
+-----+   +---+    |    +---+    |+-------------+|
|End  |-{}-|CPE|-{}-|             ||CONCENTRATOR||
|User|    +---+    |    +---+    |+-------------+|    +-----------+
+-----+            |-{}-|DSL|-{}-|               |-{}-|Application|
                   |    +---+    |               |    |Server     |
                   |             |               |    +-----------+
                   |    +---+    |               |
                   +-{}-|LTE|-{}-+---------------+
                        +---+
```

Figure 4: Network Architecture for a Hybrid Access Using Network Coding

3.4. LAN Packet Losses

This use-case considers using network coding in the scenario where a lossy WIFI link is used to connect to the SATCOM network. When encrypted end-to-end applications based on UDP are used, a PEP cannot operate hence other mechanism need to be used. The WIFI packet losses will result in an end-to-end retransmission that will harm the end-user quality of experience and poorly utilize SATCOM bottleneck resource for non-revenue generating traffic. In this use-case, adding network coding techniques will prevent the end-to-end retransmission from occurring since the packet losses will be recovered.

The architecture is shown in Figure 5.

```
 -{}- : bidirectional link
 -''- : Wi-Fi link
 C : where network coding techniques could be introduced

 +----+    +---------+    +---+    +--------+    +-------+    +--------+
 |End |    |Satellite|    |SAT|    |Physical|    |Access |    |Network |
 |user|-''-|Terminal |-{}-|   |-{}-|Gateway |-{}-|Gateway|-{}-|Function|
 +----+    +---------+    +---+    +--------+    +-------+    +--------+
    C                       C            C           C
```

Figure 5: Network Architecture for dealing with LAN Losses

3.5. Varying Channel Conditions

This use-case considers the usage of network coding to cope with sub second physical channel condition changes where the physical-layer mechanisms (Adaptive Coding and Modulation (ACM)) may not adapt the modulation and error-correction coding in time: the residual errors lead to higher layer packet losses that can be recovered with network coding. This use-case is mostly relevant when mobile users are considered or when the satellite frequency band introduces quick changes in channel condition (Q/V bands, Ka band, etc.). Depending on the use-case (e.g., very high frequency bands, mobile users) or depending on the deployment use-cases (e.g., performance of the network between each individual data block), the relevance of adding network coding is different.

The system architecture is shown in Figure 6.

```
-{}- : bidirectional link
C : where network coding techniques could be introduced

+---------+    +---+    +--------+    +-------+    +--------+
|Satellite|    |SAT|    |Physical|    |Access |    |Network |
|Terminal |-{}-|   |-{}-|Gateway |-{}-|Gateway|-{}-|Function|
+---------+    +---+    +--------+    +-------+    +--------+
     C                       C            C           C
```

Figure 6: Network Architecture for dealing with Varying Link Characteristics

3.6. Improving Gateway Handover

This use-case considers the recovery of packets that may be lost during gateway handover. Whether for off-loading a given equipment or because the transmission quality differs from gateway to gateway, switching the transmission gateway may be beneficial. However, packet losses can occur if the gateways are not properly synchronized

or if the algorithm used to trigger gateway handover is not properly tuned. During these critical phases, network coding can be added to improve the reliability of the transmission and allow a seamless gateway handover.

Figure 7 illustrates this use-case.

```
-{}- : bidirectional link
!    : management interface
C : where network coding techniques could be introduced
                                        C             C
                      +--------+    +-------+    +--------+
                      |Physical|    |Access |    |Network |
                 +-{}-|gateway |-{}-|gateway|-{}-|function|
                 |    +--------+    +-------+    +--------+
                 |                         !       !
+---------+    +---+               +---------------+
|Satellite|    |SAT|               | Control plane |
|Terminal |-{}-|   |               | manager       |
+---------+    +---+               +---------------+
                 |                         !       !
                 |    +--------+    +-------+    +--------+
                 +-{}-|Physical|-{}-|Access |-{}-|Network |
                      |gateway |    |gateway|    |function|
                      +--------+    +-------+    +--------+
                                        C             C
```

Figure 7: Network Architecture for dealing with Gateway Handover

4. Research Challenges

This section proposes a few potential approaches to introduce and use network coding in SATCOM systems.

4.1. Joint-use of Network Coding and Congestion Control in SATCOM Systems

Many SATCOM systems typically use Performance Enhancing Proxy (PEP) RFC 3135 [RFC3135]. PEPs usually split end-to-end connections and forward transport or application layer packets to the satellite baseband gateway that deals with layer-2 and layer-1 encapsulation. PEPs contribute to mitigate congestion in a SATCOM systems by limiting the impact of long delays on Internet protocols. A PEP mechanism could also include network coding operation and thus support the use-cases that have been discussed in the Section 3 of this document.

Deploying network coding in the PEP could be relevant and be independent from the specifics of a SATCOM link. This however leads to research questions dealing with the potential interaction between network coding and congestion control.

4.2. Efficient Use of Satellite Resources

There is a recurrent trade-off in SATCOM systems: how much overhead from redundant reliability packets can be introduced to guarantee a better end-user QoE while optimizing capacity usage ? At which layer this supplementary redundancy should be added ?

This problem has been tackled in the past by the deployment of physical-layer error-correction codes, but there remains questions on adapting the coding overhead and added delay for, e.g., the quickly varying channel conditions use-case where ACM may not be reacting quickly enough as was discussed on the previous section.

4.3. Interaction with Virtualized Satellite Gateways and Terminals

In the emerging virtualized network infrastructure, network coding could be easily deployed as a VNF. The next generation of SATCOM ground segments will rely on a virtualized environment to integrate to terrestrial networks. This trend towards NFV is also central to 5G and next generation cellular networks, making this research applicable to other deployment scenarios [I-D.chin-nfvrg-cloud-5g-core-structure-yang]. As one example, the network coding VNF deployment in a virtualized environment has been presented in [I-D.vazquez-nfvrg-netcod-function-virtualization].

A research challenge would be the optimization of the NFV service function chaining, considering a virtualized infrastructure and other SATCOM specific functions, in order to guarantee efficient radio-link usage and provide easy-to-deploy SATCOM services. Moreover, another challenge related to a virtualized SATCOM equipment is the management of limited buffered capacities in large gateways.

4.4. Delay/Disruption Tolerant Networks

Communications among deep-space platforms and terrestrial gateways can be a challenge. Reliable end-to-end (E2E) communications over such paths must cope with very long delays and frequent link disruptions; indeed, E2E connectivity may be available only intermittently. Delay/Disruption Tolerant Networking [RFC4838] is a solution to enable reliable internetworking space communications where both standard ad-hoc routing and E2E Internet protocols cannot be used. Moreover, DTN can also be seen as an alternative solution to transfer data between a central PEP and a remote PEP.

Network Coding enables E2E reliable communications over a DTN with potential adaptive re-encoding, as proposed in [THAI15]. Here, the use-cases proposed in Section 3.5 would legitimize the usage of network coding within the DTN stack to improve the physical channel utilization and minimize the effects of the E2E transmission delays. In this context, the use of packet erasure coding techniques inside a Consultative Committee for Space Data Systems (CCSDS) architecture has been specified in [CCSDS-131.5-O-1]. One research challenge remains on how such network coding can be integrated in the IETF DTN stack.

5. Conclusion

This document introduces some wide-scale network coding techniques opportunities in satellite telecommunications systems.

Even though this document focuses on satellite systems, it is worth pointing out that some scenarios proposed here may be relevant to other wireless telecommunication systems. As one example, the generic architecture proposed in Figure 1 may be mapped onto cellular networks as follows: the 'network function' block gathers some of the functions of the Evolved Packet Core subsystem, while the 'access gateway' and 'physical gateway' blocks gather the same type of functions as the Universal Mobile Terrestrial Radio Access Network. This mapping extends the opportunities identified in this draft since they may also be relevant for cellular networks.

6. Glossary

The glossary of this memo extends the glossary of the taxonomy document [RFC8406] as follows:

- ACM : Adaptive Coding and Modulation;

- BBFRAME: Base-Band FRAME - satellite communication layer 2 encapsulation work as follows: (1) each layer 3 packet is encapsulated with a Generic Stream Encapsulation (GSE) mechanism, (2) GSE packets are gathered to create BBFRAMEs, (3) BBFRAMEs contain information related to how they have to be modulated (4) BBFRAMEs are forwarded to the physical-layer;

- CPE: Customer Premises Equipment;

- COM: COMmunication;

- DSL: Digital Subscriber Line;

- DTN: Delay/Disruption Tolerant Network;

- o DVB: Digital Video Broadcasting;
- o E2E: End-to-end;
- o ETSI: European Telecommunications Standards Institute;
- o FEC: Forward Erasure Correction;
- o FLUTE: File Delivery over Unidirectional Transport;
- o IntraF: Intra-Flow Coding;
- o InterF: Inter-Flow Coding;
- o IoT: Internet of Things;
- o LTE: Long Term Evolution;
- o MPC: Multi-Path Coding;
- o NC: Network Coding;
- o NFV: Network Function Virtualization;
- o NORM: NACK-Oriented Reliable Multicast;
- o PEP: Performance Enhancing Proxy [RFC3135] - a typical PEP for satellite communications include compression, caching and TCP acceleration;
- o PLFRAME: Physical Layer FRAME - modulated version of a BBFRAME with additional information (e.g., related to synchronization);
- o QEF: Quasi-Error-Free;
- o QoE: Quality-of-Experience;
- o QoS: Quality-of-Service;
- o SAT: SATellite;
- o SATCOM: generic term related to all kinds of SATellite COMmunication systems;
- o SPC: Single-Path Coding;
- o VNF: Virtual Network Function.

7. Acknowledgements

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8. IANA Considerations

This memo includes no request to IANA.

9. Security Considerations

Security considerations are inherent to any access network, and in particular SATCOM systems. The use of FEC or Network Coding in SATCOM also comes with risks (e.g., a single corrupted redundant packet may propagate to several flows when they are protected together in an Inter-Flow coding approach, see section Section 3). However, this is not specific to the SATCOM use-case and this document does not further elaborate on it.

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