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Network Coding for Satellite Systems

Abstract

This document is a product of the Coding for Efficient Network Communications Research Group (NWCRG). It conforms to the directions found in the NWCRG taxonomy (RFC 8406).

The objective is to contribute to a larger deployment of Network Coding techniques in and above the network layer in satellite communication systems. This document also identifies open research issues related to the deployment of Network Coding in satellite communication systems.

Status of This Memo

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1. Introduction

This document is a 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 is intended to inform the SATellite COMmunication (SATCOM) and Internet research communities about recent developments in Network Coding. A glossary is included in Section 6 to clarify the terminology used throughout the document.

As will be shown in this document, the implementation of Network Coding techniques above the network layer, at application or transport layers (as described in [RFC1122]), offers an opportunity for improving the end-to-end performance of SATCOM systems. Physical- and link-layer coding error protection is usually enough to provide quasi-error-free transmission, thus minimizing packet loss. However, when residual errors at those layers cause packet losses, retransmissions add significant delays (in particular, in geostationary systems 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 has been deployed in commercial systems. In this context, this document identifies 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 error protection for the PHYsical (PHY) layer and are out of the scope of this document.

* Forward Erasure Correction (FEC) (also called "Application-Level FEC") operates above the link layer and targets packet-loss recovery.

* This document considers only coding (or coding techniques or coding schemes) that uses a linear combination of packets; it excludes, for example, content coding (e.g., to compress a video flow) or other non-linear operations.

2. A Note on the Topology of Satellite Networks

There are multiple SATCOM systems, for example, broadcast TV, point-to point-communication, and Internet of Things (IoT) monitoring. Therefore, depending on the purpose of the system, the associated ground segment architecture will be different. This section focuses on a satellite system that follows the European Telecommunications Standards Institute (ETSI) Digital Video Broadcasting (DVB) standards to provide broadband Internet access via ground-based gateways [ETSI-EN-2020]. One must note that the overall data capacity of one satellite may be higher than the capacity that one single gateway supports. Hence, there are usually multiple gateways for one unique satellite platform.

In this context, Figure 1 shows an example of a multigateway satellite system, where BBFRAME stands for "Base-Band FRAME", PLFRAME for "Physical Layer FRAME", and PEP for "Performance Enhancing Proxy". More information on a generic SATCOM ground segment architecture for bidirectional Internet access can be found in [SAT2017] or in DVB standard documents.

```
   +--------------------------+
   | 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 Multigateway System

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 flow. This results in non-negligible capacity savings, which 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 resources onboard 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 Network Coding

3.2. Reliable Multicast

The use of multicast servers is one way to better utilize satellite broadcast capabilities. As one example, satellite-based multicast is proposed in the Secure Hybrid In Network caching Environment (SHINE) project of the European Space Agency (ESA) [NETCOD-FUNCTION-VIRT] [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

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

Figure 3: Network Architecture for a Reliable Multicast Using Network Coding

A multicast flow (M) is forwarded to both satellite terminals A and B. M is composed of packets Nk (not shown in Figure 3). 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 coding, 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; neither of them supports more flexible sliding window encoding schemes that allow decoding before receiving the whole block, which is an added delay benefit [RFC8406] [RFC8681].

3.3. Hybrid Access

This use case considers improving multiple-path communications with Network Coding at the transport layer (see Figure 4, where DSL stands for "Digital Subscriber Line", LTE for "Long Term Evolution", and SAT for "SATellite"). 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 [ETSI-TR-2017].

To cope with packet loss (due to either end-user mobility or physical-layer residual errors), Network Coding can be introduced. Depending on the protocol, Network Coding could be applied at the Customer Premises Equipment (CPE), the concentrator, or both. Apart from coping with packet loss, other benefits of this approach include a better tolerance for out-of-order packet delivery, which occurs when exploited links exhibit high asymmetry in terms of Round-Trip Time (RTT). Depending on the ground architecture [5G-CORE-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 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 Performance Enhancing Proxy (PEP) cannot operate; hence, other mechanisms need to be used. The WiFi packet losses will result in an end-to-end retransmission that will harm the quality of the end user's experience and poorly utilize SATCOM bottleneck resources for traffic that does not generate revenue. In this use case, adding Network Coding techniques will prevent the end-to-end retransmission from occurring since the packet losses would probably be recovered.

The architecture is shown in Figure 5.

```
-{}- : bidirectional link
-''- : WiFi link
C : where Network Coding techniques could be introduced

+----+    +--------+    +---+    +-------+    +-------+    +--------+
|End |    |Sat.    |    |SAT|    |Phy    |    |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 subsecond 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., bands with very high frequency, mobile users), 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 introducing and using 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) [RFC3135]. PEPs usually split end-to-end connections and forward transport or application-layer packets to the satellite baseband gateway. PEPs contribute to mitigating congestion in a SATCOM system 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 Section 3 of this document.

Deploying Network Coding in the PEP could be relevant and 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. This is discussed in

[NWCRG-CODING].

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 Quality of Experience (QoE) while optimizing capacity usage? At which layer should this supplementary redundancy be added?

This problem has been tackled in the past by the deployment of physical-layer error-correction codes, but questions remain 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 discussed in Section 3.5. A higher layer with Network Coding does not react more quickly than the physical layer, but it may operate over a packet-based time window that is larger than the physical one.

4.3. Interaction with Virtualized Satellite Gateways and Terminals

In the emerging virtualized network infrastructure, Network Coding could be easily deployed as Virtual Network Functions (VNFs). The next generation of SATCOM ground segments will rely on a virtualized environment to integrate with terrestrial networks. This trend towards Network Function Virtualization (NFV) is also central to 5G and next-generation cellular networks, making this research applicable to other deployment scenarios [5G-CORE-YANG]. As one example, Network Coding VNF deployment in a virtualized environment has been presented in [NETCOD-FUNCTION-VIRT].

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 virtualized SATCOM equipment is the management of limited buffered capacities in large gateways.

4.4. Delay/Disruption-Tolerant Networking (DTN)

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 only be available intermittently, if at all. Delay/Disruption-Tolerant Networking (DTN) [RFC4838] is a solution to enable reliable internetworking space communications where neither standard ad hoc routing nor E2E Internet protocols can 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 case proposed in Section 3.5 would encourage the usage of Network Coding within the DTN stack to improve utilization of the physical channel 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: how such Network Coding can be integrated in the IETF DTN stack.

5. Conclusion

This document introduces some wide-scale Network Coding technique 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 document, since they may also be relevant for cellular networks.

6. Glossary

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

ACM: Adaptive Coding and Modulation

BBFRAME: Base-Band FRAME -- satellite communication Layer 2 encapsulation works 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, and (4) BBFRAMEs are forwarded to the physical layer.

COM: COMmunication

CPE: Customer Premises Equipment

DSL: Digital Subscriber Line

DTN: Delay/Disruption-Tolerant Networking

DVB: Digital Video Broadcasting

E2E: End-to-End

ETSI: European Telecommunications Standards Institute

FEC: Forward Erasure Correction

FLUTE: File Delivery over Unidirectional Transport [RFC6726]

IntraF: Intra-Flow Coding

InterF: Inter-Flow Coding

IoT: Internet of Things

LTE: Long Term Evolution

MPC: Multi-Path Coding

NC: Network Coding

NFV: Network Function Virtualization -- concept of running software-defined network functions

NORM: NACK-Oriented Reliable Multicast [RFC5740]

PEP: Performance Enhancing Proxy [RFC3135] -- a typical PEP for satellite communications includes compression, caching, TCP ACK spoofing, and specific congestion-control tuning.

PLFRAME: Physical Layer FRAME -- modulated version of a BBFRAME with additional information (e.g., related to synchronization)

QEF: Quasi-Error-Free

QoE: Quality of Experience

QoS: Quality of Service

RTT: Round-Trip Time

SAT: SATellite

SATCOM: Generic term related to all kinds of SATellite-COMmunication systems

SPC: Single-Path Coding

VNF: Virtual Network Function -- implementation of a network function using software.

7. IANA Considerations

This document has no IANA actions.

8. Security Considerations

Security considerations are inherent to any access network, in particular SATCOM systems. As with cellular networks, over-the-air data can be encrypted using, e.g., the algorithms in [ETSI-TS-2011]. Because the operator may not enable this [SSP-2020], the applications should apply cryptographic protection. The use of FEC or Network Coding in SATCOM comes with risks (e.g., a single corrupted redundant packet may propagate to several flows when they are protected together in an interflow coding approach; see Section 3). While this document does not further elaborate on this, the security considerations discussed in [RFC6363] apply.

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