Network coding for satellite systems
draft-irtf-nwcrg-network-coding-satellites-12

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 document 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 and
   above the network layer in satellite communication systems. These
   systems generally exploit PHY layer loss recovery mechanisms. The
   document also identifies open research issues related to the
   deployment of network coding in satellite communication 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 SATellite COMmunication (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 document, 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
residual errors at those layers cause packet losses, retransmissions
add significant delays (in particular 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]:

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

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

o 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 [ETSIEN2014]. 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 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|
          +----------+            +----------+
```
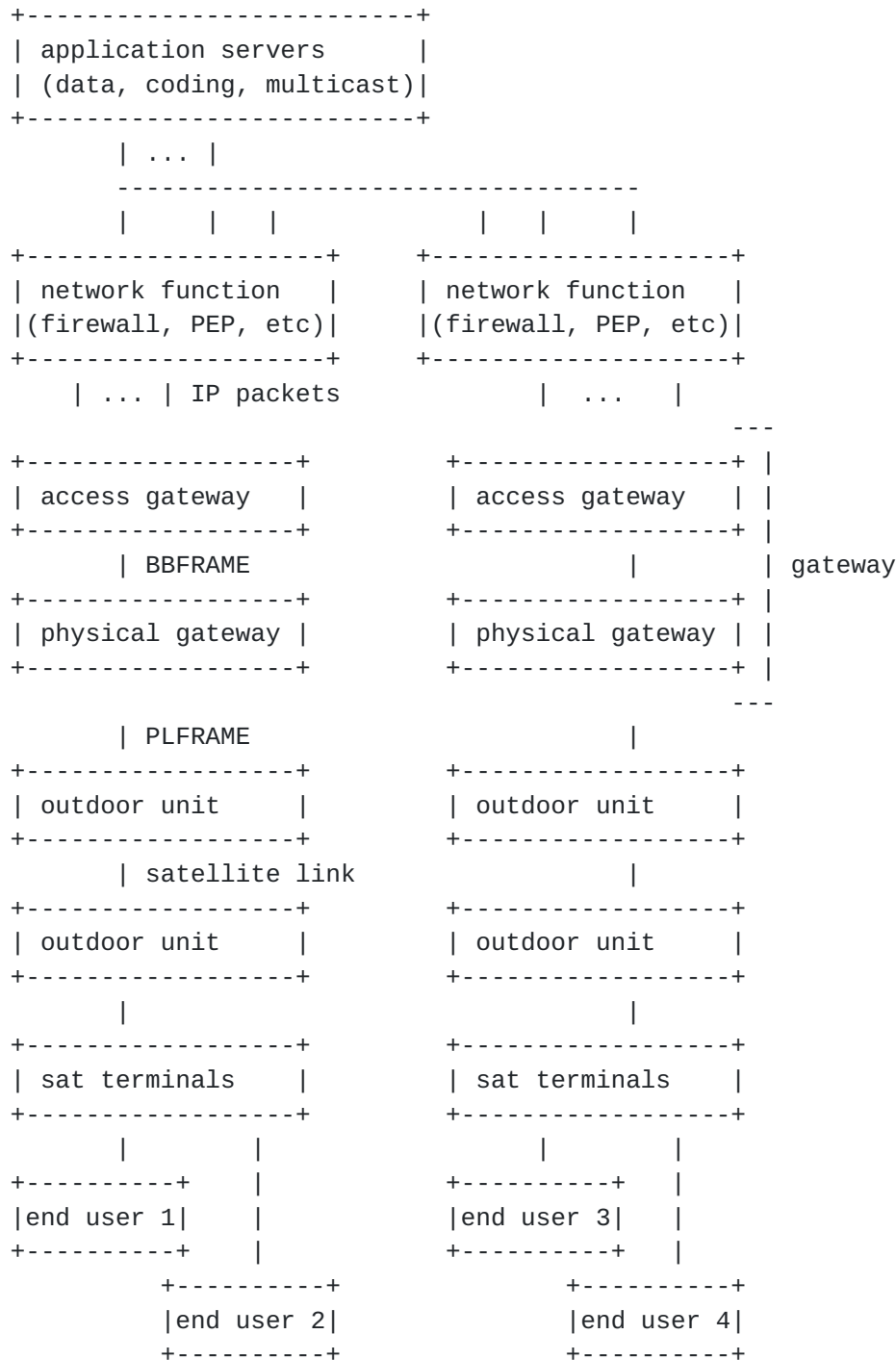
Figure 1: Data plane functions in a generic satellite multi-gateway
    system. More details can be found in DVB standard documents.

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}-+   |     |
   +-----------+        +-----+
```
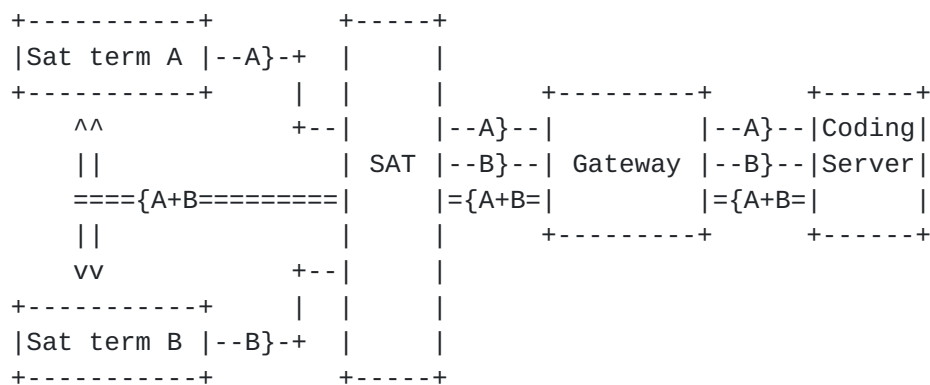
      Figure 2: Network Architecture for Two-way Relay Channel using NC

3.2. Reliable Multicast

   The use of multicast servers is one way to better utilize 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}-+ |     |
+-----------+       +-----+
```
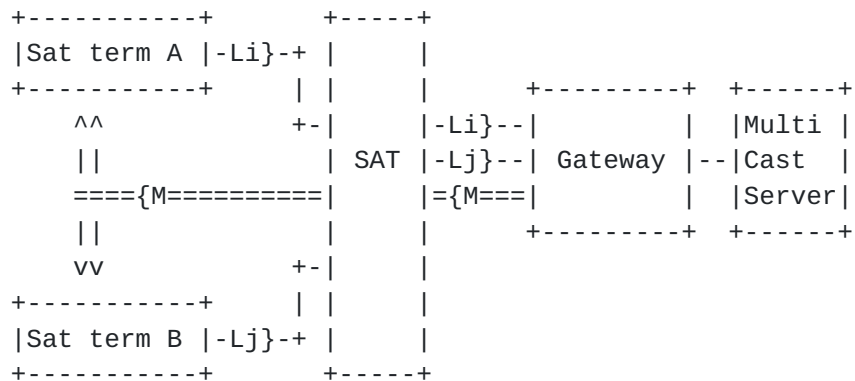
   Figure 3: Network Architecture for a Reliable Multicast using NC

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][RFC8681].

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.
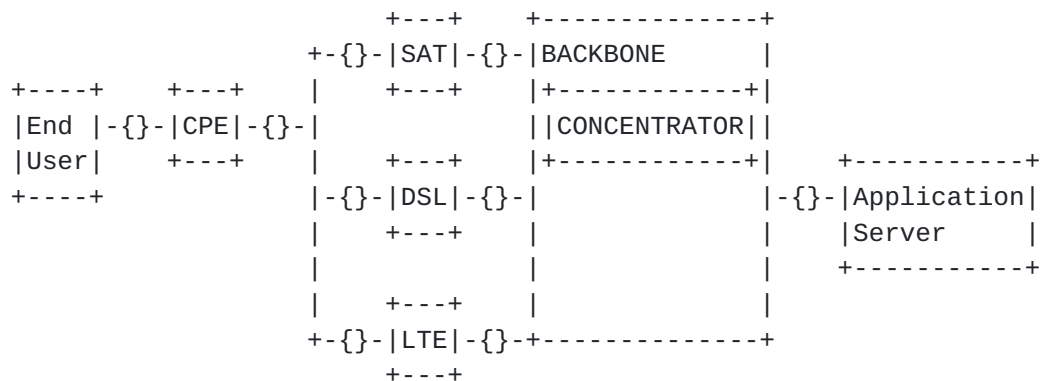
-{}- : bidirectional link

```
                         +---+     +--------------+
                     +-{}-|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 Performance Enhancing Proxy (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 would probably recovered.

The architecture is shown in Figure 5.

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


+----+      +--------+    +---+    +-------+    +-------+    +--------+
|End |      |Sat.    |    |SAT|    |Phy    |    |Access |    |Network |
|user|-''-|Terminal|-{}-|    |-{}-|Gateway|-{}-|Gateway|-{}-|Function|
+----+      +--------+    +---+    +-------+    +-------+    +--------+
   C                               C            C            C
```
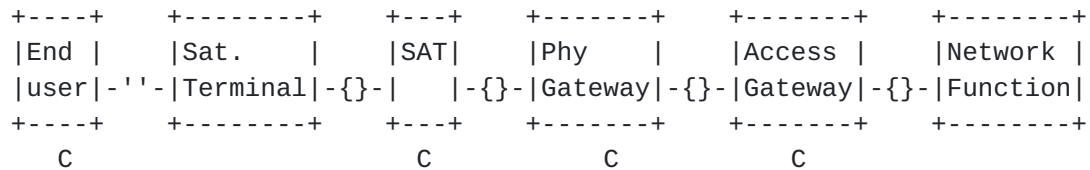
        Figure 5: Network Architecture for dealing with LAN Losses

3.5. Varying Channel Conditions

   This use-case considers the usage of network coding to cope with 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
```

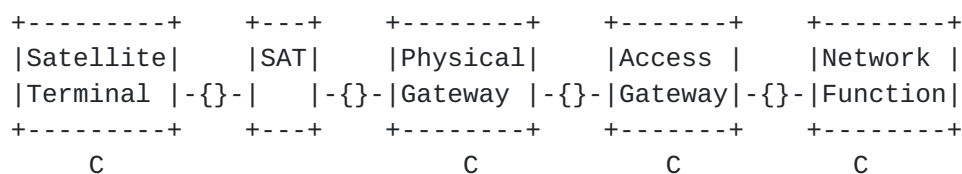   Figure 6: Network Architecture for dealing with Varying Link
                             Characteristics

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
```
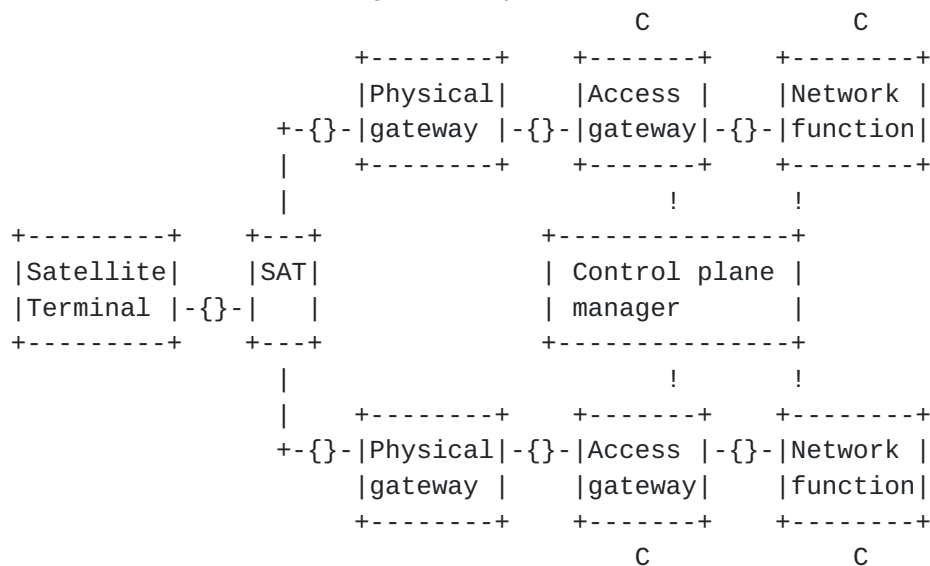
Figure 7: Network Architecture for dealing with Gateway Handover

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. This is discussed in
[I-D.irtf-nwcrg-coding-and-congestion]

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 in Section 3.5.

4.3. Interaction with Virtualized Satellite Gateways and Terminals

In the emerging virtualized network infrastructure, network coding
could be easily deployed as a Virtual Network Functions (VNF). The
next generation of SATCOM ground segments will rely on a virtualized
environment to integrate to 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
[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 document
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:

o ACM : Adaptive Coding and Modulation;

o 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;

o CPE: Customer Premises Equipment;

o COM: COMmunication;

o DSL: Digital Subscriber Line;

o 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 - concept of running
   software-defined network functions;

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 - implementation of a network
      function using software.

7. Acknowledgements

   Many thanks to John Border, Stuart Card, Tomaso de Cola, Vincent
   Roca, Lloyd Wood and Marie-Jose Montpetit for their help in writing
   this document.

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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