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Coding techniques for satellite systems
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Abstract

This document is the product of the Coding for Efficient Network Communications Research Group (NWCRG). This document follows the taxonomy document [RFC8406] and considers coding as a linear combination of packets that operate in and above the network layer. In this context, this memo details a multi-gateway satellite system to identify use-cases where coding is relevant. As example, coding operating in and above the network layer can be exploited to cope with residual losses or provide reliable multicast services. The objective is to contribute to a larger deployment of such techniques in SATCOM systems. This memo also identifies open research issues related to the deployment of coding in SATCOM systems, such as the interaction between congestion controls and coding techniques.

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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); it is not an IETF product and is not a standard. A glossary is proposed in Section 6.

Guaranteeing both physical-layer robustness and efficient usage of the radio resource has been in the core design of SATellite COMmunication (SATCOM) systems. The trade-off often resided in how much redundancy a system adds to cope with link impairments, without

reducing the goodput when the channel quality is good. There is usually enough redundancy to guarantee a Quasi-Error Free transmission. The recovery time depends on the encoding block size. Considering for instance geostationary satellite system (GEO), physical or link layer erasure coding mechanisms recover transmission losses within a negligible delay compared to link delay. However, when retransmissions are triggered, this leads to a non-negligible additional delay in particular over GEO link. Further exploiting coding techniques at application or transport layers is an opportunity for releasing constraints on the physical layer and improving the performance of SATCOM systems.

The notations used in this document are based on the taxonomy document [RFC8406]:

- o Channel and link codings are gathered in the PHY layer coding and are out of the scope of this document. It focuses on situations where coding is not widely deployed in current SATCOM systems.

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

- o This document considers coding (or coding techniques or coding schemes) as a linear combination and not as a content coding (e.g., to compress a video flow).

Figure 1 presents the status of the reliability schemes deployment in satellite systems.

- o X1 embodies the source coding techniques that could be used at application level for instance within QUIC. This is not specific to SATCOM systems since such deployment can be relevant for broadband Internet access discussions.

- o X2 embodies the physical-layer techniques exploited in SATCOM systems (note that other coding techniques can be exploited). This is out of the scope of the document.

	Upper Appl.	Middle ware	Communication layers	
	Source coding	Network AL-FEC	Packetization UDP/IP	PHY layer
E2E	X1			
NC				
IntraF	X1			
InterF				X2
SPC	X1			X2
MPC				

Figure 1: Reliability schemes in current satellite systems

We notice an active research activity on coding techniques and SATCOM. That being said, not much has actually made it to industrial developments. In this context, this document aims at identifying opportunities for further usage of coding in these systems.

2. A note on satellite topology

This section describes a satellite system that follows the ETSI DVB standards to provide broadband Internet access. A high-level description of a multi-gateway satellite network is provided. There are multiple SATCOM systems, such as those dedicated to broadcasting TV or to IoT applications: depending on the purpose of the SATCOM system, ground segments are specific. In this context, the increase of the available capacity that is carried out to end users and reliability requirements lead to multiple gateways for one unique satellite platform.

In this context, Figure 2 shows an example of a multi-gateway satellite system. In a multi-gateway system, some elements may be centralized and/or gathered: the relevance of one approach compared to another depends on the deployment scenario. More information on these discussions and a generic SATCOM ground segment architecture for bidirectional Internet access can be found in [SAT2017].

Some functional blocks aggregate the traffic of multiple users.

```
   +--------------------------+
   | 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     |        | out door unit    |
   +------------------+        +------------------+
          |                              |
   +------------------+        +------------------+
   | sat terminals    |        | sat terminals    |
   +------------------+        +------------------+
          |        |                  |        |
   +----------+    |           +----------+    |
   |end user 1|    |           |end user 3|    |
   +----------+    |           +----------+    |
             +----------+              +----------+
             |end user 2|              |end user 4|
             +----------+              +----------+
```

Figure 2: Data plane functions in a generic satellite multi-gateway system. More details can be found in DVB standard documents.

3. Use-cases for improving the SATCOM system performance with coding techniques

This section details use-cases where coding techniques could provide interesting features for SATCOM systems. Combination of the presented use-cases could also be relevant.

It is worth noting that these use-cases mostly focus on the middleware and packetization UDP/IP of Figure 1. There are already lots of recovery mechanisms at the physical-layer in currently deployed systems while E2E source coding is done at the application level. In a multi-gateway SATCOM Internet access, the deployment opportunities are more relevant in specific SATCOM components such as the "network function" block or the "access gateway" of Figure 2.

3.1. Two-way relay channel mode

This use-case considers a two-way communication between end users, through a satellite link. Figure 3 proposes an illustration of this scenario.

Satellite terminal A sends a flow A and satellite terminal B sends a flow B to a coding server. The coding server sends a combination of both terminal flows. This results in non-negligible capacity savings and has been demonstrated [ASMS2010]. In the proposed example, a dedicated coding server is introduced. Its location could be changed depending on the deployment use-case. With On-Board Processing satellite payloads, the coding operations could be done at the satellite level; although this would require lots of computational ressource on-board and may not be relevant with today's payloads.

```
-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 3: Network architecture for two way relay channel with NC

3.2. Reliable multicast

Using multicast servers is a way to better exploit the satellite broadcast capabilities. This approach 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 scarce resource saving. We propose an illustration for this scenario in Figure 4.

-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 4: Network architecture for a reliable multicast with NC

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

This could 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]. Note that both NORM and FLUTE are limited to block coding, none of them supporting sliding window encoding schemes [RFC8406]. Note that although FLUTE is defined as an unidirectional protocol, the RFC proposes a bidirectional communication method to enable full reliability transfer and for security purposes.

3.3. Hybrid access

This use-case considers the use of multiple path management with coding at the transport layer to increase the reliability and/or the total capacity (using multiple paths does not guarantee an improvement of both the reliability and the total capacity). We propose an illustration for this scenario in Figure 5. This use-case is inspired from the Broadband Access via Integrated Terrestrial Satellite Systems (BATS) project and has been published as an ETSI Technical Report [ETSITR2017]. This kind of architecture is also discussed in the TCPM working group [I-D.ietf-tcpm-converters].

To cope with packet loss (due to either end-user mobility or physical-layer impairments), coding techniques could be introduced both at the CPE and at the concentrator. Apart from packet losses, other gains could be envisioned, such as a better tolerance to out-of-order packets which occur when exploited links exhibit high asymetry in terms of RTT. Depending on the ground architecture [I-D.chin-nfvrg-cloud-5g-core-structure-yang] [SAT2017], some equipments might be hosting both SATCOM and cellular functions.

```
-{}- : bidirectional link

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

Figure 5: Network architecture for an hybrid access using coding

3.4. Dealing with LAN losses

This use-case considers the usage of coding techniques to cope with cases where the end user connects to the satellite terminal with a Wi-Fi link that exhibits losses. In the case of encrypted end-to-end applications based on UDP, PEP cannot operate. The Wi-Fi losses result in an end-to-end retransmission that would harm the quality of experience of the end user.

The architecture is recalled in Figure 6.

In this use-case, adding coding techniques could prevent the end-to-end retransmission from occuring.

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

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

Figure 6: Network architecture for dealing with LAN losses

3.5. Dealing with varying channel conditions

This use-case considers the usage of coding techniques to cope with cases where channel condition can change in less than a second and where the physical-layer codes could not efficiently guarantee a Quasi-Error-Free (QEF) transmission.

The architecture is recalled in Figure 7. In these cases, the mechanisms that are exploited to adapt the physical-layer codes (Adaptative Coding and Modulation (ACM)) may adapt the modulation and coding in time: remaining errors could be recovered with higher layer redundancy packets. Coding may be applied on IP packets or on layer-2 proprietary format packets.

This use-case is mostly relevant when mobile users are considered or when the chosen band induces a required physical-layer coding that may change over time (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 block), the relevance of adding coding techniques is different.

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

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

Figure 7: Network architecture for dealing with varying link characteristics

3.6. Improving the gateway handovers

This use-case considers the recovery of packets that may be lost during gateway handovers. Whether this is for off-loading one given equipment or because the transmission quality is not the same on each gateway, changing the transmission gateway may be relevant. However, if gateways are not properly synchronized or if the algorithm that is exploited to trigger gateway handovers shows a non negligible probability of missed detection, this may result in packet losses. During these critical phases, coding can be added to improve the reliability of the transmission and allow a seamless gateway handover. Coding could be applied at either the access gateway or the network function block. A potential control plane is in charge of taking the decision to change the communication gateway and the consequent routes.

Figure 8 illustrates this use-case.

```
-{}- : bidirectional link
!   : management interface
C : where 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 8: Network architecture for dealing with gateway handover schemes

4. Research challenges

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

4.1. On the joint-use of coding techniques and congestion control in SATCOM systems

SATCOM systems typically feature Performance Enhancing Proxy (PEP) RFC 3135 [RFC3135]. PEPs usually split TCP end-to-end connections and forward TCP packets to the satellite baseband gateway that deals with layer-2 and layer-1 encapsulations. PEP contributes to mitigate congestion in a SATCOM systems. PEP could host coding mechanisms and thus support use-cases that have been discussed in this document.

Deploying coding schemes at the TCP level in these equipment could be relevant and independent from the specific characteristics of a SATCOM link. This leads to research questions on the interaction between coding schemes and TCP congestion controls.

4.2. On the efficient usage of satellite resource

The recurrent trade-off in SATCOM systems remains: 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 coding could be added ?

This problem has been tackled in the past for physical-layer code, but there remains questions on how to adapt the overhead for, e.g., the quickly varying channel conditions use-case where ACM may not be reacting quickly enough.

4.3. Interaction with virtualized satellite gateways and terminals

Related to the foreseen virtualized network infrastructure, coding techniques could be easily deployed as VNF. Next generation of SATCOM ground segments could rely on a virtualized environment. This trend can also be seen in cellular networks, making these discussions extendable to other deployment scenarios [I-D.chin-nfvrg-cloud-5g-core-structure-yang]. As one example, the coding VNF deployment in a virtualized environment is 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, to guarantee efficient radio usage and easy-to-deploy SATCOM services. Moreover, another challenge related to a virtualized SATCOM equipment is the management of limited buffered capacities.

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 long delay and frequent link disruptions; indeed, contemporaneous E2E connectivity may be available only intermittently or never. 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 the data between a central PEP and a remote PEP.

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

5. Conclusion

This document discuses some opportunities to introduce coding techniques at a wider scale in satellite telecommunications systems.

Even though this document focuses on satellite systems, it is worth pointing out that some scenarios proposed may be relevant to other wireless telecommunication systems. As one example, the generic architecture proposed in Figure 2 may be mapped to 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 be also 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;

- CPE: Customer Premises Equipment;
- COM: COMmunication;
- DSL: Digital Subscriber Line;
- DTN: Delay/Disruption Tolerant Network;
- DVB: Digital Video Broadcasting;
- E2E: End-to-end;
- ETSI: European Telecommunications Standards Institute;
- FEC: Forward Error Correction;
- FLUTE: File Delivery over Unidirectional Transport;
- 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;
- NORM: NACK-Oriented Reliable Multicast;
- PEP: Performance Enhancing Proxy [RFC3135] - a typical PEP for satellite communications include compression, caching and TCP acceleration;
- PLFRAME: Physical Layer FRAME - modulated version of a BBFRAME with additional information (e.g., related to synchronization);
- QEF: Quasi-Error-Free;

- o QoE: Quality-of-Experience;
- o QoS: Quality-of-Service;
- o SAT: SATellite;
- o SATCOM: generic term related to all kind 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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