Network Coded Multicast and Multi-unicast over Satellite

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***Abstract*—In this paper, we investigate the use of systematic random network coding (SNC) for multicast and multi-unicast over satellite. In particular, the satellite coverage is over a large geographical area that consists of several users. These users may face different channel conditions and undergo different packet loss rates. In this work, we identify two regions of transmission. The multicast region where all users subscribed to the multicast channel can recover all the data packets and the multi-unicast region where only users with good channel conditions can recover all the data packets but those with bad channel accept transmission losses. For the two regions, we derive theoretically and by simulation the benefits of SNC against state-of-the-art end-to-end coding. Our results show that SNC can achieve up to 26.90% and 24.26% higher maximum achievable rates for multicast and multi-unicast respectively. Further, we show practical architectural and encapsulation feasibility.**

Index Terms*—Network coding, Multicast, Satellite communication, Achievable rates.

I. Introduction

SNC [1]-[6] has been studied recently as a practical network coding scheme to increase the achievable rates and reliability of wireless networks. It has been proved that SNC achieves smaller complexity, smaller delay and smaller overhead as compared to previous network coding schemes based on random network coding (RNC) [7] [8]. However, in the current literature, SNC has been investigated mainly in the networks for unicast with a source and a sink connected via several intermediate nodes.

In this paper, we investigate the use of SNC for multicast and multi-unicast over satellite. We identify two regions of transmission, one for multicast and another for multi-unicast with an in-network (re)encoding to increase the achievable rates and the reliability of satellite networks.

We consider a system topology (Figure 1) where a source is connected to all the sinks via an intermediate node. This system topology is a relevant case in satellite systems where there is one intermediate node which could be a gateway (or others) and there can be several sink nodes which are the users distributed in a large geographical area undergoing different packet loss rates. Our theoretical derivations and simulation results on the reliability and the achievable rates show the benefits of network coding with respect to state-of-the-art end-to-end forward erasure codes (FEC) codes like Reed-Solomon (RS) codes for both multicast and multi-unicast.

In this paper, we also explore the benefits of network coding in two different set of layers of a satellite network protocol architecture. These are satellite-independent layers (application, transport and IP layers) and satellite-dependent layers (link and physical layers). In particular, the satellite-independent layers are mainly significant for the application's developer who has access to the data flowing in these layers and the satellite-dependent layers are mainly significant for the system operators. In this paper, first we present the implementation of network coding in the link layer of the satellite systems and second, we focus on the implementation of network coding in the application layer for better internet communication over satellite systems.

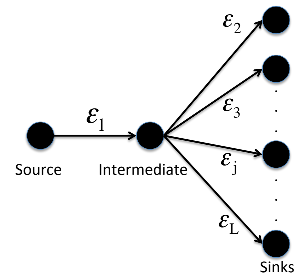

Figure. 1: System model

The rest of the paper is organized as follows. In Section II, we discuss the system model. In Section III, we describe the systematic network coding for multicast and multi-unicast. In Section IV, we present the theoretical analysis and derivation of theoretical expressions for the reliability and the achievable rate. Section V presents the implementation of SNC in the link layer of the protocol stack and Section VI presents the simulation results. In Section VII, we discuss the implementation of SNC in the upper layers of the satellite network protocol stack. Finally, Section VIII concludes this paper.

II. System Model

Consider that a source node has K data packets to send to $L-1$ sink nodes. Each packet is a column vector of length M over a finite field $\mathbb{F}_q$. The set of data packets in matrix notation is $\mathbf{S} = \left[\mathbf{s}_1 \quad \mathbf{s}_2 \quad . \quad . \quad . \quad \mathbf{s}_K \right]$, where $\mathbf{s}_t$ is the t^{th} data packet. The source is connected to all the sinks via an intermediate node as shown in Figure 1. All the links are modeled as memoryless erasure channels. There are L links in the network. The erasure probability from the source to the intermediate node is denoted by ϵ_1 and the erasure probability from the intermediate node to the sink node j is denoted by $\epsilon_j, j = 2, .., L$.

We assume there is no feedback from the sinks (or from the intermediate node) due to the inherent large latency of satellite systems. We also assume that packet transmissions occur at discrete time slots such that each node can transmit one packet per time slot. We will also assume that the coding schemes run for a total of N time slots (N is larger than or equal to K) and every node (except the sinks) transmits a packet in each time slot $t = 1, 2, ..., N$.

III. Systematic network coding for multicast and multi-unicast

A. Encoding at the source node

The SNC encoder sends K data packets in the first K time slots (systematic phase) followed by $N - K$ random linear combinations of data packets in the next $N - K$ time slots (non-systematic phase). Let $\mathbf{X} = \mathbf{SG}$ represent K systematic packets and $N - K$ coded packets transmitted by the SNC encoder during N consecutive time slots. The generator matrix $\mathbf{G} = \begin{bmatrix} \mathbf{I}_K & \mathbf{C} \end{bmatrix}$ consists of the identity matrix $\mathbf{I}_K$ of dimension K and $\mathbf{C} \in \mathbb{F}_q^{K \times N-K}$ with elements chosen randomly from a finite field $\mathbb{F}_q$. The code rate is given by $\rho = \frac{K}{N}$.

B. Re-encoding at the intermediate node

The SNC re-encoder performs re-encoding operations in every time slot and sends N packets to the sink nodes. Let $\mathbf{X}_I = \mathbf{XD}_1\mathbf{T}$ represent N packets transmitted by the SNC re-encoder during N consecutive time slots where $\mathbf{D}_1 \in \mathbb{F}_q^{N \times N}$ represents erasures from the source node to the intermediate node and $\mathbf{T} \in \mathbb{F}_q^{N \times N}$ represents the re-encoding operations at the intermediate node.

The erasure matrix $\mathbf{D}_1$ is an $N \times N$ diagonal matrix with every diagonal component zero with probability ϵ_1 and one with probability $1 - \epsilon_1$.

The re-encoding matrix $\mathbf{T}$ is modeled as an upper triangular matrix. The non-zero elements of $\mathbf{T}$ are selected as follows. During the systematic phase, if a packet $\mathbf{s}_t$ is lost i.e., $\mathbf{D}_1(t, t) = 0$ then the non-zero elements of the t^{th} column of matrix $\mathbf{T}$ are randomly selected from $\mathbb{F}_q$. This represents that if the systematic packet is lost from the source node to the intermediate node, then the intermediate node transmits a random linear combination of the packets stored in its buffer. If a packet $\mathbf{s}_t$ is not lost, i.e., $\mathbf{D}_1(t, t) = 1$ then the t^{th} column of matrix $\mathbf{T}$ is the same as the t^{th} column of identity matrix $\mathbf{I}_N$. This represents that the intermediate node forwards this systematic packet to the sinks. During the non-systematic phase, the intermediate node sends a random linear combination of the packets stored in its buffer and all the non-zero elements of last $N - K$ columns of $\mathbf{T}$ are chosen randomly from the finite field $\mathbb{F}_q$.

C. Decoding at the sink nodes

Let $\mathbf{Y}_j = \mathbf{X}_I\mathbf{D}_j, j = 2, 3, ..., L$ represents N packets received by the sink node j where $\mathbf{D}_j$ represents erasures from the intermediate node to the sink node j. $\mathbf{D}_j$ is $N \times N$ diagonal matrix of the same type as $\mathbf{D}_1$ but with erasure probability ϵ_j. If the sink node j does not receive any packet in time slot t then the t^{th} column of $\mathbf{Y}_j$ is a zero column.

The overall SNC coding strategy can be expressed using a linear operation channel (LOC) model where the output at the sink node j is $\mathbf{Y}_j = \mathbf{SGH}_j$ where $\mathbf{H}_j = \mathbf{D}_1\mathbf{TD}_j$ represents the transfer matrix from the source to the sink j. We assume that the coding vectors are attached in the packet headers so that the matrix $\mathbf{GH}_j$ is known at the sink j. However, the overhead, due to the attached coding vectors, is kept low due to the use of systematic coding (coding vectors are not attached with the systematic packets). The decoding is progressive using the Gaussian Jordan algorithm as in [6]. All the K data packets are recovered when K innovative packets are received at the sink j, i.e., $rank(\mathbf{GH}_j) = K$.

IV. Theoretical Analysis

In this section, we will present the theoretical expressions of the average reliability and the average achievable rate of the considered topology. Let us first define η as the residual erasure rate of any link that could be achieved after the overall coding and decoding operations. The reliability of the link is given by $(1 - \eta)$.

Based on the definitions of the residual erasure rate and the reliability and using the definition of achievable rate from [9], the average achievable rate of the considered topology is given by,

$$R_{av} = \rho\,(1 - \eta_{av}) \tag{1}$$

with,

$$\eta_{av} = \frac{1}{L-1}\sum_{j=2}^{L}\left[1 - (1 - \eta_1)(1 - \eta_j)\right] \tag{2}$$

as the average reliability of the considered topology, η_1 is the residual erasure rate from the source node to the intermediate node and η_j is the residual erasure rate from the intermediate node to the sink node j where,

$$\eta_l = \phi_{l1} + \phi_{l2}, l = 1, 2, ..., L \tag{3}$$

The first term represents the residual erasure rate for the case when the correctly received packets are less than K, it is given by,

$$\phi_{l1} = \epsilon_l Pr(A < K - 1) \tag{4}$$

where A is a Binomial random variable, accounting for the Bernoulli nature of the erasures. The second term represents the case of reception of K or more packets but not linearly dependent. It is given by,

$$\phi_{l2} = \epsilon_l Pr(A \geq K - 1) Pr(rank(\mathbf{GH}_j) < K) \tag{5}$$

Using the results in [10], we obtain the exact expressions of ϕ_{l1} and ϕ_{l2} in (6) and (7), respectively.

V. Implementation in link layer of satellite systems

A. State-of-the-art link layer protocols in satellite systems

The current state-of-the-art link layer protocols in the satellite systems provide efficient encapsulation of network layer (IP) protocol data units (PDUs) over the physical layer

$$\phi_{l1} = \epsilon_l \sum_{i=0}^{K-1} \binom{N-1}{i} (1-\epsilon_l)^i \, \epsilon_l^{N-1-i} \quad (6)$$

$$\phi_{l2} = \epsilon_l \sum_{i_1=0}^{K-1} \binom{K}{i_1} (1-\epsilon_l)^{i_1} \, \epsilon_l^{K-i_1} \sum_{i_2=K-i_1}^{N-K} \binom{N-K}{i_2} (1-\epsilon_l)^{i_2} \, \epsilon_l^{N-K-i_2} \left(1 - \prod_{i_3=0}^{K-i_1-1} \left(1-q^{i_3-i_2}\right)\right) \quad (7)$$

frames. For example, generic stream encapsulation (GSE) protocol [11] in digital video broadcasting by satellite - second generation (DVB-S2) based systems is used as a link layer protocol to encapsulate network layer IP packets.

The existing link layer forward erasure correction (LL-FEC) frameworks in the satellite systems are mainly based on RS or Raptor codes [12]. However, the main limitation of the existing frameworks is that they operate only in end-to-end fashion and do not utilize the coding opportunities at the intermediate node. In this section, we will present an architectural and encapsulation framework to enable link layer systematic network coding (LL-SNC) at the source and at the intermediate node of the satellite systems.

B. LL-SNC architecture and encapsulation

In Figure 2, we present the complete information flow with LL-SNC architecture and LL-SNC encapsulation where IP packets are transmitted from the source and recovered at the sink. This figure represents the case when there is only one sink in the network. When there are several sinks, the same LL PDUs are transmitted from the intermediate node to all the sink nodes.

At the source, the network layer IP packets are encapsulated into an LL-SNC frame. The LL-SNC frame consists of an application data table (ADT) to store IP PDUs, a network coding data table (NCDT) table to store network coded packets and a coefficient data table (CDT) to store coding coefficients. The data from the LL-SNC frame is then encapsulated into LL PDUs. The LL PDUs are then encapsulated into the physical (PHY) frames.

At the intermediate node, the payload of correctly received LL PDUs is stored in the LL-SNC frame. The IP PDUs are stored in the ADT of the intermediate node. The coded packets and the corresponding coefficients are stored in NCDT and CDT of the intermediate node. When the intermediate node receives LL PDU without error, it sends the LL PDU to the sink node and also stores it in the LL-SNC frame. When the intermediate node receives LL PDU with errors, it discards the LL PDU and generates new coded packet and coding coefficients as explained in Section III. These new coded packets and the corresponding coefficients are stored in NCDT and CDT of the intermediate node.

At the sink node, the correctly received LL PDUs are stored in the LL-SNC frame. The IP PDUs are stored in the ADT of the sink node. The coded packets and the coding coefficients are stored in NCDT and CDT respectively. The progressive decoding is performed and the lost IP PDUs are recovered. These IP PDUs are then passed to the upper layers.

VI. Simulation results

A. Simulation setup

In our simulation setup, we consider realistic satellite transmission scenarios with links having light rainfall (erasure rate of 0.2) and/or heavy rainfall (erasure rate of 0.6) [13]. In each case, we compare LL-SNC with LL-FEC. We assume IP PDUs of length 1500 bytes. Each IP PDU is mapped to a column of the ADTs of consecutive LL-SNC frames. Two LL-SNC frame lengths, $N \in \{50, 256\}$ and several values of code rates are considered for comparison. The size of ADT, i.e., K changes with the code rate. We set the physical layer symbol rate of $B_s = 27.5$ Mbaud/s, $\varsigma = 2$ as the modulation constellation and $r_{phy} = 1/2$ as the physical coding rate such that the bit rate is $B_s \varsigma r_{phy} = 27.5 \, Mbps$. The transmission delay is set to be 250 ms. In each case, we average over 1000 experiments for every performance metric. The number of erasures per-frame varies (according to the random erasure rate) between the 1000 experiments.

B. Performance metrics

1) Achievable rates and reliability: The theoretical expressions of the average achievable rate and the average reliability are derived in Section IV. In this section, we will present the simulation results on the average achievable rate and the average reliability. In the results, we also compare the simulation results with the theoretical expressions derived in Section IV.

2) Average delay per-packet: If a packet $\mathbf{s}_t$ is transmitted by the source at time t_j and it is recovered at the sink at time t_r then packet $\mathbf{s}_t$ incurs a delay δ_t where, $\delta_t = t_r - t_j$. For the block of K packets, the average delay per-packet is given as, $\triangle = \frac{\sum_{t=1}^{K} \delta_t}{K}$. Note that the delay is evaluated only for the packets which are recovered at the sink.

C. Results

In Figure 3, we show the results on achievable rates and reliability when there are two sinks in the network. The multicast capacity of the network is limited by one of the links joining the intermediate node to the sink node. We consider the following erasure probabilities: $\epsilon_1 = 0.2$, $\epsilon_2 = 0.2$ and $\epsilon_3 = 0.6$. In Figure 4, we show the results on achievable rates and reliability when there are ten sinks in the network. The multicast capacity of the network is limited by one of the links joining the intermediate node to the sink node. We consider the following erasure probabilities: $\epsilon_1 = 0.2$, $\epsilon_j = 0.2, j = 1, 2, ..., 9$ and $\epsilon_{10} = 0.6$. Furthermore, we present the maximum achievable rates for both multicast and

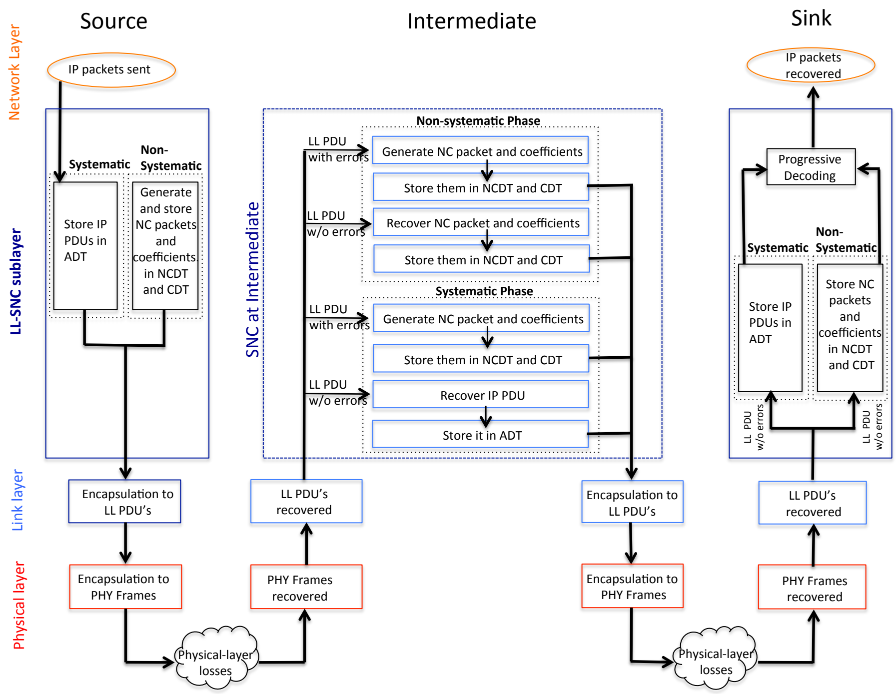

Figure. 2: Flow diagram with LL-SNC architecture and LL-SNC encapsulation in satellite system

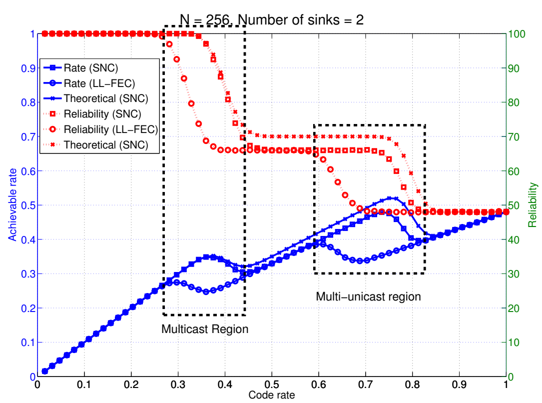

Figure. 3: LL-SNC multicast and multi-unicast region with two sinks

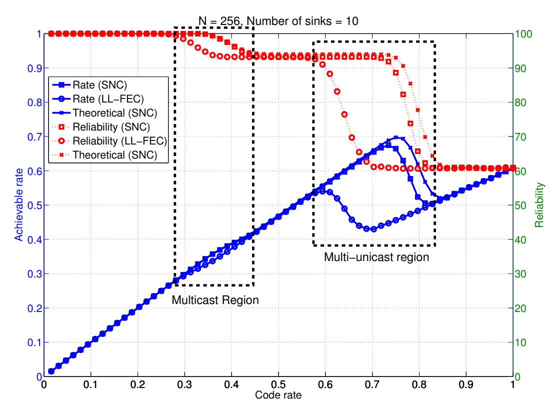

Figure. 4: LL-SNC multicast and multi-unicast region with two sinks

TABLE I: MAXIMUM ACHIEVABLE RATES FOR MUTI-CAST AND MULTI-UNICAST

N	Application	Sinks	LL-SNC	LL-FEC	Gain
256	Multicast	2	0.3486	0.2747	26.90%
256	Multi-unicast	2	0.4794	0.3858	24.26%
256	Multicast	10	0.3575	0.3043	17.48%
256	Multi-unicast	10	0.6745	0.5404	24.81%
50	Multicast	2	0.3035	0.2553	18.88%
50	Multi-unicast	2	0.3852	0.3579	7.63%
50	Multicast	10	0.3107	0.2751	12.94%
50	Multi-unicast	10	0.5406	0.4990	8.34%

multi-unicast in Table I. Following are the key conclusions from these results:

- We have identified two regions in these graphs: one for multicast and the another for multi-unicast (represented by dashed boxes). The region for multicast is corresponding to the case when the average reliability approaches 100%. This would mean that all the sinks in the network are able to recover all the data packets. We have also identified the multi-unicast region where the sinks with better channel recover all the data packets and the sink(s) with bad channel still suffer from some losses. The benefit of multi-unicast over multicast is that one can achieve overall higher transmission rates by not sacrificing the rate due to the bottleneck sink (link with higher erasure rate). Hence, based on the requirements of the users, our results provide optimal usage of available bandwidth for transmission.
- The multicast is feasible only when the code rate is smaller than the capacity of the network which is

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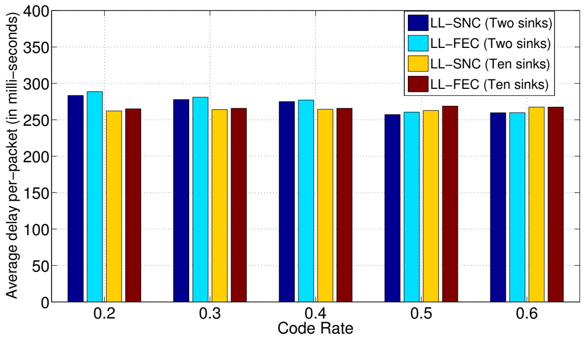


Figure. 5: Average delay per-packet

$\min_j(1-\epsilon_j) = 0.4$. However, when the code rate is higher than the multicast capacity, multi-unicast is feasible. This is because the capacity of the sinks with good channel is different and higher than the capacity of the network (in our example it is 0.8). Therefore, when the code rate is smaller than 0.8, the sinks with good channel can recover all the data packets making multi-unicast feasible.

- LL-SNC provides higher transmission rates and higher reliability than LL-FEC in all the cases. When the number of sink increases, LL-SNC can provide close to 100% reliability in the multi-unicast region itself. This is because there is only one bottleneck link in the network and only one sink suffers from the bad channel. In this case, it would be efficient to transmit in the multi-unicast region such that the higher transmission rates are achieved and almost all the sinks (except the one with the bad channel) are able to recover all the data packets. Furthermore, LL-SNC also provides higher maximum achievable rates than LL-FEC for both multicast and multi-unicast. The maximum achievable rate increases as the frame length increases or the number of sinks increases. Our results (Table I) show that LL-SNC can achieve up to 26.90% and 24.26% higher maximum achievable rates than LL-FEC for multicast and multi-unicast respectively.

In Figure 5, our simulation results also show that LL-SNC provides smaller average delay per-packet than LL-FEC. This is because of the following two reasons. First, the progressive decoding in LL-SNC allows the sinks to start decoding and recovering as soon as it receives the first packet. Second, the re-encoding in LL-SNC helps the sink to receive K degrees of freedom and complete the decoding process in fewer time slots than LL-FEC. The overall delay includes the inherent transmission delay of 250 ms of the satellite systems.

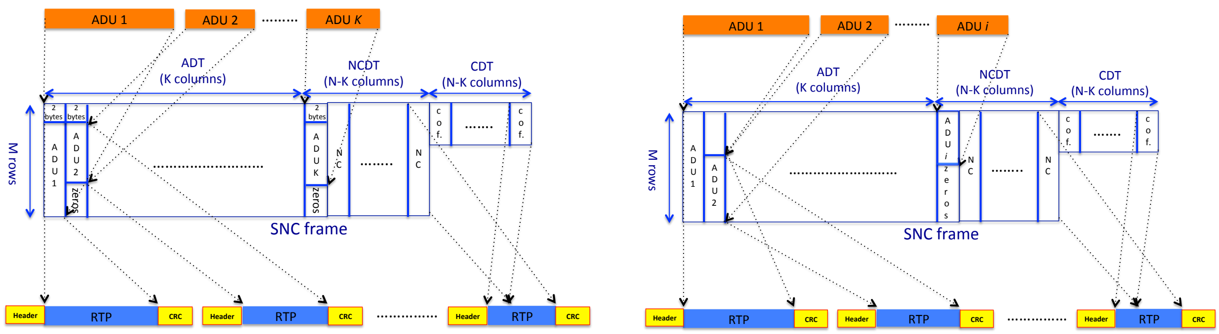
VII. Network coding in satellite independent layers

In the previous sections, we have focussed on the application of the network coding in the satellite-dependent layers, specifically in the link layer of the satellite systems. However, the use of network coding is not limited only to the satellite-dependent layers, the same network coding framework can be used in the satellite-independent layers to guarantee reliability. In this section, we will focus on the protection of application layer data units (ADUs) for better and efficient internet communication in the satellite systems.

In the previous sections, we have shown the benefits of LL-SNC to protect network layer IP packets in the lower layers of the protocol stack. Similarly, SNC can be used to protect ADUs in the upper layers of the protocol stack. The encapsulation process is one of the main factors influencing the efficient implementation of network coding in the networking protocol stack. In this section, we outline two encapsulation processes which can be used for the network coding implementation to protect ADUs for reliable internet communication.

The first encapsulation process (encapsulation process A) is shown in the Figure 6a. This way of encapsulation was used for the protection of ADUs using RS coding [14] over real-time transport protocol (RTP). In Figure 6a, we present the modified encapsulation process to be used for the network coding. A source block (ADT) consists of K ADUs in K columns. The number of rows in the source block is $M = E + 2$ where E is the length of the largest ADU. The columns, which do not have the largest ADU, are filled with zeros to be completely filled. Each column can be considered as a data packet. The first two bytes of each column in the source block contain the length of the corresponding ADU. ADUs are then encapsulated into RTP packets. The first two bytes and the zero paddings are not sent over the network. The FEC block (NCDT) contains $N-K$ columns with $N-K$ coded packets and the coefficient block (CDT) contains $N-K$ columns with $N-K$ set of coding coefficients. FEC packets and coefficients are then encapsulated into RTP packets. Each RTP packet contains RTP payload, RTP header and FEC payload ID. This FEC payload ID is used for signaling the coding parameters like source block ID, FEC packet ID, values of K and N etc. The CRC-32 is added with every RTP packet to detect errors in RTP packets at the receiving end. At the receiver, the values of coding parameters are extracted from the FEC payload ID. Now, if ADUs are lost then the complete columns are lost. So, if FEC decoding succeeds, the receiver recovers ADUs by filling the erased columns. The initial two bytes are used to remove zero padding from the data packets to recover the ADUs.

The second encapsulation process (encapsulation process B) is shown in the Figure 6b. This way of encapsulation was used for the protection of IP packets using RS coding over GSE [12]. In Figure 6b, we present the modified encapsulation process to be used for the network coding to protect ADUs. A source block (ADT) consists of K columns and stores ADUs. Now, ADUs are arranged column wise starting from the upper left corner. If an ADU does not fit in one column, it continues at the top of the following column and so on. If the ADT is not completely filled then the zero-padding bytes are inserted in last column to fill it completely. Each ADU is then encapsulated in a single or multiple RTP packets. The FEC block (NCDT) contains $N-K$ columns with $N-K$ coded packets and the coefficient block (CDT) contains $N-K$ columns with $N-K$ set of coding coefficients. Each coded packet from NCDT and the corresponding coding coefficients from CDT are encapsulated in one RTP packet. The first K bytes of RTP payload contain K coding coefficients followed



(a) Encapsulation process A

(b) Encapsulation process B

Figure. 6: The two encapsulation processes for encapsulation of application layer data units over RTP

by the corresponding NCDT column. The value of K is signaled through the RTP header of the RTP packet. Finally, the CRC-32 is added with every RTP packet to detect errors in RTP packets at the receiving end. Now, if an ADU is lost, then the corresponding part of the column or the complete column is also lost. The progressive decoding is performed and lost columns (or lost part of columns) in ADT are filled with the recovered data. The implementation efficiency of the encapsulation process based on the overhead due to headers, payload ID's, etc. Both of the above encapsulation processes inlcude filling of data tables in different ways. Specifically, the encapsulation process B does not include adding of zero bytes for each unfilled column. Therefore, the overhead due to the extra padding bytes could be reduced and higher throughput could be achieved by using encapsulation process B for network coding implementation.

VIII. Conclusions

In this paper, we have focussed on the use of SNC for multicast and multi-unicast over satellite. We have identified the transmission regions for multicast and multi-unicast over satellite by characterizing the reliability and achievable rates offered by SNC in these two different regions. We have derived the theoretical expressions for the average reliability and the average achievable rate of the considered topology. Our theoretical and simulation analysis present the benefits of SNC over end-to-end coding for both multicast and multi-unicast. Our results have shown that a higher rate is achievable for the multi-unicast however not all the users in multi-unicast can recover all the data packets. Therefore, based on the requirements from different users, the transmission region can be chosen for the optimal usage of available bandwidth. Finally, we have explored the benefits of network coding at different layers of the satellite network protocol stack. We have shown the encapsulation and architecture feasibility of network coding application in the satellite-dependent layers and we have proposed two encapsulation processes for the network coding application in the satellite-independent layers. Future work includes the investigation of SNC on more complex networks such as network with multiple sources. Furthermore, the implementation efficiency of the two proposed encapsulation processes should be compared numerically using realistic values of coding parameters, packet sizes, etc for different standards.

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