Network Coding Applications to High Bit-Rate Satellite Networks

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Abstract. Satellite networks are expected to support multimedia traffic flows, offering high capacity with QoS guarantees. However, system efficiency is often impaired by packet losses due to erasure channel effects. Reconfigurable and adaptive air interfaces are possible solutions to alleviate some of these issues. On the other hand, network coding is a promising technique to improve satellite network performance. This position paper reports on potential applications of network coding to satellite networks. Surveys and preliminary numerical results are provided on network coding applications to different exemplary satellite scenarios. Specifically, the adoption of Random Linear Network Coding (RLNC) is considered in three cases, namely, multicast transmissions, handover for multi-homed aircraft mobile terminals, and multipath TCP-based applications. OSI layers on which the implementation of networking coding would potentially yield benefits are also recommended.

Keywords: Satellite networks · Network coding · Multipath communications · OSI layers · Robustness and resiliency

1 Introduction

Satellite networks are expected to satisfy stringent Quality of Service (QoS) requirements for broadband service delivery. Towards this end, new solutions that exploit the benefits of multipath transmissions and Network Coding (NC) to minimise packet losses are being explored. The main idea of NC is to allow nodes in the network to perform coding operations at the packet level. The application of network coding to communication networks is relatively recent, dating back to year 2000 [1]. Since then, NC has shown great potentials in correcting random packet errors and errors introduced by malicious nodes, making it a powerful tool to achieve efficiency and reliability with many potential areas of application to satellite networks.

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This paper aims to identify compatibility issues and best approaches as well as to investigate pros and cons on the application of NC to a satellite network at different OSI layers, taking multipath capabilities of satellite user terminals into account; our main focus is on the adoption of Random Linear Network Coding (RLNC), ranging from integrated satellite-terrestrial networks to multicast networks [2]. In particular, the combination of multipath connectivity and NC are analysed for the following broad-scope scenarios:

– Multicast transmissions with satellite/terrestrial component and erasure channels in the presence of mobile nodes and Complementary Ground Component (CGC);
– Mobile multicast for satellite-based aeronautical applications;
– Multipath TCP-based connections with simultaneous use of multiple paths.

Taking into account the work carried out in the Network Coding Research Group (NWCRG) of the Internet Research Task Force (IRTF) [3], this paper contains a preliminary study carried out within the "Network Coding Applications in Satellite Communication Networks" working group of the ESA funded project Satellite Network of Experts (SatNEx) IV [4].

2 A Cooperative Scenario in a Vehicular Land Mobile Satellite Environment

2.1 Fundamental Concepts

IP multicasting is a key networking technique for reaching a large number of users with a single transmit operation. The most notable application of this technique is the use of satellites for distributing audio/video contents due to the inherent broadcast nature of satellites and their large coverage area. With DVB-SH (Digital Video Broadcasting - Satellite Handheld) devices [5], the satellite version of DVB-H (Digital Video Broadcasting - Handheld) [6] for both handheld and in car retrofit devices, many mobile/vehicular applications can also benefit from satellite broadcast networks for reaching a large number of customers. As far as mobile/vehicular applications are concerned, satellite transmissions can be impaired by a number of factors such as the presence of buildings and obstacles in cities. To overcome this, the use of terrestrial gap-fillers [7], also known as CGC in the DVB-SH standard, has been proposed [8]. Gap-fillers act as repeaters, extending the satellite coverage in areas where the satellite signal degrades because of the presence of obstacles. In the future, the concept of ITS (Intelligent Transportation Systems), together with a plethora of new services for customers, will foster the use of Road Side Units (RSUs) that will provide a CGC system to allow short range communications with vehicles. They are the ideal complement to existing communication infrastructures to provide high mobility support in large networks. Here, the paradigms of V2V (Vehicle-to-Vehicle), V2I (Vehicle-to-Infrastructure), I2V and, more generally, V2X arise.

Enabling Technologies. As far as V2X is concerned, IEEE 802.11p [9] is the de facto standard for terrestrial wireless communications. It is an approved amendment and enhancement to the IEEE 802.11 standard to support ITS applications for the Wireless Access in Vehicular Environments (WAVE), which was published in 2010. This standard includes data exchange between moving vehicles and between vehicles and RSUs. WAVE is in the roadmap of many ITS projects, where the satellite component may play a role as complementary network without further significant investments for setting up a consistent coverage.

Land Mobile Satellite Channel Models. Experimental Land Mobile Satellite (LMS) propagation data have been processed in [10, 11], among others, in order to characterise the channel behaviour under narrow-band transmission conditions for different environments, degrees of shadowing and elevation angles. In the Lutz's model [10], a two-state channel model was proposed: a good state under Rician fading and a bad state with Rayleigh/Lognormal fading. In the Fontan's model [11], a three-state channel model is described, accounting for Line of Sight (LOS), moderate shadow, and deep shadow conditions.

Mobility Models. The mobility model plays an important role in establishing the effectiveness of cooperation between the satellite and terrestrial segments. Data multicast by the satellite are exchanged between the mobile nodes via 802.11p, thus filling data holes that mobile nodes may experience because of signal losses. The mobility pattern in a city is different than the one outside a city. This difference may alter the effectiveness of a V2V data distribution model, thus raising the aforementioned question about the use of RSUs. In cities, vehicle clusters are frequent formed, for instance, during traffic jams or vehicles approaching traffic lights. Clearly, a model based on real collected traces, able to capture at the same time sparse and clustered network partitions, can help in simulating a scenario close to the reality. In [12], the authors proposed a mobility model, named Heterogeneous Random Walk, which is able to capture the presence of a cluster as well as isolated nodes, and the correlation between the speed and the clustering factor. Intuitively speaking, a cluster implies that nodes are of slow speed due to the large number of vehicles moving temporary together in the same direction. The slow speed of nodes inside a cluster facilitates V2V data transmissions and the short distance between them increases the probability of correct data transmissions. The cluster formation process is desirable for improving the effectiveness of a V2V data distribution scenario. Mobile nodes can also be isolated nodes outside a cluster, spreading out on the network (roads system) and moving at higher speeds. This mobility model is a better representation of the real situation than the use of a pure city section mobility model.

2.2 Cooperative Scenario in a Vehicular Land Mobile Satellite System

The scenario under investigation is depicted in Fig. 1. A transparent satellite multicasts data from a single source to multiple terrestrial nodes, including RSU units. Data packets are coded together using NC [13], applied before the network level, generating N packets out of K source packets, $N > K$. Data sent through the satellite may not be correctly received by mobile nodes because of fading and shadowing effects [10, 11]. The RSUs, equipped with a DVB-SH and an 802.11p interface, cooperate in propagating the information received on the DVB-SH interface, retransmitting it without modification on the 802.11p interface. The mobile nodes receive data via DVB-SH and also retransmit them via 802.11p, increasing the probability that closer nodes can fill possible data holes. Finally, each RSU is assumed sufficiently apart to possibly experience different satellite channel statistics. RSUs are connected via a terrestrial link, which makes the terrestrial segment as robust as possible.

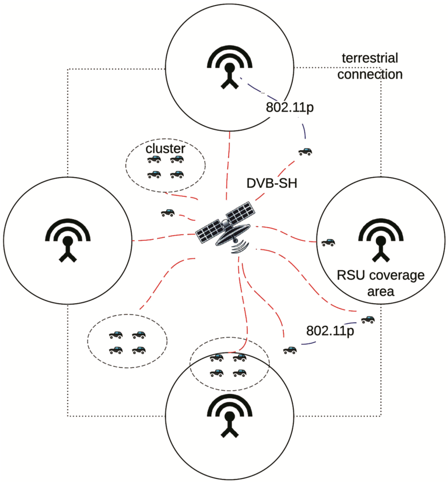

Fig. 1. Cooperative scenario for a vehicular land mobile satellite system with spatial diversity

The node mobility model is taken from [12] and described in Sect. 2.1. A cluster here can be modelled as a sort of mobile super-node, in which nodes share the maximum available fraction of received data. Four different cases are possible: (i) a set of nodes inside a cluster and inside the coverage area of an RSU; (ii) a set of nodes inside a cluster but far away from an RSU; (iii) a single node not inside a cluster but in the coverage area of an RSU; (iv) finally, a single node not part of a cluster and far away from an RSU.

Case (i) is the most favourable one: the nodes can take advantage of both situations, i.e., to be inside a cluster and close to an RSU, while case (iv) represents the worst situation: a node is isolated and can only rely on the satellite channel.

NC helps in protecting transmitted data coding different packets together at the source and also allows for recoding at intermediate nodes, for instance to deal with different channel statistics.

In a multicast scenario, the absence of a feedback channel makes it impossible for the source to know if data have been correctly received. Large redundancy can help in reducing losses but, on the other hand, it reduces the channel goodput because a fraction of the channel capacity is merely used for error correction. Thus, a trade-off must be identified between scenario requirements and channel utilization. The use of RLNC codes in a multicast scenario has been analysed in depth in [14]. It allows for a decentralized architecture (i.e., no need for network codes planned or known by a central authority), while keeping a high level of robustness. In [15], the authors dealt with the use of several communication links, for example IEEE 802.11, IEEE 802.16 and a satellite link for communication between a fixed station and mobile nodes. NC techniques are used to code together data and fully exploit the available links, achieving significant QoS improvement even in the presence of large losses on a link. In [16], multiple sources cooperate to reach a single receiver via satellite (ON/OFF channel model). Sources are supposed to be able to exchange packets among them; therefore, each source sends coded combinations of packets (RLNC) to the receiver via satellite. The different sources were spaced apart, introducing spatial diversity when transmitting to the satellite. The different geographical positions helped in reducing the system outage even in conditions of deep fading produced by the randomness of the surrounding environment. It was shown that RLNC was an effective strategy to counteract random losses in communication channels at the expenses of channel capacity: a trade-off must be identified, taking bandwidth requirements and channel statistics into account. The large performance gain shown in real satellite scenarios [17, 18] proved that the benefits of NC far exceed its shortcoming introduced by the delay in collecting at least K packets for coding in the source buffer plus the coding/decoding delay.

3 Network Coding for Mobile Multicast in a Satellite-Based Aeronautical Scenario

In satellite-based aeronautical communications, IP multicasting remains the most bandwidth efficient technology for group communication. It can further take advantage of NC to minimize the effects of random packet errors and erasures that frequently occur in satellite communications, especially in a mobile environment. During handover in a multi-beam satellite scenario where the mobile multicast receiver is in the overlapping area of two satellite beams, the benefits of NC can be even more significant as the overlapping area is always at the beam edge, which is prone to random packet errors and erasures due to the weak signal strength.

There are typically three types of handover for satellite communications, namely, beam handover, gateway handover and inter-satellite systems handover. Gateway handover entails beam handover and inter-satellite systems handover entails gateway handover. Both gateway handover and inter-satellite system handover require handover at the IP layer, while beam handover of the same satellite system is carried out at the link layer. This paper concentrates only on gateway handover in order to investigate the effect of NC on the IP layer.

3.1 Network Coding and IP Multicast Receiver Mobility in Satellite-Based Aeronautical Communications

Figures 2 and 3 present the gateway handover scenario considered in this paper. The footprint of each satellite is divided into two gateway (GW) beams (GW_B1 and GW_B2) where each GW beam represents a separate IP network. The IP multicast source is located in the terrestrial network and receivers are aircrafts equipped with a return channel satellite terminal, for example, a DVB Return Channel Satellite Terminals (RCSTs) [19]. As the reception of every single multicast packet is essential, then there is the need of feedback/acknowledgement channels from receivers (aircrafts). Different IP multicast receiver mobility support schemes do exist today, but here Home Subscription (HS)-based and Remote Subscription (RS)-based approaches are considered [20].

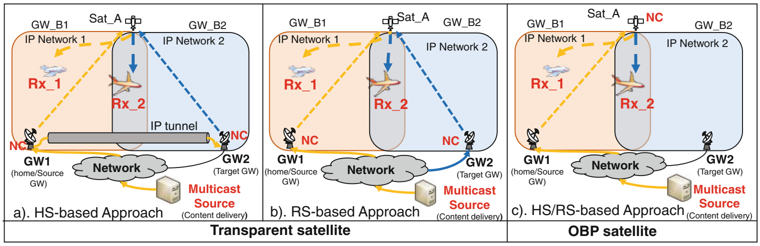

Fig. 2. NC and IP multicast receiver mobility support at gateway handover

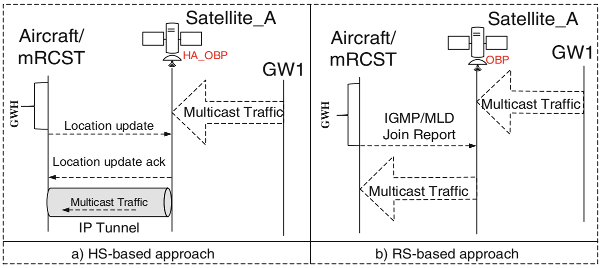

Fig. 3. Multicast reception signalling after gateway handover

3.2 Gateway Handover

Transparent (Bent-Pipe) Payload. In this scenario, intra-flow Systematic Random Linear Network Coding (S-RLNC) [21] is implemented at the satellite air interface of each GW. S-RLNC here implies that for transparent payloads the GWs will first transmit the original packets to the satellite and then the coded packets of the already transmitted packets. The transmission of the coded packets could be due to requests from some receivers or to pre-emptive measures to prevent receivers from generating retransmission requests since the satellite channel is prone to random packet errors and erasures. If there are no packet losses, then any redundant transmission is a waste of satellite resources. But if packets losses occur in a reliable IP multicast scenario over satellite where the receiving satellite terminals' population could be very large, then pre-emptive transmissions of a few coded packets could compensate for the lost packets, thus saving satellite resources by preventing terminals from generating and transmitting NACKs. The gain in throughput is proportional to the number of receivers that suffer from packets loss and also to the NC generation size. In Fig. 2, the multicast receiver aircraft RX_2 entering the overlapping area between GW_B1 and GW_B2 will signal a handover for a specified target beam.

On-Board Processing (OBP) Payload. Figure 3 presents the gateway handover scenario with OBP satellites for both HS-based and RS-based approaches. With a layer 3 regenerative OBP payload, the satellite can join the multicast groups on behalf of all multicast receivers within the satellite footprint and can also replicate multicast packets. This also gives an option of implementing NC on-board the satellite. If intra-flow S-RLNC is implemented on-board the satellite, more satellite bandwidth resources will be saved and the packet end-to-end delay will be reduced especially for retransmitted packets since they will now be sent from the OBP satellite. Since the OBP satellite acts as a multicast router to receivers in both IP networks 1 and 2, as shown in Fig. 2c, the path taken by the multicast traffic before and after the gateway handover remains the same in both HS-based and RS-based approaches. Figure 3a and b show the signalling required to receive multicast traffic after the gateway handover. For the HS-based approach, when aircraft RX_2 completes the gateway handover, it will register its newly acquired Care-of-Address (CoA) to its Home Agent (HA) located at the OBP satellite [22]. The HA now intercepts and tunnels to aircraft RX_2 the traffic from all multicast groups that aircraft RX_2 is a member of as shown in Fig. 3a. For the RS-based approach, after gateway handover is completed, aircraft RX_2 simply uses its CoA to re-subscribe to all the multicast groups that it belonged to before gateway handover, as shown in Fig. 3b. Therefore, the multicast router in the OBP satellite adds aircraft RX_2 to the list of downstream receivers in GW_B2.

3.3 Performance Evaluation

Suppose that n aircrafts in the overlapping beam area are subscribed to receive IP multicast traffic from the multicast source (see Figs. 2 and 3) and that the packet loss rate is R_L%. Assuming that there are no packet losses in the terrestrial/wired network and that Negative ACKnowledgement (NACK) is used to request for any lost packet to ensure reliability, then the total expected number of transmissions (multicast packet + NACKs) required per multicast session, $E[N_{T/S}]$, for all n aircrafts to receive E_s packets successfully over the overlapping area of the two beams with and without networking coding for transparent and OPB satellites is as follows:

Without Network Coding:

For transparent satellites:

$$E\left[N_{T/S}\right] = \left\lceil \frac{\psi_S h_{GW\_A}}{1 - R_L/100}(1+n) \right\rceil \qquad \text{for } R_L > 0 \tag{1}$$

For OBP satellites:

$$E\left[N_{T/S}\right] = \left\lceil \frac{\psi_S}{1 - R_L/100}\left(h_{GW\_A} + n h_{A\_S}\right) \right\rceil \qquad \text{for } R_L > 0 \tag{2}$$

where $E[N_{T/S}]$ = expected value of $N_{T/S}$, h_{GW_A} = number of hops between GW and aircraft via satellite; h_{A_S} = number of hops between aircraft and satellite; $\lceil x \rceil$ = ceiling function of x; E_s = average multicast session length in number of packets; n = total number of receivers (aircrafts).

With intra-flow S-RLNC, after sending K original packets, NC is performed on copies of the K original packets (generation size) to produce each coded packet that is transmitted as redundant packet. The number of redundant coded packets transmitted depends on the packet loss rate R_L. With S-RLNC, it assumed that the original packets received are used to decode each redundant coded packet received.

With Network Coding:

If Ψ_s/K is the number of coded packets produced from one multicast session, then the total number of transmissions (original + coded packets) required for all n aircrafts to receive all packets in one multicast session $N_{T/S}^{NC}$ is given by the sum of the number of transmissions of original packets plus redundant coded packets.

For transparent satellites:

$$E\left[N_{T/S}^{NC}\right] = \left\lceil \left(\frac{\Psi_S\, h_{GW\_A}}{1 - R_L/100}\right) + \left(\frac{h_{GW\_A}\left(\Psi_S/K\right)}{1 - R_L/100}\right) \right\rceil \qquad \text{for } R_L > 0 \tag{3}$$

$$E\left[N_{T/S}^{NC}\right] = \left\lceil \frac{\Psi_S\, h_{GW\_A}}{1 - R_L/100}\left(1 + \frac{1}{K}\right) \right\rceil \qquad \text{for } R_L > 0 \tag{4}$$

For satellites with OBP:

$$E\left[N_{T/S}^{NC}\right] = \left\lceil \left(\frac{\Psi_S\, h_{GW\_A}}{1 - R_L/100}\right) + \left(\frac{h_{A\_S}\left(\Psi_S/K\right)}{1 - R_L/100}\right) \right\rceil \qquad \text{for } R_L > 0 \tag{5}$$

$$E\left[N_{T/S}^{NC}\right] = \left\lceil \frac{\Psi_S}{1 - R_L/100} + \left(h_{GW\_A} + \frac{h_{A\_S}}{K}\right) \right\rceil \qquad \text{for } R_L > 0 \tag{6}$$

where $E\left[N_{T/S}^{NC}\right]$ is the expected value of $N_{T/S}^{NC}$.

Numerical Results. The following parameters are used for numerical results: $n = 50$, $R_L = 20$ %, $E_s = 10$, $K = 5$, $h_{GW\_A} = 2$, $h_{A\_S} = 1$. From Fig. 4, it can be seen that the total number of transmissions required with NC is 97.6 % less compared with that without NC for a transparent satellite payload. Similarly, for OBP payload, the total number of transmissions required with NC is 95.8 % less compared with that without NC.

Figure 5 shows the effect of packet loss rate in the overlapping area on the total number of transmissions required for all receivers to receive all transmitted multicast packets for transparent/OBP satellite payloads with and without NC. It can be seen that the difference in the number of transmissions required for transparent satellite payload with and without NC is huge throughout the whole range of R_L. Similar huge differences are seen for OBP satellite payload with and without NC.

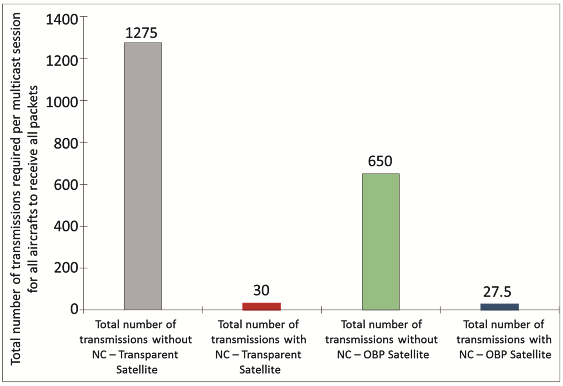

Fig. 4. Total number of transmissions with and without NC for transparent and OBP satellites

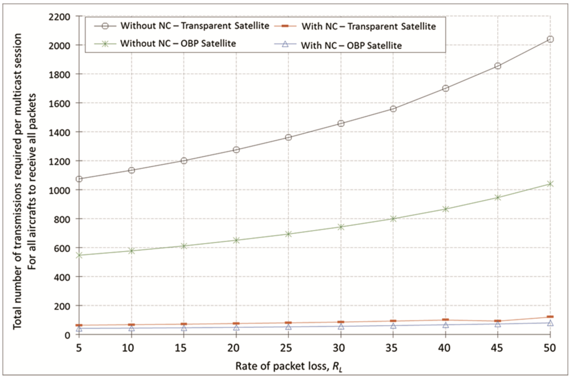

Fig. 5. Effects of packet loss rate on the total number of transmissions with and without NC

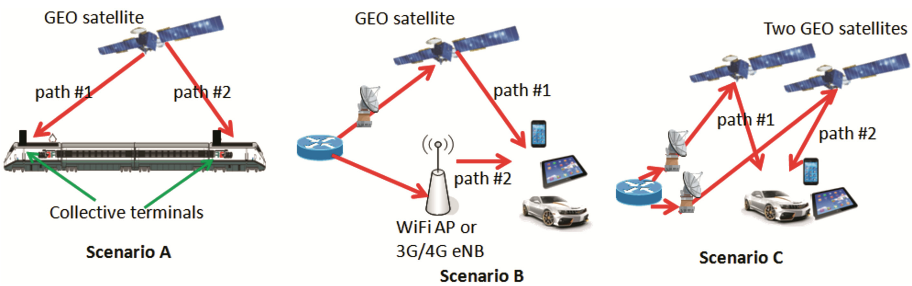

Fig. 6. Envisaged MSS scenarios for multipath TCP-based connections

4 Multipath TCP-Based Scenario

Mobile Satellite Systems (MSSs) can provide communication services in areas where a terrestrial cellular infrastructure is not available. This section considers mobile users affected by ON/OFF (Markov) channel due to their movement and the presence of obstacles. The focus is on MSS scenarios where an end user can connect via two paths simultaneously using two transceivers having either the same air interface but different carriers or different air interfaces connecting to different wireless systems. In particular, the following subcases are considered as depicted in Fig. 7:

- **Scenario A**: A train with a collective terminal and two antennas in the front and at the back of the train;
- **Scenario B**: A multi-Radio Access Technology (multi-RAT) system where the mobile terminals can use different air interfaces (hybrid system), such as: satellite, WiFi, and 3G/4G;
- **Scenario C**: A satellite diversity case, where two GEO satellites are adopted to reach the mobile user.

In Scenario A, the train employs two antennas to receive the traffic and a collective terminal is used to exploit the data received from both paths. The collective terminal can connect local users on the train by means of an onboard WiFi system. In Scenario B, mobile terminals are expected to simultaneously use multiple air interfaces. The presence of different paths with different propagation delays and packet loss conditions may be a critical issue. This asymmetry could cause the receiver buffer to fill up while waiting for the recovery of lost packets on the slowest path. Finally, Scenario C considers a complex mobile device (or collective terminal) that uses two antennas and two independent transceivers to connect and to simultaneously synchronise with two GEO satellites. This allows path diversity and can better cope with user mobility and the occurrence of occasional path disconnections due to obstacles. In all these scenarios, the mobile user receives from two independent paths affected by independent ON/OFF channel behaviours on the wireless segment. Multipath protocols allow the exploitation of the inherent path diversity; these protocols are considered here in combination with NC solutions. Note that each multipath scenario above has its own unique characteristics. For instance, the two paths of Scenario B are characterised by different air interface conditions and different propagation delays.

The ON/OFF Markov channel model is characterised as follows: the mean ON (OFF) time is T_{ON} (T_{OFF}). During the OFF phase, packet transmissions are affected by erasures according to probability p, while in the ON phase all packet transmissions are considered to be received correctly. The ON and OFF state probabilities are:

$$P_{ON} = \frac{T_{ON}}{T_{ON} + T_{OFF}} \quad , \quad P_{OFF} = \frac{T_{OFF}}{T_{ON} + T_{OFF}} \tag{7}$$

The values of T_{ON} and T_{OFF} are on the order of seconds for MSSs and can be determined according to [10] considering user speed and S and L (2 GHz) bands.

RLNC is adopted here as it seems to offer a simple and robust solution; each coded packet generated from a block of packets is just another packet that can contribute to fulfil the degrees of freedom needed at the decoder. Other NC codes such as Raptor codes [23] could be more complex to implement even though the decoding complexity is linear with the block size K, O(K), while RLNC have complexity O(K^3). Hence, RLNC requires to keep a small-enough block size K for an efficient decoding; the encoding block size could also be differentiated from path to path in case of different channel conditions on the two paths (asymmetry).

This Section investigates the combination of MP-TCP at transport layer with NC of the RLNC type implemented as shim layer. Note that in order to achieve the maximum transparency at end-hosts (both servers and end-users), MP-TCP and RLNC are not implemented end-to-end, but inside the network between two transport-layer Performance Enhancing Proxies (PEPs), at an intermediate router and at a collective terminal (user side) with a feedback loop between them. If the receiving PEP is unable to decode a block due to a loss of degrees of freedom, it is then possible to ask the PEP-sender to transmit further encoded packets to recover the losses. The PEP implements a TCP split approach, performing a 'conversion' from TCP to MP-TCP that is used inside the satellite network [24]: each TCP flow is divided into two subflows that exploit two independent paths (see Fig. 6). Each subflow is protected by RLNC that is implemented as a shim layer below the transport layer (i.e., MP-TCP/TCP subflow/NC) to recover packet losses due to channel effects. If IP packets are end-to-end encrypted with IPsec before they are sent via the PEP-based satellite network, it would be impossible to perform PEP functions at the intermediate node, since we could not access IP packet payload data (TCP header). However, IPsec could be applied between the two PEPs.

In our scenario, the two paths experience independent ON/OFF channel behaviours. Hence, even if one path is affected by losses, the other path may experience good conditions, thus allowing path diversity with error recovering capabilities that can be exploited by NC.

There are other techniques proposed in the literature to combine TCP-based transport-layer protocols with NC, as those in [15, 25, 26]. In particular, the authors of [25] introduced TCP/NC where TCP is combined with NC at a shim layer between transport and network layers. A TCP/NC source transmits random linear combinations of all packets in a coding (sliding) window that is related to the congestion window. The receiver acknowledges every degree of freedom (i.e., a new encoded packet that provides new information). Another TCP version that includes NC is called Coded TCP (CTCP) [26]. The CTCP sender divides the data stream into blocks with a fixed number of packets; then, linear combinations are generated for the packets of each block. CTCP estimates the packet loss rate and adaptively computes the number of necessary coded packets to be transmitted. Finally, MPTCP/NC adopts two layers of network coding [15]. The first NC layer is applied before packets are injected into a TCP subflow; this layer does not add redundancy, but is useful so that packets of both subflows can be combined together for NC decoding purposes. Instead, the second NC layer, based on TCP/NC (subflow level), introduces redundancy for protecting subflows from packet losses.

In this project, we will apply MP-TCP to our scenarios in Fig. 6, where encoded packets (RLNC) of one path are sent on the other path to improve robustness to packet losses in the case of mobile users (path-coding diversity). This technique is called Path-

Based Network Coding MP-TCP (PBNC-MP-TCP). The encoding scheme can be applied both as intra-flow NC at the PEP (i.e., using multiple encoders, one for each subflow) or as inter-flow coding (i.e., using a common buffer and one encoder at the intermediate PEP). The number of redundancy packets generated for each subflow depends on the channel conditions experienced on the path and can be determined according to a cross-layer approach to maximize transport layer goodput.

In our scenario, we adopt the S-RLNC analysis proposed in [27] to study the successful decoding probability P_{suc} of an encoded block, taking the behaviour of the ON/OFF channel into account (coded blocks can pick the channel in OFF or ON state according to the respective state probabilities). If the transmission of the coded block occurs while the channel is in the OFF state, packets are subject to an erasure rate p. If the transmission occurs in the ON state, packets are received successfully. This approach is possible because the satellite channel has a much slower behaviour than the transmission time of a coded block: the transmission of a coded block just samples the satellite channel in ON or OFF states according to the corresponding probabilities of the ON/OFF Markov chain. In what follows, K is the information block size, N is the size of the encoded block, $N - K$ is the number of redundancy packets, $\delta \in [0, 1, \ldots, N - K]$ is the number of redundancy packets sent on the secondary path, q is the field size of the Galois field used for NC. The following formulas (8)–(10) are adapted from [27] to account for δ packets out of $N - K$ redundancy packets sent on the secondary path and experiencing an ideal lossless channel. This assumption is made to emphasize the impact of using a secondary path.

$$P_{suc} = \left[\sum_{r=K-\delta}^{N-\delta} \binom{N-\delta}{r} (1-p)^r p^{N-\delta-r} f_k(r+\delta, N) \right] P_{OFF} + f_K(N,N) P_{ON} \tag{8}$$

where $f_K(r + \delta, N)$ is determined as follows:

$$f_K(r+\delta,N) = \frac{\binom{N-K}{r+\delta-K} + \sum_{h=h_{\min}}^{K-1} \binom{K}{h}\binom{N-K}{r+\delta-h} \prod_{j=0}^{K-h-1}\left(1-q^{h+j-r-\delta}\right)}{\binom{N}{r+\delta}} \tag{9}$$

$$h_{\min} = \max\{0, r+\delta-N+K\} \tag{10}$$

Hence, the block decoding failure P_{fail} can be obtained as $P_{fail} = 1 - P_{suc}$. Figure 7 shows the performance of S-RLNC ($K = 5$ packets is the encoding block size and $N = 9$ is the coded block size) for different field sizes q for an ON-OFF channel (primary path) with $T_{ON} = 4$ s, $T_{OFF} = 2$ s, and packet erasure rate in the OFF state $p = 0.5$. The $N - K = 4$ redundancy packets can be sent in part ($\delta \leq N - K$) on a secondary path.

Note that without network coding the average packet loss rate is equal to $p \times P_{OFF} \approx 0.17$ that would practically cause TCP goodput to drop to zero. Hence, NC can significantly reduce the packet loss corresponding to P_{fail} as shown in the graph, thus allowing a better TCP behaviour. In particular, the case where all redundancy packets are sent on the secondary path permits to reduce the packet decoding failure with respect to the case where all redundancy packets are sent on the main path (classical, MPTCP/NC-like case). For instance, with field size $q = 256$, this reduction is by a factor about equal to 15 that can roughly correspond to a TCP goodput increase of four times. Hence, we expect that our diversity approach for sending redundancy packets can provide a positive impact on the PBNC-MP-TCP technique proposed.

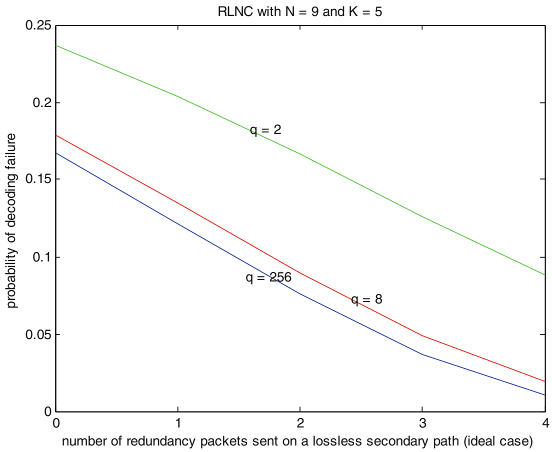

Fig. 7. RLNC performance for different field sizes and different number of redundancy packets sent on an ideal path without losses

5 Conclusion and Future Directions

NC has many potentialities to improve the performance of satellite networks. This paper surveys some of these opportunities identifying key scenarios and presenting preliminary results. The future activity will concern with the implementation of simulators dealing with the described scenarios to provide numerical quantitative evidences to the considerations made in this paper.

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