Network Coding for Multicast Communications over Satellite Networks

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Abstract. Random packet errors and erasures are common in satellite communications. These types of packet losses could become significant in mobile satellite scenarios like satellite-based aeronautical communications where mobility at very high speeds is a routine. The current adaptive coding and modulation (ACM) schemes used in new satellite systems like the DVB-RCS2 might offer some solutions to the problems posed by random packet errors but very little or no solution to the problems of packet erasures where packets are completely lost in transmission. The use of the current ACM schemes to combat packet losses in a high random packet errors and erasures environment like the satellite-based aeronautical communications will result in very low throughput. Network coding (NC) has proved to significantly improve throughput and thus saves bandwidth resources in such an environment. This paper focuses on establishing how in random linear network coding (RLNC) the satellite bandwidth utilization is affected by changing values of the generation size, rate of packet loss and number of receivers in a satellite-based aeronautical reliable IP multicast communication. From the simulation results, it shows that the bandwidth utilization generally increases with increasing generation size, rate of packet loss and number of receivers.

Keywords: Aeronautical communications networks · IP multicast · Network coding · Satellite networks

1 Introduction

Satellites with their large geographical coverage and the ability to reach large satellite terminal populations present an unrivaled platform for group communication. For satellite broadband service providers to satisfy these large terminal populations and also meet the service level agreements, the efficient utilization of the available satellite bandwidth capacity becomes essential. In order to increase the available satellite capacity and high data rates, new satellite systems are now designed to support multiple spot beams (frequency reuse) and operate at high frequency bands (e.g., the Ka-band). Satellites operating at Ka-band (and higher) will likely experience an increase in random packet

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errors and erasures, thus reducing throughput in the satellite network as a whole and wasting bandwidth resources especially in reliable communication.

Nowadays, most satellite terminals have return channel capabilities. These return channel satellite terminals (RCSTs) [1] in remote locations can therefore send back acknowledgments, their channel conditions, etc. to the Network Control Centre (NCC) [1] or satellite gateway for retransmission in reliable communication and for efficient utilization of the channel respectively. In satellite communications, efficient utilization of the allocated bandwidth resources is crucial to both the satellite service providers and the customers if they are to maximize their profits and get best value for money respectively. For reliable multicast communication, one of the most intriguing challenge when designing a satellite-based content distribution platform is the efficient bandwidth management scheme. Despite the use of negative acknowledgments (NACKs) in reliable multicasting in order to reduce bandwidth overhead, the lossy nature of satellite channels and the potentially large satellite terminal populations imply that a huge volume of NACKs can still be generated. This bandwidth management challenge can become more acute in mobile satellite scenarios like the satellite-based aeronautical communication which is more likely to witness higher random packet errors and erasures due to mobility at high speeds.

Although the introduction of adaptive coding and modulation (ACM) in some satellite systems like the DVB-RCS2 [2] has proved to increase throughput and save some bandwidth in satellite networks, ACM offers no solution to the problems presented by erasures. Network coding (NC) has been shown to effectively solve the problems of erasure channels and random packets errors which are common in satellite networks [3] as well as increasing throughput in the network by communicating more information with fewer packet transmissions. For content distribution using reliable IP multicasting in satellite-based aeronautical communication, NC can save considerable amount of satellite bandwidth resources in scenarios where many aircrafts at different locations with varying channel conditions (under one satellite footprint) are subscribed to the same multicast group. The transmission of a few redundant coded multicast packets in such a scenario could reduce or even prevent the NACKs from being generated as the redundant coded packets can compensate for various original packets lost. This will not only lead to an increase in throughput and bandwidth conservation but also, will reduce the time required to successfully transmit a certain number of packets over the satellite considering the long satellite propagation delay.

Using Random Linear Network Coding (RLNC) [4], this paper investigates the impact on bandwidth utilization of varying generation size, number of receivers and rate of packet loss on content distribution using reliable IP multicasting in a satellite-based aeronautical communications. Unlike in most existing NC schemes over satellite networks which require the satellite terminals to be multi-homed in order to exploit the multipath scenario, the proposed scheme here is designed for a RCST with only one satellite interface. The focus here is to determine how the changing values of the above stated parameters affect the bandwidth usage i.e., number of transmissions required for all group members (aircrafts) to receive all the multicast packets transmitted over the lossy satellite network.

2 Literature Review of Network Coding over Satellite

Recently, some research works on NC over satellite networks have been published in open literature. In [5], the authors examined the feasibility of applying NC on different types of satellite network architectures. For transparent (bent-pipe) satellites, the authors proposed that the Analogue Network Coding (ANC) be implemented on-board the satellite. Here, two satellite terminals that want to exchange data via satellite use the same time-slot. ANC is performed at the physical layer on-board the satellite on the signals transmitted by the two terminals using the same time-slot. During the second time-slot, the satellite then transmit the coded signal to the two terminals which will individually use their own transmission and signal cancellation techniques to recover the signal from the other terminal. The advantage of using ANC is that only 2 time slots are used to transmit and also receive data by the two terminals instead of 4, implying savings to satellite bandwidth resources and an increase in network throughput. The ANC scheme faces two major drawbacks: signal saturation and interference caused by mixing signals from the same uplink beam before NC is performed and the requirement for the two signals to arrive at the satellite at the same instant. In reality, a time shift always exist between two signals even when transmitted at same time. For regenerative satellites, the authors in [5] proposed the use of XOR NC where the mixing of the two data streams is done at bit level on-board the satellite and the coded data broadcasted to the two terminals. According to [5], the advantage of using XOR NC in regenerative satellites is that the downlink capacity required by the two terminals is reduced by half.

The authors in [3, 6, 7] proposed the use of RLNC in multipath scenarios in a satellite network. In a satellite-based reliable multicast scenario in [3], RLNC is implemented at layer 2 in the satellite Hub for all traffic destined for the satellite network. The multipath scenario is created here by making use of gap-fillers which relay transmission from the satellite to the group members (subscribers). Each subscriber can therefore receive coded packets directly from the satellite (line-of sight) and also indirectly through gap-fillers. So, the redundancy of receiving two copies of each coded packet (one from each path) will compensate for any loses in any of the two paths. This compared with the traditional NACK-based reliable multicast, showed a remarkable improvement in terms of throughput. The cost of gap-fillers and the requirement for the receivers to be multi-homed are some of the weaknesses of this proposal. In [6], multipath scenario is created by making use of the overlapping area of 2 beams as each terminal located here can receive transmissions through both beams. This is also a satellite-based reliable multicast communication where RLNC is implemented at layer 2 in the satellite gateway. With NC according to [6], the multicast receivers within the overlapping area (where the erasure rate is generally higher due to weak signal strength at beam edge), witnessed a 25 % increase in throughput compared to the scheme with no NC. The authors in [7] proposed how RLNC can be used to support soft-handovers by mobile multi-homed satellite terminals in reliable unicast communication. Once the mobile terminal enters the overlapping area of two beams, the satellite starts transmitting coded packets through both beams for the roaming terminal. The advantages here are: increase in throughput due redundant packets provided by multipath which compensates for lost packets, thus preventing any retransmissions over the satellite; no specific coordination between codes at physical layer is required and load-balancing between two beams for terminals located with the overlapping area. In all proposed multipath-based NC schemes [3, 6, 7], one main common drawback is that they offer no solution to single-interface satellite receivers which cannot benefit from the multipath scenario.

In all the proposed NC schemes described above, none has examined how the throughput increases or bandwidth conservation due to NC implementation is affected by varying the generation size, rate of packet loss and number of receivers (i.e., in multicast scenarios). This paper seeks to study how changing the values of these parameter will affect the satellite bandwidth saved by implementing NC.

3 Proposed Network Architecture

Figure 1 shows the network architecture for IP multicast application in satellite-based aeronautical communications. The multicast source (content delivery) is located in the terrestrial network while the receivers are aircrafts, each equipped with a RCST for satellite communication. The satellite has a transparent payload (bent-pipe). The satellite gateway (GW) or its local network is assumed to have a multicast enabled router.

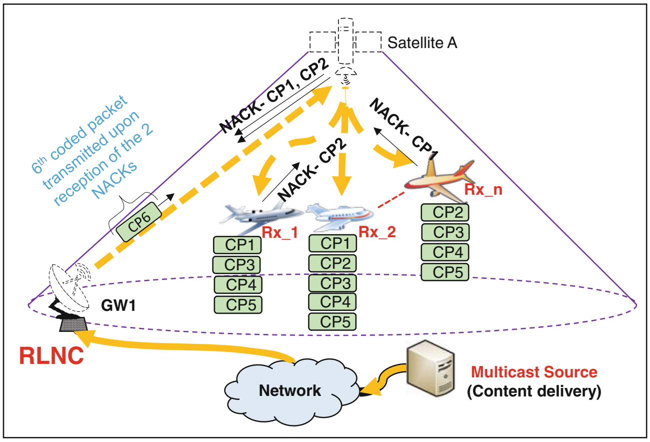

Fig. 1. Reliable IP multicast in satellite-based aeronautical communications with RLNC

Aircrafts wishing to join any multicast group send their Internet Group Management Protocol (IGMP) [8] or Multicast Listener Discovery (MLD) [9] to the GW. Upon reception of IGMP/MLD, the GW subscribes to the multicast group on behalf of the aircrafts. So, when GW1 (Fig. 1) receives multicast packets from the source, it performs RLNC on a number of original packets according to the set generation size (i.e., number of original packets mixed together) to produce a coded packet (CP) i.e.,

$$CP1 = a_{11}P1 + a_{12}P2 + a_{13}P3 + \ \ldots\ldots a_{1n}Pn. \quad (1)$$

Where **n** = generation size, $\mathbf{a_{11}}$, $\mathbf{a_{12}}$, $\mathbf{a_{13}}$, $\mathbf{a_{1n}}$ are randomly chosen coefficients from a finite Galois field. The coded packets are then forwarded to the aircrafts according to their subscription. The minimum number of coded packets required at the receiver to correctly retrieve the original packets from the coded packets is equal to the number of original packets contained in each coded packet.

With content delivery, reliability is the key parameter for quality of service consideration unlike in real-time applications where delay and jitter are the main parameters. So, reliable IP multicast where a NACK is sent back to the multicast router (located at GW) for each packet lost is used for content delivery. Due to the different location and therefore channel conditions of the aircrafts, different packets are likely to be lost by each aircraft. Figure 1 shows a RLNC example of generation size 5. As illustrated in Fig. 1, out of the 5 coded packets transmitted by GW1, aircrafts Rx_1 lost packet *CP2*, Rx_n packet *CP1* and Rx_2 received all the 5 coded packets transmitted. Aircrafts Rx_1 and Rx_n then generate 2 NACKs and sent to GW1 as shown in Fig. 1. Upon reception of the 2 NACKs, GW1 then transmits the 6th coded packet (CP6) to the multicast group. If *CP6* is successfully received by Rx_1 and Rx_n, then all the multicast receivers in Fig. 1 will therefore be able to retrieve the 5 original packets contained in the received coded packets. It should be noted that all the coded packets received for each generation by the aircrafts are linearly independent packets but contain exactly the same original packets. Figure 2 shows the minimum number of transmissions over the satellite air interface required for the 3 aircrafts to receive all the original packets for the example describe above (Fig. 1). It is the minimum number of transmissions required because if any of the NACKs (or the 6th coded packet) are lost then the total number of transmissions required will definitely increase.

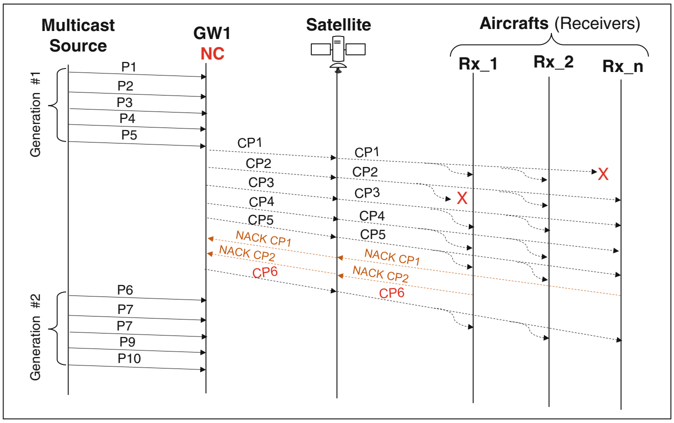

Fig. 2. RLNC example for satellite–based multicast scenario

4 Bandwidth Utilization in RLNC with Changing Generation Size, Number of Receivers and Rate of Packets Loss

In a reliable IP multicast scenario like the one illustrated in Fig. 1 above, the impact on satellite bandwidth utilization of changing generation size, number of receivers and rate of packet loss in RLNC is investigated. The amount satellite bandwidth utilization is measured here in terms of the number of transmissions over the satellite required for all the receivers to successfully retrieve all the original packets from the received coded packets. To carry out this investigation, the number of receivers are set to 20, 50 and 100, and the generation size 5 and 10. For the generation size of 5 the minimum number of data transmissions over the satellite required for all 20, 50, and 100 aircrafts to successfully retrieve all the original packets from the coded packets are separately measured for the rate of packet loss of 10 %–50 %. This process is repeated for generation size of 10.

5 Simulation Results and Analysis

Using Network Simulator 3 (NS3), the scenario illustrated in Fig. 1 was simulated with the generation size, number of receivers and rate of packet loss set as described in Sect. 4. The minimum number of data transmissions over the satellite required for all aircrafts to successfully retrieve all the original packets from the coded packets were measured. This was done for all settings of the generation size, number of receivers and rate of packet loss described in Sect. 4.

Figure 3 shows how the generation size and the number of receivers affect the number of data transmissions required for all receivers (aircrafts) to successfully retrieve the original packets contained in the received coded packets.

Figure 3 shows that for a generation size of 5 and rate of packet loss of 10 %, there is an average increase of about 10.0 % and 20.0 % in the number of data transmissions required when the number of receivers increases from 20 to 50 and from 20 to 100 respectively. One of the main reasons why the minimum number of data transmissions required increases with increasing number of receivers is that there is a higher probability for the transmitted packets to be lost when the number of receivers is higher than when it is smaller. From the percentage increase in the minimum number of data transmissions required, it is clear that this increase is not directionally proportional to the increase in the number of receivers.

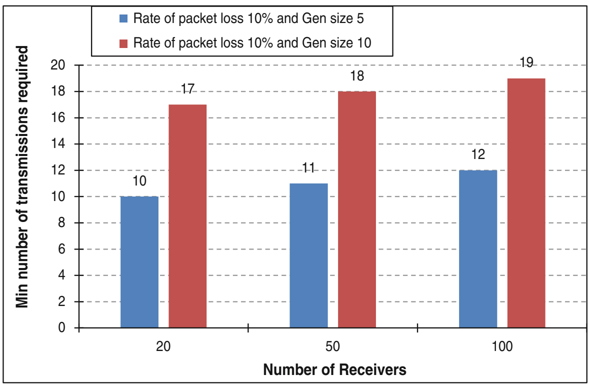

Fig. 3. Impact of varying generation size and number of receivers on minimum number of data transmissions required

For 20, 50 and 100 receivers at a constant rate of packet loss of 10 % in Fig. 3, the minimum number of data transmissions required increases on the average by 70.0 %, 63.6 % and 58.3 % respectively when the generation size is increased from 5 to 10. The general increase in the minimum number of data transmissions required when the generation size increases is mainly because the minimum number of data transmissions required must be at least equal to the generation size.

With the generation size of 10 and rate of packet loss 10 %, the average increase in the minimum number of data transmissions required when the number of receivers increases from 20 to 50 and from 20 to 100 is about 5.9 % and 11.8 % respectively. Compared to those with the generation size of 5, these increases are significantly smaller (i.e., almost half). This makes sense since combining more original packets to produce one coded packet implies one coded packet can compensate for many different lost packets which could have required more than one coded packet to compensate for.

Figure 4 shows how the minimum number of data transmissions over the satellite required for all aircrafts to successfully retrieve the original packets contained in the received coded packets is affected by varying rate of packet loss at a constant generation size for 20, 50 and 100 receivers. From Fig. 4, it can be seen that the minimum number of data transmissions required generally increases as the rate of packet loss increases for each set of receivers. Although the relationship between the minimum number of data transmissions required and rate of packet loss is not linear, at a constant generation size of 5, the average increase in the minimum number of data transmissions required for 20, 50 and 100 receivers as the rate of packet loss changes from 10 % to 50 % is 58.00 %, 58.18 % and 73.33 % respectively. This trend is expected since an increase in rate of packet loss implies an increase in the minimum number of coded packets transmissions required in order to compensate for the high loss.

Also, Fig. 4 shows that the minimum number of data transmissions required increases with both increasing rate of packet loss and number of receivers. This is mainly due to the fact that at a constant generation size, increasing the number of receivers increases the probability of different packets being lost. If many different packets are lost, then more transmissions will have be made to compensate for them since the generation size is constant or fixed.

Figure 5 shows a similar scenario to Fig. 4 except for the fact that the generation size here is now set to 10. The general trend here is similar to that in Fig. 4. Similarly to Fig. 4, at a constant generation size of 10, the average increase in the minimum number of data transmissions required for 20, 50 and 100 receivers as the rate of packet loss changes from 10 % to 50 % is 42.35 %, 50.00 % and 52.63 % respectively. Comparing these values to those in Fig. 4 shows that the average increases in the minimum number of data transmissions required for 20, 50 and 100 receivers in Fig. 5 are generally lower compared to those in Fig. 4. This is expected due to the fact that increasing the generation size will increase the probability of each coded packet compensating many more different packets lost, thus reducing the minimum number of data transmissions required.

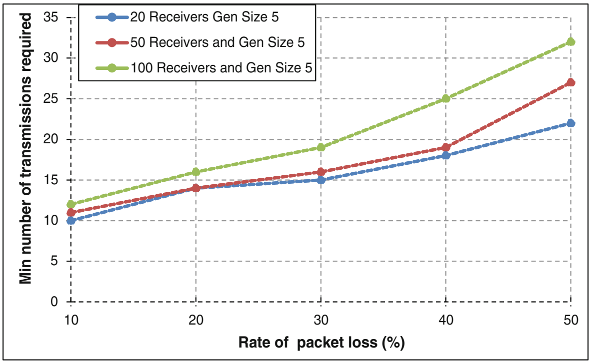

Fig. 4. Effects of rate of packet loss on minimum number of data transmissions required - at generation 5

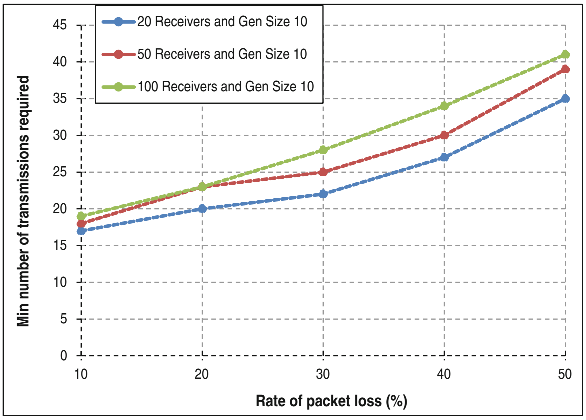

Fig. 5. Effects of rate of packet loss on minimum number of data transmissions required - at generation 10

6 Conclusion

This paper presents a detailed account of how RLNC could be implement in an IP multicast scenario over satellite-based aeronautical communications. The paper sets out to investigate the effects in RLNC of varying generation size, rate of packet loss and number of multicast receivers on the bandwidth utilization of the allocated satellite bandwidth resources.

From the investigation, it was discovered that for a constant:

- Generation size and rate of packet loss, the satellite bandwidth utilization (minimum number of data transmissions required) increases generally as the number of multicast receivers increases.

- Rate of packet loss, the satellite bandwidth utilization increases with both increasing generation size and number of receivers.
- Generation size, the satellite bandwidth utilization increases with both increasing rate of packet lost and number of receivers

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