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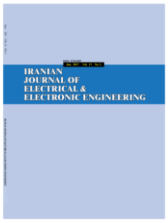

Performance Benefits of Network Coding for HEVC Video Communications in Satellite Networks

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Abstract: High-Efficiency Video Coding (HEVC) is the latest video encoding standard that achieves much better compression efficiency compared to the earlier encoding standards. Satellite channels have a long round trip time (RTT) making it difficult to use packet acknowledgments. Real-time video streaming applications preclude such packet acknowledgments in satellite networks due to strict delay constraints. We propose a combined use of Turbo Coding (TC) and Network Coding (NC) techniques to achieve better video quality over the noisy satellite links using UDP at the transport layer. We evaluate the performance improvement of turbo network coding (TNC-UDP) over the traditional turbo-coded (TC-UDP) protocol for HEVC video streaming in satellite networks. The simulation results show that compared to TC-UDP, the proposed scheme achieves PSNR improvements ranging from 14-20 dB for poor channel conditions (1-2 dB) for the two selected video sequences.

Keywords: HEVC, Turbo Coding, Systematic Coding, Multimedia Streaming, Packet Loss.

1 Introduction

SATELLITE networks provide content distribution service with high efficiency and reliability. Most Internet-based real-time multimedia services employ User Datagram Protocol (UDP) as their transport protocol [1]. Satellite-based platforms present significant advantages of scalability, ubiquitous coverage, simple topologies, and more stable bandwidth. However, the resource utilization in satellite networks is expensive and the need for efficient communications protocols is increasing [2]. Also, large latency and high Packet Error Rate (PER) of satellite networks poses issues for TCP protocol and significantly affects the throughput performance.

Quality of user experience over satellite links is a long-standing issue for network operators. The variability of the satellite latency and its impact on TCP has been the focus of research for many years. Multimedia video streaming stringent delay requirements of 10 ms, low packet loss rate, and short-bulky transactions is a challenge over satellite networks using traditional protocols. Various special configurations for multimedia streaming design over satellite were presented for one-way and two-way channels for light and high loading links. A common configuration requires the use of Performance Enhancing Proxies (PEPs) [2] and additional software for TCP protocol adjustments, one of which is presented by Manor research [3].

For satellite networks, Network Coding (NC) has recently emerged as a viable transmission protocol candidate both for the software and hardware implementation aspects. NC for reliable multicast over satellite channels with a feedback link has shown to achieve near real-time performance at near theoretical

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bounds of efficiency. For example, NC has been translated to provide power saving (4.6 dB) or time-saving (50%) and implemented in hardware in NEXT project over satellite networks [4]. The NEXT project forms part of the Heinrich Hertz Satellite Mission. NC protocol (NETCOP) has been demonstrated for videoconferencing over satellite with 90% of theoretical gains achieved [5]. A connection between Cagliari (Italy) and DLR headquarters in Cologne (Germany) with the satellite hub in DLR premises in Oberpfaffenhofen (Germany) over EUTELSAT Eurobird 3 was demonstrated. A 3 Mb/s UDP video stream was exchanged between the two terminals via the DVB-S2 satellite modem. NETCOP builds on encapsulating IP packets into Ethernet frames at the sender and de-encapsulating it back at the receiver, making NC operation layer agnostic. NETCOP reports bandwidth savings that increase with the size of the NC buffers used at the satellite. Bandwidth savings of up to 50% is reported for various asymmetry ratios between the sender and receiver traffic in an end-to-end transmission topology assuming a client and server video communication scenario. Even though, NC works best when data rates are identical, packet concatenation is performed before the NC operation and bandwidth savings of 20% were achieved for traffic rate source mismatch of 25%. Systematic NC simplifies the channel encoding and decoding process as un-encoded packets reduce complexity and the video decoding could succeed even if NC decoding fails [6].

Link-layer NC protocol for DVB-S2X/RCS is investigated in [7]. The Link Layer Systematic NC (LL-SNC) protocol is employed as Forward Error Correction (FEC) scheme with re-encoding at intermediate node in a 3-node simulation setup. The percentage throughput gain from LL-SNC for various erasure channel rates of links was established, ranging from 18% (non-symmetric erasure channels) to 158% (symmetric erasure channels). The average delay per packet was also smaller compared to the link-layer FEC protocol.

Moreover, while NC provides network level reliability, it has channel codes error control features and hence several research studies have focused on joint Source-Network-channel coding (JSNC) implementations with higher throughput and lower BER compared to separate source-network-channel coding over both and AWGN channels [8]. Network Coded TCP (CTCP) is proposed in [9] in order to overcome a large number of issues when transmitting over satellite networks. CTCP showed improved performance over TCP variants (i.e., Cubic TCP and Hybla TCP) for high packet loss rates (e.g., greater than 2.5%). Moreover, the addition of appropriate congestion control mechanism showed larger improvements over TCP protocol variants.

Other than changes to TCP, PEP is another solution used for satellite transmissions. Proprietary TCP protocols, implemented in conjunction with specialized PEP hardware were shown to improve the multimedia performance over satellite networks. However, TCP protocols based on NC are generally capable of removing the need for PEPs with careful design. Several other contributions provide implementations frameworks for NC over wired and wireless networks, e.g. NC for cellular mobile networks in [10, 11]. For video transmission, NC has shown performance improvements, but for the case of intermediate nodes performing coding, careful design of delay mechanism is needed to maximize opportunities for coding packets as demonstrated in [3].

For satellite networks, PHY layer (synchronization), MAC layer (TDMA) and network layer protocols need careful joint design in order to tackle various issues at different layers. While recognizing this, we have found that limited research has focused on understanding the unique characteristics of NC packets and their incremental role in improving decoding performance at the receiver which consequently is the core feature for all possible benefits in throughput, delay, and reliability from NC.

Recent studies have investigated the advantages of HEVC and NC with satellite video transmission. A disaster transmission network exploited HEVC encoding to fully utilize the satellite network bandwidth and to conserve resources [12]. In this work, NC is integrated with Network Function Virtualisation (NFV) for NC design domains as a structured design that does not address the video data specifically or its related constraints. The gains described assume that NC is deployed not only at the source but also at all the intermediate nodes along the path, as shown in [13], which can increase the delay and computation overhead. An adaptive casual network coding algorithm is proposed that requires the availability of a feedback channel to acknowledge each packet so as to adjust the retransmission rates [14]. A comparison with selective repeat–Automatic Repeat reQuest (ARQ) is provided showing an improvement. However, the objective was to retransmit only those packets that are lost based on a window [14] that will require keeping track of each packet reception and its re-transmission. A protocol stack is designed for reducing the satellite air-time and associated costs for video transmission by combining network coding with torrent-based transmission [15]. The framework utilizes multiple communications channels but requires video to be divided into files, which are divided as chunks, further divided as slices to be transmitted over UDP protocol. The chunks are encoded with NC and a second layer of NC is used to encode the slices [15]. A design framework is described comprising encoding and decoding nodes along with a satellite network with SNC for comparison of different NC schemes that showed advantages of re-encoding [16].

In contrast to the above studies, our proposed technique has the advantage of not relying on a feedback channel or packet acknowledgments, multiple channels or complex operations like re-encoding or video data sub-division. We explore the performance of combined network coding and turbo coding protocol for transmitting multimedia content over UDP. The aim is to provide insights into the potential resilience performance gains from NC in both low and high RTT environments in the presence of packet loss. We specifically focus on NC characteristics under No-packet loss scenarios in order to pinpoint specific characteristic relevant to Group of Pictures (GOP) in multimedia streaming. The error protection scheme in this paper is novel, as to the best of the authors' knowledge, it is a first attempt to evaluate the performance of the combined error protection with systematic network coding and physical layer turbo coding for HEVC video transmission over satellite channels.

This paper provides a performance comparison of video broadcasting using turbo coded systematic network coded video over UDP (TNC-UDP) and turbo coded video over UDP (TC-UDP) protocols for satellite communications. Network Coding is applied at the application layer whereas turbo coding is used at the physical layer. This paper is organized as follows. Section 2 provides background information on transport protocols and network coding. Section 3 discusses the simulation methodology for the selected protocols. Results are presented in section 4. Section 5 discusses the characteristics of the TNC-UDP protocol and the implications for multimedia streaming in satellite networks. Finally, Section 6 concludes the paper.

2 Background

This section discusses the video encoding and network protocols used in simulation study for an end-to-end topology of client and server.

2.1 HEVC

HEVC is the latest video coding standard [17]. It has twice the compression efficiency of H.264/AVC for the same data rate and as such is an enabler for networks with limited bandwidth [12]. Although commercial implementations such as [18] exist for satellite networks, despite its numerous benefits no research study as yet has investigated the utility of HEVC transmission over satellite channel with turbo and network coding. The reason for this late adoption could be that MJPEG and H.264 are widely deployed in commercial products [12].

2.2 Network Protocols

TCP is not considered appropriate for satellite channels due to long RTTs but there have been various schemes like PEP that are designed to overcome the limitations of TCP [2]. However, those schemes do not favor video streaming as video data is loss tolerant but delay intolerant, and thus any attempts to resend the lost packets are counter-productive.

A UDP packet consists of a header and payload. UDP employs a cyclic redundancy check (CRC) to verify the integrity of packets; therefore, it can detect any error in the packet header or payload. If an error is detected, the packet is declared lost and discarded. Similarly, NC packets are also CRC checked and may be discarded due to packet error, however due to linear combinations of packets no performance degradation results due to a packet loss. Hence NC reduces the impact of an individual packet loss on the overall video quality, useful for providing unequal error protection [19].

UDP-Lite relies on constructing CRC based on packet header only. UDP-Lite [20] avoids the unnecessary discarding of packets due to minor errors within the packet. While this is useful, SNC avoids the whole issue from the beginning.

2.2.1 Systematic Network Coding (SNC) Protocol

Consider the transfer of K packets between a server and a client. The random linear combinations are created using coefficients chosen over a Galois Field large enough to create linear dependencies with a high probability. Such a scheme is very useful for various applications, some of which are also relevant to the proposed performance improvements in this paper. These are applicable to reliable multicast, where NC-packets are used for packets retransmissions, and bidirectional data exchange where savings of transmission time are usually gained. In a simple 3 node tree scenario [9], NC has proven to provide 50% reduction in the number of transmitted bits.

SNC brings more benefits as packet transmission takes place in two stages: In stage 1, each packet is sent un-coded (after the packet generation, such as Group of Pictures (GOP) is finished) followed by stage 2, when a number of network coded packets are sent as a random linear combination of the original packets [6]. SNC reduces the encoding and decoding complexity of NC as most packets are sent un-coded. Moreover, compared to non-systematic NC, if the decoding of NC packets fails, there would still be correctly received un-coded packets which could be fed to HEVC decoder to obtain a low-quality video, which is preferable to losing a whole NC GOP that fails to decode.

2.2.2 Packet Buffering

Network coding is generally applied over a generation (GOP in videos) of packets. Thus, there is a need to buffer the packets comprising a GOP before a packet can be transmitted and it is only after all GOP packets have been transmitted that the encoding of packets for the next GOP can begin. Similarly, at the receiver, the decoding can only be performed after a GOP has been aggregated. This raises the need to buffer packets at the transmitter and receiver which adds to the delay. In this paper, we use the SNC scheme to get around this problem.

2.2.3 Innovative Packets

In systematic coding, the systematic phase transmits the source packets without any encoding, thus ensuring that each packet is an innovative packet. In the second or non-systematic phase, random linear combinations are transmitted which can help recover any missing packet from the systematic phase. The advantages are firstly, that with an increased probability all packets are innovative. Secondly, the encoding and decoding complexity are reduced, and finally, under low loss conditions, a non-systematic phase may not be required, resulting in increased performance benefits from the SNC protocol.

2.3 Combining Systematic Network Coding With Physical Layer Coding

Turbo codes (TC) have been commonly applied for error correction for various applications due to their high code gain and ability to achieve low bit/packet error rate for low SNR values [21]. The iterative nature of turbo codes decoding phase has made them popular even for high latency and high error rate channels including satellite channels. For example, [22] proposed an integrated FEC coding scheme based on turbo codes for ATM transmission on broadband satellite channels. Currently known applications for turbo codes range from deep space to cellular mobile and recently satellite using Digital Video Broadcast-Return Channel via Satellite and over Terrestrial (DVB-RCS and DVB-RCT respectively). In DVB applications, 8 state circular terminal turbo codes are used with typical rates in the range of 1/3 to 6/7 (for DVB-RCS) and 1/2 to 3/4 (for DVB-RCT) [23]. The DVB-RCS2 scheme offers improvements in the link margin at both the physical and link-layer by implementing Adaptive Modulation and Coding (AMC) on the return link [24] however it comes with higher implementation complexity at the central satellite stations.

Rate compatible turbo codes (TC) are utilized in satellite broadcasting systems where a set of repeaters and ground stations cooperate to achieve transmit diversity gains [25]. Simulation results demonstrated a gain of 0.8 and 2.3 dB for this diversity scheme using maximal ratio combining compared to convolutional TC scheme. Performance comparison takes into account outage probability and not the probability of successful decoding at the application layer. Some research studies have focused on ways to incorporate TC schemes for video transmission in satellite networks. A performance comparison between TC, error-resilient entropy codes, and two-way decoding using reversible codes for MPEG-4 and H.263 is provided in [26]. TC showed Peak Signal-to-Noise Ratio (PSNR) improvements over traditional FEC schemes for various channel conditions.

However, none of the above studies [24-26] has focused on incorporating TC in the HEVC standard nor application-layer performance comparisons have been made e.g. to the UDP protocol. We combine SNC with turbo codes at the physical layer (TNC-UDP) and directly compare its performance to TC-UDP. This combination is achieved by calculating the TC PER for each SNR value (obtained from the NS3 simulation) as input to the TC protocol at the network layer. Such a model allows for the incorporation of the impact/improvements of the turbo codes at the physical layer on the overall decoding probability of the SNC scheme. Thus effectively treating the PER output from the turbo codes as a transmission channel for the network layer (where SNC).

3 Simulation Methodology

The approach taken in this paper is for evaluating NC performance for multimedia streaming for various PER and RTT environments at various link speeds.

The block diagram for the evaluation of video sequences using the two protocols is depicted in Fig. 1. First, the source video files (YUV files) are fed to the HEVC encoder and then segmented into video packets while at the same time a trace file is fed into the NS3 simulator.

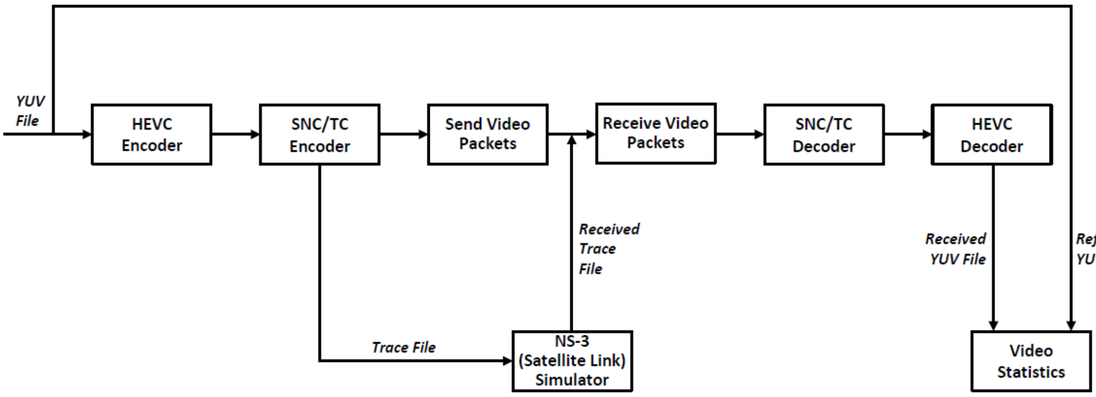

Fig. 1 System block diagram for video evaluation.

Table 1 Video encoding and packetization.

Sequence	1 Mbps			2 Mbps		
	Type of Frame	Size in Bytes	No. of TS Packets	Type of Frame	Size in Bytes	No. of TS Packets
BasketBallPass	I	11868	63	I	28916	154
	P	9158	48	P	11710	63
	Total	21026	112	Total	40626	217
RaceHorses	I	14717	78	I	33418	178
	P	6878	37	P	9284	50
	Total	21595	115	Total	42702	228

The simulator takes into account the video transmission rate, number, and types of frames (I, P frames) and stores the received packets indices into another trace file. For TNC-UDP, SNC is applied at the application layer and turbo coding at the physical layer. The PER-vs-SNR curves [22] are used in the simulations for various code rates for turbo codes. For the other scheme, that is, TC-UDP only turbo coding is applied at the physical layer. This file is utilized to reconstruct the received video which is then fed to the HEVC decoder. Comparison to the reference YUV file and the received YUV files are performed and video statistics calculated.

3.1 Video Encoding and Packetization

We use two test video sequences, BasketballPass and RaceHorses in WQVGA (416x240). These video sequences are commonly used in video communications research [27, 28] and have different video characteristics. These were encoded with HM software version 16.9 using the main profile [17]. The GOP size was fixed to 4 (with an intra (I) frame every 4 frames) and the total of 4 frames were coded in IPPP encoding structure. Each of the video sequence was encoded using HEVC encoder rate control to 1 and 2 Mbps [29].

We treat the whole GOP as a generation for NC and the encoded video for each generation is divided into packets of size 188 bytes to generate MPEG TS packets. The packetization details of the selected configurations are shown in Table 1.

3.2 Network Setup for Multimedia Streaming

The simulation model is characterized by the triplet data rate, latency, and packet loss of the link between the sender and the receiver. We use intra flow network coding to better protect the video sequence with SNC over UDP (SNC). The network coding performance benefits are compared against the UDP protocol which is a protocol of choice for satellite and other long delay communications.

Our approach relies on utilizing the frame error information at the UDP and application layer. The link rate is set as 1Mbps and 2 Mbps, and the latencies used were 784ms, 1000 ms, 1500 ms, and also for a small RTT of 100 ms. The simulations are repeated for 100 runs and the results for PSNR are averaged.

In order to ensure a fair comparison between the two schemes, the number of packets transmitted was always kept as 10% more than the encoded packets [30]. For TC-UDP schemes this additional 10% rate is utilized to re-transmit I frame packets for the first GOP whereas for the TNC-UDP scheme, this additional rate is used to transmit NC packets. If the packets comprising the first I frame are lost then the HEVC decoder will fail to decode the sequence. In such cases, we consider a reduced PSNR as h% lower than the full PSNR. With systematic NC, there are no such cases where the decoding for NC packets fails as all packets are sent un-coded during the systematic phase.

For multimedia streaming, the design of transmission protocol and retransmission mechanism is as important as the reliability of the UDP protocol itself. In order to calculate the above measures, we measure the PSNR of the received signal as the video file being decoded at the client (after requesting video from the server). We count and compare I, P & B frames for both TNC-UDP and TC-UDP protocols. For both protocols, we compare the probability of success of video decoding at the client over time. In the process, we provide some insights into the ratio of the received innovative packets at the client, defined as the packet that would increase the number of frames decoded at the client, for the TNC-UDP protocol. This helps illustrate the mechanism for NC performance gains.

4 Simulation Results

4.1 Throughput vs. PER

The throughput for the Basketballpass sequence over 1 Mbps link at packet loss rate of 2, 4, 6, 8 and 10% corresponding to different satellite link latency values is shown in Fig. 2. A significant drop in throughput is

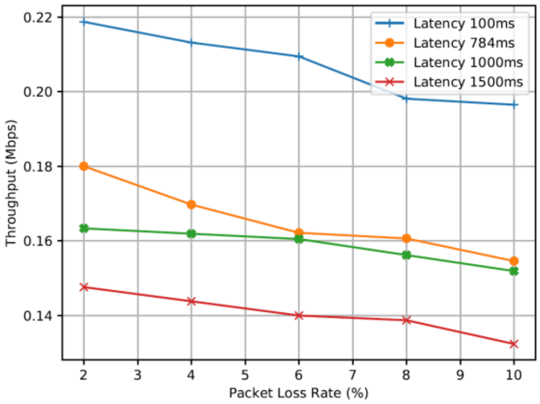

Fig. 2 Video throughput for the UDP protocol at packet loss rates of 2, 4, 6, 8, and 10%.

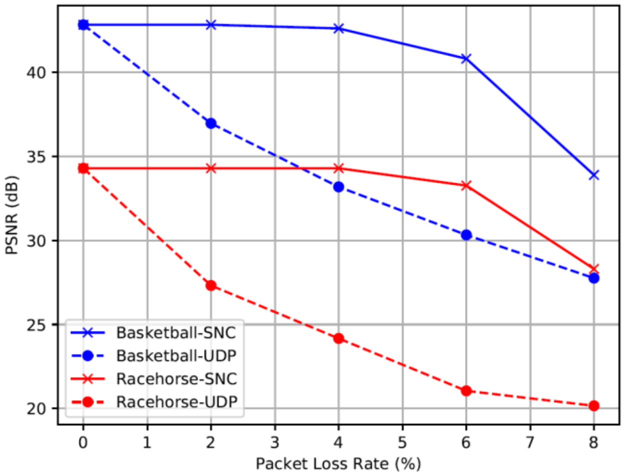

Fig. 3 PSNR for SNC and UDP protocol at packet loss rates of 2, 4, 6, and 8% for the two video sequences at 1Mbps.

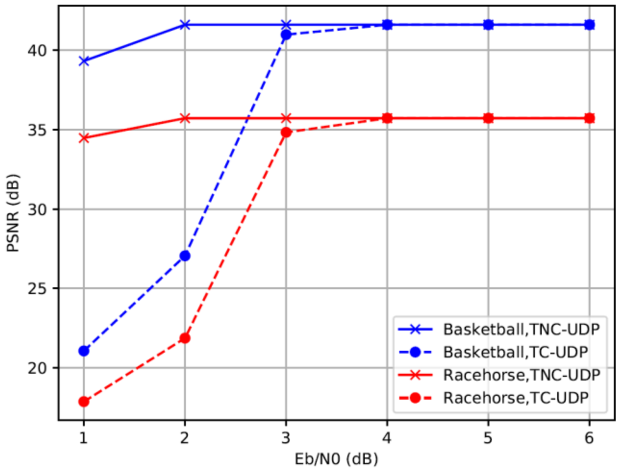

Fig. 4 PSNR for BasketballPass and RaceHorses sequence at 1Mbps for TC-UDP and TNC-UDP.

observed as the channel PLR increases. For example, the drop is 14.6% between a typical WAN latency (100 ms) and a satellite link (784 ms) as the channel deteriorates. Such drop is the main driving issue for finding protocols that improve the throughput for high latency links with high PERs, for which network coding is a promising technique.

4.2 SNC Protected Video Streams

The PSNR versus packet error rates is shown in Fig. 3 for the BasketballPass and Racehorses video sequence at 1Mbps with the unprotected UDP and SNC protected transmission. The SNC configuration for both sequences has better performance overall but there is a performance penalty at 8% PLR when the NC protection is not sufficient to protect all the packets, but still, NC gains are realized.

It can be seen that the video sequence protected with SNC has much better quality even at higher packet loss rates. The PSNR advantage for both sequences at a PLR of 4% is around 9 dB.

4.3 Video Quality Assessment

The PSNR versus the state of the channel condition is shown in Fig. 4 for the BasketballPass and Racehorses video sequence at 1Mbps with TNC-UDP, and TC-UDP packets. The TNC-UDP configurations for both sequences have been plotted for various Eb/N0 (dB).

It is interesting to note that for both video sequences, the TNC-UDP protocol outperforms the TC-UDP protocol in the received PSNR as the channel quality increases. When the channel conditions are bad, the network coding protocol gains are higher. This could be attributed the systematic nature of the protocol and that packet combinations provide incremental innovative packets that increase the PSNR and hence video quality at the decoder. There is a trade-off as in the case of NC the bandwidth is also utilized by the overhead of sending coded coefficients. However, SNC overcomes it to some extent as initially the whole GOP is sent as un-encoded packets which can provide successful video decoding precluding the need to send more packets. Similar trends of results are obtained for both sequences at 2Mbps (not shown).

4.4 Error Resilience

HEVC decoder does a good job of error concealment by using frame copy for the lost frames. This is useful as with low error rates the error concealment alone could yield an acceptable video. To establish the loss in PSNR corresponding to the lost frames, we dropped the 2nd frame from the GOP (4 frames) of the BasketballPass and Racehorse sequence at (1Mbps). We then extracted frame 4 from the reconstructed video and measured its PSNR. The results for both the sequences are shown in Fig. 5.

As can be seen from the figures there are some visual artifacts visible and the PSNR also has gone down. The video quality can be helped by considering error concealment techniques at the decoder. However, for TNC-UDP because the entire GOP is sent un-coded first so even if the network decoding fails for the GOP, the HEVC video decoding would succeed in preventing the annoying frame freezing problems, etc.

5 Discussion

In this paper, we have shown that combining turbo and network coding can be advantageously used to support the transmission of video over the satellite channel. We have shown the performance benefits of network coding implemented with turbo coding at the physical layer over UDP (TNC-UDP) compared to turbo coding over UDP (TC-UDP) for satellite link conditions simulated in NS3.

The simulation allows for monitoring the packet loss for the network coding scheme. It also allows for

(a) (b)

(c) (d)

Fig. 5 The frame extracted from the original and reconstructed (with losses) sequences; a) Original frame 4, PSNR 42.03 dB, b) Frame 4 with losses, PSNR 23.16 dB, c) Original frame 4, PSNR 33.10 dB, and d) Frame 4 with losses, PSNR 15.08 dB.

obtaining the receiver PSNR; measuring the video quality at the receiver. We have also obtained significant PSNR (maximum 20 dB at 1dB) improvements from the TNC-UDP protocol for various channel error rates. While the PSNR gain reduces as the channel improves, the TNC-UDP protocol guarantees at least the same PSNR performance as the TC-UDP protocol (Fig. 4) for both video sequences simulated in this paper.

While the video generation size affects the delay at the encoder and decoder, the network coding step could also be performed by the progressive encoding at the encoding stage to reduce the delay. The encoder keeps a buffer that keeps accumulating the packets, effectively creating more opportunities for network coding. A possible area of expansion from the current work is incorporating adaptive modulation in addition to the encoding stage. This is expected to improve the PSNR further and hence the throughput and reliability performance of the TNC-UDP protocol. By dropping frames and measuring the PSNR at the decoder, we have shown HEVC video’s resilience to frame errors. This resilience is expected to provide more leverage with the use of the proposed protocol.

There are also trade-offs as in the case of NC some redundant information needs to be transmitted. Also for the implementation of NC, there are buffering requirements at both the sender and receiver. These factors can add to the delay and computational complexity. However, our simulation showed that NC offers better resistance to frame freezing and visual artifacts compared to traditional UDP, as it offers better error concealment by design (whole GOP sent uncoded first). This results in a reduced requirement to use error concealment techniques at the decoder and hence fewer costs and complexity.

6 Conclusion

This paper presented a protocol for transmitting High-Efficiency Video Coding (HEVC) video using systematic network coding and turbo codes over UDP protocol (TNC-UDP) for a satellite channel. The protocol incorporates a novel error protection scheme created from the combination of systematic network coding and physical layer turbo coding for HEVC video. The performance of the proposed technique is compared to the traditional UDP protocol with turbo coding (TC-UDP). The simulation results show that network coding based protocol is helpful for such long RTT and delay networks and provides much better PSNR and video quality compared to only UDP flow. TNC-UDP Improvements in the PSNR between 14-20 dB for poor channel conditions (1-2 dB) were obtained over the TC-UDP protocol for the two video sequences used. The simulations also demonstrated HEVC resilience to frame loss, when used in conjunction with the TNC-UDP, as a small reduction in PSNR was observed. The use of HEVC video with proposed TNC-UDP protocols results in better PSNR and energy per bit performance as compared to the TC-UDP protocol and we anticipate that this will help towards further adoption of HEVC in satellite networks. Future work will investigate the implementation requirements and trade-offs of the proposed scheme that may affect the standardization of network coding in satellite networks.

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