Hierarchical Random Linear Network Coding for Multicast Scalable Video Streaming

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***Abstract*—Network coding (NC) has been exploited to minimize delay, energy per bit and to maximize throughput over lossy networks. However, applying network coding for scalable video transmission over packet-lossy networks is still an active research topic because of the challenge in trading off between rank deficiency problem and scalability of the video bitstream. Scalable video coding promises providing flexible broadcasting to heterogeneous user equipments, but the rank deficiency problem in NC limits the scalable capability in video streaming since the time of waiting for full rank causes long delay. In this paper, we exploit the combination of hierarchical and random linear network coding for solving the above issue. The hierarchical network coding provides unequal erasure protection for scalable layers and addresses the process of decoding layer by layer according to importance. Otherwise, random linear network coding provides error-correcting capability and makes the scheme resilient to packet loss. Our proposed network coding scheme benefits from these two schemes for multicast scalable video streaming. The simulation results and performance analysis are provided to evaluate the efficiency in terms of averaged decoding probability and peak signal-to-noise ratio. The proposed scheme achieves same performance of random linear network coding in good channel and approximately hierarchical network coding scheme in bad channel.**

***Index Terms*—hierarchical network coding, random linear network coding, scalable video transmission, cellular networks.**

I. Introduction

The scalable video coding (SVC) [1], [2] standard provides high decoding efficiency and the scalability of temporal, spatial and quality resolution. The scalability of a video bitstream is particularly relevant to packet-lossy networks since user equipments (UEs) experience various video qualities depending on amount of decoded video signal. The video bitstream is partitioned into scalable layers, base layer (BL) and enhancement layers (ELs), with different importance to provide the various qualities of service. The portions of the stream can be lost in such a way that the substream forms another valid bitstream with lower video quality than the complete original bitstream. The BL guarantees the basic quality of supported video performance. On the other hand, the ELs provide the refinement information of the aforementioned BL. The scalable video transmission naturally combines with prioritization methods such as unequal error protection (UEP) [3], [4], [5], [6], [7], selective retransmission [8], or hierarchical modulation scheme [9]. The differentiation in protection of the scalable layers accords to their importance. The major idea is to robustly protect the most important layer (the BL) and give less protection to ELs because of the decoding process of the SVC. The decoded layer is valid if and only if all prior layers are decoded successfully.

The high decoding efficiency and scalability benefits of the SVC are regarded as a promising candidate for enabling digital wireless broadcast applications such as mobile television, video conferencing, digital video broadcast (DVB) and high-definition video on demand (HD-VOD) in order to cope with bandwidth variations in lossy networks and heterogeneous mobile devices. All of these services have significantly various requirements especially in terms of delay, latency and packet loss.

Network coding (NC), firstly proposed in 2000 [10], is a promising generalization of routing because of the potential benefits of resource (e.g., bandwidth and power) efficiency, computational efficiency, and robustness to network dynamics. The NC allows each node in the network the capability of performing some computations such as mixing (encoding), unmixing (decoding) and remixing (reencoding). Thus, each output link of the intermediate node can be some function or mixture of packets that arrived earlier on the input links. While the first two functionalities are well-known techniques, the last one recoding is a new one. Recoding functionality allows each node the capability of coding again on already coded packets without the need of decoding the incoming packets first and even can be done with partial information. The NC has been exploited for the internet and wireless networks with the potential advantages of minimum delay, energy per bit and maximum throughput [11]. Especially, multicast capacity only can be maximized by using the NC [10] and random linear network coding (RLNC) for distributed manner [12].

Even though the potential advantages of the NC satisfy significantly various requirements for the SVC in terms of delay, latency and packet loss, but one main drawback is rank deficiency. The user equipment (UE) can decode all received packets if and only if the number of received packets is equal or higher than the rank of coefficient matrix. This issue limits the scalability property in video streaming because the waiting time for full-ranked data causes long delay. Hierarchical network coding (HNC) was proposed to provide unequal erasure protection for scalable layers and addressed the decoding process on layer-by-layer from higher to less importance [13]. But the HNC also faces one drawback to achieve error resilience. The UE cannot decode all scalable layers even though it receives enough number of packets.

Our proposed NC scheme is the combination of the RLNC and HNC for multicast scalable video streaming called HNC-RLNC. The HNC-RLNC is able to achieve the benefits and to tackle the drawbacks of each scheme. The major contribution of this paper can be summarized as follows:

1) For the reliable transmission of scalable video over packet-lossy networks with limited-bandwidth resource, the efficient combination of two network coding schemes, i.e. HNC and RLNC, is proposed at application layer not only providing more reliability but also the scalability for the transmitted video.

2) The HNC coded packets satisfy the capability of scalability in scalable video coding. The receiver is still able to enjoy the typically basic video quality evenly when experiencing bad channel condition or deep fading. The most important layer, i.e. BL, is protected with highest protection. The dependency of scalable layers is exploited by using the HNC scheme which provides unequal error protection. The higher important layer gets higher protection.

3) The RLNC redundant coded packets provide the capability of error resilience to the transmitted video. The proposed scheme is able to activate the reliable transmission and full quality of supported performance in case of receiving sufficiently redundant packets.

The remainder of the paper is organized as follows. Section II introduces related works. Section III describes proposed multicast scalable video streaming using HNC-RLNC. Section IV provides the performance analyses related with scalable video for various coding techniques and conclusion remark follows in Section V.

II. Related Work

A. Random Linear Network Coding

Ahlswede *et al.* [10] and Koetter *et al.* [14] showed that maximum capacity in a network can be achieved by allowing the intermediate nodes to mix incoming packets. Ho *et al.* [12], [15] showed that the RLNC with finite symbol size is sufficient for achieving maximum network capacity in multicasting. A new coded packet of intermediate nodes output link is linear combination of incoming packets. The intermediate node includes the information of coding efficient in header of each new coded packet so that the decoder can use this information and Gaussian elimination method to decode the stream and recover the original packets, i.e. native packets. Assume that the header is perfectly protected without loss during transmission.

The network coding operation can be presented as follows. Source node S generates k native packets called one generation [16] into the m^{th} network coded packet with the form

$$c_m = \sum_{p_i(S) \in G(S)} f_{m,i} \cdot p_i(S) \tag{1}$$

, where i is the index of i^{th} packet at node S, $G(S)$ corresponds to the generation of k native packets which can be coded together, $p_i(S)$ denotes either native packet or coded packet evenly partial information of coded packet, and $f_{m,i}$ is coding efficient chosen randomly over the Galois field of size q, $GF(q)$. The typical Galois field size is set to $q = 256$ which guarantees high symbol diversity and low probability of building duplicate packets [16].

In order to exploit the benefits of the RLNC for the SVC transmission, Nikolaos *et al.* [17] proposed network path diversity via a novel randomized network coding approach that provides the UEP to the packets conveying the video content. Mingkai *et al.* [18] proposed a novel layered multicast that allows network coding of data in different layers. Kim *et al.* [19] proposed the integration of NC, multiple-input multiple-output and hierarchical modulation over cellular relay networks.

B. Hierarchical Network Coding (HNC)

The RLNC is able to exploit error resilience for the SVC transmission. But one important observation is that it causes additional delay prior to any of the native packets can be decoded because of the rank deficiency problem. In general, if a generation size is k, then receiver must receive at least k coded packets in order to decode any one of the original packets. Therefore, the HNC was proposed to enable the receiver to recover the important data gracefully in the presence of limited bandwidth causing decoding delay [13], [20], [21].

Let us consider the video bitstream with n scalable layers consisting of the BL and ELs. The stream is split into a number of relatively large consecutive generations. Let k_n be the number of native packets within layer n and p_1^n, p_2^n , ..., $p_{k_n}^n$ denote these packets. Then, the number of native packets within one generation will be coded together using the following coding structure

$$c_n = \sum_{i=1}^{k_1} f_i^1 \cdot p_i^1 + \sum_{i=1}^{k_2} f_i^2 \cdot p_i^2 + \dots + \sum_{i=1}^{k_n} f_i^n \cdot p_i^n \tag{2}$$

, where i is the index of i^{th} packet within one layer, f_i^n is non-zero coding coefficient in layer n chosen randomly over the Galois field, k_n is the number of packets from layer n and p_i^n is the i^{th} native packet of layer n. The importance of individual layer decreases from layer 1 to n. Therefore, each coded packet always contains the information of the BL and belongs to one of the n classes. Let L_1 to L_n denote these classes. The L_1 is the most important class and the L_n is the least important class. The coded packets belonging to the first class contain only information about the BL. On the other hand, the coded packets belonging to the last class contain information of all scalable layers. In general, class n represents the coded packets containing information from layer 1 to n.

The HNC structure providing UEP for scalable layers addresses the decoding process on layer-by-layer from higher to less importance. The probability of decoding native packets from a BL is always higher than those of other layers. The receiver is able to decode the important layer even not to receive sufficient number of native packets. Otherwise, when

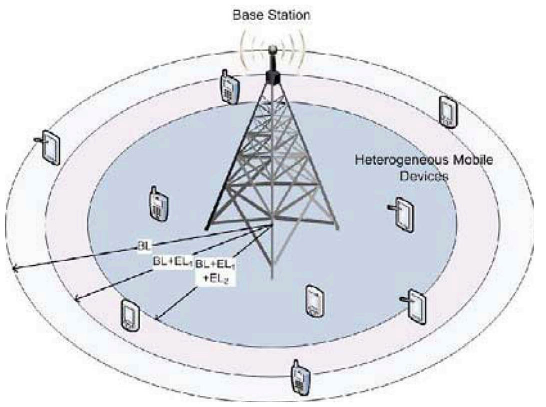


Fig. 1: Single source-multicast communication system.

the receiver receives sufficient number of native packets, the HNC scheme cannot guarantee for decoding all native packets belonging to all classes because the receiver must wait to receive all coded packets within each class. This issue restricts the error resilience for the SVC transmission.

III. Proposed Hierarchical-Random Linear Network Coding (HNC-RLNC) for Multicast Scalable Video Streaming

A. System Architecture

In this subsection, we present a system architecture of hierarchical-random linear network coding for multicast scalable video streaming. We study a single-source multicast communication. The video content is transmitted from a single base station (BS) to heterogeneous mobile devices. The video is encoded into a BL and multiple ELs. The receiver is able to enjoy video quality depending on the amount of received scalable layers. The BL is corresponding to a typical basic quality of the video. The ELs carry the refinement information of aforementioned BL and help the receiver to enjoy full video quality of supported performance. The HNC-RLNC should enable the efficient usage of limited-bandwidth and reliable transmission. The scenario of one-hop transmission is shown in Figure 1 with three layers. The channel is partitioned into three sub-channels, each sub-channel carries individual scalable layer [22]. In our proposed scheme, each sub-channel carries different information. The first sub-channel carries information of the BL only, next sub-channel conveys the information of the BL and enhancement layer 1 (EL_1). The last one transmits the information of all scalable layers. The transmissions of redundant packets for error resilience are different with different coding operations. Section IV-A shows further information of adding redundant packets.

Figure 2 represents the system architecture of multicast scalable video streaming using the HNC-RLNC. The video is encoded by using SVC encoder [23] into multiple scalable layers, then by applying packet arrangement. The number of packets within one group of picture (GOP) will be called one generation which means that they can be coded together by using HNC-RLNC structure. The number of sub-channels corresponds to the number of scalable layers. The mapping of each packet to each sub-channel is described in Section IV. The decoding process is the inverse of encoding process, the receiver uses Gaussian elimination in order to decode the video data, then applying packet retrieval to get the transmitted video bitstream and send to SVC decoder [23] for decoding back the video. We also propose one more coding operation called hierarchical-hierarchical network coding (HNC-HNC). The system architecture with the HNC-HNC scheme is similar to the HNC-RLNC excepting for changing the HNC-RLNC Encoder by HNC-HNC Encoder.

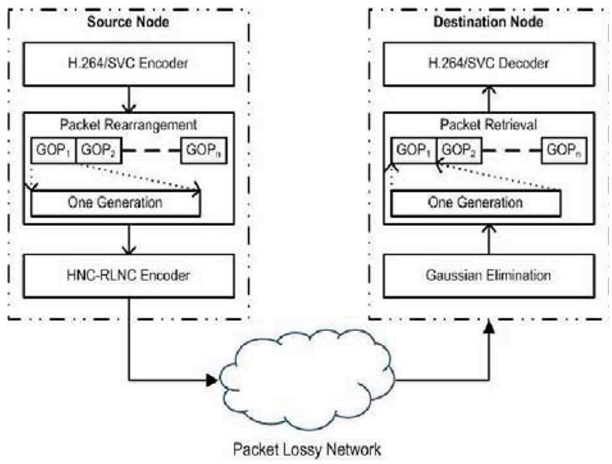


Fig. 2: System Architecture of multicast scalable video streaming.

B. Packet Rearrangement and Packet Retrieval

In order to apply the HNC-RLNC, the number of packets within each layer must be similar to other scalable layers. In case of differentiation in the size of scalable layers, the BS needs to use packet rearrangement to re-organize the number of packets within each layer. As mentioned above, the higher layer has less importance, the priority of scalable layers decreases from layer 1 to layer n. Assume that the size of individual layer increases inversely to the importance of each layer. The more important layer has smaller size than less importance. This assumption enables the enhancement layers carrying more refinement information and makes the receiver achieving more supported video quality. The bitstream of each layer is partitioned into packets, using zeros-padding to solve the issue of the differentiation in packet size and layer size. Since the layer size of higher layer has bigger size, the BS applies the most basic error-correcting codes for packet level. The number of packets is picked up randomly for generating the error-correcting packets in the case the BS cannot exploit full repetition codes for all packets. The repetition number depends on the lack of packets within each layer on the basis of highest-length layer. The protection degree of a layer is increased as the length of redundant bits, but causing more load for video transmission. We select this technique for the

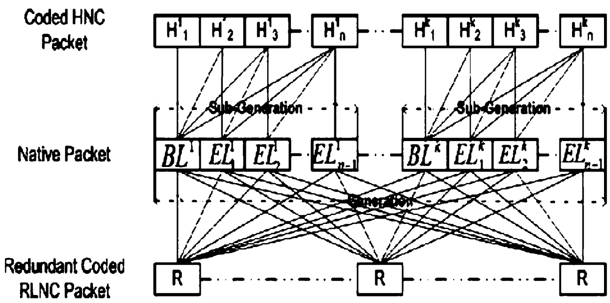


Fig. 3: Proposed HNC-RLNC coding structure.

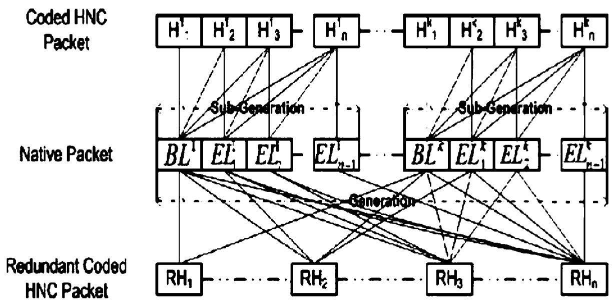


Fig. 4: Proposed HNC-HNC coding structure.

ease of implementation and simulation. The efficient technique for the packet rearrangement and packet retrieval is out of scope in this paper. We skip this issue for future work.

C. Hierarchical-Random Linear Network Coding (HNC-RLNC)

The RLNC has been exploited in many works in order to increase throughput, bandwidth efficiency and energy per bit. However, in order to apply the RLNC for scalable video transmission is one of the challenging research topics because of rank deficiency issue. The RLNC is so helpful for error resilience since the receiver only needs to receive sufficient number of the RLNC coded packets. For example, the base station broadcasts three packets, assuming that receiver only decodes successfully two packets. The receiver just requires for one more packet without considering the packet type or packet loss position. But the receiver faces one big issue in scalability in case of the lack of received packets. Good channel condition means all packets decoded, bad channel condition means that all packets are not decoded. This is the most challenging issue for considering the RLNC for scalable video transmission. Since the SVC is proposed to provide the scalabilities of temporal, spatial and quality to heterogeneous mobile devices or different channel condition. The HNC was proposed to solve this issue, but the solution causes another issue of error resilience in case of receiving sufficient number of coded packets. The HNC scheme cannot decode all layers even receiving enough coded packets. In order to solve these both issue, we propose the combination of the HNC and RLNC. The proposed HNC-RLNC is able to achieve the benefits and tackle the drawbacks from two schemes the HNC and RLNC.

The HNC-RLNC architecture is shown in Figure 3. The video bitstream is partitioned into scalable layers. We select a priority inside the SVC according to the quantization points, encoding rate, frame rate and group of picture size. Each GOP represents a generation. Picking up one packet in each layer denotes sub-generation. The HNC is applied in each sub-generation by using (2). H_n^k denotes coded HNC packet in class L_n of the k^{th} native packet, k be the number of native packets. In order to exploit error resilience over packet-lossy networks, all packets within one GOP will be coded by using the RLNC to produce redundant coded packets coming from (1). Let i be i_{th} GOP, m_i be the total number of packets consisting of native packets and redundant packets, r_i be the number of redundant packets of the i_{th} GOP, PLR_i be the packet loss rate of the output link of generation i. The number of redundant packets is determined by using (3)

$$\frac{r_i}{m_i} = \frac{PLR_i}{1 - PLR_i} \tag{3}$$

We only apply the RLNC for redundant coded packets to be resilient to error. Since the HNC is applied for coded packets and the RLNC is applied for redundant packets. Therefore, the receiver achieves approximate performance of the HNC in case of bad channel condition, without receiving any redundant packet because of packet loss. The RLNC redundant coded packet is only useful for achieving a full rank. On the other hand, the receiver experiences same performance of the RLNC in case of good channel, receiving more redundant packets.

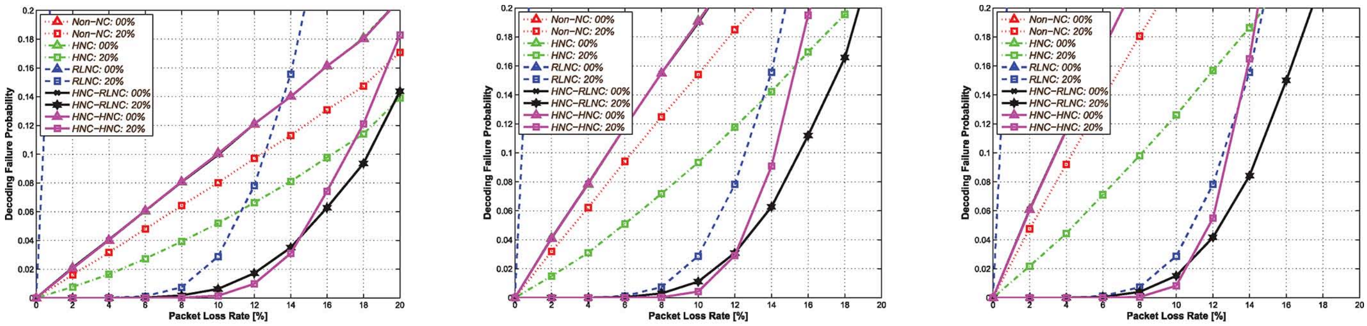
D. Hierarchical-Hierarchical Network Coding (HNC-HNC)

Figure 4 represents the proposed HNC-HNC structure, especially effective for bursty traffic. The HNC is also applied in each sub-generation as the HNC-RLNC scheme using (2). One key different point, the redundant coded packets are created by using the HNC instead of the RLNC. Since there are n scalable layers, therefore the number of various kinds of redundant coded packets is n. The RH_n denotes the HNC redundant coded packet at class L_n. Each HNC redundant coded packet within each class is becoming useful as the full rank condition of each generation is satisfied. This motivation makes the HNC-HNC scheme achieve better performance in case of bursty traffic. However, the receiver needs to reach full rank of all generations for decoding successfully all transmitted packets. The number of each kind of redundant packets will be determined by the following expression

$$m_n^i - k_n^i = \left\lfloor \frac{r_i}{n} \right\rfloor + \alpha_n \tag{4}$$

$$\alpha_n = \begin{cases} 0 & \text{if } r_i \bmod max\{n\} < \text{n} \\ 1 & \text{otherwise} \end{cases}$$

, where r_i is the number of redundant packets of i_{th} GOP, k_n^i and m_n^i are the number of native packets and total packets of layer n at GOP i^{th}, respectively.



(a) Base layer (b) Base layer and enhancement layer 1 (c) All layers

Fig. 5: Decoding failure probability versus packet loss rate with redundancy of 0% and 20%.

IV. Performance Evaluation

In this section, we investigate the decoding probability performance and video quality transmission (measured by peak signal-to noise ratio (PSNR), a widely used objective metric) of the proposed scheme. The BS streams test sequence video, *City*, over single source-multicast communication system. The video is encoded into three scalable layers using JSVM 9.19 reference software with SNR scalability. The *City* sequence has 150 frames with the frame rate of 15 frames/s. The group of picture size is 16 frames having hierarchical prediction structure and CIF resolution (352x288 pixels).

A generation for coding operation is one GOP. The sub-generation contains three different packets corresponding to the number of scalable layers. In case that the GOP size is large and it causes header overload, the GOP will be divided into a certain number of generations. The number of generations depends on the GOP size and header load. We use three sub-channels to carry information of all scalable layers with same transmit power. The finite field size is 2^8 for all the network coding operations. The number of redundant packets is determined by using (3), except for the HNC-HNC using (4).

A. Decoding Probability Performance

The proposed scheme is compared to different coding schemes of interest: Uncoded (called non-network coding), HNC, RLNC and HNC-HNC (described in Section III-D).

Non-Network Coding (Non-NC): Packets are not coded. They are grouped into three classes corresponding to the number of scalable layers. The BS maps three types of packets to three sub-channels and broadcasts to the UEs. The redundant packets are picked up randomly for additional transmission to tackle packet loss.

HNC: The BS employs the HNC in sub-generation which produces three classes of packets as described in the coded HNC packet Section III-C. The redundant packets are only the HNC coded packets in class three which contains information from all scalable layers. The UE only needs one more redundant packet for error resilience in case of losing one transmitted packet regardless of the packet type.

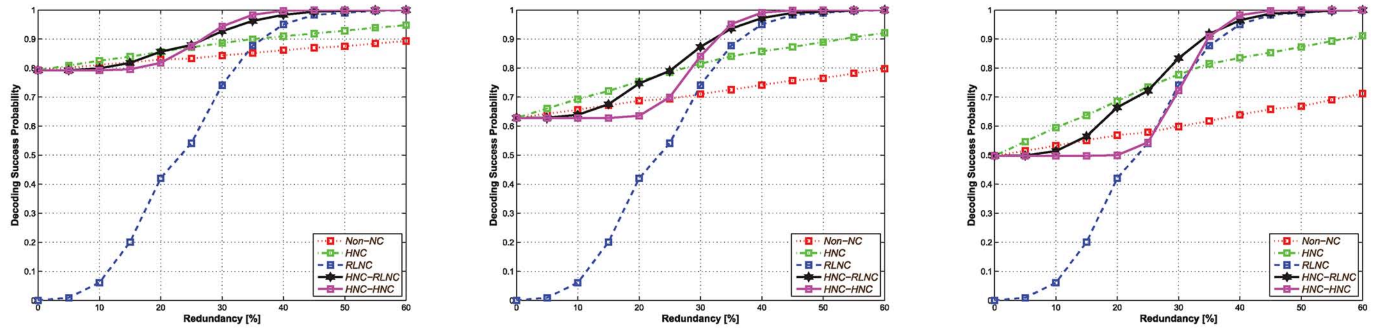
RLNC: The BS generates randomly a number of packets as linear combination of packets in one generation (GOP) for each coding operation. Note that all RLNC coded packets consisting of redundant packets are mapped to three sub-channels with same behavior and equal probability.

HNC-RLNC: The HNC coded packets, similar to the HNC coding scheme, are encoded within one sub-generation presented in Figure 3. But the redundant packets are not the packets in class three as the HNC scheme. The RLNC coded packet in one generation (one GOP or a portion of GOP depends on the GOP size) will be used as redundant packets. We use (3) to determine the number of redundant packets in individual generation. The each sub-channel carries different RLNC coded packets with different coefficient vectors.

HNC-HNC: The HNC coded packets are similar to the HNC coded packets in the above HNC-RLNC. The redundant packet is the HNC coded packet in one generation shown in Figure 4. The number of redundant packets applied to individual generation are determined by using (4). There are three different redundant packet types with this setting. Each sub-channel carries each type of redundant packet for additional transmission in order to be resilient to error. The scheme is able to increase the scalability in bursty traffic because the UE can decode all packets in each layer when full rank achieved at the considering generation.

The simulation results characterize the decoding probability of a receiver being able to decode certain number of layers for different coding schemes. A layer is decodable as all packets in the layer are coded. On the other hand, if any packet within the layer is not recoverable, a layer is un-decodable. We simulate for 1000 users and do the same simulation for 100 times to get the reliable results.

Figure 5 shows the decoding failure probability versus packet loss rate (PLR) with two various values of redundancy. As seen, when the redundancy is 0%, the Non-NC, HNC, HNC-HNC and the HNC-RLNC scheme are linear to PLR and have same performance. Except for the RLNC, the probability failure is almost 100% because of rank shortage. On the other hand, when the redundancy is 20%, there are big changes in different coding operations. The performances of Non-NC

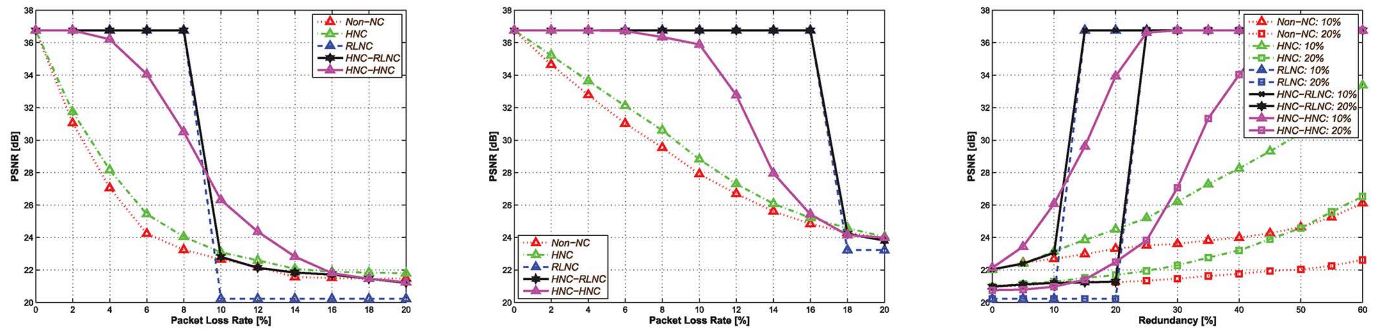


(a) Base layer

(b) Base layer and enhancement layer 1

(c) All layers

Fig. 6: Decoding success probability versus redundancy with packet loss rate of 20%.



(a) PSNR performance with redundancy of 10%

(b) PSNR performance with redundancy of 20%

(c) PSNR performance with packet loss rate of 10% and 20%

Fig. 7: The video performance comparisons.

and HNC keep increasing linearly. But the RLNC, HNC-HNC and HNC-RLNC achieve the best performance with failure probability of 0% with small PLR corresponding to good channel. When channel condition goes badly corresponding to the increase in PLR. The failure probabilities of three schemes (RLNC, HNC-HNC and HNC-RLNC) increase exponentially. But the HNC-RLNC is still the smallest probability of failure, followed by HNC-HNC, RLNC. It is easy to see that the failure probabilities of scalable layers are different at each certain value of PLR. The decoding failure for all layers is the highest, followed by two layers and the BL. The higher important layer achieves smaller failure probability.

Inversely, Figure 6 presents the decoding success probability versus the redundancy from 0% to 60% with PLR of 20%. As seen, increasing the PLR value lets the decrease in video quality. The higher priority layer has higher decoding probability. As the redundancy range is from 0 to 20% corresponding to bad channel condition. The performance of Non-NC, HNC, HNC-HNC and HNC-RLNC are approximately similar, but the HNC-HNC achieves the best performance. All original packets within each priority layer can be recovered if the full rank of the considering generation is satisfied. On the other hand, when the redundancy level is higher than 20%, the capability of error resilience is getting to show the benefits. The performances of the HNC-HNC and HNC-RLNC are quite similar in case of decoding the BL or the EL1. The proposed scheme is much better than the HNC-HNC when the number of scalable layers increase. Since the UE must wait for full rank to decode all layers at each layer in the HNC-HNC.

B. Scalable Video Performance

Based on the performance analysis of Sections IV-A, we provide the performance of the corresponding quality of scalable video in term of the PSNR. We simulate for 100 users generated uniformly distributed in coverage cell and take average PSNR. Figure 7a and Figure 7b present the PSNR performance versus PLR with the redundancy values of 10% and 20%, respectively. Increasing the redundancy (number of redundant packets) gives the corresponding increase in the PSNR. As seen in Figure 7a, the HNC-RLNC achieves the best performance at PLR of 8% (moderate channel condition) similar to the RLNC. The HNC-HNC cannot get full quality of supported performance from this range of PLR. The reason is that the UE needs to wait for receiving sufficiently redundant packets in separate layers because of three types of the HNC redundant packets. When the PLR range from 10% to 20% corresponds to bad channel condition, the HNC-HNC performance is the best because any received redundant packet may be useful for recovering the lost packets in each layer from higher to less importance. The PSNR performance of the proposed scheme is quite similar to the Non-NC and HNC. The scalability is still guaranteed and is able to support the basic video quality, i.e. decodable BL. Increasing the redundancy to 20% in Figure 7a, the performance pattern is similar to redundancy of 10% but better video quality.

Figure 7c shows the PSNR performance versus various values of redundancy with PLR of 10% and 20%. The order of performance is also similar to aforementioned results. The UEs are able to enjoy the full video quality of supported service when receiving sufficient number of redundant packets. The simulation results strongly show that the proposed HNC-RLNC scheme achieves the performance of the RLNC in good channel condition and the HNC in bad channel condition. It means that the HNC-RLNC benefits the capability of scalability and error resilience from two schemes the HNC and RLNC, respectively. The HNC-HNC also achieves nearly same performance with the RLNC in good channel condition. But the PSNR shows the best performance in bad channel condition because the error resilience is completed by receiving all packets within each generation in one GOP.

V. Conclusions

We propose the combination of hierarchical network coding (HNC) and random linear network coding (RLNC). The HNC-RLNC coding structure is able to achieve the benefits of each scheme (HNC and RLNC). The RLNC provides the capability of error resilience to the SVC in case of full rank. However, it is so sensitive to error if the receiver cannot receive sufficient number of packets. The HNC has capability of decoding the important layer in case of rank shortage. But it cannot guarantee that the receiver is able to decode all layers in case of full rank. The simulation results show that the performance of the proposed coding scheme is able to strive the good balance between the HNC and the RLNC. Besides, the HNC-HNC coding structure is effective for bursty traffic.

Future work, we will consider the help of relay to engage the capacity of decoding all layers for as many UEs as possible. The packet arrangement and retrieval will be investigated to solve the issue of differentiation in the size of scalable layers.

Acknowledgment

This research was funded by the MSIP (Ministry of Science, ICT & Future Planning), Korea in the ICT R&D Program 2014.

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