

R^2 NC: Redundant and Random Network Coding for Robust H.264/SVC Transmission

Cuiping Jing*, Xingjun Zhang*, Feilong Tang[†], Scott Fowler[‡], Huali Cui*, Xiaoshe Dong*

*Department of Computer Science & Technology, Xi'an Jiaotong University, China
Email: xjzhang@mail.xjtu.edu.cn

[†]Department of Computer Science & Engineering, Shanghai Jiaotong University, China
Email: tang-fl@cs.sjtu.edu.cn

[‡]Department of Science & Technology, Linköping University, Sweden
Email: scott.fowler@liu.se

Abstract—In this paper we are interested in improving the performance of constructive network coding schemes for video transmission over packet lossy networks. A novel unequal packet loss protection scheme R^2 NC based on low-triangular global coding matrix with ladder-shaped partition will be presented, which combines redundant and random network coding for robust H.264/SVC video transmission. Firstly, the error-correcting capabilities of redundant network coding make our scheme resilient to loss. Secondly, the implementation of random network coding at the intermediate nodes with multiple input links can reduce the cost of network bandwidth, thus reducing the end-to-end delay for video transmission. Thirdly, the low-triangular global coding matrix with ladder-shaped partition is maintained throughout R^2 NC process to provide unequal erasure protection for H.264/SVC priority layers. The redundant network coding avoids the retransmission of lost packets and improves error-correcting capabilities of lost packets. Based only on the knowledge of the loss rates on the output links, the source node and intermediate nodes can make decisions for redundant network coding and random network coding (i.e., how much redundancy to add at this node). However, the redundancy caused by redundant network coding makes the network load increases; in order to improve network throughput, we perform random network coding at the intermediate nodes. Our approach is grounded on the overall distortion of reconstructed video minimization by optimizing the amount of redundancy assigned to each layer. Experimental results are shown to demonstrate the significant improvement of H.264/SVC video reconstruction quality with R^2 NC over packet lossy networks.

Index Terms—Network coding, scalable video coding, unequal error protection.

I. INTRODUCTION

With the proliferation of the Internet, the robust transmission of video has become a promising service for a lot of applications such as video conference, security monitoring and so on. However, providing high quality video over packet lossy networks is a challenging problem, due to the delay, packet loss and network intrusions [1] and the strict real-time delivery requirements of video traffic.

One issue is the capability of the video transmission system to adjust the system resources for variable channel conditions. This problem can be relieved by scalable video coding (SVC) [2] since it provides flexibility and convenience for achieving

the desired visual quality. Another issue is that the packet loss leads to serious video quality degradation in compressed bitstream with strong spatial-temporal dependency. The third and most important issue is how to effectively use network resources, which is very important to improve transmission efficiency. The redundant packets generated by forward error correction (FEC) will increase the network load which is the waste of network bandwidth, although the system reliability can be improved [3]. More recently, network coding (NC) [4] breaks through the traditional mode, which allows packets to be combined together at intermediate nodes, and has been proved to have the ability to improve throughput, reliability etc [5]. This is a great advantage in balancing network load and improving the network resource utilization. Given that optimal network coding for video transmission is an open problem, constructive approaches are used in practice [6]. COPE [6] is the first and most influential optimal network coding system for wireless networks. After coding packets from different unicast sessions, COPE effectively forwards multiple packets based on the knowledge of what their neighbors have. Without considering packets loss in the network, COPE is certainly the most effective constructive approach. However, in the presence of medium-high loss rate, the coding efficiency of COPE is severely affected.

Reliability and efficiency are both essential to robust video transmission, however, a simple superposition of FEC and NC may not only reduce the system reliability, but also lower the transmission efficiency. FEC (coding in application layer) improves the reliability by adding redundant packets, which will reduce the transmission efficiency in terms of bandwidth consumption. NC (coding in network layer) can reduce the number of relayed packets at the cost of higher computational complexity and communication overhead at the intermediate nodes. How to encode packets successively with two coding mechanisms in two different layers (network layers and application layers) is essential to improve the reliability and efficiency of robust video transmission system.

In this paper, we propose a solution to this problem by introducing redundant network coding and random network

coding for H.264/SVC video transmission over packet lossy networks. In particular, we apply unequal error protection (UEP) [7] with network coding efficiently for H.264/SVC video to ensure that each scalable layer can be obtained in an incremental order. Our approach for combining redundant network coding with random network coding, which we refer to as R^2 NC, has following benefits to video transmission system. First, the robustness of H.264/SVC video transmission system is ensured by redundant network coding, which can correct packet loss. Second, in terms of bandwidth consumption, it is more efficient than FEC without network coding, which expands the boundary conditions for the addition of redundancy, because random network coding can reduce the number of relayed packets. Finally, R^2 NC eliminates the need to know the knowledge of neighbors in COPE.

This paper is organized as follows. Section 2 outlines the background of network coding applied to the streaming media. Section 3 gives an overview of the system model. Section 4 describes the overall distortion of reconstructed video minimization formulation and solution. Section 5 presents the packet loss protection scheme- R^2 NC for video streaming transmission over packet lossy networks in detail. In Section 6, we provide experimental results and performance analysis. Section 7 concludes the paper.

II. RELATED WORKS

Existing works with NC for video transmission. While most NC research has been carried out in the field of information theory, its potential benefits for media streaming applications have spurred a lot of interest in the multimedia community. Most existing works based on NC to design a robust video transmission system, focus on the application of random linear network coding [8] [9] [10]. Nguyen et al [8] proposed a scheme on multipath transmit joint network coding to meet the demand of high bandwidth for video transmission, but the best strategy proposed does not take into account optimization and the variable quality of service. Hulya Seferoglu [11] presented an opportunity network coding mechanism which is exactly the same as in the original COPE for video transmission in the wireless network. The decodability at the receivers is improved, but the intermediate nodes need to learn the contents of the virtual buffers of all their neighbors. Taking into account the basic characteristics of streaming data, [10] proposed a robust transmission scheme based on unequal error protection (UEP) with RLNC for scalable video data, but how to assign unequal redundancy of NC codes to different video layers is not shown. Our proposed network coding scheme- R^2 NC is built on [11] and [10], a practical network coding scheme for H.264/SVC video transmission over the packet lossy networks. Our main differences are: (i) we show how to assign unequal redundancy of R^2 NC codes to different scalable layers based on low-triangular global coding matrix with ladder-shaped partition. (ii) we consider the effect of packet loss, in order to generate the right amount of redundancy for each layer at the source node and intermediate nodes. (iii) the intermediate

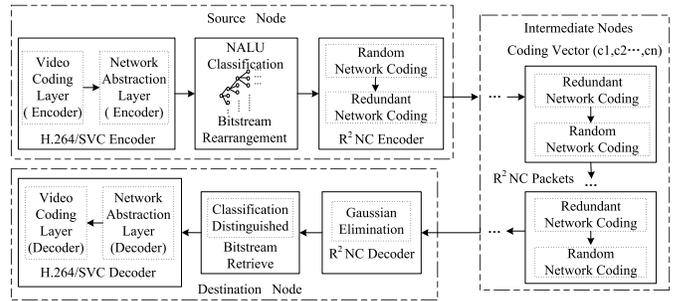


Fig. 1. System Architecture

nodes does not need to learn the knowledge of what their neighbors have overheard.

Combination of two coding for video transmission. Both NC and FEC are erasure correction codes, essentially having one thing in common: both are based on a finite field to encode the original packets to a new set of coding packets, and as long as the receiver get enough number of packets, they can be decoded successfully. The main difference is: FEC code is implemented in the end systems, while network coding is carried out at the intermediate nodes. Clearly, both the two codes can be implemented in the streaming system, but mostly traditional methods treat them separately which can not share information. The cooperative work [12] of NEC and university of California was the first study on network coding and FEC to improve the performance of video transmission system over the wireless network, and they just planed to optimize the performance of Ad hoc network with two coding at present. So far, the results of relevant research has not been publicly published. [13] explored the performance of scheme combined network coding with FEC in depth. They proposed a scheme joint network coding based on time-domain and FEC in application layer, but the decoding process of NC and FEC were treated separately at the destination nodes, which will result in too much space cost and the end-to-end delay of video transmission system. So far the combination of NC and FEC is just a simple superposition. First, the decoding process of NC and FEC is completed separately at the destination node. Second the combination of NC and FEC can not share information during the coding process. This paper also improves the quality of video streaming by the combination of the two coding-redundant network coding and random network coding, but our scheme is not a simple superposition. The decoding process of the two coding can be completed simultaneously and the boundary conditions of the redundancy added by redundant network coding can be expanded by random network coding at the intermediate nodes.

III. SYSTEM OVERVIEW

A. System Description

The architecture of H.264/SVC video transmission system using R^2 NC technique over packet lossy networks is shown in Fig. 1. We study a single-source multicast communication

over packet lossy networks, where all nodes are fixed and one source node transmits video to multiple destination nodes. At first, H.264/SVC encoder, bitstream re-arrangement, and R^2 NC encoder are performed at the source node respectively. Then, the redundant network coding and random linear network coding (RLNC) [4] techniques are conducted at intermediate nodes. At the destination node, the Gaussian elimination method is used for R^2 NC decoding, which is followed by bitstream retrieve and video reconstruction.

B. Distortion of Reconstructed Video Minimization Formulation

In order to provide the reliability for H.264/SVC video transmission over packet lossy networks, our goal is to minimize the overall distortion of reconstructed video. In the new H.264/SVC standard, new tools including combined spatial, temporal and quality scalability are added. In this paper, in order to simplify the optimization model, we only consider the temporal and quality scalability. Each temporal layer can contain several quality layers. Each quality layer in each temporal layer is defined as a scalable unit (SU) [14]. Due to the dependency between quality layers, the effect of packet loss is severe when compressed video data is transmitted over packet lossy networks. As a result, we need to reorganize SVC bitstream with prioritization within one GOP to make the transmission more efficient and robust under the same bandwidth condition of network.

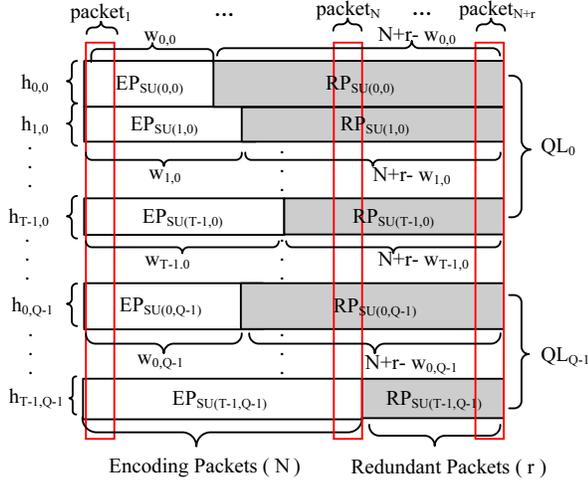


Fig. 2. Bitstream Rearrangement with R^2 NC for Scalable Units (SU)

Fig. 2 shows unequal protection scheme (UEP) for scalable unit (SU) to rearrange the H.264/SVC bitstream and the package format with R^2 NC. The number of temporal layer is T and each temporal layer is further divided into Q quality layers. If we represent i as the temporal level and j as the quality level where $i = 0, 1, \dots, T-1$ and $j = 0, 1, \dots, Q-1$, the scalable video data for the unit (i, j) is defined as $SU(i, j)$ [14]. The width and the height of each $SU(i, j)$ are $w_{i,j}$ and $h_{i,j}$ bytes respectively. The bitstream rearrangement method based on $SU(i, j)$ and the data packing interleaving

algorithm is shown in Fig. 2. The data $EP_{SU(i,j)}$ rearranged for $SU(i, j)$ generates the encoding packets, and the residual packets are filled with redundancy parity packets $RP_{SU(i,j)}$ for $SU(i, j)$ with valid coding vectors instead of zero. In Fig. 2, the white part is the packets which are rearranged by bitstream rearrangement algorithm and then encoded with valid coding vectors of the low-triangular GCM with ladder-shaped partition. The gray part is the redundant parity packets for each $SU(i, j)$ generated by redundant network coding based on the low-triangular GCM with ladder-shaped partition. Here, for convenience, we denote $w_{T-1,Q-1}$ as N . We can see the number of the redundant parity packets for each $SU(i, j)$ is $N+r-w_{i,j}$. Our object is to find the best R^2 NC code assignment for minimizing the overall distortion of reconstructed video, including the choosing of $w_{i,j}$, redundancy r at the source node, and redundancy R at the intermediate nodes. In this paper, we adopt the PSNR value to measure the amount of distortion. The overall distortion can be calculated as follows

$$D_{overall} = \sum_{i=0}^{T-1} \sum_{j=0}^{Q-1} \delta_{i,j} \cdot p_{i,j}^{su} \quad (1)$$

where $\delta_{i,j}$ is the PSNR decrement from the erasure of $SU(i, j)$ and $p_{i,j}^{su}$ is the loss rate of $SU(i, j)$ over packet lossy networks with R^2 NC. The $\delta_{i,j}$ value can be calculated experimentally. If the number of lost packets is greater than the number of the parity packets, the original streaming can not be recovered completely. The $p_{i,j}^{su}$ can be formulated as

$$p_{i,j}^{su} = \sum_{m=N+r-w_{i,j}+1}^{N+r} C_{N+r}^m (p')^m (1-p')^{N+r-m} \quad (2)$$

Where $C_{N+r}^m (p')^m (1-p')^{N+r-m}$ is the probability of losing m packets among $N+r$ packets over packet lossy networks. The p' is the average packet loss rate over packet lossy networks with R^2 NC, which is relative to packet loss channels and the R^2 NC mechanism. In order to minimize (1), p' should be determined. Its a complex problem and may have different results for different topology. In this paper, we use simulation as well as curve fitting to find p' .

The intermediate nodes are classified into two types simply, nodes with only single input link and nodes with multiple input links. N_{SI} is defined as the set of nodes with only single input link, and N_{MI} is the set of nodes with multiple input links. We denote $I_link(I)$ as the set of input links of node I , and $x_k(i)$ is the number of packets transmitted on the input link i of node k . Our goal is to minimize (1), and the problem is formulated as

$$\text{minimize } D_{overall}$$

subject to

$$\sum_{i=0}^{T-1} \sum_{j=0}^{Q-1} h_{i,j} + H \leq M \quad (3)$$

$$\begin{aligned} w_{i,j} &\leq w_{i+1,j}, \quad i = 0, 1, \dots, T-2 \\ w_{i,j} &\leq w_{i,j+1}, \quad j = 0, 1, \dots, Q-2 \end{aligned} \quad (4)$$

$$\sum_{i=0}^{T-1} \sum_{j=0}^{Q-1} h_{i,j} \cdot (N+r) \leq B_{tot} \quad (5)$$

$$\begin{aligned} \forall k \in N_{SI} \text{ and } N_{SI} = \{N_1^S, N_2^S, \dots, N_{k^*}^S\} \\ \frac{x_k \cdot (1 + \alpha(k))}{1 - P_k^{out}} \leq R_k^{out} \end{aligned} \quad (6)$$

$$\begin{aligned} \forall I \in N_{MI} \text{ and } N_{MI} = \{N_1^M, N_2^M, \dots, N_{i^*}^M\} \\ \forall i \in I_link(I) \text{ and } I_link(I) = \{l_1, l_2, \dots, l_{i^*}\} \\ \frac{\max\{x_I(i) \cdot (1 + \alpha_I(i))\}}{1 - P_I^{out}} \leq R_I^{out} \end{aligned} \quad (7)$$

$$\begin{aligned} \forall k \in N_{SI}, \quad \forall m \in N_{MI}, \quad \text{and } \forall i' \in I_link(m) \\ \sum_{k=1}^{k'} \alpha(k) + \sum_{m=1}^{k^*} \sum_{i'=1}^{i^*} \alpha_m(i') = 1 \end{aligned} \quad (8)$$

where B_{tot} is the total number of bits to be allocated for a GOP and M represents the length of a packet. P_k^{out} is the average packet loss rate of the output link of node k and $\alpha_k(i)$ is the redundancy rate of i th input link of node k with redundant network coding. R_k^{out} is the capacity of the output link of node k . The constraint of (4) means that the smaller width $w_{i,j}$ is assigned to $SU(i, j)$ with lower temporal and quality layers than that with higher temporal and quality layers with large impact on the quality of reconstructed video. From Fig. 2 we can also observe that the smaller $w_{i,j}$, the more important $SU(i, j)$, and the more redundancy allocated for $SU(i, j)$, which is ensured by the bitstream rearrangement algorithm on the constraint of (4). (6) is the capacity constraint for each flow from the single input link of intermediate nodes which performs redundant network coding. The second term of (6) refers to loss on the output link, which is the amount of redundancy (via redundant network coding) added against loss. (7) is the capacity constraint for the intermediate nodes with multiple input links performing R^2NC , which determines the redundancy (via redundant network coding) added for each flow from the input link and the amount of packets (via random network coding) combined together. (8) is the boundary constraint of redundancy added (via redundant network coding) at the intermediate nodes.

In order to simplify the optimization algorithm, the complex optimization problem need to be decomposed into a serious distributed optimal solutions. In this paper, by relaxing the capacity constraint in (6) (7) and (8), the optimization problem can be decomposed into two sub-optimization problems with different levels if some variables are fixed, which can be solved by the Lagrange multiplier method.

IV. SYSTEM IMPLEMENTATION

In this section, we propose practical implementations of the R^2NC scheme at the source node and intermediate nodes for H.264/SVC video transmission.

A. Operation of Source Node

Our proposed R^2NC -based UEP method is performed at the source node, as is shown in Fig. 3. The GCM with ladder-shaped partition consists of submatrices $M_{(N+r) \times w_{0,0}}, \dots, M_{(N+r) \times N}$, where submatrix $M_{(N+r) \times w_{i,j}}$ corresponds to $SU(i, j)$ for R^2NC . Submatrix $M_{(N+r) \times w_{i,j}}$ consists of two parts. The first part has $w_{i,j}$ rows, which is used to generate $w_{i,j}$ encoding packets and the second part has $N+r-w_{i,j}$ rows, which is used to generate $N+r-w_{i,j}$ redundant coding packets for $SU(i, j)$. The process of R^2NC -based UEP scheme with the low-triangular GCM is shown in Fig. 3. $P = (P_1^* P_2^* \dots P_{N+r}^*)$ denote a set of NC packets (via R^2NC) at the source node, and $a_i = (a_{i,1} a_{i,2} \dots a_{i,i} 0 \dots 0)$ denote the coding vector associated with P_i^* . $(P_1 P_2 \dots P_N)$ is the set of packets generated by bitstream rearrangement algorithm. The GCM with ladder-shaped partition is generated by a_i , w.h.p. any matrix $M_{w_{i,j} \times w_{i,j}}$ of the sub-matrix $M_{(N+r) \times w_{i,j}}$ of $SU(i, j)$ can attain full rank. Therefore, $SU(i, j)$ can be decoded successfully if the destination nodes receive any $w_{i,j}$ coding packets, which is ensured by the low-triangular global coding matrix. From the GCM with ladder-shaped partition we observed, the larger $w_{i,j}$, the more coding packets for $SU(i, j)$ needed at the destination node, and the smaller decodability of $SU(i, j)$.

$$\begin{bmatrix} P_1^* \\ P_2^* \\ \vdots \\ P_{w_{0,0}}^* \\ \vdots \\ P_N^* \\ P_{N+1}^* \\ \vdots \\ P_{N+r}^* \end{bmatrix} = \begin{bmatrix} a_{1,1} & 0 & \dots & \dots & \dots & 0 \\ a_{2,1} & a_{2,2} & & & & \vdots \\ \vdots & \vdots & \ddots & & & \vdots \\ a_{w_{0,0},1} & a_{w_{0,0},2} & \dots & a_{w_{0,0},w_{0,0}} & & \vdots \\ \vdots & \vdots & \ddots & \vdots & & \vdots \\ a_{N,1} & a_{N,2} & \dots & a_{N,w_{0,0}} & \dots & a_{N,N} \\ a_{N+1,1} & a_{N+1,2} & \dots & a_{N+1,w_{0,0}} & \dots & a_{N+1,N} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ a_{N+r,1} & a_{N+r,2} & \dots & a_{N+r,w_{0,0}} & \dots & a_{N+r,N} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_{w_{0,0}} \\ \vdots \\ P_N \end{bmatrix}$$

$\underbrace{\hspace{15em}}_{M_{(N+r) \times w_{0,0}}} \quad \underbrace{\hspace{15em}}_{M_{(N+r) \times N}}$

Fig. 3. Illustration of R^2NC -based UEP scheme that preserves the low-triangular GCM with ladder-shaped partition

B. Operation of Intermediate Nodes

1) *Receiving a packet and redundant network coding*: Supposing the intermediate node does not need to decode, it just combine the packets in the same group and updates their global coding vectors. To reduce the packet loss over packet lossy networks, the redundant network coding is performed at the intermediate nodes. After $x_k(i)$ packets in a group are received

by intermediate node k from input link i , $R_k(i)$ redundant coding packets are generated (via redundant network coding) depending on the packet loss rate of the output link. The redundancy $R_k(i)$ added by the intermediate node for input link i can be calculated as follow

$$R_k(i) = \frac{x_k(i) \cdot P_k^{out}}{1 - P_k^{out}} \quad (9)$$

In Fig. 4, we describe redundant network coding at the intermediate nodes. The packets transmitted by A and B are a_1, a_2, a_3, a_4 and b_1, b_2, b_3 , respectively. The packet loss rate over I-A and I-B output links are assumed 0.1 and 0.25. Firstly, the redundancy added for input link A-I is $R_I(A-I) = 2$, and the redundant packets (a'_1 and a'_2) can be generated by the combination of a_1, a_2, a_3 and a_4 (via linearly independent coding vectors). The redundancy added for B-I is $R_I(B-I) = 1$, and b'_1 is generated by the combination of b_1, b_2 and b_3 (via linearly independent coding vectors).

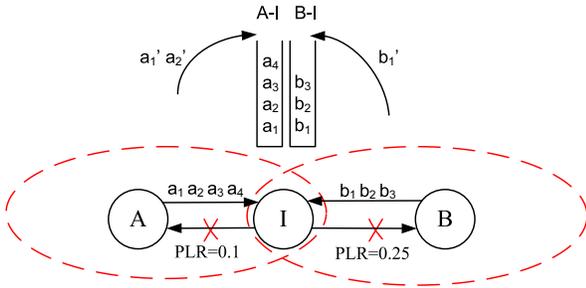


Fig. 4. Example of Redundant Network Coding at Intermediate Node I

2) *Transmitting a packet and random network coding*: After intermediate node k generates the redundancy $R_k(i)$ for input link i , it treats all $x_k(i) + R_k(i)$ packets as equal parts of the same input link. Considering the actual network load, we expand the boundary conditions of adding redundancy by random network coding at intermediate nodes and the number of transmitted packets at node k is $\max\{x_k(i) + R_k(i)\}$. For example, in Fig. 4, after random network coding performed at intermediate node I, the number of relayed packets is 6. Obviously, the bandwidth utilization of output links is improved by random network coding.

V. PERFORMANCE EVALUATION

A. Experiment Design

Visual Studio 2008 is used to build the experimental H.264/SVC transmitting system based on R^2NC . We use two QCIF video sequences “Foreman” and “Coastguard”. They are encoded using the version 9 of the Joint Scalable Video Model. One spatial layer is encoded with one quality base layer and two quality enhancement layers. For the encoding condition of key pictures with GOP size of 16 frames, the number of maximum temporal layers is 5. The proposed unequal error protection scheme based on R^2NC is used to test the performance of the video transmission system. We considered various topologies: 4 layers, 5 layers and 6 layers

with a source node, multiple intermediate nodes and multiple destination nodes.

B. Performance of Video Transmission Scheme with R^2NC

To compare the video quality with different network coding method fairly, all NC schemes are performed with the same bitstream rearrangement algorithm based on scalable unit. Fig. 5 shows the PSNR comparison at 15% PLR for different sequence with different NC scheme. We observe that R^2NC method with proposed low-triangular GCM can provide better PSNR values than other schemes. Because COPE based method does not take the packet loss into account and RLNC scheme based on general GCM with rectangular-shaped partition is performed without using valid coding vectors at the intermediate nodes, which result in a decrease of the decodability of scalable unit.

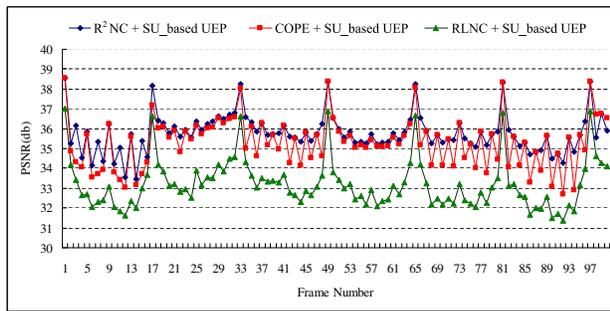
Fig. 6 (a) presents the average PSNR values based on different NC schemes at different PLR with respect to the video quality. We can see that: (1) Average PSNR values are improved for protection R^2NC scheme against other schemes; (2) When the PLR is very low, all NC schemes can recover the majority of lost packets; and (3) R^2NC scheme maintains higher PSNR values compared to other schemes at high packet loss rates from 15% to 25%; Fig. 6 (b) shows the average PSNR values with different bitstream rearrangement algorithm. The quality-based UEP scheme is performed with unequal protection ratio in quality layers without considering the unequal importance of temporal layers. And the temporal-based UEP scheme is performed with unequal protection ratio in temporal layers without considering the unequal importance of quality layers. We can see that: (1) The SU-based UEP scheme can provide better performance than that of other schemes; and (2) The quality-based UEP scheme can provide better performance than that of temporal-based UEP since the temporal-based UEP does not take into account the unequal importance of the quality layers, and the scalable units in lower quality layers obtain rather low protection bits which results in larger distortion. That is, the video transmission system based on $R^2NC + SU$ -based UEP method is more reliability and robust.

VI. CONCLUSIONS

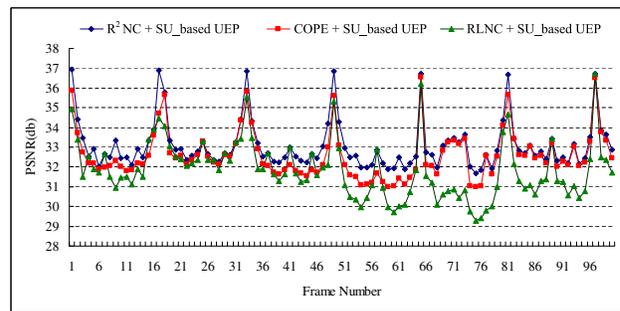
In this paper, a novel unequal packet loss protection scheme- R^2NC based on low-triangular GCM with ladder-shaped partition is presented for robust H.264/SVC video transmission over packet lossy networks. R^2NC can improve the performance of H.264/SVC video transmission system in two aspects: it is resilient to loss due to the perform of redundant network coding without knowledge of the neighbors and the network bandwidth utilization is improved by random network coding. The experimental results also show that the video transmission system based on R^2NC can significantly improve the video PSNR values over packet lossy networks.

VII. ACKNOWLEDGMENTS

This work was supported by the State 863 project of China (Grant No. 2009AA01A135), the NSFC projects (Grant Nos.

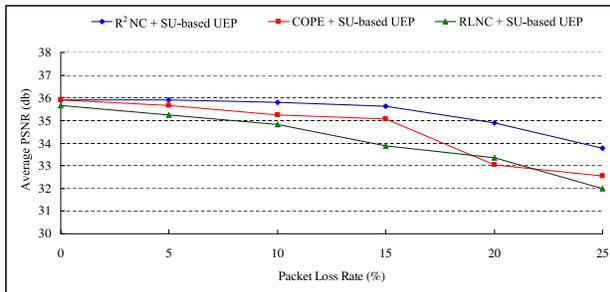


(a)

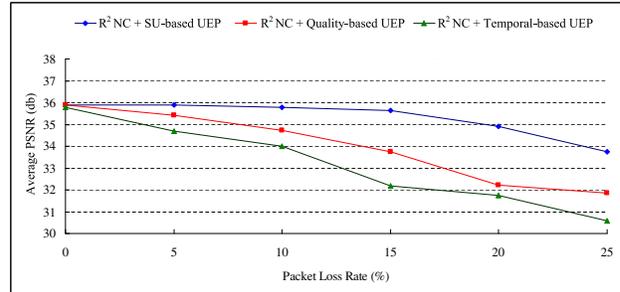


(b)

Fig. 5. PSNR comparison at 15% PLR for different sequence: (a)'foreman' (b)'coastguard'



(a)



(b)

Fig. 6. Average PSNR Values Comparison at different PLR for sequence 'foreman': (a)NC scheme (b)bitstream rearrangement

61073148 and 60773089), and the Natural Science Foundation of Shaanxi Province, China (Grant No. 2009JM8002-5). Part of the work was supported by the XJTU multi-disciplinary project under grant No. 2009xjtujc30.

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