Reliable Scalable Video Multi-cast with Source Diversity and Inter-source Network Decoding in Lossy Networks

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Abstract*—This paper presents a reliable scalable video multi-cast with source diversity and inter-source network decoding in lossy networks. The source diversity technique gives path diversity providing a better quality of layered video transmission under hostile environments. For each source, an optimization formulation is set up to find the best transmission route of each transmitting video layer. The objectives of the formulation are to maximize the summation of information values of video layers and transmission reliability. The source providing the best overall achievable data rate is selected to be the primary source, while the rest will be secondary sources. When the Quality-of-Service (QoS) guarantee of some transmitting video layers cannot be fulfilled by the primary source, the secondary source with the best QoS parameters is selected to transmit the layers to destinations. The number of secondary sources used for transmissions is increased until the QoS guarantees of all transmitting video layers are satisfied or all network resources are utilized. Network coding is deployed to multi-cast video layers from the same source for efficient resource usage. Network coded data from different sources can be used together to decode the transmitting video data. In other words, at each destination, it needs only a sufficient number of video packets from different sources to recover all transmitting video data. Simulations with different network topologies show the improvement in both objective and subjective qualities of layered video multi-cast under lossy environments.

I. Introduction

Reliable transmissions in hostile networks can be achieved by utilizing path diversity and network coding. Furthermore, when there is more than one transmitting source in the network, data from other sources can be used to improve the reliability of data at all destinations resulting in better multimedia qualities. However, it may affect the efficiency in network resource usage, when a number of source transmitting the same data is increased. Scalable video coding encodes a video sequence into a basic layer plus a couple of successive refinement layers to allow heterogeneous transmission rates. Scalabilities of a video sequence can be in either or the combination of SNR, temporal, and spatial scalabilities. A destination that can receive more layers perceives better video quality than a destination that receives fewer layers. A received packet of a low layer contributes to the end-quality of a video sequence more than that of a high layer. Thus, prioritizing transmission of data layer is essential for layered video transmission.

In this work, we investigate QoS-aware scalable video multi-cast in lossy networks with two objectives: 1) to support layered multi-cast transmissions with QoS guarantee and 2) to improve transmission reliability and network resource usage by applying a new inter-source network decoding technique. In the first step, the scheme uses an optimization formulation to compute transmission paths of all layered multi-cast flows for each source. The constraints of the optimization problem such as the transmission rate of each data layer are derived for QoS guarantee. In the second step, the scheme decides whether or not the primary source multi-casts video layers with their QoS requirements. If not, the secondary sources will multi-cast the same set of video layers to destinations. The utilized number of secondary sources is increased until the QoS requirements of video layers are achieved or the network resources are depleted. Inter-source network decoding can be further applied in the second step to enhance reliability by allowing destinations using packet data from different sources to decode transmitted data. Destinations need only to obtain a sufficient number of packets to decode data regardless of where they comes from.

There are two major contributions in this research. First, the proposed scheme provides the method to select the optimal path for layered multi-cast transmission maximizing information values of transmitted layers and the reliability. Layered multi-cast transmission is suitable to be used in heterogeneous network environments. Destinations with different network capacities or device displays can select to receive an amount of data matching with their capabilities. The proposed optimal path selection maximizes the summation of information values of transmitting layers and their reliabilities for each

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multi-cast session subject to limited resources. The maximal reliability is provided to each multi-cast based on link quality in terms of packet loss probability. The network resource usage is considered in terms of bandwidth utilization. Second, more robust and efficient transmission is achieved by source diversity, network coding, and inter-source network decoding technique. Random network coding is applied at intermediate nodes. Since the reliability obtained from the optimization formulation may not achieve the QoS requirements of transmitting layers, using multiple sources and inter-source network decoding enhance the decoding probability of layered data.

The rest of this paper is organized as follows. Related work is discussed in Section II. Section III defines a network model and assumptions used in this paper. Section IV sets up the optimization formulation to compute the optimal routes for layer video transmissions. Section V describes the proposed QoS-aware multi-source routing scheme for multi-cast transmission and the use of random network coding in multi-cast transmissions. Section VI demonstrates a concept of the inter-source network decoding. Section VII evaluates the advantages of our routing scheme using objective and subjective qualities obtained from computer simulations. Conclusion remarks are in Section VIII.

II. Related Work

Network coding was first introduced by Ahlswede *et al.* [1], where destinations can receive data equaling their max-flow under multicast transmission. Previous works on multi-rate multi-cast with network coding include [2], [3], [4], [5], [6], [7], [8], [9]. Zhu *et al.* [2] presented a set of distributed algorithms to significantly improve the data rate of the end-to-end multi-cast session using network coding. They used redundant paths from a single source to multiple sinks to achieve a better achievable data rate. Sundaram *et al.* [3] proposed a polynomial-time algorithm for multi-casting to heterogeneous receivers using network coding. The algorithm yields a transmission rate equal to max flows of all receivers. Supittayapornpong *et al.* [4] proposed a framework for multi-casting layered data with QoS guarantee. Their approach used an optimization problem to select reliable paths for layered data transmission. They set reliability as a constraint in a binary linear optimization to provide QoS guarantee to selected paths. A heuristic algorithm for selecting static network codes was proposed. However, the use of the scheme is limited to single source transmission in networks with low packet loss rate. Kim *et al.* [5] proposed the *pushback algorithm* for multi-resolution multi-cast. The goal of this algorithm is to maximize the total rate achieved by all receivers, while guaranteeing the decodability of the base layer at each receiver. However, QoS guarantee and packet loss were not considered in their work. Xu *et al.*[6] proposed the Layered Separated Network Coding Scheme that aims at maximizing total layers received by all receivers. Zhao *et al.* [7] proposed a solution to improve throughput of an overlay multi-cast session with slightly higher delay and network resource consumption. However, this work only was applied in lossless environment. Ho *et al.*[8], [9] presented a distributed random linear network coding for transmission and compression of information in multisource multicast network. Each node in a network independently and randomly selects linear codes, which explain the correlation of input and output information. They proposed a general bound on successful transmission probability of such codes for arbitrary networks, showing that the successful decoding probability increase exponentially with the code length. They assumed that the channels are lossless. When one or more sources want to transmit N packets to one or more nodes, the effectiveness of the random linear network coding depends on the probability that at least N packets reach their destination, and they represents linearly independent encoding of the original data. Trullols-Cruces *et al.* [10] proposed an exact decoding probability under random network coding. They computed the exact decoding probability that a receiver exactly obtains N linear independent packets over $K \geq N$ received packets under random network coding over a Galois Field, where K denotes transmitted packets from sources. Zhao [11] demonstrated less complicated derivations of the previous exact decoding probability. We proposed a bound on successful decoding probability and a practical use of the bound to determine a suitable field size for a target of decoding probability in [12]. However, packet losses in networks were not taken into account.

Generally, a network may have either multiple sources, servers, or even buffered memories containing replicated contents. To give an example, when a client initiates a data request, it can receive data not only from the servers, but also from the surrounding peers that have buffered the same data [13]. The recently proposed work showed the efficient caching mechanism that encourages the streaming data in multiple sources environments [14]. Nodes of network can cooperate to exploit the diversities of sources and paths to access data to improve the reliability of data transmission. Han [15] presented a necessary and sufficient condition for reliable transmission over a network for multi-casting multiple correlated sources to multiple sinks in lossy channels. Li *et al.* [16] set up a route selection problem for Video-on-Demand streaming system in wireless mesh network using rate/interference-distortion optimization framework. When caching at nodes in wireless mesh network is possible, the video file can have multiple replicas from previous request. Consequently, the newly requesting client might have multiple sources for accessing the video file. They proved that the source diversity can improve wireless video streaming quality [17]. Xu *et al.* [18] proposed a peer-to-peer video-on-demand system using multiple description and source diversity, where they use multiple ordinary computers (peers) as servers and the client can stream different layers of the same video file from these peers. Selvam *et al.* [19] presented a cluster based approach for multiple sources multicast routing protocol in mobile ad hoc network. However, they did not provide path selection focusing on the reliability. Although there is the path diversity, the bandwidth may not be used efficiently since redundant data are transmitted through lossy paths. Ao *et al.* [20] proposed a packet combining scheme based on network coding to reduce transmission delay between end hosts connected by multiple disjoint paths. Their scheme improved the reliability of transmission.

III. System Model

A. H.264 Scalable Video Coding

H.264 Scalable Video Coding (SVC) [21] is introduced to provide an attractive solution in adapting video bitstreams to the various needs or requirements of end users, terminal capabilities, or network conditions. In SVC bitstreams, all key components of H.264/AVC [23] such as intra prediction, motion compensation, and Network Abstract Layer Unit (NALU) are included to achieve both coding and transmission efficiency. Scalability in SVC consists of spatial, temporal, and quality or SNR scalabilities [21]. SVC bitstreams contain a base layers and several enhancement layers. Spatial,temporal, and SNR scalabilities describe subsets of bitstreams representing video contents with a reduced resolution, frame rate, and quality, respectively. Generally speaking, base layer affects the end-to-end video quality more than those of the enhancement layers. Therefore, it is reasonable to let the base layer to be transmitted via more reliable network paths comparing to less important layers. In this paper, video layer i will be more important than video layer j, when $i < j$.

B. Network Model

We model a lossy network as a directed graph $G(N, E)$, where N and E are sets of nodes and links in the network, respectively. Let S and D be sets of source and destination nodes of a multi-cast transmission, respectively. For generality, we define the multi-cast transmission flows as a set of unicast flows (s, d), where $s \in S$ and $d \in D$. Each s has the same set of data, which can be chosen to transmit data to nodes in D.

Define (a, b) as a link conveying data from node a to node b. For link $l \in E$, let $t(l)$ and $r(l)$ be the transmitter and receiver nodes of link l, respectively. For each node $n \in N$, let $T_O(n) = \{l \in E | n = t(l)\}$ and $T_I(n) = \{l \in E | n = r(l)\}$ be sets of outgoing and incoming links of node n, respectively. Let Γ be the set of all pairs of source and destination nodes in the network, where $(s, d) \in \Gamma$.

Each link has a positive integral capacity denoted by c_l. For the link having a capacity c_l where $c_l > 1$, we split the link to c_l links in parallel with a capacity equal to one for each link. The probability of a packet loss of link l is p_l, where $0 \le p_l \le 1$. Each $(s, d) \in \Gamma$ transmits M layers of data, where L_i is the i^{th} layer with transmission rate r_i. Let the set of layer indices of each (s, d) be I_M, where $I_M = \{0, 1, 2, \ldots, M-1\}$.

C. QoS Guarantee

Definition 1*: The QoS guarantee for $(s, d) \in \Gamma$ and $i \in I_M$ is a lower bound of the probability that source s can transmit a packet of L_i to destination d successfully.*

The probability of a successful packet transmission for L_i, called the reliability and denoted by $P_i^{(s,d)}$, can be expressed as

$$P_i^{(s,d)} = \prod_{l \in E} (1 - p_l)^{f_{l,i}^{(s,d)}}, \tag{1}$$

TABLE I
Summary of notations I

$G(N, E)$	: directed graph that represents the network
N	: set of nodes in the network
E	: set of links in the network
S	: set of source nodes
D	: set of destination nodes
(s, d)	: pair of source node s and destination node d
(a, b)	: link conveying data from node a to node b
$t(l)$	: transmitter node of link l
$r(l)$	: receiver node of link l
$T_O(n)$	: set of outgoing link of node n
$T_I(n)$	: set of incoming link of node n
Γ	: set of all pairs of source and destination nodes in the network
c_l	: capacity of link l
p_l	: probability of a packet loss of link l
M	: number of layers of data
L_i	: i^{th} layer
r_i	: transmission rate of the i^{th} layer
I_M	: set of layer indices, where $I_M = \{0, 1, 2, \ldots, M-1\}$
I_{M-1}	: set of layer indices, where $I_{M-1} = \{0, 1, 2, \ldots, M-2\}$
$P_i^{(s,d)}$	: probability of a successful packet transmission for L_i of (s, d), called the reliability
$f_{l,i}^{(s,d)}$	: variable that indicates whether or not link l is used to transmit a packet of L_i for (s, d)
$R_i^{(s,d)}$	: set of links used to transmit packets of layer L_i from source s to destination d
$x_i^{(s,d)}$	: variable that indicates whether or not packets of layer L_i are transmitted from source s to the destination d
κ_i	: information value used to prioritize data layers
$t_{l,i}$	: total capacity used by the i^{th} layer

where $f_{l,i}^{(s,d)}$ indicates whether or not link $l \in E$ is used to transmit a packet of L_i. If it is used, $f_{l,i}^{(s,d)} = 1$. Otherwise, $f_{l,i}^{(s,d)} = 0$.

IV. Optimum Path Selection for Layered Multi-cast

Definition 2*: A path for $(s, d) \in \Gamma$ and $i \in I_M$ is a set of links, denoted by $R_i^{(s,d)}$, used to transmit packets of layer L_i from source s to destination d. An optimal set of paths is such that $R_i^{(s,d)}$, $(s, d) \in \Gamma$, $i \in I_M$, maximize the objective function under a set of constraints.*

The optimal set of paths selection based on the optimization framework is formulated in this section. The objectives of the formulated framework are to maximize the summation of information values of transmitted layers and the transmission reliability.

We discuss the objective function as well as the set of constraints in the following subsections.

A. Objective Function

1) Maximizing the Summation of Information Value: Define $x_i^{(s,d)}$ as a variable, where $x_i^{(s,d)} = 1$ indicates that packets of layer L_i are transmitted from the source s to the destination d. Else, $x_i^{(s,d)} = 0$. To prioritize data layers, we define the information value of each layer as κ_i, where $\kappa_i \ge \kappa_j$, when $i < j$. This means that a lower data layer means a higher priority of that data. Based on the defined variables, the first sub-objective function is defined for the optimal path selection of all destinations as

$$K_G = \sum_{i \in I_M} \sum_{(s,d)\in\Gamma} \kappa_i x_i^{(s,d)}. \tag{2}$$

K_G is the summation of the guaranteed information value from all unicasts in the network. K_G varies proportionally with a number of transmitted layers of (s,d).

2) Maximizing the Reliability: When there is more than one path to agree with the first sub-objective function, this sub-objective function selects a path having a maximal reliability.

The reliability of each data layer can be maximized via the following sub-objective function.

$$K_R = \sum_{i \in I_M} \sum_{(s,d)\in\Gamma} \kappa_i \log P_i^{(s,d)}. \tag{3a}$$

According to (1), we rewrite (3a) to

$$K_R = \sum_{i \in I_M} \sum_{(s,d)\in\Gamma} \kappa_i \sum_{l\in E} \overline{p_l} f_{l,i}^{(s,d)}, \tag{3b}$$

where $\overline{p}_l = \log(1-p_l)$.

The κ_i is used to assign links with better channel conditions to more important layers of (s,d). To maximize K_R, a lower layer with a larger κ_i will be placed on the link with higher $\overline{p}_l$ or lower p_l.

The first sub-objective, K_G, dominates the second sub-objective function, K_R. While K_G is sum of product between integer numbers, K_R is sum of product between integers and logarithmic fractional numbers having values less than one. Therefore, the objective function gives priority to the sum of information value for each destination greater than the reliability. The scheme maximizes reliabilities of transmitted layers in best-effort manner, which is not limited by a QoS constraint, to support the multiple sources transmission described in Section V.

We can combine (2) and (3b) to

$$\sum_{i \in I_M} \sum_{(s,d)\in\Gamma} \kappa_i x_i^{(s,d)} + \sum_{i \in I_M} \sum_{l\in E} \overline{p_l} \sum_{(s,d)\in\Gamma} \kappa_i f_{l,i}^{(s,d)} \tag{4a}$$

$$= \sum_{i \in I_M} \sum_{(s,d)\in\Gamma} \kappa_i \{x_i^{(s,d)} + \sum_{l\in E} \overline{p_l} f_{l,i}^{(s,d)}\}. \tag{4b}$$

B. Problem Formulation

To compute the optimal set of paths of all $(s,d) \in \Gamma$, an integer linear optimization problem is established as follows.

Maximize

$$\sum_{i \in I_M} \sum_{(s,d)\in\Gamma} \kappa_i \{x_i^{(s,d)} + \sum_{l\in E} \overline{p_l} f_{l,i}^{(s,d)}\} \tag{5a}$$

Subject to

$$\sum_{l\in T_O(n)} f_{l,i}^{(s,d)} - \sum_{l\in T_I(n)} f_{l,i}^{(s,d)} = \begin{cases} r_i x_i^{(s,d)}, & n = s \\ -r_i x_i^{(s,d)}, & n = d \\ 0, & otherwise \end{cases} \tag{5b}$$

$\forall i \in I_M$, $\forall (s,d) \in \Gamma$, $\forall n \in N$,

$$f_{l,i}^{(s,d)} \leq t_{l,i}, \forall (s,d) \in \Gamma, \forall i \in I, \forall l \in E, \tag{5c}$$

$$\sum_{i\in I} t_{l,i} \leq 1, \forall l \in E, \tag{5d}$$

$$x_i^{(s,d)} \geq x_{i+1}^{(s,d)}, \forall i \in I_{M-1}, \forall (s,d) \in \Gamma, \forall l \in E, \tag{5e}$$

$$f_{l,i}^{(s,d)} \in \{0,1\}, \forall i \in I_M, \forall (s,d) \in \Gamma, \forall l \in E, \tag{5f}$$

$$t_{i,l} \in \{0,1\}, \forall i \in I_M, \forall l \in E, \tag{5g}$$

$$x_i^{(s,d)} \in \{0,1\}, \forall i \in I_M, \forall (s,d) \in \Gamma, \tag{5h}$$

where $I_{M-1} = \{0, 1, \ldots, M-2\}$ and $t_{l,i}$ is the capacity used by the i^{th} layer.

- Constraint (5b) is the flow conservation constraint.
- Constraint (5c) and (5d) are link capacity constraints under network coding condition. They allow the flows of different (s,d) with common L_i to share link capacity. Note that the network coding is executed separately layer by layer to maintain the QoS guarantee of each layer transmission.
- Constraint (5e) is the layered data constraint. A path for a higher layer will be chosen only if a path for a lower layer can be selected.
- Constraints (5f), (5g), and (5h) are the feasible values of $f_{l,i}^{(s,d)}$, $t_{i,l}$, and $x_i^{(s,d)}$, respectively.

We obtain the maximum reliability of each path from the optimization formulation, which will be used in the next section.

V. Reliable Layered Multi-cast with Multiple Sources and Network Coding

A. Transmission Reliability of Layered Multi-cast with Multiple Sources

Transmission reliability of layered data can be improved by using source and path diversities. Destinations can expect to receive layered data from alternative routes, when primary transmission paths experience severe packet loss or the QoS requirements of transmitted data cannot be fulfilled at destinations. Let q_i^d be a QoS requirement of transmitting data layer L_i to destination d. $P_i^{(s_1,d)}$ is the transmission reliability

TABLE II
SUMMARY OF NOTATIONS II

q_i^d	: QoS requirement of transmitting data layer L_i to destination d
$P_i^{(s_j,d)}$	: transmission reliability of paths used to transmit L_i to destination d by a source j
$\overline{P}_i^d(N)$	: transmission reliability of data L_i to destination d using N sources
S_k	: event that destination d receives data L_i successfully from source k
Ω_s	: individual lower-bound achievable data rate obtained by single source routing from source s, called QoS parameter
Ψ	: set of achievable data rate for all sources
$P_{dec,i}^{(s_k,d)}$	: decoding probability of layer L_i from source s_k

of paths used to transmit L_i to destination d by a primary source. This reliability is an outcome from Section IV. When $P_i^{(s_1,d)} < q_i^d$, the QoS guarantee of L_i of destination d can not be achieved by the primary source. Therefore, it may be helpful to increase a number of transmitting sources to improve reliabilities. Let $P_i^{(s_j,d)}$ be the transmission reliability of paths used to transmit L_i to destination d by secondary source s_j, where $j \in I$, $j > 1$, and I is a set of positive integer. The set of paths to destination d of the primary source s_1 and every secondary source s_j are independent for all j. The reliability of L_i, when we use N transmitting sources, can be written as

$$\begin{aligned}\overline{P}_i^d(N) &= P\{\bigcup_{k=1}^{N} S_k\}, \\ &= 1 - \prod_{k=1}^{N}(1 - P_i^{(s_k,d)}),\end{aligned} \tag{6}$$

where $\overline{P}_i^d(N)$ is the transmission reliability of data L_i to destination d using N sources and S_k is the event that destination d receives data L_i successfully from source k. As we can see, the term $\prod_{k=1}^{N}(1-P_i^{(s_k,d)})$ of (6) is the probability that destination d can not obtain layer L_i from any source.

B. QoS-aware Multi-cast with Multiple Sources and Network Coding

In this section, we present the algorithm in using multiple sources to reliably multi-cast data to destinations, when the required QoS guarantee cannot be achieved by a single source as in Section IV. However, the improved QoS guarantee comes with more network resource usage. Therefore, the multi-source multi-cast technique must be selectively used only with the data with high priorities. The QoS-aware multi-cast with multiple sources and network coding algorithm can be stated step-by-step as follows.

Step 1: The primary source is selected by choosing the source s giving the highest lower-bound achievable data rate obtained by the single source routing, denoted by Ω_s, where $\Omega_s = \sum_{i\in I}\sum_{d\in D} r_i P_i^{(s,d)} x_i^{(s,d)}$. The single source routing is performed by using our proposed optimization framework in Section IV. The optimal solution of the framework gives the maximized summation of information values of transmitted layers and the maximum transmission reliability, but may not achieve the QoS guarantees to some L_i of some destinations. The Ω_s for all $s \in S$ will be kept in a set of individual achievable data rate for all source, denoted by Ψ.

Step 2: Determine whether all L_i of (s, d), $i \in I$, $d \in D$, can obtain its required QoS guarantee q_i^d or not. If all layers L_i of (s, d) , $i \in I$, have QoS guarantees, use the optimal routes to convey the layered data. Otherwise, the secondary source is needed and go to Step 3.

Step 3: Select the secondary source $\hat{s}$ from the subordinate sources according to Ω_s from Ψ. To obtain path diversity, we modify the set of links E by removing all links having the end nodes in the set of paths from the previous steps, except the destination nodes.

Step 4: The secondary paths of the layers with the unfulfilled QoS guarantees are obtained by using the proposed optimization framework in Section IV. Note that only layers with the unfulfilled QoS guarantees are considered.

Step 5: Compute the new reliabilities of the layers with unfulfilled QoS guarantees, which is computed from (6). The algorithm then determines the QoS guarantees for all L_i, $i \in I$, of all d. If there is any L_i of d that does not obtain QoS guarantee, repeat Steps 3, 4, and 5 until the QoS guarantees of all layers are achieved or all network resources and all sources are used.

At the end of our algorithm, the set of optimal paths used to convey all layer L_i, $i \in I$, will be determined. These paths will be the input for network code assignment using network coding to ensure that destinations can receive their max-flow rates. Network coding will be applied only transmitting data from the same source and same layer. Therefore, decoding layer L_i successfully depends on whether or not the random network code can be decoded at destinations and transmitting data packets arrive at destination successfully. Suppose that data layer L_i can be divided to be K transmitting packets, $L_{i,0}, \ldots, L_{i,K-1}$. The decoding probability of layer L_i from source s_k can be expressed as

$$P_{dec,i}^{(s_k,d)} = \prod_{j=0}^{K-1}(1 - \frac{1}{|F|^{K-j}}) \times P_i^{(s_k,d)}, \tag{7}$$

where the first expression of (7) is the decoding probability of random network coding [10] with field size $|F|$, whereas the second expression is the reliability of transmission of L_i from source s_K to destination d over the chosen optimal paths. After replacing (7) to $P_i^{(s_k,d)}$ in (6), we obtain the decoding probability of data layer L_i from source s_k taking network coding into consideration.

VI. Inter-source Network Decoding

Network coding is used in Section V-B to combat with the bottlenecks in the network [8], [9]. In this section, the inter-source network decoding is presented to further improve the reliability of transmitting layered data based on the multi-source multi-cast routing proposed in Section V-B. The algorithm in Section V-B uses only the packet data from the same source for network decoding. If some packets are lost during transmission, the other network coded data from the considering source are useless. Inter-source network decoding can alleviate this problem by allowing the use of network coded data of the same layer from other sources to help recovering data at the considering destination. To recover the coded layer, each destination just needs to obtain a sufficient number of packets from any source so that it can successfully decode the data. Suppose that each source transmits layer L_i with k units or packets, $L_{i,0}, L_{i,1}, \ldots, L_{i,k}$ and these packets may have to be coded at intermediate nodes. Obtaining k linearly network coded packets, coded data can be recovered by solving linear

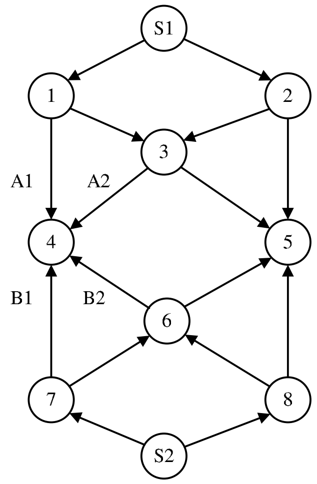

Fig. 1. An example network using inter-source network coding.

equations. This is equivalent to global encoding kernels of random network coding for all k packets will form a matrix with rank k [12]. If there are N sources transmitting layer L_i, with inter-source network decoding, to recover all k units of layer L_i, each destination needs to obtain k network coded packets from total $N \times k$ to successfully decode L_i.

Let us consider the specific example of inter-source network decoding. Consider the network in Fig. 1. The network has two source nodes S_1 and S_2 transmitting the same set of data. Each source separately multi-casts layer L_i with two data packets, i.e., $L_{i,0}$ and $L_{i,1}$, to nodes 4 and 5. At intermediate nodes, packets from the same source can be linearly coded, where the network coding coefficients are selected randomly and independently from other intermediate nodes. Based on Theorem 3 in [12], the random linear network coding can possibly be applied to transmitting data starting from the source node.

The encoded data are transmitted to Nodes 4 and 5 through the determined set of paths. At Node 4, it obtains a set of encoded data as follows $A_1 = a_{1,1}L_{i,0} + a_{1,2}L_{i,1}$, $A_2 = a_{2,1}L_{i,0} + a_{2,2}L_{i,1}$, $B_1 = b_{1,1}L_{i,0} + b_{1,2}L_{i,1}$, and $B_2 = b_{2,1}L_{i,0} + b_{2,2}L_{i,1}$, where A_i and B_i are randomly linear coded data transmitted from S_i, where $i = 1, 2$.

The probability that Node 4 successfully obtains $L_{i,0}$ and $L_{i,1}$ is equal to the probability of an event that at least two encoded data either from S_1 or S_2 arrive at the destination. For instance, when node 4 receives A_1 and B_2, we can formulate a matrix containing global encoding kernels as [12]

$$Y = \begin{bmatrix} a_{1,1} & a_{1,2} \\ b_{2,1} & b_{2,2} \end{bmatrix}$$

and its linear equations can be written as

$$X = \begin{bmatrix} a_{1,1}L_{i,0} + a_{1,2}L_{i,1} \\ b_{2,1}L_{i,0} + b_{2,2}L_{i,1} \end{bmatrix}.$$

We can write the linear equation in terms of matrix of global encoding kernel as

$$Y \begin{bmatrix} L_{i,0} \\ L_{i,1} \end{bmatrix} = X.$$

When matrix Y is nonsingular, we can decode $L_{i,0}$ and $L_{i,1}$ by solving linear equations using the Gaussian elimination. As we can see from the example, the source has more degree of freedom in choosing the packets from any source. It needs only two data packets to recover all transmitted data.

VII. Experimental Results

To evaluate our proposed reliable layered video multi-cast scheme, we compare the simulation results with the following routing schemes:

Single source routing schemes

- QoS-oblivious routing using network coding (QoS-oblivious w/ NC), which was partly used in [7], [9]
- The shortest path routing (QoS-oblivious w/o NC), which was partly used in [24], [25]
- QoS-aware routing for layered multi-cast transmission (QoS-aware w/ NC) [4]

Proposed multi-source routing schemes

- QoS-aware routing using network coding and multiple sources (QoS-aware w/ NC and multiple sources)
- QoS-aware routing using inter-source network decoding and multiple sources (QoS-aware w/ inter-source ND and multiple sources)

We simulate these routing schemes on 10 randomly generated network topologies containing 30 nodes. Node positions are chosen randomly in a square whose the length of each side is 200 meters. Each link capacity is determined by a distance between a transmitter and a receiver at each end of the link. For simplicity of the experiment, we assume that each link capacity is approximately integral as shown in Table III, where $1 \leq c_l \leq 3$ units. One unit is equal to 512 kbps. The successful data transmission of each link is randomly generated, where $Z \leq 1 - p_l \leq 1$. Z is a set of numbers labeled on x-axis of all graphs in this section, where $Z \in \{0.60, 0.65, 0.70, 0.75, 0.80, 0.85, 0.90, 0.95\}$. Achievable data rate is calculated from a sum of products between the transmission rates and reliabilities of data layers. When some layers cannot be transmitted from the source due to limited network resources, achievable data rate of those layers will be zero.

The objectives of our experiments are to show achievable data rate gains and QoS guarantee improvements of multi-cast transmissions, when the proposed routing scheme is used. In addition, we simulate scalable video multi-cast and show the improvement both in subjective and objective qualities. Video codec is based on H.264 Joint Scalable Video Model (JSVM) [21]. The group of picture (GOP) size is 8. Here, we consider only SNR scalability. A video sequence is encoded to be 3 layers, i.e., a base layer and 2 enhancement layers. The frame rate and the resolution of the 4:2:0 YUV video sequences are 30 Hz and CIF (352×288), respectively. Error

TABLE III
DISTANCE THRESHOLDS FOR DIFFERENT TRANSMISSION DATA RATES

Distance(m)	Link Capacity (unit)
63-100	1
40-63	2
0-39	3

concealment mode of JSVM is enabled in our simulations. There are 4 sources and 3 destinations in each network. Each destination requires 3 layers of data. The transmission rates of L_0, L_1, and L_2 are 2, 1, and 1 units, respectively. The imposed QoS requirements of L_0, L_1, and L_2 are 0.90, 0.85, and 0.80, respectively. The information values of L_0, L_1, and L_2, are 3, 2, and 1, respectively. The optimal route solution is computed using the Python programming language [26] together with the PulP package [27] and the GLPK solver [28].

A. Comparison of Achievable Data Rate and Reliability

Fig. 2 shows the average achievable data rate with a successful transmission probability. The QoS aware w/ inter-source ND and multiple sources give the highest average achievable data rate among all routing schemes. The performance gain is more obvious when we encounter with hostile channel conditions. Our proposed routing scheme achieves an average gain of 10.35%, 36.79% and 58.63% in average achievable data rate with respect to the QoS-aware w/ NC, QoS-oblivious w/ NC and the QoS-oblivious w/o NC, respectively. Note that the achievable data rate gained by using our multi-source routing scheme slightly drops at some values of successful transmission probability. This is because we do not need to use multiple sources when QoS guarantee can be achieved by only one source. Therefore, achievable data rate gain decreases in this scenario. Moreover, the higher number of sources used, the higher gain we achieved.

To give specific results in terms of reliability, Figs. 3, 4, and 5 demonstrate the average reliabilities in terms of successful transmission probability of data transmission of L_0,L_1, and L_1 of different routing schemes. For transmission data layer 0, L_0, the proposed routing scheme give an average gain of 14.70%, 34.36% and 57.97% over the QoS-aware w/ NC, QoS-oblivious w/o NC and the QoS-oblivious w/ NC, respectively. For transmission data layer 1, L_1, the proposed routing scheme give an average gain of 5.76%, 21.89% and 47.54% over the QoS-aware w/ NC, QoS-oblivious w/o NC and the QoS-oblivious w/ NC, respectively. Finally for transmission data layer 2, L_2, the proposed routing scheme achieves an average gain of 6.36%, 17.53% and 197.96% over the QoS-aware w/ NC, QoS-oblivious w/ NC and the QoS-oblivious w/o NC, respectively. Note that the gain over the QoS-oblivious w/o NC is high because most data of L_2 cannot be transmit due to the lack of available channels when the QoS-oblivious w/o NC is used.

B. Comparison of Objective and Subjective Qualities

In this section, we show the advantage in terms of peaked-signal-to-noise ratio (PSNR) in scalable video multi-cast with

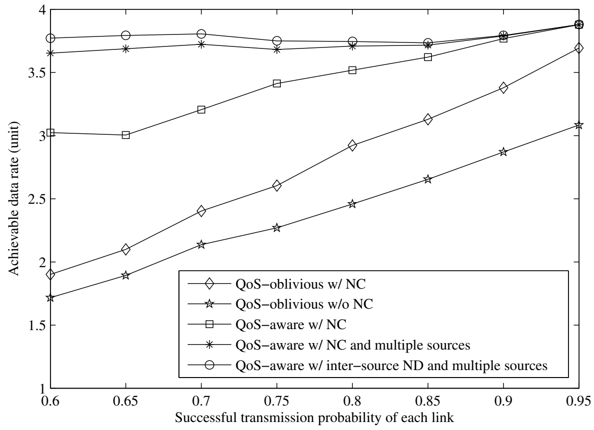

Fig. 2. Comparison of average achievable data rate for various link conditions.

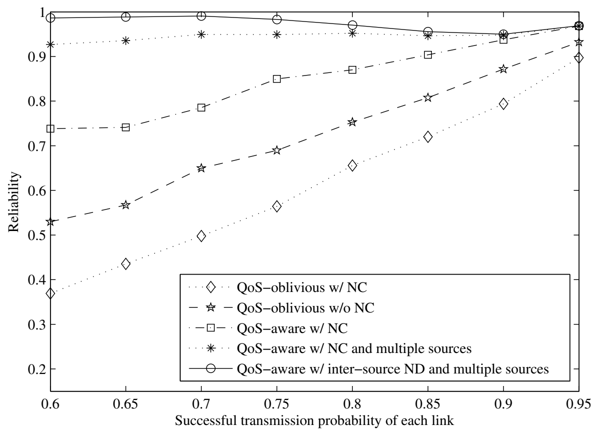

Fig. 3. Comparison of reliability of data transmission of layer 0 for various link conditions.

our proposed scheme. We use 4 video sequences consisting of “Paris”, “Bus”, “Football” and “Mobile” in our simulation. The packet loss rate of each video layer is calculated from the reliability in Section VII-A. Figs. 6, 7, 8, and 9 shows the PSNR comparison among different routing schemes of video sequences “Paris”, “Bus”, “Football” and “Mobile”, respectively. As we can see from the results, the PSNR improvement using our proposed multi-cast scheme is significant, when the channel conditions are hostile, *e.g.* the range of packet loss probability is between 0.6 to 0.8. The PSNR gain between our routing scheme and QoS-oblivious w/ NC is approximately 2-4 dB. This implies that the multi-sources and inter-source network decoding should be used, when the channel is hostile. When the channel is in good conditions, single source and network coding should be sufficient to give an acceptable transmitted video quality. Because multi-source multi-cast requires more network resource usages, it should be selectively used.

Next, Figs.10, 11, 12, and 13 show the subjective qualities

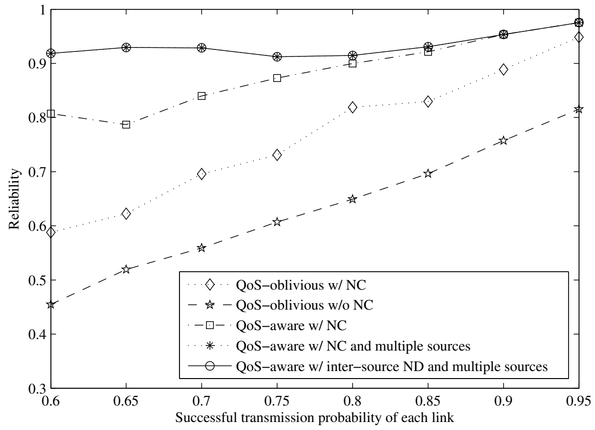

Fig. 4. Comparison of reliability of data transmission of layer 1 for various link conditions.

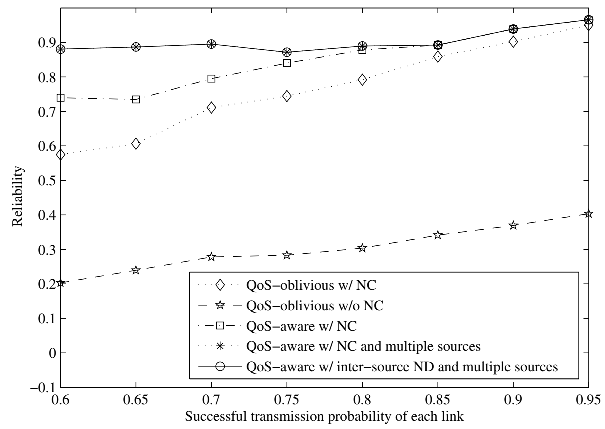

Fig. 5. Comparison of reliability of data transmission of layer 2 for various link conditions.

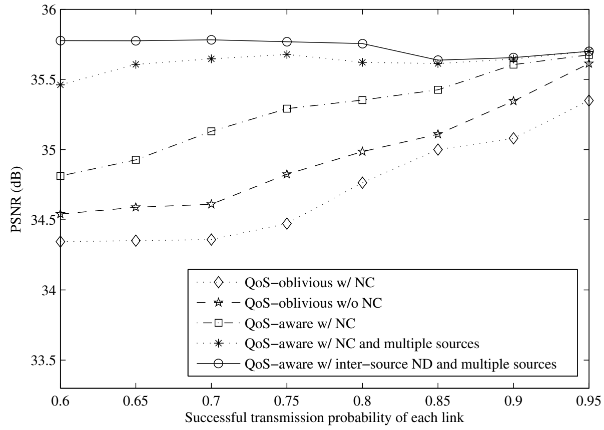

Fig. 6. Comparison of the average PSNR of the video sequences "Paris" for various link conditions.

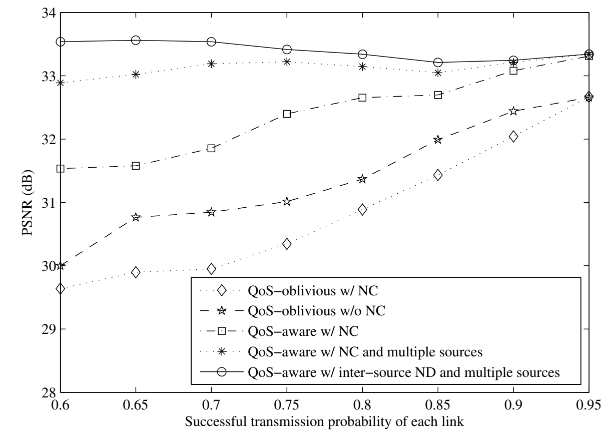

Fig. 7. Comparison of the average PSNR of the video sequences "Bus" for various link conditions.

of video frames from "Paris", "Bus", "Football" and "Mobile" video sequences, respectively. We compare the video frames obtained from the proposed scheme and QoS-oblivious w/o NC. As we can see from the results, our scheme gives superior visual qualities to QoS-oblivious w/o NC, especially in high movement video sequences such as "Football" video sequence.

VIII. Conclusion

The reliable layered multi-cast using multiple sources and inter-source network decoding is proposed. The multi-source technique gives the path diversity that yields a better achievable data rate for layered transmissions. An optimization framework is formulated to find the optimal set of paths under several constraints. When the QoS guarantee of the considering layered data cannot be achieved from the computed routes and some network resources are still available, a secondary source will find its optimal path and transmits the same layered data to the considering destinations. This process will run repeatedly until the QoS guarantee is met or the network resource becomes unavailable. The network coding is applied to the optimal set of paths. The inter-source network decoding is proposed to further improve the achievable data rate, where if the sufficient number of network coded data is received not necessary from the same source, the transmitted data can be recovered. Our experimental results show the improvement in the achievable data rate with QoS guarantee obtained from the proposed algorithm compared to previous works. The simulations of SVC show the PSNR gains resulted from the achievable data rate with QoS guarantee.

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(a) Original (b) QoS-aware w/ inter-source ND and multiple sources (c) QoS-oblivious w/o NC

Fig. 10. Visual example selected from the video sequence “Paris” from various routing schemes.

(a) Original (b) QoS-aware w/ inter-source ND and multiple sources (c) QoS-oblivious w/o NC

Fig. 11. Visual example selected from the video sequence “Bus” from various routing schemes.

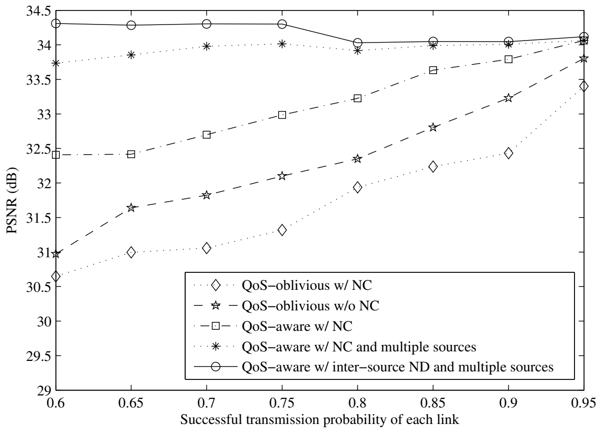

Fig. 8. Comparison of the average PSNR of the video sequences “Football” for various link conditions.

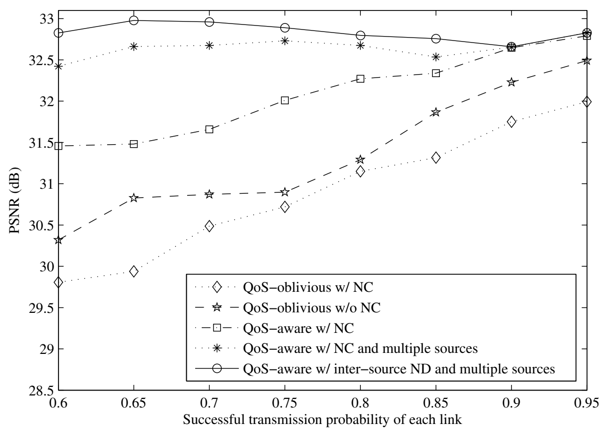

Fig. 9. Comparison of the average PSNR of the video sequences “Mobile” for various link conditions.

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(a) Original (b) QoS-aware w/ inter-source ND and multiple sources (c) QoS-oblivious w/o NC

Fig. 12. Visual example selected from the video sequence “Football” from various routing schemes.

(a) Original (b) QoS-aware w/ inter-source ND and multiple sources (c) QoS-oblivious w/o NC

Fig. 13. Visual example selected from the video sequence “Mobile” from various routing schemes.

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