COLLABORATIVE VIDEO STREAMING WITH RAPTOR NETWORK CODING

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ABSTRACT

We investigate the problem of collaborative video streaming with Raptor network coding over overlay networks. We exploit path and source diversity, as well as basic processing capabilities of network nodes to increase the overall throughput and improve the video quality at the clients. We consider an architecture where several streaming servers simultaneously deliver video information to a set of clients. The servers apply Raptor coding on the video packets for error resiliency, and the forwarding peer nodes further combine the Raptor coded video packets in order to increase the packet diversity in the network. We find the optimal source and channel rate allocation in such a collaborative streaming system. The resulting scheme efficiently exploits the available network resources for improved video quality. The experimental evaluation demonstrates that it typically outperforms Raptor video streaming systems that do not use network coding.

***Index Terms*—** Network coding, optimal rate allocation, overlay networks, error resiliency

1. INTRODUCTION

During the last decade peer-to-peer and wireless mesh networks have attracted much attention as they can self organize peer nodes for exploiting more efficiently the network infrastructure. These networks offer several streaming paths between servers and clients. The network diversity can be used to assist video communication systems to achieve high quality. It can also enhance the robustness of the transmission and compensate for the lack of quality of service in best effort networks. For exploiting the network diversity the video information can be streamed over multiple paths. These paths can be completely independent or share some common links. However, overlapping paths may result into significant redundancy and packet replication. Appropriate streaming mechanisms are therefore necessary in order to avoid wasting network resources by taking advantage of the computing capabilities of peer nodes. These can be advantageously used for increasing both the throughput of the system and the packet diversity.

The Raptor codes [1] have been shown to be an efficient channel coding techniques which guarantees high symbol diversity in overlay networks. The rateless property allows for the generation of potentially limitless number of symbols from a given source reducing significantly the probability of multiple packet reception from the sources. Network coding [2] has been proposed as a promising method to improve network throughput utilization and approach max-flow min-cut bound. The network coding systems do not only forward the received packets but perform operations with packets for exploiting network diversity. This work builds upon our recent work [3] in which we presented a network coding system that takes benefits from both network coding and Raptor codes. This scheme is very resilient to erroneous channel estimations, especially at high loss rates and limited network diversity. We propose here to increase the performance of the Raptor network video coding solution by optimal source and channel rate allocation.

It has to be noted that a method similar in many aspects with [3] has been presented in [4] where network coding is used for video streaming over wireless mesh networks. It considers the significance of each video packets and intelligently selects network codes for combining packets that can be decoded by several peers. In [5] a network coding system was used for WLAN-like Access Point or WiMAX-like broadcast stations. This method employs an optimized scheduling algorithm based on the Markov Decision Process to maximize the multimedia transmission in both broadcast and unicast settings. LT codes [6] has been proposed for peer-to-peer multimedia delivery [7] to avoid reconciliation among peer nodes. This approach ensures very low but not negligible probability of multiple reception of the same packet. Although the scheme is efficient it has high computational complexity as it applies LT decoding/encoding in every peer node.

In this work we concentrate on deriving an efficient rate allocation algorithm for Raptor network coding in collaborative streaming scenarios. We consider that all servers have the same video which is protected by Raptor codes. We formulate the optimization problem as *minmax* problem, since the algorithm seeks for the optimal source rate allocation maximizes the source rate for the less reliable clients. Given the network status, the optimization algorithm estimates the rank decrement of the equation system built on the received network coded packets. It then determines the optimal source rate as the solution of a convex optimization problem, since it represents a typical trade-off between source distortion, and resiliency to packet loss. We evaluate the resulting system for various random topologies and we show that it outperforms Raptor coding systems that do not exploit peers for network coding.

2. RAPTOR NETWORK VIDEO CODING

2.1. System description

We consider video streaming over overlay packet networks with lossy channels as illustrated in Fig. 1. In this topology the video is distributed into several servers which are connected with the streaming clients through several forwarding peer nodes. The forwarding peers are arranged in successive stages or hops, depending on the distance to the sources (computed as the number of overlay nodes traversed by information flow). An overlay network with s sources,

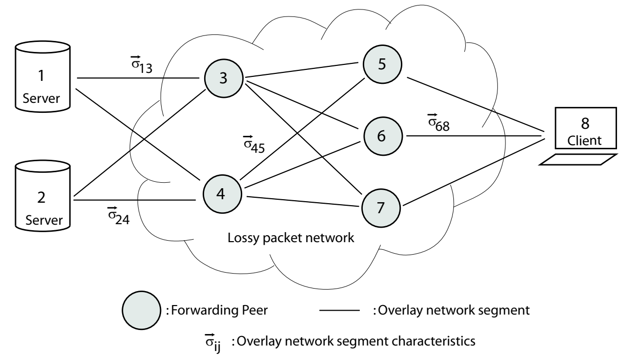


Fig. 1. Streaming over overlay packet networks with network diversity.

y_x nodes in the x_{th} hop, and r client is denoted in this paper as a $s - y_1 - \cdots - y_x - r$ architecture. Each segment between nodes i and j in this infrastructure is characterized by a set of parameters $\vec{\sigma}_{ij} = [r_{ij}, \pi_{ij}, \alpha_{ij}]$, which respectively represent the available bandwidth, the packet loss ratio and the average length of bursts of errors.

2.2. Raptor codes

The Raptor codes [1] are packet erasure codes which are usually described by the pair (N, K), where N denotes the number of output symbols and K stands for the number of input symbols. They perform close to perfect codes as they can recover the source symbols from any set of encoded symbols slightly larger than the set of encoded symbols. The performance of Raptor codes is determined by the overhead ϵ which is the rate penalty of the code, (*i.e.* $K \cdot (1 + \epsilon)$ symbols should be received for successful decoding).

Raptor codes are low complexity codes endowed with the rateless property that permits the generation of unlimited number of symbols. The Raptor encoding is succession of two steps. First, the input symbols are encoded by a pre-coder which is a perfect coder and then are fed in a weakened LT coded for generating the output symbols. The output symbols are random XORs of the input symbols according to a degree distribution function that determines the number of XOR-ed symbols and the symbols combined. Each Raptor symbol is augmented with a small header (ESI) for passing at the decoder the structure of the Raptor codes Tanner graph. Raptor decoding is performed solving the linear system of equations correspond to the received symbols using Gauss-Jordan elimination.

2.3. Raptor network coding

We apply Raptor coding in the network nodes as presented in [3], in order to improve the overall throughput of the streaming application. Specifically we use non-systematic Raptor codes as they offer linear encoding/decoding time and provide effective symbol diversity for network coding. Raptor coding is applied in overlay nodes, as illustrated in Fig. 2. A node n gathers coded symbols from ancestors nodes. It combines the input set of symbols $\{I_{in}, I_{jn}, I_{kn}\}$ and transmits a subset O_{np} of the re-encoded symbols to the node p. The Raptor re-encoding matrix $\mathbf{A}^{'}$ is constructed using the ESI's of the received symbols. The Raptor re-encoder generates new symbols combining some of the received symbols in order to compensate for losses. The re-encoded symbols are generated whenever there are losses or the overall outgoing link capacity is larger than the incoming. Then, the re-encoded symbols are forwarded with the received symbols to the child nodes. Note that the transmitted symbols can be erased before reaching the children peers, and we can write $I_{np} = (1 - \pi_{np}) O_{np}$, where I_{np} is the set of symbols finally arrive at node p that originally have been sent from node n.

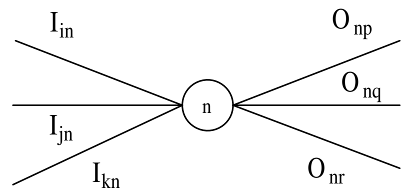


Fig. 2. Raptor network coding peer.

The selection of symbols to be combined in network peer is crucial for high performance, since some symbol combinations can mislead the decoding process (i.e., the matrix $\mathbf{A}^{'}$ stays full rank, but the solution differs from the original one). In order to avoid problems with the Gauss-Jordan elimination process at the receiver, we combine symbols that satisfy the following conditions : (a) they correspond to rows of the matrix $\mathbf{A}_i^{'}$ that are orthogonal to all rows of the original matrix $\mathbf{A}$ corresponding to erased symbols; (b) the rows $\mathbf{A}_i^{'}$ and $\mathbf{A}_j^{'}$ corresponding to combined symbols are orthogonal to each other. The first condition ensures that the new symbols are independent from the erased symbols. The second condition avoids the combination of non-orthogonal symbols, which could result in erroneous codewords. The Raptor re-encoding algorithm is applied as long as the previous conditions can be satisfied, otherwise we apply replication to fill in the available bandwidth on the outgoing links.

3. CHANNEL RATE ALLOCATION

3.1. Problem formulation

Let's examine multi-hop networks as in Fig. 1 where we consider streaming of a single video sequence. We define as H the number of hops of the longest path in the network. M_h and m_h are respectively the set of nodes and the index of a peer node at the h_{th} hop, where $h = 0, \ldots, H$ with M_0 and M_H be the sets of senders and clients. Similar to Section 2, $I_{m_h, m_{h+1}}$ is the number of packets arriving at m_{h+1} and originally sent from $\forall m_h \in M_h$, while $O_{m_h, m_{h+1}}$ is the number of the packets depart from m_h and their destination node is m_{h+1}.

The presented network coding system requires an optimization algorithm for determining the optimal code rate of the employed Raptor codes. However, due to network coding we can exploit at maximum the capacity all network links and the optimization is simplified to finding the optimal channel protection. The network statistics are gathered by each peer node and periodically are sent back to the servers, which performs the rate allocation.

The proposed centralized optimization algorithm is formulated as a *minmax* problem. Therefore, the algorithm seeks for the channel rate allocation which minimizes the maximal distortion among the clients. Thus, we have

$$\min_{\forall m_H \in M_H} \left\{ \max \left\{ (1 - p_R(l, K)) \cdot D_s + p_R(l, K) \cdot D_c \right\} \right\} \quad (1)$$

where D_s and D_c are respectively the source (video) distortion and the concealed distortion whenever Raptor decoding fails. Actually, D_s is function of the number of source packets K. $p_R(l,K)$ is the probability of Raptor decoding failure at the client m_H when $l = \sum_{m_{H-1} \in M_{H-1}} I_{m_{H-1},m_H}$ packets are received. It corresponds to the expected number of packets received by each client given the channel conditions. Thus, we are looking for the optimal value of K which minimizes eq. (1) subject to the following constraints:

$$\begin{array}{l} O_{m_h,m_{h+1}} \leq r_{m_h,m_{h+1}} \\ O_{m_h,m_{h+1}} \leq \sum\limits_{m_{h-1} \in M_{h-1}} I_{m_{h-1},m_h} \end{array} \quad (2)$$

where $r_{m_h,m_{h+1}}$ is the capacity of the link between m_h and m_{h+1}. The second constraint is imposed by the network coding and states that the number of packets sent over a link can not exceed the overall number received by the streaming node. This constraint allows the transmission of the network packets and the packets XOR-ed for the generation of these packets over different links.

3.2. Optimization based on rank decrement estimation

For determining the optimal Raptor code protection we propose an efficient method which is based on estimating the rank decrement[1] at each client. The rate decrement is caused by the successive network codings at peer nodes which leads in generation of some symbols multiple times and to reception of linear systems of equations not solvable. Since our scheme employs non-systematic 3GPP Raptor codes [8] we model them as in [9]. To take into account the expected rank decrement we modify the formula given in [9] for calculating the probability of unsuccessful Raptor decoding $p_R(l,K)$ considering the rate decrement δ. The modified probability $p_f(l,K)$ is

$$p_f(l,K) = \begin{cases} 1, & l < K \\ 0.85 \cdot 0.567^{l-K-\delta}, & l \geq K \end{cases} \quad (3)$$

The updated probability $p_f(l,K)$ replaces $p_R(l,K)$ into the optimization problem of eq. (1). For finding the optimal value of K we should first estimate the expected rank decrements δ which is equal to the expected number of network coded triples (i.e., network coded packets and two packets XOR-ed for the generation of this packet) received by each client.

In order to calculate δ we define the number of packets that depart from node m_h as

$$N_{O(m_h)} = \sum_{m_{h+1} \in M_{h+1}} O_{m_h,m_{h+1}}$$

the $N_{O(m_h)}$ is the summation of the number of packets sent over all the outgoing links of m_h. $N_{NC(m_h)}$ is the number of network coded packets generated at node m_h and is equal to the number of network coded packets that should be generated for filling the outgoing link capacity.

Since, in general, a client m_H is connected with its ancestor nodes m_h through multiple paths the expected number of packets $N_{EXP(m_h)}$ arrive at m_H from those sent by m_h are

$$N_{EXP(m_h)} = \sum_{\mathcal{L} \in \mathcal{N}_\mathcal{L}} N_{O(m_h)} \cdot \left\{ \prod_{i \in \mathcal{L}} \rho_{m_i,m_{i+1}} \cdot \left(1 - \pi_{m_i,m_{i+1}}\right) \right\}$$

[1]From the packets received each client forms an equation system which is solved by gauss-jordan elimination process

where $\mathcal{N}_\mathcal{L}$ is the number of paths connecting nodes m_h and m_H and $\rho_{m_h,m_{h+1}}$ denotes the percentage of packets sent over the link connecting nodes m_h and m_{h+1}. To estimate the rank decrement at client $m_H \in M_H$ we should consider that network coding is applied in every node. Thus, we have

$$r(m_H) = \sum_{\mathcal{L} \in \mathcal{N}_\mathcal{L}} \sum_{i \in \mathcal{L}} \sum_{m_i \in M_i} \left(\frac{N_{EXP(m_i)}}{N_{O(m_i)}} \right)^3 \cdot N_{NC(m_i)}$$

As δ is the expected rate decrement at the less reliable user, it is written as $\delta = \max\limits_{m_H \in M_H} r(m_H)$. After calculating the value of δ, a bisection search is applied for determining the optimal source rate K. The resulting optimization problem is convex, since D_s and $p_f(l,K)$ are also convex with K.

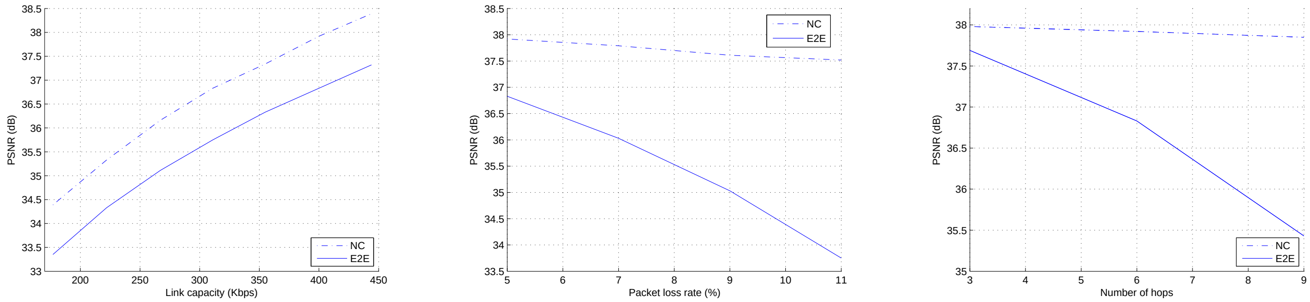
4. EXPERIMENTAL RESULTS

We analyze the performance of the proposed scheme for streaming of videos encoded by the multiple description variant of the JM 12.2 [10] described in [3] which divides the original video sequence in two sub-bitstreams one with odd frames and the other with even ones. The video encoder assigns one packet per NALU. We use packets of 512 bytes as proposed in $3GPP$ which are augmented with the RTP/UDP/IP header. We also append ESI information to each packet as a header of 2 bytes for passing at clients the Raptor encoding structure. The GOP size is set to 60 frames while the frame rate is equal to 30 *fps*. All results reported are averages of 150 simulations. The employed Raptor coder is the non-systematic version of $3GPP$ Raptor codes which is appropriate for small size codes and provides high symbol diversity. Losses are generated based on a Gilbert-Elliott model, which is a two-state Markov chain whose transition probabilities drive the packet loss ratio and the average error burst length.

For evaluating the performance of our scheme we consider transmission of "Foreman" CIF sequence. We compare the proposed Raptor network coding system employing the optimization algorithm of Section 3 with end-to-end Raptor coding scheme. The peer nodes at the end-to-end scheme just forward packets except last hop nodes which randomly replicate packets to fill the outgoing links and provide additional robustness on the last hop segments. We restrict replication policy at last hop nodes to keep the probability of multiple reception packet negligible. Replication in every node may lead to replication of some packets multiple times. The optimal source rate K is found by applying exhaustive search to the optimization problem of eq. (1) assuming that the servers are aware of the channel statistics, in the particular case where no network coding is performed in the peers.

We analyze the behavior of both schemes as function of the link capacity. The packet loss ratio is set to 5%, while the link capacity ranges from 170 kbps up to 450 kbps. The considered network is regular with six hops between the encoders and the decoders. Each hop has 3 intermediate nodes. The schemes are optimized for the above channel conditions. The results are presented in Fig. 3(a) from where we can see that the performance difference is roughly 1 dB which is attributed to the efficiency of the Raptor network coding scheme. We also note that the performance gap remains unaltered as the link rate capacity increases. This is due to fact that the schemes are not sensitive to bandwidth variations, but rather to the cumulative packet loss rate.

We also investigate the influence of the packet loss rate for the above 6-hop topology. We assume that the link loss rate is between



(a) (b) (c)

Fig. 3. PSNR comparisons for transmission of the "Foreman" CIF. The schemes compared is the proposed Raptor network coding (NC) and an end-to-end Raptor coding systems (E2E). Results for (a) regular network topology with six hops considering for various link capacities, (b) regular network topology with six hops considering for various loss rate and (c) for regular network topologies with various number of hops.

5% and 11% and the link capacity is 400 kbps. As earlier, we do not consider channel mismatch. From Fig. 3(b) it is obvious that for low loss rates the schemes have similar performance. However, when the channel conditions deteriorate the performance of the network coding schemes degrades smoothly while the end-to-end scheme collapses. For 11% packet loss ratio the difference is close to 3.5 dB. This impressive performance difference shows the resiliency of the network coding schemes for channels with heavy losses. For these conditions the replication policy can not assist the end-to-end scheme as the source rate is too low.

Finally, we compare both schemes for regular topologies of three nodes per hop with the number of hops between the encoder and the decoder. The link capacity is set to 400 kbps and the packet loss ratio to 5%. The results in Fig. 3(c) shows that for small topologies the end-to-end scheme performs close to the Raptor network coding. As the number of hops increases the advantages of the network coding become more apparent and the performance of the network coding scheme remains unaltered while the end-to-end scheme performs poorly. This is attributed to the high loss rate which reduces the source rate and to the network coding which results to set of packets with full rank, and thus almost always decodable.

5. CONCLUSIONS

A source and channel rate allocation algorithm has been proposed for collaborative streaming with Raptor network coding. The network coding system performs re-encoding in the network nodes, before transmission to the next hop towards the media client. The optimization algorithm is based on estimating the expected rank decrement of the sets of symbols received by each receiver. The algorithm finds the optimal source and channel rate allocation and clearly highlights the benefits of the network coding scheme. The experimental evaluation demonstrates that the rate allocation algorithm outperforms Raptor video streaming systems whose end-to-end performance are optimized in the absence of network coding.

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