Multilevel Diversity Coding via Rateless Codes for Reliable and Scalable Video Multicasting

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***Abstract*—The delivery of high quality video to multiple viewers accessing the content from various devices and networks with varying conditions is a challenging task. Transferring the same content (often with large volume) to multiple viewers drives unicast transmission inefficient. Furthermore, traditional multicasting is not an optimal solution for heterogeneous networks since it either overwhelms slow receivers or starves the fast ones. Hence, new delivery solutions with the goal of reducing the output rate of the source and tailored to heterogeneous networks is necessary. In this paper, we present a novel scheme for layered video multicasting to viewers with the flexibility to access the content from various devices (in a heterogeneous network) and loss/erasure prone networks. In this scheme, the source node uses Scalable Video Coding (SVC) to obtain scalability together with modern elastic Forward Error Correction (FEC) for loss protection. There exists a non-trivial advantage in using elastic FEC in conjunction with SVC which enables us to introduce a new architecture that brings considerable savings in required source output bandwidth. Our solution adapts to the specific needs of viewers, shows resilience against packet loss, e.g. less than 5dB drop in Peak Signal-to-Noise Ratio (PSNR) for up to 30% loss rate, and especially, can reduce the source output rate by half for typical 3-layer SVC.**

***Index Terms*—Rateless codes, scalable video, multilevel diversity, video multicast, heterogeneous networks.**

I. INTRODUCTION

THE convergence of multimedia delivery technologies to an all-IP infrastructure has enabled video providers to serve a broad range of video services to a variety of client devices ranging from high definition TVs to laptops and handheld devices. Delivering high quality video, tailored to each screen, can result in explosive bandwidth requirements.

In this paper, we propose a novel solution to address the challenges in video delivery to heterogeneous devices. We adopt SVC as a promising video coding that enables adaptation of the video quality to each device [1]. A traditional solution for video source coding is to prepare separate pre-encoded video streams according to the capability of each targeted device such as screen size, computational power, and available bandwidth. However, this approach results in relatively large storage requirements at the server as well as a significant bandwidth adaptation problem in the wireless network. Another more advanced solution is transcoding technology with downsampling. By transcoding, one high resolution and high bitrate video is adapted to targeted screen sizes and bitrates of clients. Transcoding solution is able to reduce storage requirements and adapt to bandwidth fluctuations. But, this technology has a computational complexity problem which makes it hard to apply in a real-time system. However, the SVC approach we are taking is very appropriate for supporting multiple clients since it can provide a one-source multi-use method using its multiple layered bitstreams [1], [2].

Further, our solution applies modern elastic FEC to SVC at the source in a new architecture involving multiple gateways. This new architecture for multi-rate and scalable multicast is inspired by a non-trivial advantage in using elastic FEC in conjunction with the scalable video stream that we aspire to in this paper. Recent research activities [3] have been mainly focused on the adaptation of network coding for multi-resolution multicast. However, multi-gateway association is a feature of our work that has not been investigated. Also, in many solutions each layer is associated with a multicast group and coding is performed within each layer, i.e., intra-session coding. But, there is much to be gained by extending the coding strategy across layers, i.e., inter-session coding. Our solution investigates this opportunity and we provide a practical solution that forms new multicast groups by combining coded packets from all layers which achieves the minimum output rate at the source.

Devices today are typically equipped with multiple wireless interfaces or are capable of associating with multiple gateways with a single interface [4]. The multi-gateway connection, FEC coding and SVC combined together offer numerous advantages that solves the issue of packet loss and especially, requires less bandwidth for the same quality in multicast. Utilizing the SVC in conjunction with rateless coding and multi-gateway association distinguishes our approach. In short, our objective for multicast video delivery is to introduce a solution that 1) adapts to the specific needs of heterogeneous viewers and is robust against varying network dynamics (e.g., packet loss), and 2) requires less bandwidth compared to conventional multicast.

II. BACKGROUND AND RELATED WORK

A. Scalable Video Coding (SVC)

Today many investigations address the distribution of high-quality video over an error-prone network. Video coding techniques include algorithms for efficient transmission and methods resilient to errors that may occur during transmission such as resync markers, reversible variable length codes (RVLC), arbitrary slice order (ASO), flexible macro block ordering (FMO), and redundant slice. Among them, the H.264/SVC is in particular of importance because it envisions methods for controlling video characteristics such as resolution, quality, and frame rate according to the network condition. For this purpose, SVC uses a layered coding approach to provide

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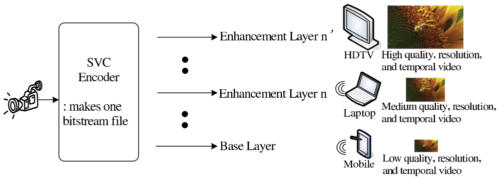


Fig. 1. The layered structure of SVC technology.

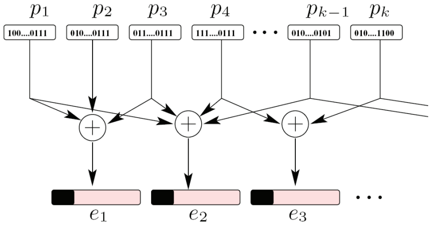


Fig. 2. Rateless encoding process.

combined spatial, temporal, and quality scalabilities, as shown in Fig. 1. Due to the layered feature, SVC coding offers several advantages. First, it enables service providers to reduce total BW, storage, and computational complexity for transcoding by supporting many clients with a single video content file. Second, it lends itself well to FEC and unequal error protection methods [5]. Third, its layer switching method enables adapting to variable bandwidth by extracting and playing appropriate layers from several spatial/temporal/quality layers of SVC bitstream according to the bandwidth [2].

B. Rateless Coding

These codes, unlike conventional algebraic codes do not possess any fixed rate. From a finite set of data packets, the encoder can generate an infinite stream of encoded packets. In [6], it was shown that for k data packets, on the average, the destination requires $k\Gamma_k$ encoded packets, where $\Gamma_k = 1 + O(k^{-1/2} \log \frac{k}{\delta})$ is the overhead, to decode all the k data packets with a probability of $1 - \delta$. Moreover, the encoding and decoding processes introduce very low computational complexity and are performed in the following manner. A parameter that is key in the design of rateless codes is the degree distribution polynomial $\Omega(x) = \sum_{1 \le x \le k} \Omega(i) x_i$ where $\Omega(i) \in [0, 1]$ for $i = 1, \ldots, k$. This degree distribution induces a probability distribution on the set of data packets $\{p_1, \ldots, p_k\}$ in the following manner. For any subset V of packets, $P_\Omega(V) = \Omega(|V|)/\binom{k}{|V|}$. To generate a packet, the encoder generates an instance of a random variable Z that selects each subset V of packets with the aforementioned probability. Such a selection can be effected by equivalently selecting the weight $|V|$ of the selection using the distribution Ω and then selecting $|V|$ packets uniformly at random from set of d data packets. To generate the encoded packet, the encoder does a packet-level XOR of the selected packets and appends each packet with the IDs of all the packets XORed to generate the encoded packet. Fig. 2 illustrates the encoding process.

To decode the data packets from the received packets e_i, the decoder employs iterative message passing algorithm. To decode k data packets, at least k encoded packets must be collected at the receiver. However, in practical coding schemes with small k (of the order of 10^3), more than k packets are needed for successful decoding with high probability.

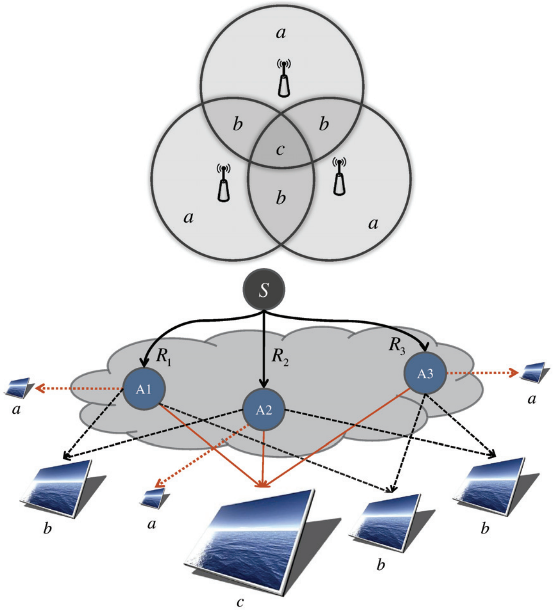


Fig. 3. Multi-gateway Association: clients in different coverage regions can connect to a number of gateways (top). Association of each client to more gateways result in higher quality (bottom).

III. MULTI-GATEWAY OPTIMIZATION

Unlike the short-lived connections for delivery of web pages, for large media content a long-duration connection is required. Maintaining a connection to a single gateway can be challenging, as changing network conditions or a failure can result in a poor viewer experience. A natural solution to this problem is to enable devices to associate with multiple gateways. Multi-gateway association can also offer other benefits such as reducing the load on the backbone network. This load reduction is an important feature, especially for multimedia applications.

In this section, we explore multi-gateway association and take a theoretical approach to study the efficient use of multi-gateway multicast for transmission of the scalable video. We formulate our problem as an optimization problem with the objective of minimizing the total bandwidth of the video delivery. We first introduce an abstract model and describe the optimal solution for multi-gateway multicast of scalable content and demonstrate that traditional multicast, which requires all the gateways in the network fully deliver all the layers of a SVC content, is not optimal. Our model captures all the essential elements we need to construct the optimal solution. We then describe the rateless-based optimal coding scheme.

The main idea is that having access to more gateways should result in receiving more layers and hence higher video quality. The layers are incrementally combined at each client to provide progressive refinement for the heterogeneous clients. Therefore, for every client the quality of video is correlated with the number of gateways it can connect to. For example, consider a network with three gateways illustrated for three nodes $A1, A2, A3$, as shown in Fig. 3. We can distinguish three different regions with regard to the number of gateways a client can connect to. In the following, we state the multi-gateway association problem and show its connection to multilevel diversity coding [7], [8] in Information Theory literature.

A. Problem Statement

Consider a source node S which provides scalable video with L layers $l_1, \ldots, l_L$. The source streams the layered video to the gateways. Each client can connect to a number of gateways. We optimize for the total output rate of the S such that connection to any N_α number of gateways (out of N) should enable the client to successfully receive layers $\{l_1, \ldots, l_\alpha\}$. We always assume $\alpha \le L$ and $L \le N$.

Denote the N gateways by $A_1, \ldots, A_N$, and consider all the possible client varieties in terms of gateway connections. Without loss of generality, from this point on, we assume $N_\alpha = \alpha$ and $L \le N$. As an example, for the special case of $N = 3$, every client connecting to one gateway recovers l_1, every client connecting to any two gateways recovers l_1 and l_2 and every client with access to all three recovers l_1, l_2, l_3. We further assume that packets from different layers are not combined with each other at any gateways. Our problem setup in this paper is related to Multilevel Diversity Coding introduced in [7], [8]. Roche et al. in [8], prove that for our problem setup the optimal solution minimizing the total output rate of the source does not require coding packets from different layers together. However, each gateway should receive packets from all layers from S. Hence, we should focus on finding the optimal rate of each layer sent by S to different gateways.

With slight abuse of the notation, let l_i also stand for the rate of i-th video layer. Now, consider the n-th gateway and let $r_n^1, r_n^2, \ldots, r_n^L$ be the rate of the layers 1 through L provided by S to the n-th gateway, correspondingly. Define

$$R_n = \sum_{\alpha=1}^{L} r_n^\alpha,$$

as the total rate sent to n-th gateway.

Let $[N]$ be the set of integers $\{1, 2, \ldots, N\}$ and $\mathbf{A}_{[N]}$ be the set of all gateways. Further, let

$$r^\alpha_{\mathbf{A} \subseteq \mathbf{A}_{[N]}} = \{r_n^\alpha : A_n \in \mathbf{A}\}.$$

To successfully recover a layer α, the sum of the rates $r^\alpha \ge 0$ received by a client from all the gateways should be l_α. Therefore, constraints on successful recovery of layers result in the following optimization problem:

$$\begin{array}{ll} \text{minimize} & \sum_{n=1}^{N} R_n \\ \text{subject to} & \sum_{\substack{\mathbf{A} \subseteq \mathbf{A}_{[N]} \\ |\mathbf{A}|=\alpha}} r^\alpha_{\mathbf{A}} = l_\alpha. \end{array} \tag{1}$$

The solution of the optimization problem (1) has an interesting structure which we discuss below.

Proposition 1 *The solution of the optimization problem* (1) *is*

$$r_n^\alpha = \frac{l_\alpha}{\alpha} \quad \alpha \in [L], n \in [N]. \tag{2}$$

Proof: The optimization problem (1) is an LP problem in canonical form [9]. The set of constraints in (1), considering the symmetry in the structure of the problem (Fig. 3), can equivalently be written as

$$\begin{array}{lcll} r_n^1 & = & l_1 & \forall n \\ r_n^2 + r_{n'}^2 & = & l_2 & n < n' \\ r_n^3 + r_{n'}^3 + r_{n''}^3 & = & l_3 & n < n' < n'' \\ \vdots & & & \end{array} . \tag{3}$$

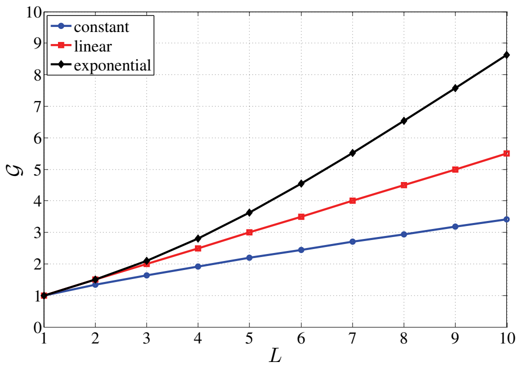


Fig. 4. Relative gain of the proposed solution to traditional multicast for different SVC layer size growths.

Thus, the dual problem of (1) with variables $p_1, \ldots, p_L$, is

$$\begin{array}{ll} \text{maximize} & \sum_{\alpha=1}^{L} \binom{N}{\alpha} l_\alpha p_\alpha \\ \text{subject to} & \binom{N-1}{\alpha-1} p_\alpha \le 1 \quad \alpha \in [L]. \end{array}$$

Using the combinatorial identity $\binom{N}{i} = \frac{N}{i}\binom{N-1}{i-1}$, and the duality theorem in [9], we have

$$\sum_{\alpha=1}^{L} \binom{N}{\alpha} l_\alpha p_\alpha \le \sum_{\alpha=1}^{L} \frac{N}{\alpha} l_\alpha \le \sum_{n=1}^{N} R_n. \tag{4}$$

Now, by replacing (2) in (4), we would arrive at

$$\sum_{n=1}^{N} R_n = \sum_{\alpha=1}^{L} \sum_{n=1}^{N} r_n^\alpha = \sum_{\alpha=1}^{L} \frac{N}{\alpha} l_\alpha.$$

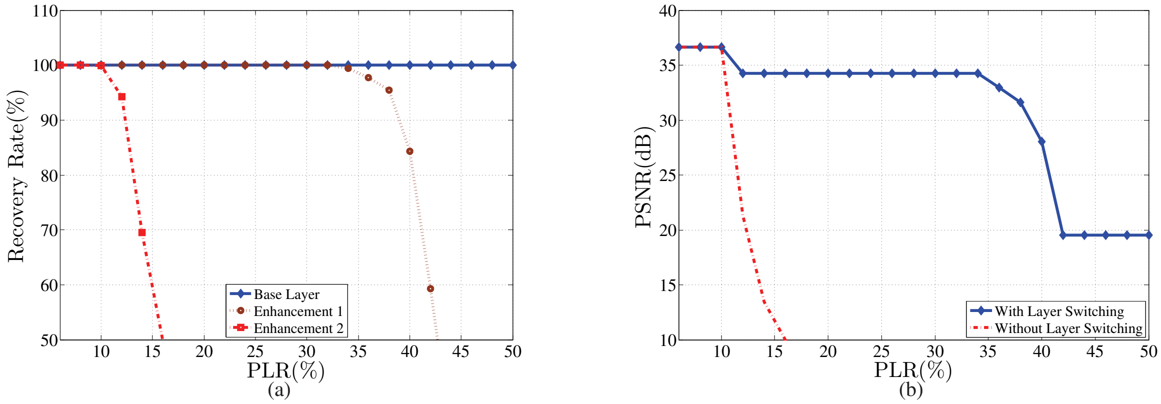
Therefore, we conclude that (2) is an optimal solution of (1). ■

There is an interesting connection between (2) and recent results in distributed storage. In [10], it is shown that given enough budget for storing a file in a distributed network, spreading of the budget similar to (2) maximizes the recovery probability for a collector with random access to a set of storage nodes.

B. Achieving the Optimal Solution with Rateless Coding

In short, the result of Proposition 1 indicates that the source should provide every gateway the whole of layer 1, and $1/i$ of the layer i. While the case of layer l_1 is clear, achieving the optimal solution for $l_i, i > 1$ is not so obvious since the simple splitting of the layers is not sufficient. For example, for the case of $N = L = 3$ shown in Fig. 3, if we simply split l_2 into two parts (e.g., separating even and odd packets) and send each half to a gateway, there is always a starved client.

As discussed earlier, rateless coding provides the flexibility to encode every block of k packets into an infinite number of packets such that every subset of size k of those packets are independent. This property proves to be useful in achieving the optimal solution. We break the SVC bitstream into blocks of size k such that each block contain corresponding packets from all layers with hierarchical dependencies. Let κ_i be the number of packets corresponding to layer l_i in a block of size k. According to the optimal solution in (2), the source node generates $\frac{N\kappa_i}{i}$ encoding packets out of κ_i packets. Each gateway then provides $\frac{\kappa_i}{i}$ packets to viewers. By encoding the layers separately, the hierarchical and temporal dependencies of the packets remain intact which is crucial for playing SVC.



(a)

(b)

Fig. 5. Performance evaluation: (a) performance of the rateless code with optimal layer rates as in (2) vs. PLR, for a three layer SVC; (b) PSNR vs. PLR for layer switching enabled and layer switching disabled cases.

Comparison of the Optimal Solution with Simple Multicast: It is of interest to compare the benefits of the proposed solution in terms of bandwidth with simple multicast solution. We define a gain parameter $\mathcal{G}$ which is the relative gain of the proposed solution to the case where we have to send all layers of the SVC video stream to all gateways. From (2), we have

$$\mathcal{G} = \frac{N\sum_{i=1}^{L} l_i}{\sum_{n=1}^{N} R_n} = \frac{\sum_{i=1}^{L} l_i}{\sum_{i=1}^{L} \frac{l_i}{i}}. \tag{5}$$

Fig. 4 depicts the gain $\mathcal{G}$ for various layer growths. The relative size of layers in SVC can vary according to the technology used. We considered constant size ($l_i = l \quad \forall i$), linear growth ($l_i = il$), and exponential growth ($l_i = 2^i l$).

IV. PERFORMANCE EVALUATION

Here, we describe the performance evaluation of the proposed multicast architecture that consists of SVC and multi-gateway association solution combined with rateless coding. The rateless codes that are used are inspired from the Raptor code design [11], i.e., we used a fixed rate erasure code as outer-code. The encoded packets of the outer-code are then input to an inner-code as described in Sec. II-B. The total coding overhead introduced is 12%.

To mimic the source operation in Fig. 3, we first packetize the SVC layers and consider blocks of 8000 packets within each layer. The rateless code is applied on each block and a large number of encoding packets is produced. Then, source creates three separate streams with rates R_1, R_2, and R_3 using the encoded packets of all layers according to the rates obtained in (2).

The performance of the rateless code is depicted in Fig. 5(a). PLR ranges from 6% to 50% and the performance of the rateless code is averaged over 10 runs of the simulation. The rateless code shows resilience against packet loss and viewers, in region c, with less than 10% loss can recover all three layers and viewers with less than 35% loss can always recover the first two layers successfully. Viewers with more than 35% loss are still able to recover the base layer which demonstrates a natural unequal error protection in the design. Our simulation results show that viewers in region b can recover the first two layers and viewers in region a can recover the base layer for PLR less than 10%.

The other quantity of interest is PSNR against PLR. The PSNR is measured from the output of the rateless decoder using a SVC decoder and playback module. Our implementation provides a single player for all viewers independent of their channel quality. Hence, we have to actively detect the optimal setting for playback. As such, we have implemented a layer switching module that can actively tune the number of layers used for SVC decoding and playback upon reaching a loss rate intolerable by our SVC player. The PSNR of the output of the player is depicted in Fig. 5(b). The layer switching technique shows its importance as when we disable layer switching the output PSNR degrades drastically because if we do not change SVC layers, the decoder may suffer severe quality degradation.

Our layer switching module switches from three layers to two layers when the loss rate exceeds 14% and switches from 2 layers to 1 layer when the loss rate exceeds 40%. As shown in Fig. 5, if layer switching is not employed, the playback quality suffers greatly from packet loss.

Discussion on Complexity: The complexity of the proposed scheme is comparable to [2] as we use similar SVC and FEC schemes. The complexity of generating rateless encoded packets and the decoding complexity are both linear in k.

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