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An unequal error protection scheme for reliable peer-to-peer scalable video streaming ☆

Chi-Wen Lo [a], Chao Zhou [b], Chia-Wen Lin [c,*], Yung-Chang Chen [c]

[a] Information and Communications Research Laboratories, Industrial Technology Research Institute, Hsinchu, Taiwan
[b] Institute of Computer Science and Technology, Peking University, Beijing, China
[c] Department of Electrical Engineering, National Tsing Hua University, Hsinchu, Taiwan

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ABSTRACT

This paper proposes an unequal error protection (UEP) scheme for transporting scalable video packets over packet-lossy peer-to-peer networks. In our scheme, given an estimated system uplink capacity, a receiver-driven joint source-channel coding (JSCC) mechanism is proposed by which each child-peer minimizes the received visual distortion by subscribing to appropriate numbers of source and channel coding packets. Because the bandwidth for inter-peer transmissions may fluctuate largely due to peer dynamics, in our method, a peer estimates the available system uplink capacity based on consensus propagation to avoid the fluctuating allocations of JSCC. To efficiently utilize the uplink bandwidth of peers, parent-peers utilize sender-driven contribution-guided peer selection to reject the low-contribution subscriptions requested from candidate child-peers. Simulation results demonstrate that our method significantly improves the visual quality, compared to other state-of-the-art schemes.

1. Introduction

Peer-to-peer (P2P) video streaming is an emerging streaming service, which can support large-scale services with a lower infrastructure cost compared to traditional client–server structures. The key of a successful video streaming system lies in the video quality perceived by users. However, one of the major challenges to P2P video streaming services is packet loss. Since current IP-based networks only support best-effort delivery, video packets are not well protected. Moreover, the packet loss problem becomes more serious in P2P video streaming systems because peer dynamics lead to more packet loss opportunities for peers, and the packet loss of a peer will propagate to its neighboring peers through inter-peer transmissions. Such packet loss can seriously damage the quality of reconstructed video.

There are two kinds of methods to overcome the packet loss problem: retransmission-based and FEC-based schemes. In retransmission-based schemes [1,2], a receiver sends a message to a sender to request a lost packet from the sender, and the sender resends the lost packet if the available bandwidth allows. Retransmission-based schemes are particularly useful for non-interactive unicast applications with bursty packet loss. However, since the retransmission-based schemes introduce additional round-trip time latency, they are not suitable for delay-sensitive video transmissions.

Packet-level FEC has proven to be an efficient means for packet loss recovery in P2P video streaming systems [3–7]. In a packet-level FEC based protection scheme, the channel encoder, such as Reed-Solomon code, encodes the video bitstreams into k data packets and additional n–k redundant packets, denoted as FEC(n,k). On one hand, a receiver can completely recover the original data should at least any k out of n packets be received. On the other hand, FEC(n,k) scheme can only tolerate loss of n–k packets at most. XOR-based error correction method was also considered in [8].

In delay stringent streaming environments, FEC based schemes outperform retransmission-based schemes [9]. However, FEC-based video protection schemes would consume additional bandwidth resource to transmit the redundant packets. If the available bandwidth of a P2P system cannot afford the additional amount of redundant packets, packets may get dropped due to traffic congestion. Hence, efficient bandwidth resource utilization for packet-level FEC is desirable.

In P2P video streaming, system channel capacity may vary largely since heterogeneous peers usually have various channel bandwidths. A key technique for achieving bit-rate adaptation is

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* Corresponding author at: Department of Electrical Engineering, National Tsing Hua University, Hsinchu 30013, Taiwan.

E-mail addresses: kenlo0425@gmail.com (C.-W. Lo), zhouchaoyf@gmail.com (C. Zhou), cwlin@ee.nthu.edu.tw (C.-W. Lin), ycchen@ee.nthu.edu.tw (Y.-C. Chen).

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scalable video coding (SVC) [10,11] or layered coding. In SVC, the encoder encodes a video into a scalable bitstream which generally contains one base layer (BL) and one or more enhancement layers (ELs). According to the requirements of channel bandwidths of users, a sender can transmit one base layer for basic visual quality or one base layer plus one/more enhancement layers for higher visual quality. SVC is thus a flexible solution to transmitting scalable video contents over heterogeneous networks. With SVC, peers can adapt video quality according to their channel capacity.

Layered coding-based P2P video streaming has been studied recently [12–15]. In the method proposed in [12], child-peers select their parent-peers to maximize its priority sum measured by the importance of layers. In the LayerP2P scheme [13], child-peers categorize their subscriptions into two types: regular subscriptions and probing subscriptions. Child-peers request regular subscriptions, including the substreams of lower layers. The substreams in the regular subscriptions are not prioritized among different layers, whereas those in the probing subscriptions are requested layer by layer. In [14], taxation-based P2P layered streaming designs, including layer subscription strategy, chunk scheduling policy, and mesh topology adaptation, were proposed to adjust the balance between the social welfare and individual peer welfare. Peers can dynamically adjust their subscriptions of layers based on a TCP-style additive-increase-additive-decrease scheme. In [15], layered video data scheduling schemes were proposed to achieve a high delivery ratio of layered video, where the scheduling of requested video blocks was based on the importance factors of video blocks.

To efficiently utilize available bandwidth resource, FEC can protect the layered streams with unequal error protection (UEP). The performance of UEP scheme in FEC-based video streaming can be further improved by using joint source-channel coding (JSCC) [16–21], by which the constrained resource (e.g., uplink bandwidth, transmitted bits) can be optimally allocated between *source coding* (i.e., layered video encoded by SVC) and *channel coding* (i.e., the FEC redundant packets) to minimize the visual distortion at the receiver side. However, JSCC for P2P streaming has not yet been well addressed. Several technical challenges still remain:

1. Packet loss estimation for a P2P network is much more complex than that for traditional client–server structures, since video packets are sourced from multiple peers rather than a single server. Moreover, peers will usually unexpectedly join and leave a system, and such peer churns can cause serious packet loss. Hence, an accurate packet loss model for P2P networks is desirable so that appropriate error protection can be taken to mitigate packet loss.
2. When a parent-peer leaves from or joins in a P2P network, the accessible bandwidths for its child-peers would decrease or increase. Since such peer dynamics make the accessible bandwidth of child-peers from their parent-peers unstable, the allocation results of JSCC schemes would also fluctuate. Instead, peers can estimate the uplink capacity of their parent-peers based on the average capacity of their neighboring peers to avoid short-term fluctuations. However, since the uplink bandwidth of peers is highly heterogeneous in a real-world P2P network, peers may not be able to correctly estimate their parent-peers' average uplink capacity from the statistics of their neighboring peers. The inaccurate bandwidth estimation would lead to incorrect bandwidth allocation between source-coding packets and channel-coding packets.
3. Parent-peers allocate their uplink bandwidth to transmit source-coding packets and channel-coding packets subscribed by child-peers. However, due to the limited uplink capacities of parent-peers, the uplink bandwidth has to be optimally allocated to maximize streaming performance, which is usually difficult considering the irregular inter-peer transmissions in a P2P system.

To address the first problem, a few models for packet loss estimation in P2P networks were proposed [4,5]. In [4], an analytic model was proposed to estimate the packet loss probability of a candidate child-peer in a tree-based P2P network. In a tree-based P2P network, each peer is located in a specific depth in the tree. Therefore, the parent peers of each peer have the same packet loss accumulation if the channel drop rates between peers are homogeneous. In contrast, in a mesh-based P2P network, the peers are randomly located in an irregular mesh structure. As a result, the packet loss accumulation from the multiple parent peers is so heterogeneous that the tree-based packet loss model in [4] cannot correctly characterize the packet loss and propagation behavior. Since many popular P2P streaming systems, such as CoolStreaming [22], PPStreaming [23], and PPLive [24] are based on mesh structures, an accurate mesh-based packet loss model is desirable. In [5], we proposed a model which takes into account the channel packet drop rate, peer dynamics, and FEC protection to characterize the heterogeneous packet loss behavior of individual video substreams transmitted over the irregular transmission paths in a mesh network.

To estimate the available system capacity of a P2P network, peers can exchange bandwidth information with their neighbors through "consensus algorithms" [25], which reach an agreement of a certain quantity depending on the state of all peers. Consensus propagation [26] was proposed for distributed averaging through simple iterative computation at each node and message exchange among peers. It has found applications in constructing a minimal energy topology in wireless sensor networks [27], where the energy cost of transmission nodes is averaged among nodes. Besides, with consensus propagation, the user rating (e.g., on movies, restaurants) can be shared to P2P social networks [28], where no centralized server collects these rating messages. We shall show in Section 3 that consensus propagation can be used to accurately estimate the average uplink capacity of a P2P network.

To address the issue of parent-peers' uplink bandwidth allocations, a few sender-driven peer selection methods have been proposed in [5,13,29–31]. In sender-driven peer selection, each parent-peer proactively allocates its uplink resource to deliver video data to a selected set of child-peers, that have requested data from the parent-peer, to maximize the overall system performance in throughput, delay, etc. In LayerP2P [13], parent-peers give higher priority in peer selection to those child-peers who have also sent video chunks to the parent-peers in recent historic records. In CoDiO [29], parent-peers schedule the delivery of packets to their child-peers according to the packets' impacts on visual distortion. In addition, those child-peers who have contributed more uplink bandwidth to distribute packets to more succeeding descendants would have higher priorities in packet scheduling and resource allocation for requesting packets from their parent-peers. In the method proposed in [30], parent-peers maximize their available throughput by executing a child-peer selection process. The uplink bandwidth resources are optimally allocated to child-peers based on the available bandwidth of uplink/downlink links and the playback deadline of parent/child-peers. In the rank-based peer selection scheme proposed in [31], a centralized server collects the uplink bandwidth contribution of each peer and gives a rank to each peer according to the peer's bandwidth contribution. Based on the ranking, a parent would serve its child-peers whose ranks are higher than the rank of the parent-peer itself. Therefore the video qualities for high-ranking peers can be guaranteed. In our previous work in [5], a packet loss model is proposed to characterize the packet gains of recovering a lost pack to a peer's