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Frame-based forward error correction using content-dependent coding for video streaming applications

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ABSTRACT

Forward error correction (FEC) is a common error control technique to improve the quality of video streaming over unreliable channels by recovering packet losses during transmission. The traditional frame-level FEC adopts the independent FEC coding method, regarding each video frame as one coding block, and protects each block with its respective FEC data according to the principle of unequal error protection (UEP). In contrast, emerging content-dependent FEC coding schemes explore the performance improvement provided by the expandable block structure. For the frame-level FEC with an expandable block structure, a high-priority frame is involved in the FEC processing of its following frame, and thus the frames with a dependency relation in the video coding stage are also correlated in the FEC coding stage. In this paper, an analytical content-dependent FEC model is developed to estimate video streaming quality in terms of playable frame rate. Based on this model, optimized FEC configuration can be found given the inputs of the video and transmission channel parameters. A comprehensive performance study is conducted for the proposed model to observe the redundancy assignment behavior, the reconstructed video quality and the FEC coding complexity, under the various network situations. The performance results show that the expanding-block FEC can be superior in balancing the trade-off between FEC complexity and loss recovery capacity.

1. Introduction

In transmitting video streams over lossy networks, forward error correction (FEC) utilizes additional redundant data to recover the lost video data and can improve the quality of video streaming without retransmission delay. The general FEC schemes have two major features, namely independent FEC coding and unequal error protection (UEP). Based on the video coding structure, each video data item is encoded individually by an FEC encoder to generate the required redundancies and is then transmitted along with its redundancies. Therefore, for frame-level FEC, one video frame and the corresponding FEC redundancies construct an FEC coding block. The receiving end can collect block data packets for the FEC decoder to reconstruct the video frame in the presence of packet loss. Since FEC coding between blocks is independent, each video frame can be protected from packet loss only by its own FEC redundant data. In contrast, UEP considers the hierarchical video coding structure to achieve graceful quality degradation as the network capacity cannot provide enough FEC bandwidth budget to combat the given packet loss rate (PLR). In UEP, video frames are classified according to their video coding dependency, and the differentiated FEC protection level (i.e., amount of redundant data) can be assigned among frames to ensure reliable video coding and presentation. The related work in [1] combine independent FEC coding and UEP to establish a frame-level FEC model as a set of video coding, FEC coding, and network transmission parameters. Based on this FEC model, the UEP rate allocation decision for video frames can be determined to obtain the optimal reconstruction quality of video streaming under network capacity constraints.

Although the independent FEC coding scheme is easily implemented, the resultant FEC efficiency has its limitations owing to the following facts: (1) FEC recovery is unaware of video coding dependency even under the redundancy management of UEP; and (2) since a video stream is fragmented into independent FEC blocks, small blocks can be unfavorable in maximizing the FEC efficiency. In UEP, a high-priority FEC block either receives more redundancies or allocates its required redundancies earlier, than the low-priority blocks, which usually depend on high-priority blocks in the video coding stage [16,17]. In the case of the failed

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reconstruction of high-priority blocks, low-priority blocks can still be successfully recovered even though they cannot be correctly decoded by the video decoder and generally are regarded as lost data. In this case, the FEC redundancies allocated to failed blocks cause a resource waste and the FEC performance is degraded accordingly. Additionally, using small blocks in the FEC coding stage leads to a potential FEC performance degradation. When the low delay requirement is considered, a video frame is typically adopted as the maximum FEC coding unit to satisfy the real-time transmission for FEC-based video streaming. Due to the different spatial and temporal activities, inter-coded video frames, which are the majority in the video stream, generally have smaller sizes than the intra-coded frames. Given the same ratio of redundant data to video data within an FEC block, a small-block FEC achieves lower loss recovery performance than a long-block FEC [2–4]. Consequently, distributing the available FEC redundancies among many small blocks can be an inefficient strategy in redundancy allocation.

In tackling the performance degradation problem described above, the major question that arises is: is it possible to design an FEC scheme with content-dependent FEC coding? In contrast to independent FEC coding, content-dependent FEC coding needs to build the FEC coding dependency among the FEC blocks in accordance with application content. Reviewing the literature, typical approaches to achieving content-dependent FEC coding for video streaming applications focus on studying the windowing technique with an expandable FEC block structure [5–8], where each block is covered in the next block and source data can be shared by multiple blocks. Since the succeeding block becomes larger, the high-priority data can be protected in several blocks and receive a better recovery performance due to the long-block construction. Accordingly, the expandable FEC blocks can provide the two following advantages: (1) the FEC coding dependency is coupled with a hierarchical video coding mechanism, and (2) the source block length can be virtually increased to obtain the higher error correction capacity. Based on the advantages of the expandable block structure, the content-dependent FEC schemes construct FEC blocks across video quality layers for scalable video, whereas for non-scalable video (i.e., single-layer video), FEC blocks can be formed across video frames. While the optimized UEP mechanism is common in the related works of layer-based FEC to dynamically adjust the FEC parameters [5,6], the existing frame-based FEC utilizes either equal error protection (EEP) in [7] or static UEP parameters in [8], to exploit the performance improvement provided by content-dependent FEC coding. Most importantly, all these frame-based approaches targeting non-scalable video are proposed without a general model, which can be used to analyze and optimize the performance of content-dependent FEC coding. In this paper, we derive an analytical content-dependent FEC model at the video frame level to estimate the video streaming quality given the available video transmission parameters, including frame size, group of picture (GOP) length, PLR, and data transmission rate. For video quality measurement, a distortion-based approach generally requires high computational cost to compare the quality difference induced by transmission errors for each frame [9,18,19]. Whereas the expandable block structure can further complicate the calculation of FEC allocation results, the playable frame rate (PFR), which expresses the expected amount of video frames reconstructed at the receiving end, is adopted as a practical tool to estimate the reconstructed video quality in our proposed model. The PFR-based model was first presented in [10], and was then extensively used in analyzing and evaluating the FEC performance for streaming video with independent FEC coding [1,11,12]. This paper aims to integrate the content-dependent FEC coding within the PFR-based model. Based on the content-dependent FEC model, we can explore the optimal FEC allocation configuration to yield the best quality under the transmission rate constraint.

The rest of the paper is organized as follows. Section 2 describes related works on content-dependent FEC. Section 3 reviews the general FEC scheme with independent FEC coding and expanding-block FEC used as the content-dependent FEC scheme in this paper. Section 4 presents our content-dependent FEC model on a frame basis, and further provides a simplified model to reduce the optimization overhead. The performance results are discussed in Section 5. Finally, Section 6 provides some brief concluding remarks.

2. Related works

In [13], expanding window fountain (EWF) code is presented to achieve UEP properties by means of using an expandable windowing technique to select the encoding data according to a probability distribution. In the EWF code, FEC blocks with different lengths are referred to as windows. Then the same authors apply EWF codes to real-time scalable video multicast applications and then distortion-based analysis is conducted to determine the optimal system parameters [5]. Based on the same concept, layer-aware FEC (LA-FEC) is proposed to undertake FEC coding across dependent video layers [6]. In contrast to [5], this approach preserves layered video processing in constructing FEC blocks to ease the backwards compatibility of the existing system. When calculating the required UEP parameters, the LA-FEC approach currently utilizes a two-layer model to derive the successful decoding probability for each base and enhancement layer. On the other hand, Bouabdallah and Lacan applied the expandable FEC block structure to video frames for non-scalable video [8]. The limited FEC redundancies are unequally distributed among blocks according to the user-specified decisions. In [7], Xiao et al. proposes the expanding Reed–Solomon (RS) code with randomized packet reordering for non-scalable video. In order to achieve real-time transmission, the expanding RS code evenly assigns the available redundancies to all blocks. Since this EEP behavior can be inefficient in the presence of a high PLR, the expanding RS code further randomly reorders the source packets before FEC encoding to distribute the burst losses among different blocks. An extreme case of content-dependent FEC coding is the GOP-level FEC [14]. The GOP-level FEC covers the entire GOP with all available FEC redundancies to form one big block and strong protection against data losses can be obtained accordingly. As the amount of data losses exceeds the error correction capacity, the video quality could fluctuate due to the non-UEP behavior in the GOP-level FEC.

Additionally, several works have proposed partially achieving content-dependent FEC coding. In [15], Bagino et al. utilized a sliding window approach, where fixed size windows are overlapped in chronological order of the data, to benefit the FEC recovery performance by extended blocks. Based on the overlapped windows, the succeeding block only covers a portion of data included in the previous one. The same concept is adopted in [7] to mitigate the FEC coding complexity of large blocks. In contrast to block overlapping, Xiao et al. introduced a dynamic sub-GOP FEC (DSGF) approach to partition video frames into multiple independent blocks with different lengths [9]. Since any portion of data is protected by only one block, failed FEC recovery in the block can lead to video quality oscillations.

In conclusion, the related works about partial content-dependent FEC, such as sliding-window FEC [7,15] and sub-GOP FEC [9], can be regarded as the lightweight version of a general content-dependent FEC. For the content-dependent FEC schemes, the related work of video-layer-based FEC [6] and the works applying EWF codes [5,13] introduce the dynamic UEP mechanism within their FEC algorithms. In the scenario that RS codes are applied to the non-scalable video, the existing works utilize either EEP [7] or static UEP mechanism [8] to obtain the preliminary results of content-dependent FEC. In contrast to those preliminary