Enhancing Packet-level Forward Error Correction for Streaming Video in Wireless Networks

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Abstract

Forward error correction (FEC) is a common error control technique in which the streaming video is protected by adding redundant data to the encoded bitstream such that the original source information can still be recovered in the event of errors or losses. Based on the information on the video content and channel status, an optimal packet-level FEC model can be built to obtain the best video delivery quality of streaming video under the transmission rate constraints. However, the wireless channel properties such as burst errors and limited bandwidth impair the FEC efficiency since the FEC schemes typically adopts large packets to achieve a high data throughput. Accordingly, this study integrates a packet size control (PSC) mechanism with the optimal packet-level FEC in order to enhance the efficiency of FEC over wireless networks. In the proposed approach, both the degree of FEC redundancy and the transport packet size are adjusted simultaneously in accordance with a minimum bandwidth consumption strategy. The experimental results show that compared to the existing optimal packet-level FEC schemes in which the packet size is fixed, the proposed FEC-PSC scheme achieves a higher FEC efficiency (i.e. a better video quality with a lower bandwidth overhead).

Keywords: *forward error correction, packet size control, video transmission, wireless network.*

1. Introduction

Video streaming applications are generally sensitive to loss, and thus when streaming video over best-effort networks, some form of error control scheme is required to improve the perceptual quality of the video at the receiving end [1, 2]. Forward error correction (FEC) is a well-known error control scheme in which the data throughput at the receiving end is increased by recovering errors/losses by means of redundant data items encoded into the transmitted blocks. The source data items can therefore be successfully reconstructed provided that a sufficient number of total sending data items are captured at the receiving end.

In general, the efficiency of the FEC recovery process depends on the level at which redundancy is introduced into the encoded video stream, i.e. at the byte-level or the packet-level. In the byte-level FEC scheme, the transport data are divided into multiple data blocks, and the corresponding FEC-encoded blocks are packetized with the data blocks to form a single transport packet. Since the FEC recovery is performed on a packet-by-packet basis, the byte-level FEC is generally adopted in the data-link layer to improve the transport robustness over wireless channels [3-5]. When the byte-level FEC is considered in video transmissions, a cross-layer architecture is necessary for video applications to communicate with lower link layer. Shan in [6] packs the radio link protocol (RLP) blocks into an application packet, and the FEC blocks required to protect RLP blocks are then attached to the tail of the application packet. Given the different user-specified loss probabilities for video data classes, the author assigns the available bandwidth budget to generate the required FEC blocks for video data classes in their priority order. In the packet-level FEC scheme, on the other hand, the video stream is packetized into a series of fixed-length packets. Then the source packet stream is grouped into blocks, and FEC produces the required redundant packets for each of packet blocks to achieve the required reconstruction quality [7]. In [8], an optimal packet-level FEC model within transmission rate constraint is presented for MPEG video to obtain the highest playable frame rate (PFR) of group of picture (GOP). In their model, unequal error protection (UEP) is applied to produce different amount of FEC redundancies for different frame types, while the temporal scaling technique is used to adjust the stream data rate by discarding frames based on the frame dependency of MPEG video.

In [9], it was shown that compared with the byte-level FEC, packet-level FEC yields the maximum recovery efficiency in error-prone wireless networks. The packet-level FEC can perform cross-packet loss recovery to effectively deal with continuous error-corrupted packets. However, designing an efficient packet-level FEC scheme is highly challenging under the transmission rate constraint in wireless networks. The video application generally transmits large packets over the network in order to obtain a high data throughput, and accordingly generates the redundant packets which have the same size as the source packet, to combat wireless bit errors. Specially, a redundant packet is produced to recover any number of wireless bit errors within the source packet. This leads an inefficient FEC bandwidth allocation since a large number of redundant data is used to combat few wireless bit errors. Consequently, the optimal packet-level FEC scheme may discard a large amount of low-priority frames in order to accommodate more redundant packets assigned to high-priority video frames within the transmission rate budget. Although the optimal FEC scheme aims at achieving the highest PFR value under the transmission rate constraint, the severe frame dropping may lead to an interrupted video presentation at the end-user side. In attempting to resolve the error-prone problem in wireless transmissions, several schemes have been proposed for increasing the transmission reliability for video streaming applications by increasing the block size [10] or interleaving several blocks to distribute burst errors [11]. However, such an approach usually induces the excessive end-to-end delay, and is therefore unsuitable for video streaming applications which require a minimal end-to-end delay in order to maximize the perceived quality at the receiving end. Accordingly, a requirement exists for an alternative means of enhancing the efficiency of FEC for video transmissions over wireless networks.

The basic principle of FEC enhancement is to increase the video goodput at the receiving end in such a way that a better error recovery performance is achieved with no significant increase in the bandwidth overhead and delay. In wireless networks, packet size control (PSC) determines the tradeoff between transmission efficiency and packet corruption rate. The use of a large packet size improves the bandwidth efficiency, but increases the data corruption rate under poor channel conditions. Conversely, using a small packet size reduces the degree of packet corruption to enhance the error correction capacity of FEC, but degrades the bandwidth utilization efficiency due to the additional header overhead. In practice, the threshold used to control the packet size is generally determined in accordance with the bit error rate and the available bandwidth. Existing packet size control schemes adapt the network-layer packet size or even the link-layer frame size in such a way as to achieve a maximum data goodput [12, 13]. The works in [14, 15] integrated the adaptive FEC and dynamic packet sizing to provide the robust wireless transmission, but they only considered the data packet delivery quality in the network layer. The authors of [16] proposed a byte-level FEC scheme with an adaptive packet size assignment mechanism to maximize the received quality in scalable video applications, but the effects of overhead cost on the efficiency of the FEC recovery process were not addressed.

Accordingly, this study proposes an enhanced FEC control scheme in which both the degree of FEC redundancy and the transport packet size are adjusted adaptively in such a way as to maximize the video goodput at the receiving end while simultaneously minimizing the bandwidth consumption. We integrate the packet size control (PSC) mechanism with the optimal packet-level FEC scheme presented in [7] to improve the video reconstruction quality in wireless networks. In addition, a novel independent packetization mechanism is proposed to minimize the data dependency between the redundant packets, thereby providing the error-resilient redundant packets and improving the recovery performance as a result. The experimental results show that compared with the optimal packet-level FEC scheme using a fixed packet size, the proposed FEC-PSC scheme can enhance performances in terms of peak signal-to-noise ratio (PSNR) and playable frame rate, with the reduced bandwidth overhead.

The remainder of this paper is organized as follows. Section 2 describes the optimal packet-level FEC scheme for the transmission of MPEG-encoded video streams. Section 3 describes the integration of the packet-level FEC scheme with a packet size control mechanism in order to optimize both the number of redundant packets and the transport packet size. Section 4 introduces the proposed packetization method for the FEC redundant data and reports the corresponding performance analysis. Section 5 presents the experimental results. Finally, Section 6 provides some brief concluding remarks.

2. Optimal packet-level FEC for MPEG video flows

In this section, we review the background of MPEG video and FEC, and briefly restate the optimal packet-level FEC scheme presented in [8].

2.1 MPEG video

In MPEG video flows, the raw video data are encoded as intra-coded (I), predictive (P), or bidirectional (B) video frames. The I frames are encoded independently of any previous frames. However, the P frames are encoded based on the change in motion from the previous I or P frame, while the B frames are encoded based on the motion difference between the preceding I or P frame, and the following I or P frame. Following coding, the I, P and B frames are arranged in a periodic sequence referred to as the group of pictures (GOP). The GOP is typically arranged as follows:

$$I\,B_{0,0}\cdots B_{0,N_{BP}-1}P_1\cdots P_m B_{m,0}\cdots B_{m,N_{BP}-1}P_{m+1}\cdots P_{N_P}B_{N_P,0}\cdots B_{N_P,N_{BP}-1}, \tag{1}$$

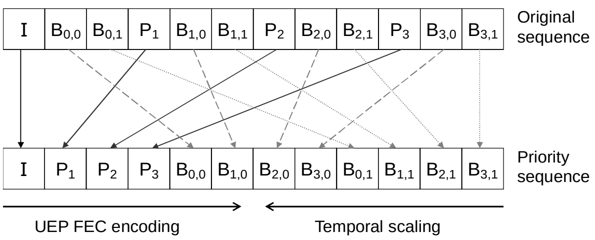


Fig. 1 Frame priority arrangement.

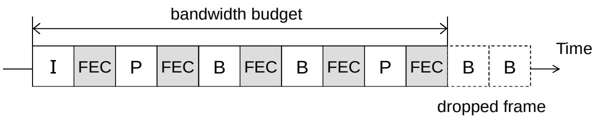


Fig. 2 Packet-level FEC scheme.

where N_P is the number of P frames in the GOP and N_{BP} is the number of B frames between successive I and P frames, or successive P frames. In other words, the total number of B frames in the GOP is equal to $N_B=(1+N_P)\times N_{BP}$. For instance, the typical GOP pattern has the form IBBPBBPBB, i.e. the GOP has a length of 9 frames. The effective GOP transmission rate is given by

$$G=\frac{R_F}{1+N_P+N_B}, \tag{2}$$

where the encoding frame rate per second as R_F.

Within the GOP, the video frames can be classified in terms of their type and their distance from the I frame. The loss of an I frame has a significant effect on the video quality of the entire GOP, and hence the I frame is assigned the highest priority. The P frames have a temporal dependency, and thus P frames which are closer to the I frame are assigned a higher priority than those located further from the I frame. Finally, the B frames are not used as references by any of the other frames in the GOP, but cannot be dropped continuously since this will result in a temporal quality degradation. Thus, the B frames are selected evenly throughout the GOP in accordance with their distance from the reference I frame, and are assigned a progressively reducing priority accordingly. That is, the first B frame after the I frame is assigned the highest priority, the first B frame after the first P frame is assigned the next highest priority, the first B frame after the second P frame is assigned the next highest priority, and so on. As a result, the original GOP pattern shown in (1) is re-organized as follows:

$$\mathrm{I\,P_1P_2\cdots P_{N_P}B_{0,0}B_{1,0}\cdots B_{N_P,0}B_{0,1}\cdots B_{N_P,1}\cdots B_{0,N_{BP}-1}\cdots B_{N_P,N_{BP}-1}}. \tag{3}$$

Figure 1 presents a schematic illustration comparing the original GOP frame sequence and the prioritized frame sequence. As shown, the original GOP pattern "$\mathrm{IB_{00}B_{01}P_1B_{10}B_{11}P_2B_{20}B_{21}}$" is re-organized as "$\mathrm{IP_1P_2B_{00}B_{10}B_{20}B_{01}B_{11}B_{21}}$".

2.2 Packet-level FEC

In packet-level FEC, the systematic linear erasure code (n, k) is used to protect the video frames. Specifically, the FEC encoder generates $h=n–k$ redundant packets for the video frame, where n is the actual number of packets launched into the network. Each packet is assigned a unique sequence number indicating its position within the block. Using this information, the FEC decoder is readily able to locate the positions of any lost packets with the frame and to correct these losses accordingly. Since the number of redundant packets in the frame is equal to $n–k$, the decoder can successfully reconstruct the frame provided that any k or more packets amongst the original n transport packets are received. In other words, the success of the reconstruction process is guaranteed if the total number of corrupted packets does not exceed h. Given the number of source video packets k, the estimated packet loss rate P_{pkt}, and the value of h, the reconstruction probability B can be computed as

$$B=\sum_{j=k}^{h}\left[\binom{k+h}{j}\times P_{pkt}^{j}\times(1-P_{pkt})^{k+h-j}\right]. \tag{4}$$

According to Eq. (4), the probabilities of successful transmission for three frame types are obtained from

$$\begin{aligned} Q_I &= B(S_I+S_{IF}, S_I, P_{pkt}),\\ Q_P &= B(S_P+S_{PF}, S_P, P_{pkt}),\\ Q_B &= B(S_B+S_{BF}, S_B, P_{pkt}), \end{aligned} \tag{5}$$

where Q_I, Q_P, and Q_B are the probability of successful transmission of an I, P, or B frame, respectively; S_I, S_P, and S_B are the I, P, B frame size (in packets); S_{IF}, S_{PF}, and S_{BF} are the number of FEC redundant packets for I, P, and B frames.

2.3 Optimal playable frame rate

To evaluate the video streaming performance, the playable frame rate (PFR) can be used as a good measure in the lossy network. The PFR is defined as the expected number of decodable frames at the receiver within one second, and can be calculated according to [8]:

$$R = G \times Q_I \times \left[\begin{array}{l} 1 + \dfrac{Q_P - Q_P^{N_P+1}}{1-Q_P} + \\ N_{BP} \times Q_B \left(\dfrac{Q_P - Q_P^{N_P+1}}{1-Q_P} + Q_I \times Q_P^{NP} \right) \end{array} \right]. \qquad (6)$$

Eq. (6) describes the PFR value when no video frames are discarded. Within the transmission rate constraint, the FEC scheme can consider the temporal scaling mechanism to discard the least important video frames prior to transmission. Figure 2 illustrates the packet-level FEC scheme under the bit rate budget constraint. Utilizing the prioritized sequence shown in Figure 1, the FEC scheme assigns a required number of redundant packets to the frames progressively, starting from the frames at the head of the sequence and moving toward the frames at the tail of the sequence. When the allocated FEC bandwidth reaches the allowed bit budget, the temporal scaling approach discards the other remaining frames in the sequence. Denote N_{PD} and N_{BD} as the number of P frames and B frames, respectively, sent after temporal scaling. Combined with the temporal scaling approach, the FEC allocation problem to obtain an optimal PFR value under the constraint of transmission rate becomes

$$\begin{array}{l} \text{Maximize:} \\ R = R\big((N_{PD}, N_{BD}), (S_{IF}, S_{PF}, S_{BF}), P_{pkt}\big). \\ \text{subject to:} \\ G \times \left(\begin{array}{l} (S_I + S_{IF}) + N_{PD} \times (S_P + S_{PF}) + \\ N_{BD} \times (S_B + S_{BF}) \end{array} \right) \times S \le T, \\ 0 \le N_{PD} \le N_P, 0 \le N_{BD} \le N_B, \\ 0 \le S_{IF} \le S_I, 0 \le S_{PF} \le S_P, 0 \le S_{BF} \le S_B, \end{array} \qquad (7)$$

where S is the packet size in bytes and T is the target transmission rate in bytes per second. More details about the optimal packet-level FEC scheme can refer to [8].

3. Joint FEC and packet size control scheme

This section describes the integrated packet-level FEC / packet size control (FEC-PSC) scheme proposed in this study for wireless video transmissions. In the proposed approach, the optimal packet-level FEC scheme generates redundant data in accordance with the current network conditions, while the PSC mechanism adapts the packet size of both the video data and the redundant data in such a way as to increase the video goodput. As a result, the proposed scheme improves the bandwidth utilization efficiency and thus enhances the FEC recovery performance.

For a k–packet block associated with video frame i, the block can be completely reconstructed provided that k or more packets are captured at the receiving end. In other words, the total number of corrupted packets must not exceed h if the block is to be successfully recovered. Based on the loss distributions of the source and redundant packets, Eq. (4) can be rewritten as

$$B = \sum_{j=0}^{h} \left[\begin{array}{l} \binom{k}{j} \times P_{pkt}^{j} \times (1-P_{pkt})^{k-j} \times \\ \sum_{m=j}^{h} \left[\binom{h}{m} \times P_{pkt}^{h-m} \times (1-P_{pkt})^{m} \right] \end{array} \right], \qquad (8)$$

where the first term describes the probability of j source packets being lost, while the second term describes the probability of $(h-j)$ redundant packets being lost.

In a practical network system, P_{pkt} is usually estimated as the ratio of the number of corrupted packets to the total number of transmitted packets. In order to obtain a reliable estimate of the current network conditions, the packets considered in the packet error rate calculation should be of the same size. Let the average bit error rate in the channel be denoted as P_b. The packet error rate can then be obtained as

$$P_{pkt} = 1-(1-P_b)^{\tau}, \qquad (9)$$

where τ is the packet size in bits and $\tau = S \times 8$. In adapting the packet size, the packet length is modified to τ', and the segmentation factor is therefore given by $f = \tau / \tau'$. Accordingly, the packet error rate of the modified packet under the same channel conditions can be estimated as

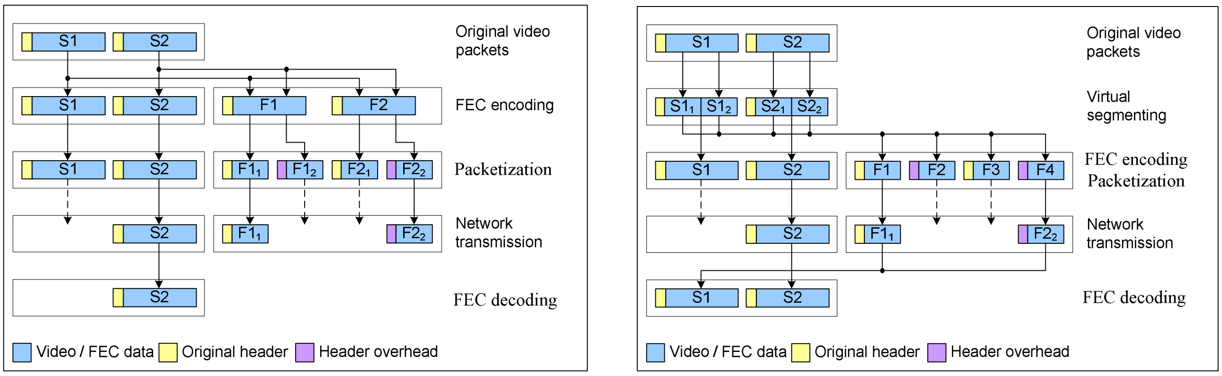
$$P_{pkt}^{f} = 1-(1-P_b)^{\tau/f} = 1-((1-P_b)^{\tau})^{1/f} = 1-(1-P_{pkt})^{1/f}. \qquad (10)$$

Eq. (10) provides a simple method for computing the packet error rate for packets of different sizes without a priori knowledge of the current channel bit error rate. Note that in the proposed PSC mechanism, the source packet size and the redundant packet size are adjusted independently of one another, thereby optimizing the bandwidth utilization. In accordance with Eq. (10), the predicted packet error rates of the source packets, P_{src}, and redundant packets, P_{fec}, can be computed as follows:

$$P_{src} = P_{pkt}^{fs}, \quad P_{fec} = P_{src}^{fr} = P_{pkt}^{fs \times fr}, \qquad (11)$$

where fs is the segmentation factor of the source packets and fr is the segmentation factor of the redundant packets. As a result, the recovery probability of the FEC-PSC scheme can be expressed as

$$B = \sum_{j=0}^{\frac{h}{fr}} \left[\begin{array}{l} \binom{k}{j} \times P_{src}^{j} \times (1-P_{src})^{k-j} \times \\ \sum_{m=j \times fr}^{h} \left[\binom{h}{m} \times P_{fec}^{h-m} \times (1-P_{fec})^{m} \right] \end{array} \right]. \qquad (12)$$



(a) (b)

Fig. 3 Packetization schemes for redundant data:
(a) Dependent packetization; (b) Independent packetization.

In the proposed FEC-PSC scheme, the PFR optimization process basically follows the steps introduced in Section 2 except that Eq. (12) replaces Eq. (4) to calculate the target recovery probability defined in Eq. (5) for each video frame *i*. Let N_i be the total number of transport packets associated with video frame *i* and let *H* be the network header size in bytes. The total bandwidth overhead of FEC-encoded frame *i* is therefore given by

$$C_i = N_i \times H + h_i \times S. \tag{13}$$

The problem of determining the number of redundant packets and the size of the transport packets associated with video frame *i* which together achieve the target reconstruction probability B_{target} whilst simultaneously minimizing the bandwidth consumption can be formulated as follows:

$$\begin{aligned} &\text{Minimize } C_i \\ &\text{subject to:} \\ &B_{target} \le B_i(k_i, P_{pkt}), \\ &fr \ge fs \ge 1. \end{aligned} \tag{14}$$

It is noted that more than one solution may be obtained for Eq. (14). In this event, the FEC-PSC scheme chooses the result which involves the minimal number of transport packets in order to minimize the end-to-end delay [17].

4. Independent packetization scheme for redundant data

In this section, we describe a novel packetization scheme to packetize the redundant data into independent redundant packets and therefore the data dependency between redundant packets can be minimized to facilitate the FEC recovery. Then, the analytical results are presented to discuss the performance comparison between the conventional dependent packetization scheme and the proposed independent packetization scheme.

4.1 Scheme overview

In general, video applications need some form of packetization scheme to packetize the application data into a series of packets for transport purposes. Typically, such schemes can be categorized as either *dependent* or *independent*. In dependent packetization schemes, each video data item is fragmented into segments of a fixed length, and a transmission packet is formed by attaching a transport control header to the front of the segment. This approach is computationally straightforward, but results in a dependency between adjacent packets. Consequently, the loss of one packet can corrupt all of the packets associated with the data item. In independent packetization schemes, each independent packet enables resynchronization between the video decoder and the bitstream after errors have been detected. In other words, the decoder localizes the errors within the bitstream to facilitate the error concealment capacity of video presentation at the receiving end.

The packetization schemes described above for video data can also be applied to the redundant data added to the bitstream by the FEC encoder. Figure 3(a) shows the dependent packetization of the FEC redundant data using linear erasure code (n, k)=(4,2) for illustration purposes. In Figure 3, packets labeled “S” represents video source packets while packets labeled “F” stands for FEC redundant packets. As shown, two redundant data items are generated and are then fragmented into four segments, where each segment is half the size of the original redundant item. Compared to the transport of the original redundant data item over the network, the transport of the

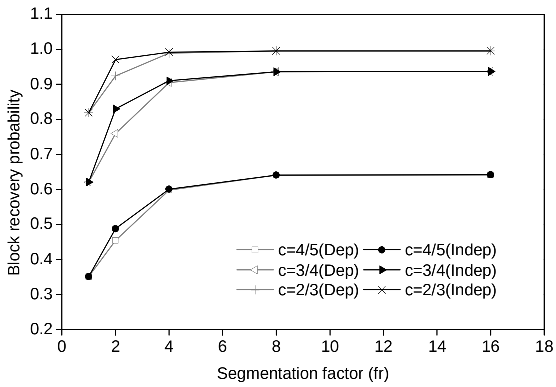


Fig. 4 FEC recovery rate comparison for various values of segmentation factor (*fr*).

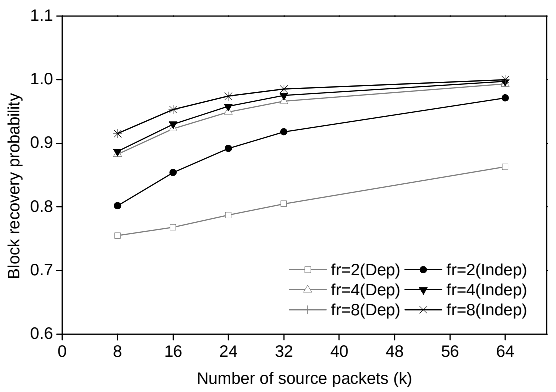


Fig. 5 FEC recovery rate comparison for various numbers of source packets (*k*).

two fragmented redundant packets requires an additional header. As a result, the total overhead incurred in transmitting the redundant data is increased by two headers. Furthermore, the loss of any transport packet results in a decoding failure at the receiving end due to the dependency between adjacent packets. Thus, the dependent packetization scheme is not only wasteful of the available bandwidth, but also leads to a poor FEC recovery performance.

Accordingly, the present study proposes an independent packetization scheme for the FEC redundant data to facilitate a robust packet transmission performance and to render the FEC decoding process resilient to transmission errors. In the proposed scheme, the k source packets are virtually fragmented into segments such that the total number of source segments is increased to k' ($k' \geq k$). The FEC encoder then utilizes these k' source segments to encode ($n'-k'$) redundant segments, where each segment has the same size as the virtual source segment. Transmission packets are then formed by adding a transport control header to each redundant segment. In this way, each source packet consists of k'/k data segments while each redundant packet contains one data segment only. At the receiving end, the FEC decoder performs the error correction process in the normal way using the (n', k') erasure code. Figure 3(b) illustrates the proposed packetization scheme for RS coding parameters of (n', k')=(8, 4). As shown, two source packets are virtually fragmented into four source segments, and these four segments are then used to generate four redundant segments of the same size. A transport control header is added to each redundant segment, and the segments are then transmitted to the receiving end together with the original source packets. Since FEC coding is performed at the segment level, the receiving end must split the source packets into segments and collect up to four segments in order to successfully reconstruct the original data. As shown in Figure 3(b), the independent redundant packets can successfully recover the source data in the presence of packet losses similar to Figure 3(a). As with the dependent packetization scheme, the independent packetization scheme incurs an increased header overhead. However, the data independency amongst the redundant packets improves the FEC correction capacity and therefore facilitates error-resilient packet transport over error-prone transmission channels.

4.2 Recovery rate analysis

In this analysis, we use a fixed FEC-PSC scheme to observe the results as the dependent and independent packetization schemes are applied to the redundant packets individually. In the fixed FEC-PSC scheme, the FEC control parameters (n, k) are assigned to the static values, and the packetization scheme segments the redundant packets according to a given segmentation factor fr. Therefore, for a FEC block (n, k), the amount of redundant packets used for network transmission is $(n-k)\times fr$. Based on Eq. (10), the error probability of the original redundant packet for the dependent packetization scheme can be expressed as

$$P_{pkt} = 1-(1-P_{fec})^{fr}, \tag{15}$$

where P_{fec} is the predicted error rate of the redundant packets in Eq. (11). By calculating Eq. (15) in Eq. (8) for redundant packets, we can obtain the recovery probability of a FEC block for the dependent packetization scheme. On the other hand, Eq. (12) provides the FEC recovery probability for the independent packetization scheme. Table 1 presents the settings of system parameters in the analysis.

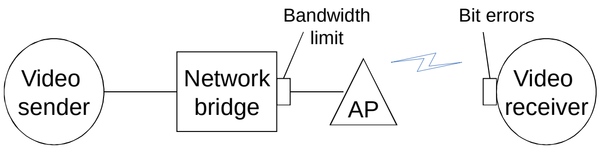


Fig. 6 Experimental set-up.

In the first analytical scenario, we set the number of source packets to 12 and vary the number of redundant packets to observe the performance comparison between two packetizatoin schemes. Figure 4 shows the probability that the FEC block is successfully reconstructed for three different cases and two different packetization schemes as the value of the segmentation factor is varied from 1 to 16. By defining the FEC coding rate, c , as k/n, the three cases are: 1) c=4/5; 2) c=3/4; and 3) c=2/3. From Figure 4, it can be seen that for three FEC coding rates: 1) the recovery probability dramatically increases as the value of *fr* increases from 1 to 4, and rises slowly as the values of *fr* exceeds 4; and 2) the independent packetization scheme achieves the higher recovery probability than that of the dependent packetization scheme when the values of *fr* are set to 2 and 4, but the performance enhancement is not significant as the value of *fr* is 4. Figure 5 presents the analytical results for another scenario. In this scenario, the FEC coding rate is fixed to 2/3, and we vary the number of source packets to produce different block sizes. In Figure 5, we first observe that for two packetization schemes, increasing the segmentation level (i.e., the value of *fr*) leads the higher recovery probability. By comparing three different cases (*fr*=2, 4, and 8) in Figure 5, we also observe that the independent packetization scheme enhances the recovery performance as the values of *fr* are set to 2 and 4, and significantly improve the performance as the value of *fr* is 2. For *fr*=2, the difference in the recovery probability between two packetization schemes is ranged from 0.05 to 0.11. It is noted that the performance enhancement provided by the independent packetization approach and the corresponding effective *fr* can vary according to the system parameter settings. To conclude from Figure 4 and 5, the independent packetization scheme is effective in increasing the error resilience capacity of redundant packet delivery to enhance the FEC recovery performance.

5. Performance results

Figure 6 illustrates the experimental set-up used to evaluate the performance of the proposed adaptive FEC-PSC scheme. As shown, the set-up consists of a video sender, a video receiver and a network bridge. The wired links in the set-up were connected via Fast Ethernet. The network bridge transferred packets between the wired and wireless networks, and limited the input/output data flows to a specified channel transmission rate. At the video sender, the video output rate budget was determined by the channel transmission rate. The wireless network used an 802.11b access point (AP) operating in a distributed coordination function (DCF) mode to connect the video receiver to the video sender. In performing the evaluation experiments, the video sender streamed the "*Foreman*" MPEG-4 sequence in CIF format to the video receiver at an average data rate of 800 kbps (corresponding to a frame rate of 25 frames per second) and with a GOP size of 9 frames. The video receiver was arranged in clear line of sight (LoS) of the AP in order to ensure the channel quality and generated bit errors to cause packet losses. Bit error patterns with an average bit error rate ranging from 10^{-1} to 10^{-6} and an average burst bit error length of 80 bits were generated using a two-state Markov model. In accordance with the bit error pattern, a packet with a bit size of L was dropped whenever one or more of the L bits was corrupted. Finally, the default packet size and the network header were set to 1000 bytes and 40 bytes, respectively.

Table 1: System settings

Parameters	**Scenario 1**	**Scenario 2**
P_b	5×10^{-5}	5×10^{-5}
τ	8000	8000
k	12	8, 16,24, 32, 64
c	4/5, 3/4, 2/3	2/3
fr	1, 2, 4, 8, 16	2, 4, 8
fs	1	1

In performing the experiments, the performance of the proposed FEC-PSC scheme was compared with that of the optimal packet-level FEC scheme, in which the video data and FEC redundant data are both packetized using a default packet size. The performance of the two schemes was evaluated by measuring the bandwidth overhead at the video sender side, and the peak signal-to-noise ratio (PSNR) and playable frame rate (PFR) at the video receiver side. The bandwidth overhead was defined as the total number of redundant packets and packet headers associated with each video frame. In calculating the PSNR and PFR, a frame was considered to be playable if the entire frame was received correctly and all of the frames upon which it depended were also playable. For those frames which were not playable, the PSNR value was computed using the nearest playable frame. For the FEC-PSC scheme, the dependent packetization mechanism is applied to source data in order to examine the performance effects on the proposed independent packetization mechanism for redundant data.

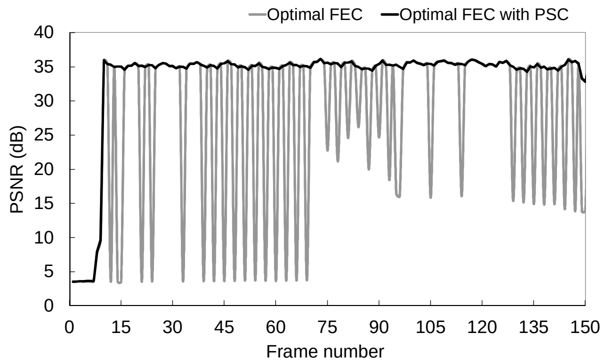


Fig. 7 PSNR comparison curve of optimal packet-level FEC and optimal packet-level FEC with PSC for the '*Forman*' sequence.

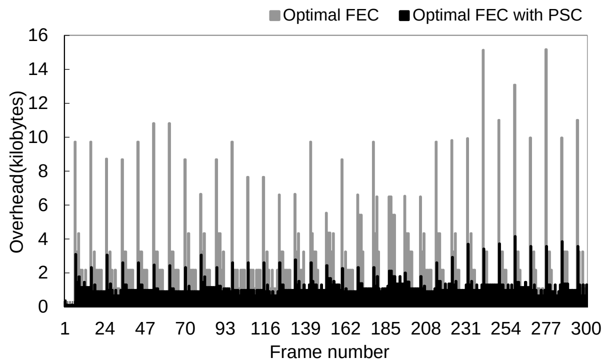


Fig. 8 Overhead comparison curve of optimal packet-level FEC and optimal packet-level FEC with PSC for the '*Forman*' sequence.

In the first experimental scenario, the average bit error rate, average burst bit error length, and target channel transmission rate were specified as 10^{-3}, 80, and 1 Mbps, respectively. Figure 7 compares the frame-by-frame PSNR results for the two schemes. In general, the results show that the proposed FEC-PSC scheme yields both a higher PSNR and a higher PFR than the optimal FEC scheme due to its use of an adaptive packet size and an independent packetization scheme for the redundant data packets. Compared to the optimal FEC scheme, the FEC-PSC scheme improves the average PSNR by around 7.2 dB and the average PFR by approximately 7 frames per second (fps). Figure 8 compares the overheads incurred by the two schemes for the first experimental scenario. The results show that for both FEC schemes, the peak overhead coincides with the periodic insertion of the I frames since the I frames generally contain the greatest number of source data and redundant packets amongst all the frames in the GOP. However, it is noted that the overhead incurred by the FEC-PSC scheme is far lower than that incurred by the optimal FEC scheme with no PSC capacity. From inspection, the total bandwidth overhead accumulated over all the video frames is found to be 738 kilobytes for the optimal packet-level FEC scheme and 378

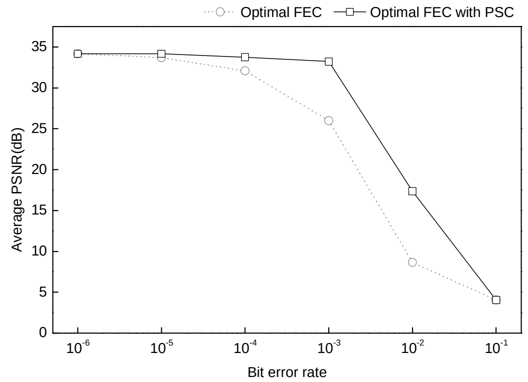


Fig. 9 PSNR comparison with varied bit error rate.

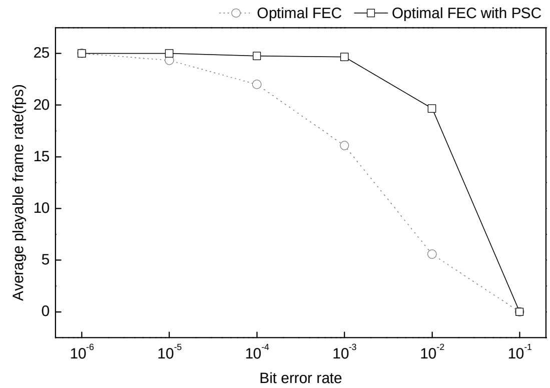


Fig. 10 PFR comparison with varied bit error rate.

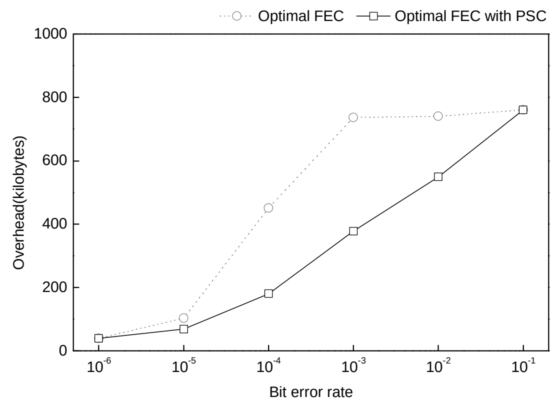


Fig. 11 Overhead comparison with varied bit error rate.

kilobytes for the proposed FEC-PSC scheme. The improved overhead performance of the proposed scheme is to be expected since, compared to the optimal FEC scheme, it generates far fewer redundant data packets. In the FEC-PSC scheme, the available transmission rate budget can accommodate more video frames to improve the PSNR and PFR performances.

In the second experimental scenario, the experiments were performed using various values of the bit error rate and channel transmission rate, respectively. The remaining experimental set-up was unchanged. In the first series of experiments, the bit error rate was assigned in the range 10^{-} 10^{-6} to 10^{-1} and the channel transmission rate was specified as 1 Mbps. Figures 9 ~ 11 show the results obtained by the two compared schemes for the average PSNR, average PFR, and average overhead, respectively. It is noted that for a bit error rate of 10^{-1}, all of the packets are lost in both schemes, and thus no frames are available for measurement purposes. Figures 9 and 10 show that the performance improvement afforded by the proposed scheme is particularly significant as the bit error rate is increased from 10^{-5} to 10^{-2}. From inspection, the maximum PSNR improvement obtained by the proposed scheme is equal to 8.7 db (at a bit error rate of 10^{-2}), while the maximum PFR improvement is equal to 14 fps (also at a bit error rate of 10^{-2}). Figure 11 shows that the bandwidth overhead of both schemes increases with an increasing bit error rate due to the corresponding increase in the number of redundant packets (in both schemes) and the reduction in the packet size (in the FEC-PSC scheme). Due to the limited transmission rate budget, the overhead incurred by the optimal FEC scheme saturates at a bit error rate of 10^{-3} or more. By contrast, the overhead incurred by the FEC-PSC scheme increases progressively as the bit error rate is increased from 10^{-6} to 10^{-1}, and is consistently lower than that incurred by the optimal scheme for all values of the bit error rate other than 10^{-1} and 10^{-6}. From inspection, the maximum improvement in the overhead cost is obtained at a bit error rate of 10^{-3} and is found to be around 50%.

In the second series of experiments, the channel transmission rate was varied in the range 800 kbps to 1.6 Mbps and the bit error rate was assigned a constant value of 10^{-3}. Figure 12 compares the average PSNR results for the two schemes. It is seen that the FEC-PSC scheme achieves a higher PSNR than the optimal FEC scheme for all values of the channel transmission rate up to 1.5 Mbps. In addition, the proposed scheme achieves a constant PSNR of 33.3 dB for all values of the transmission bit rate greater than 1 Mbps. By contrast, for the optimal FEC scheme, the PSNR increases progressively with an increasing transmission bit rate due to the corresponding increase in the bit rate budget available for the FEC redundant packets. The PSNR of the optimal FEC scheme saturates at a value of 33.3 dB for all values of the channel transmission rate greater than 1.5 Mbps. Although both schemes achieve a maximum PSNR of 33.3 dB, the proposed FEC–PSC scheme saturates at a transmission rate of 1 Mbps, whereas the optimal FEC scheme saturates at a bit rate of 1.5 Mbps. The budget saving of 500 kbps

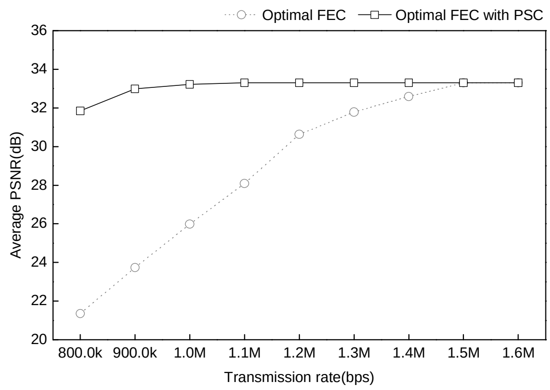


Fig. 12 PSNR comparison with varied transmission rate.

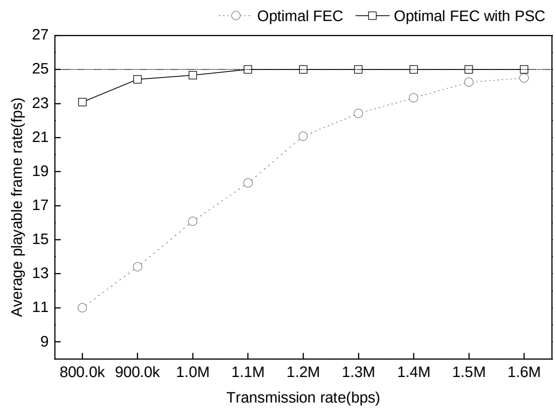


Fig. 13 PFR comparison with varied transmission rate.

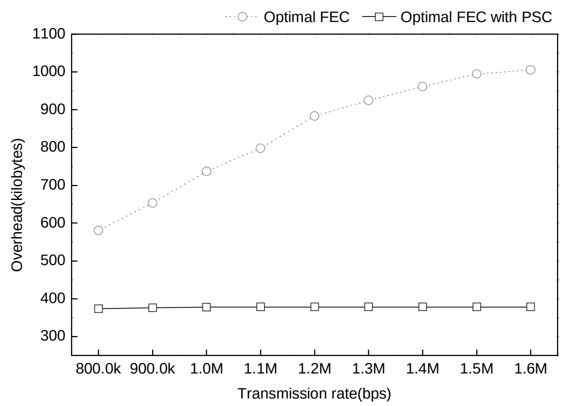


Fig. 14 Overhead comparison with varied transmission rate.

achieved by the FEC-PSC scheme is beneficial to service providers in increasing the service capacity. The PSNR improvement afforded by the FEC-PSC scheme is particularly significant at lower transmission rates. For example, at a transmission bit rate of 800 kbps, the average PSNR of the proposed scheme is around 10.48 dB higher than that of the conventional scheme.

Figure 13 presents the average PFR results for the two schemes. It is observed that the FEC-PSC scheme achieves a higher PFR than the optimal FEC scheme at all values of the transmission bit rate. As with the PSNR results, the PFR performance improvement obtained by the FEC-PSC scheme is particularly significant at lower values of the transmission bit rate. In addition, it is observed that the optimal FEC scheme fails to achieve full motion presentation (i.e. 25 fps) even under the highest considered transmission bit rate of 1.6 Mbps. Figure 14 shows that the overhead incurred by the optimal FEC scheme increases significantly with an increasing transmission bit rate. By contrast, that incurred by the FEC-PSC scheme has a low and stable value at all values of the transmission bit rate. Overall, Figures 12 ~ 14 show that the proposed FEC-PSC scheme can better adapt to various transmission rates thanks to the controlled bandwidth overhead and therefore provides a constant perceptual quality of the streaming video at the receiving end.

6. Conclusions

This study has proposed a joint packet-level FEC / packet size control scheme to improve the efficiency of FEC for wireless video transmissions. In the proposed scheme, the number of redundant packets and the size of the transport packets are adjusted adaptively in such a way as to maximize the goodput at the receiving end whilst simultaneously minimizing the bandwidth consumption. The experimental results have shown that the proposed scheme achieves a better perceptual quality than the optimal packet-level FEC scheme in which the packet size is fixed, thanks to a lower overhead cost.

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