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Error prevention and concealment for scalable video coding with dual-priority transmission☆

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Abstract

In this work, we present an efficient error resilient system against ATM cell loss using a hybrid error concealment and error propagation prevention (ECP) technique with dual-priority transmission scheme (DPTS). DPTS performs traffic policing to form dual-priority cells in ATM connections and manages to make most cell losses occur in a low priority layer. However, cell loss may still occur in the high priority layer if the bandwidth is not reserved enough for the usually variable bitrate video traffic. Therefore, the ECP technique can still be utilized to reduce the error damage and limit the impact of cell loss to the erroneous slices. Simulation results of two-layer MPEG-2 coding over DPTS in ATM networks demonstrate that ECP with feedback over DPTS can effectively isolate errors and reduce the damage to yield a satisfactory performance, even when the cell-loss rate is as high as 8%.

Keywords: Error propagation; Error prevention; Error concealment; Video coding; Asynchronous transfer mode; Dual-priority

1. Introduction

Most current video applications are based on international standards, such as MPEG-1/2 (LeGall, 1991; ISO/IEC/JTC1/SC29/WG11, 1993; ISO/IEC 13818-2,

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1995) or H.26x, i.e., H.261 or H.263, (Draft ITU-T Recommendation, 1996;Ghanbari, 1992), that have been implemented by hardware or software, and applied over all sorts of networks, such as internet, wireless, and asynchronous transfer mode (ATM) networks. All of these video compression techniques are based on discrete cosine transform (DCT) coding, variable length coding (VLC), and motion compensation, which are very sensitive to the channel disturbances. Any single bit error may cause serious error propagation in both the spatial and the temporal domains. Reducing the error damage of the video coding incurred by imperfect networks is thus an important task. ATM is more appropriate for transmitting video bitstreams than conventional packet switched networks because it uses a small packet (cell) size that is more flexible to handle time sensitive traffic and reduce the error damage when cell loss occurs. In addition, ATM allows transmissions with distinct priority classes of cells through the setting of cell-loss priority (CLP) bit. The layered video coding can be matched with a priority transmission to make a high performance video compression and delivery system. A combined video coding and delivery system with a focus on video quality guarantee and error resilience to cell loss is developed herein.

The MPEG-2 international standard supports four scalable techniques to generate layered video bitstreams: data partitioning, signal-to-noise (SNR) scalability, spatial scalability, and temporal scalability. All of these scalable techniques eventually generate two layers of bitstreams: the base layer (BL) and the enhancement layer (EL). The base layers of these scalability techniques are generated as follows. The data partitioning technique reduces the number of DCT coefficients. The SNR scalability uses a coarse quantization step. The spatial scalability reduces the spatial resolution, i.e., the image size. Finally, the temporal scalability reduces the temporal resolution by skipping frames. The enhancement layer of each scalable technique, which cannot be decoded alone, improves the base layer video quality. The base layer bitstream of a two-layer scalable coding over dual-priority ATM transmission is usually regulated to become a near constant bit rate (CBR) bitstream and set to high priority to ensure guaranteed delivery with the requested bandwidth. The enhancement layer is set up as a low priority layer that may allow variable bit rate (VBR) and cell loss. However, video coding with CBR source rate control generally degrades the video quality of the base layer in certain areas or frames. A poor quality base layer may also damage the performance of the two-layer decoding.

The base layer is sensitive to error propagation regardless of the scalable coding technique chosen since the motion information is usually included in the base layer. The error damage effect in the enhancement layer depends on the scalability technique (Aravind et al., 1996). According to the standardized spatial scalable decoding, the enhancement layer in spatial scalability may perform both the spatial prediction from the base layer and the temporal motion compensated prediction from the enhancement layer. The temporal prediction will cause error propagation in the enhancement layer video bitstream if there are cell losses. The data partitioning scalability divides the low frequency data and the high frequency data as BL and EL, respectively. The drift effect will cause incorrect prediction of the base layer even when only the enhancement layer is erroneous. Thus both layers are sensitive to errors. The EL in temporal scalability may not contain motion information if only

B-frames are included in the EL. However, BL uses most of the bitrate and the bitrate allocation is not flexible with this constraint. In contrast, the base layer in SNR scalability contains all the motion information including motion vectors and motion compensation modes. The enhancement layer does not have motion information and, thus, is the least affected by cell losses. Therefore, this work focuses on SNR scalable video coding.

Ghanbari (Ghanbari, 1989) discussed the transmission problems of two-layer video coding on VBR networks where the transmission of certain amount of packets is guaranteed. In particular, the two-layer video transmission on ATM networks was discussed in (Tubaro, 1991). Kieu and Ngan (Kieu and Ngan, 1994) proposed cell-loss concealment techniques for dual-priority video coding on ATM networks. That investigation assumed that the base layer is transmitted over an error-free channel with all cells in high priority. Aravind et al. (Aravind et al., 1996) studied four MPEG-2 scalable techniques with cell losses, concluding that concealment with dual-priority transmission in ATM networks has a better performance than non-layer coding. Pang and Cheng (Pang and Cheng, 1997) proposed several priority traffic policing mechanisms to ensure good video quality in ATM transmission. The base layer cells in a two-layer video coding are called guaranteed cells, as they require guaranteed transmission without loss. However, in most cases, the bitrate of the base layer is substantially larger than the enhancement layer to ensure a minimum quality, e.g., the ratio could be as high as 9:1 in many literatures. In practice, allocating a large guaranteed bandwidth to guard against loss in the base layer for VBR video coding may be unaffordable.

This study extends temporal error propagation prevention technique (Wang and Chang, 1999) of non-layer video coding to two-layer video coding. In particular, the decoder reports the loss information to the encoder when a cell loss exists in the base layer bitstream. The encoder then marks the possible damaged area and the normal encoding process continues. Consequently, the motion compensation of the following frames will not refer to the damaged area of the current frame, and the error propagation in the temporal domain is then terminated by this feedback mechanism. Only a small amount of information is needed for feedback, which markedly differs from the data requirements of the commonly used automatic retransmission mechanism. This approach can be applied to either MPEG or H.26x video coding over networks with feedback channels and limited delay. The erroneous blocks in the enhancement layer incurred by cell losses are ignored because the error propagation does not occur in the enhancement layer. In this case, the reconstructed images are only based on the base layer.

Hereinafter, a two-layer real-time MPEG coding over prioritized ATM networks is employed as an example to discuss the operation and performance. According to our observation, the round trip delay, which includes the video delivery to the decoder and the feedback to the encoder, is less than several video frames in time in most cases. The quick response ensures that the encoder has adequate time to avoid referring to the damaged areas in the next P-frame encoding. Together with the error concealment techniques, the error propagation damage is greatly reduced.

The rest of this paper is organized as follows: Section 2 briefly describes the real-time, two-layer video delivery system with a dual-priority transmission scheme. Section 3 presents the proposed two-layer error propagation prevention method. The simulation environment is described and the simulation results of the ECP–DPTS system are presented in Section 4. Conclusions are finally made in Section 5.

2. A dual-priority layered video delivery system

The capacity of broadband-ISDN (B-ISDN) makes high quality real-time video applications possible. In particular, ATM networks have been proposed to provide a unified transport structure for B-ISDN. ATM networks can deliver high quality video sequences coded by scalable MPEG for high-end real-time video services via its high bandwidth capacity (Hyman et al., 1991; Sahai et al., 1995). Fig. 1 depicts a dual-priority transmission scheme with an error concealment and prevention (ECP) system model. The system includes two-layer video coding, dual-priority transmission scheme, and error propagation prevention algorithm as discussed below.

2.1. Two-layer video coding

Two levels of priority have been proposed to secure the delivery of the video bitstream through an ATM network. A two-layer source coding with SNR scalability generates two video layers of the same spatial and temporal resolutions but with different video quality. The base layer encoding process works as non-layer encoding. The quantization errors are quantized again after the DCT coefficients in base layer are quantized to form the enhancement layer bitstream. The base layer that contains the most important video information is typically coded using a relatively large quantization scale. The base layer, which is transmitted with a high priority, should ensure the delivery of acceptable video quality. The enhancement layer containing residual errors, which are typically coded with smaller quantization scales, is transmitted as a low priority layer.

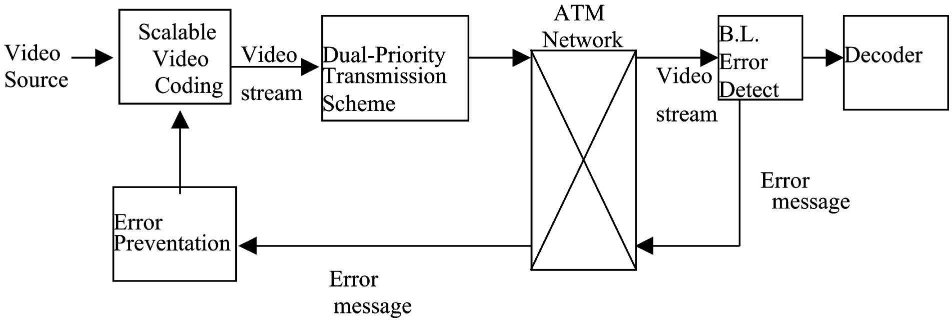


Fig. 1. The ECP–DPTS system model.

A two-layered SNR scalable video coding generates base layer and enhancement layer bitstreams, which both have their importance in video reconstruction. The reconstruction process is the same as the single layer when only the decoder receives the base layer video stream and the basic video quality is obtained. The enhancement layer data can only improve the video quality since it cannot reconstruct the video sequence by itself. Enhanced video quality is obtained if enhancement layer bitstreams are decoded with base layer together. Therefore, both layers have distinct sensitivities to cell loss. Any cell loss in the base layer may result in serious error propagation in both spatial domain and temporal domain because the base layer includes the most important video information and motion prediction information. Many concealment techniques can reduce the damage from errors, but concealment alone cannot prevent propagation errors.

The enhancement layer in SNR scalability contains the residual error signal between the base layer and the original video information. The error will not propagate in the temporal domain since it does not contain motion information. Hence, only the wrong enhancement layer data need to be removed and the base layer bitstream is normally decoded to get basic video quality when errors are detected in the enhancement layer.

2.2. Dual-priority transmission scheme

The ATM network supports VBR video coding to ensure consistent video quality and it also allows dual-priority classes of cells in ATM networks through the setting of cell-loss priority (CLP) bit. A dual-priority traffic control for real-time video services over ATM networks enhances the video quality by the proper assignment of cell priorities against cell loss. The priority leaky bucket transmission scheme over layered video, shown in Fig. 2, is generally used as a model of dual-priority traffic

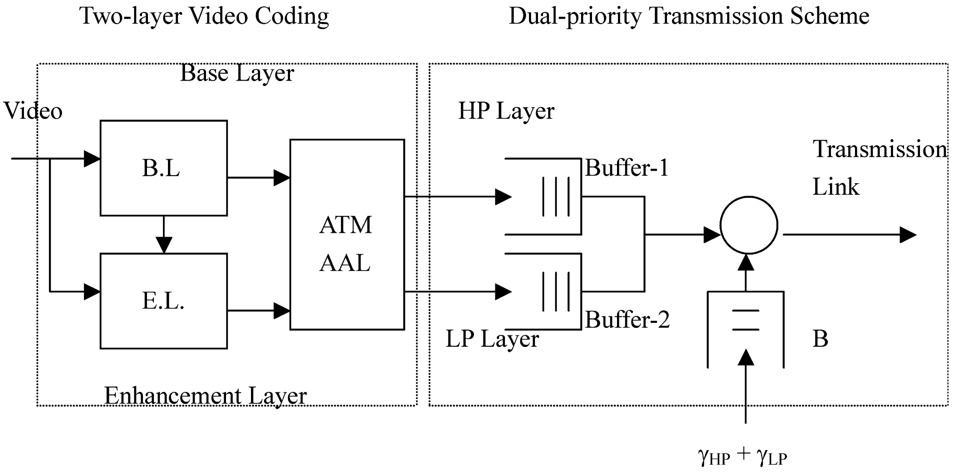


Fig. 2. A dual-priority scalable video delivery scheme.

control (Pang and Cheng, 1997). The token generation rate is defined as $\gamma = \gamma_{\mathrm{LP}} + \gamma_{\mathrm{HP}}$, where γ_{HP} is the average transmission rate of high priority layer and γ_{LP} is the average transmission rate of low priority layer. A two-priority buffer is used to buffer the two classes of cells with the token pool size B. The arriving cells are served according to FIFO discipline: high priority cells enter the buffer-1 and low priority cells enter buffer-2. One token is consumed for each forwarded cell. High priority cells are served as long as there are tokens in the token pool whereas low priority cells are served only if buffer-1 is empty. The cell that may be lost when congestion occurs in the network is tagged if there is no token left. In other words, the high priority cell will not be tagged and the transmission is guaranteed but low priority cells will be tagged first if there are no tokens left. Given the maximum token pool size B, the maximum admitted number of cells N within time interval T, can be expressed as

$$N = \gamma \ast T + B. \tag{1}$$

If the burst rate of the high priority bitstream exceeds N, some of the high priority cells are also possible to be tagged which may result in cell loss (Pang and Cheng, 1997).

3. Two-layer error propagation prevention

The damages from the error propagation effects on two-layer video coding are now discussed. An efficient temporal error propagation prevention technique with feedback assuming a low-rate reverse channel is available is proposed.

3.1. Base layer error propagation and concealment

The base layer error propagation exists in both the spatial and the temporal domains. The I-picture is intra-coded and will be a reference frame for the succeeding pictures in a GOP. Thus, the error will propagate to all the succeeding pictures within a GOP until the I-frame of the next GOP. The P-picture is a forward motion-compensated prediction picture with a reference to the previous I-frame or P-frame. The P-frame itself will be again referred by the motion compensation operations of the following pictures in a GOP. Thus, the errors in P-pictures also propagate to all the succeeding pictures in a GOP. On the other hand, since the B-picture is a motion compensated interpolation picture, the errors in the decoded B-frames will not propagate in the temporal domain because it is never used as a reference picture by any other frames (Aign and Fazel, 1995; Fern'andez et al., 1996; Wada, 1989).

I-frames and P-frames are more likely to have cell losses in a network because they usually generate higher rates than B-frames. In addition, B-frames do not have the temporal error propagation problem. Hence, only the error prevention and concealment for I- and P-pictures are examined herein.

Error concealment is commonly used to reduce the damage from the propagation of errors. Utilizing the combined spatial and temporal error concealment technique resulted in notable improvement in a non-layer coding (Aign and Fazel, 1995). The spatial error concealment is used for damaged areas of I-frames because the temporal concealment is not applicable due to existing no motion estimation. It interpolates each pixel of the whole damaged MB with the adjacent pixels of the four neighboring MBs (Aign and Fazel, 1995; Fern'andez et al., 1996). The combined spatial/temporal error concealment with motion vector interpolation is applied to the P-frames and B-frames. In particular, the spatial error concealment is used for intra-coded MBs and the temporal error concealment with motion vector interpolation is used for inter-coded MBs (Jeng and Lee, 1991; Kinoshita et al., 1993; Ohta and Kitami, 1991).

3.2. Enhancement layer error propagation and concealment

The enhancement layer cells consist of the residual error signal between the base layer and original video sequence. Errors in the enhancement layer will not cause serious image quality degradation since no temporal error propagation exists. Therefore, we simply ignore the damaged area when errors in the enhancement layer are detected and only use the base layer information to reconstruct the images.

3.3. Two-layer error propagation prevention algorithm

The error propagation in the temporal domain is caused by out-of-synchronization between the encoder and the decoder states. The encoder cannot reach the same state as the decoder because it does not have the information about the errors in the decoding bitstream. For instance, the MBs pointed by the motion vector at the decoder may contain incorrect data and the reconstructed image quality will be deteriorated if the frames buffered in the encoder and the decoder have different contents due to transmission errors.

The temporal error propagation prevention method is applied to two-layer video coding assuming that a low-rate reverse channel is available (Wang and Chang, 1999). The error propagation prevention is only necessary for the base layer bitstream since temporal error propagation exists only in the base layer. The procedure resembles the non-layer error propagation prevention algorithm. The receiver acknowledges the starting address of the damaged MBs via the reverse channel when it detects an error in the I- or P-frames. The transmitter, having received the notice, simply fills in all the pixels in the rest of the erroneous slice with an extreme value, e.g., 'infinity,' and continues the encoding process. With the 'infinity' marked MBs, the following P- or B-pictures are unlikely to have motion estimation referred to these MBs because of the large differences in pixel values. Thus, further error propagation is prevented. Practically, the 'infinity' symbol can be represented by the most positive number in the processor or by a separate bit. In addition to referring to a different area with low distortion for a damaged slice, the encoder can also change the encoding mode to the intra-mode for P-pictures or to the backward prediction mode for B-pictures. Thus, the reconstructed image quality can be maintained. Furthermore, the overhead for the feedback operation is low as only the ID of the lost MB, which includes the frame ID and the MB location in a frame, needs to be acknowledged.

The error prevention concept and the error concealment techniques are combined into two procedures performed at the receiver and the transmitter as shown in Figs. 3 and 4, respectively. At the receiving end, it performs error detection for each type of frames when the receiver gets a frame. The cell loss is detected by the base layer bitstream in the receiver. Prevention and error concealment are performed for the base layer and the damaged slices of the enhancement layer are ignored. At the transmitting end, the error prevention action is only applied to the P- and B-pictures of the base layer.

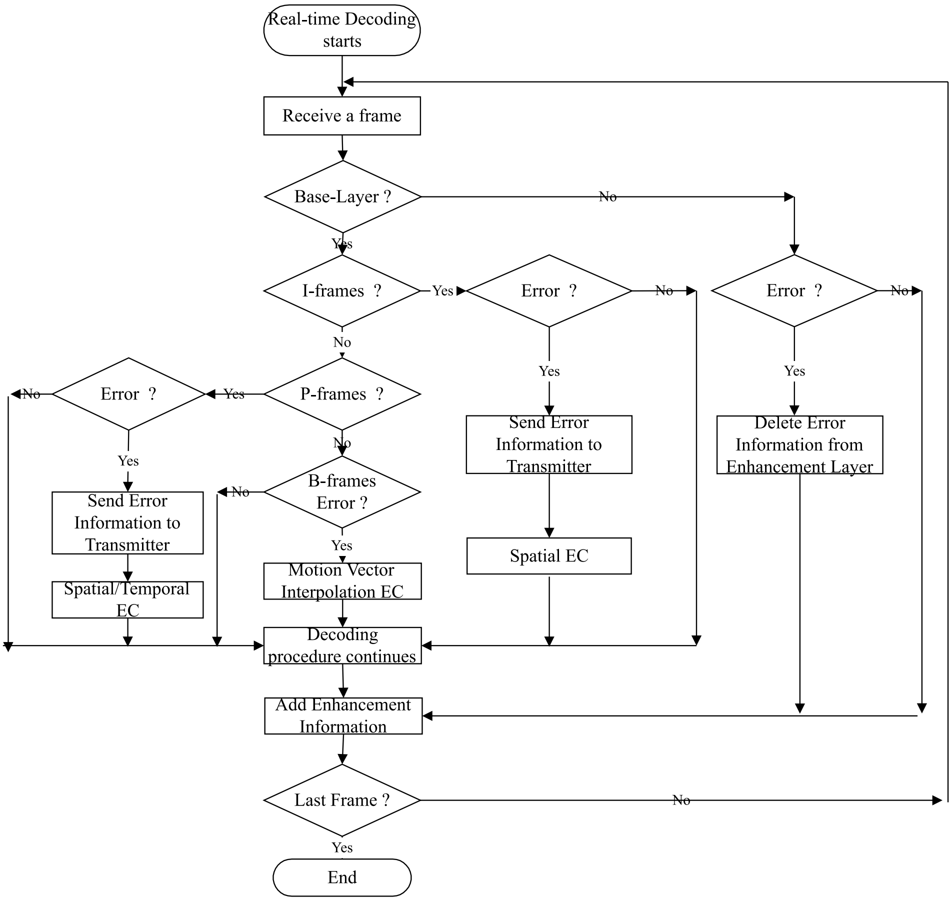


Fig. 3. The error prevention and concealment procedure of two-layer video source coding operated at the receiver.

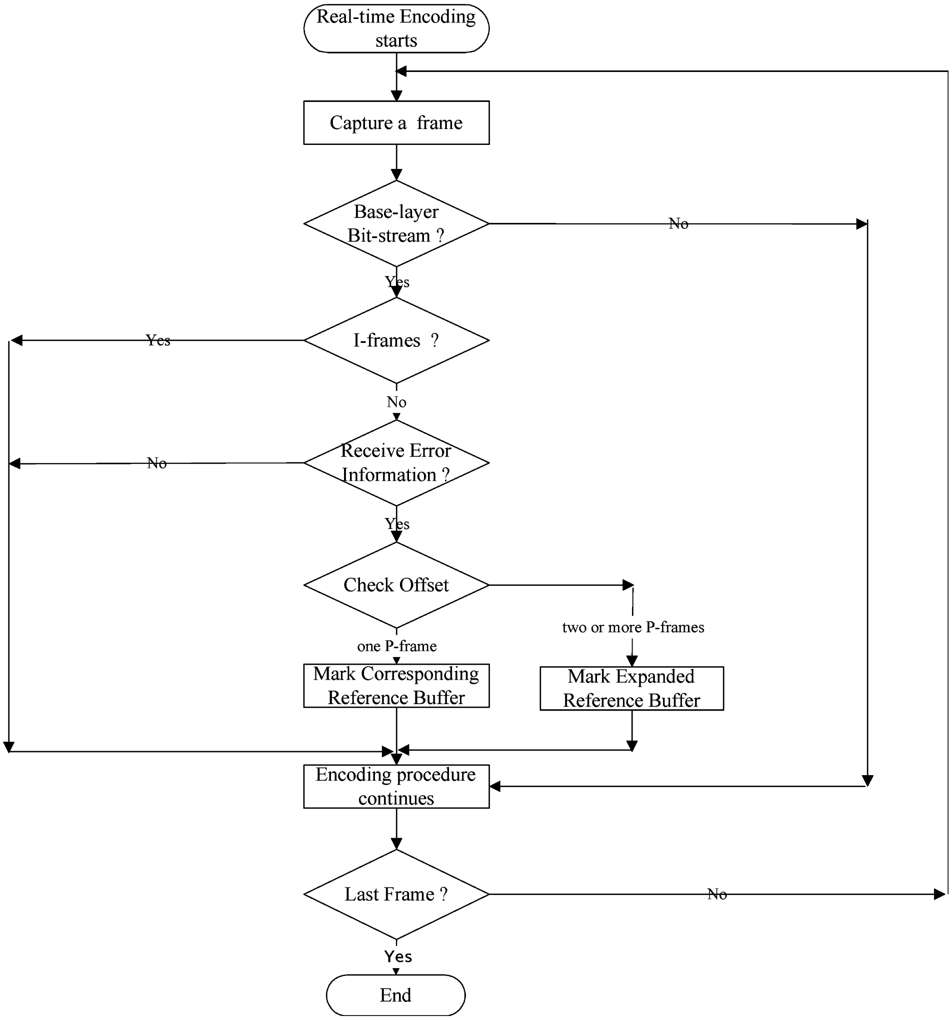


Fig. 4. The error prevention procedure of two-layer video source coding operated at the transmitter.

4. Simulation results

An MPEG coder based on TM5 was used in the error prevention and concealment simulations (ISO/IEC/JTC1/SC29/WG11, 1993). The video coding and ATM networking functions were run under Unix operating system. The simulations were carried out under conditions that the overall cell-loss rate was controlled fewer than 8%. The peak signal-to-noise ratio (PSNR) between the reconstructed and original images was used as an objective image quality measure. The video sequences, including 'Table Tennis,' 'Football,' and 'Flower,' with CIF format (24 fps, 352×240 pels, 4:2:0 chrominance format, twelve pictures per GOP, fifteen slices per picture, and one slice per MB row) were MPEG coded at 2.5 Mbps, i.e., 6511 cells/s. The average bitrate of base layer is 1.75 Mbps and the average bit rate of enhancement layer is 0.75 Mbps. The feedback channel was assumed error-free.

4.1. Two-layer video coding with single priority transmission scheme

The random cell loss in certain frames is controlled to examine the impact of errors in different types of frames. The average PSNR reductions for whole sequence with various concealment and prevention techniques at the cell-loss rate 10^{-2} are given in Table 1 for I-frame errors, and in Table 2 for the first P-frame (frame 3) errors, respectively. Comparisons of different concealment and prevention/concealment techniques revealed that the spatial interpolation error concealment (EC) could substantially reduce error damage. However, the degradation is still serious compared with the error-free case as the proposed ECP technique yielded the best performance among all tested techniques: 0.43–0.55 dB degradation.

Fig. 5 shows the PSNRs with the various concealment and prevention techniques of the 12 frames of the first GOP in the 'Football' sequence. The cell loss was randomly generated with a loss rate of 2×10^{-3}. One-cell losses took place in frame 0 (I-frame), 2 (B-frame), 3 (P-frame), 4 (B-frame), 5 (B-frame), and two-cell or three-cell losses occurred in frame 7 (B-frame), 8 (B-frame) in the base layer of this specific example. In the enhancement layer, one-cell losses happened in

Table 1
Average PSNR reductions of 'no EC & EP' (no error concealment and error prevention), 'EC' (spatial interpolation), and 'ECP' (error concealment and error prevention) for Y, U, and V components of I-frames at cell-loss rate 10^{-2}

	Average PSNR reductions in dB		
	No EC & EP	EC	ECP
Y	10.19	1.93	0.43
U	14.48	0.37	0.06
V	17.55	0.88	0.11

Table 2
Average PSNR reductions of 'no EC & EP' (no error concealment and error prevention), 'EC' (spatial interpolation), and 'ECP' (error concealment and error prevention) for Y, U, and V components of the first P-frames in GOPs at cell-loss rate 10^{-2}

	Average PSNR reductions in dB		
	No EC & EP	EC	ECP
Y	9.68	1.61	0.55
U	13.32	0.15	0.05
V	15.95	0.16	0.10

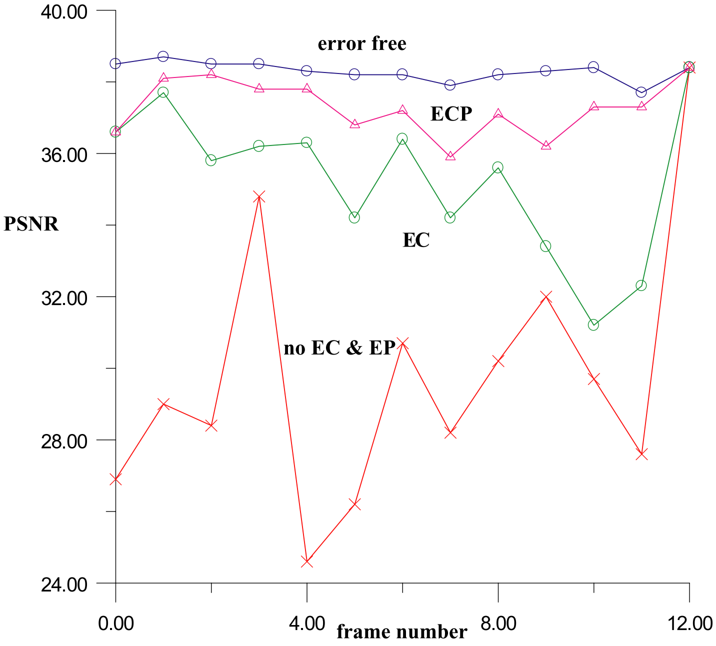


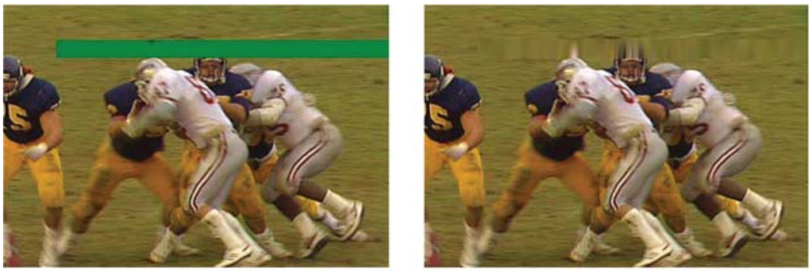
Fig. 5. The PSNRs of the video sequence 'Football' 12 frames with various techniques against random cell loss at the rate 0.2%.

frame 2 (B-frame), 10 (B-frame), 6 (P-frame), and two-cell losses occurred in frame 0 (I-frame). In other frames, the quality is also degraded even though no cell loss occurs, except when the ECP technique effectively terminates the error propagation.

Fig. 6 shows the effect of error prevention and error concealment for the above case. Fig. 6a presents an example of a video frame 0 (I-frame) that was contaminated by one error in the base layer bitstream and by two errors in the enhancement layer bitstream. The spatial propagation of errors was manifested as the loss of a slice. Fig. 6b presents the one new error in the base layer bitstream and the errors propagated from the previous frame 0 (I-frame). Fig. 6c and d demonstrate that although frame 4 (B-frame) and frame 5 (B-frame) had only one error, serious error propagation took place from the previous frame 0 (I-frame) and 3 (P-frame). Fig. 6e displays the I-frame with spatial interpolation EC. Fig. 6f–h illustrate the corresponding P-frames and B-frames with ECP that yielded notably improved quality.

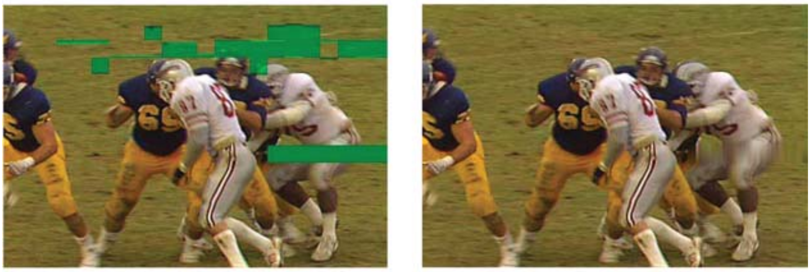
4.2. Two-layer video coding with dual-prioritized transmission scheme (DPTS)

Two-layer coding with VBR base layer and enhancement layer was also used in the simulations. Some simulation parameters of DPTS are given below with a brief explanation for the numerical values selected.



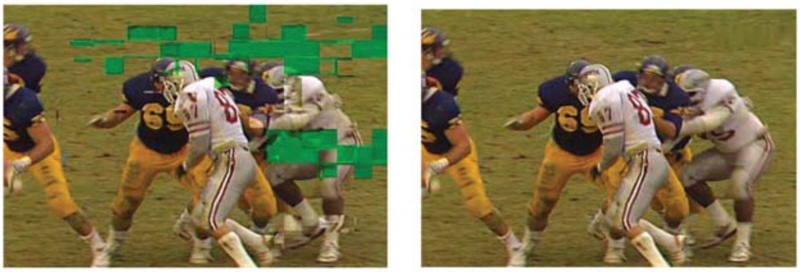
(a) Frame 0 (I-frame) with cell losses in BL and EL.

(e) Frame 0 (I-frame) with two-layer spatial EC.



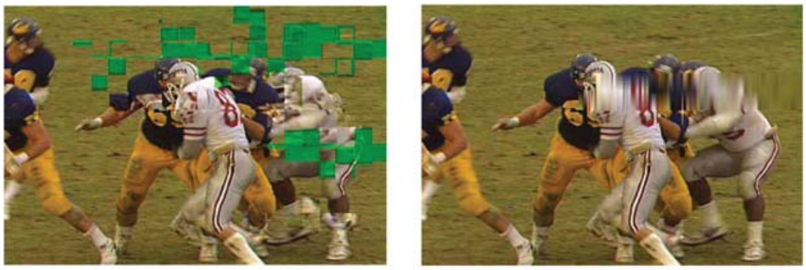
(b) Frame 3 (P-frame) with cell losses in BL with error propagation.

(f) Frame 3 (P-frame) with two-layer ECP.



(c) Frame 4 (B-frame) with cell losses in BL and EL with error propagation.

(g) Frame 4 (B-frame) with two-layer ECP.



(d) Frame 5 (B-frame) with error propagation.

(h) Frame 5 (B-frame) with two layer ECP.

Fig. 6. The effect of error propagation prevention and error concealment for the ‘Football’ sequence.

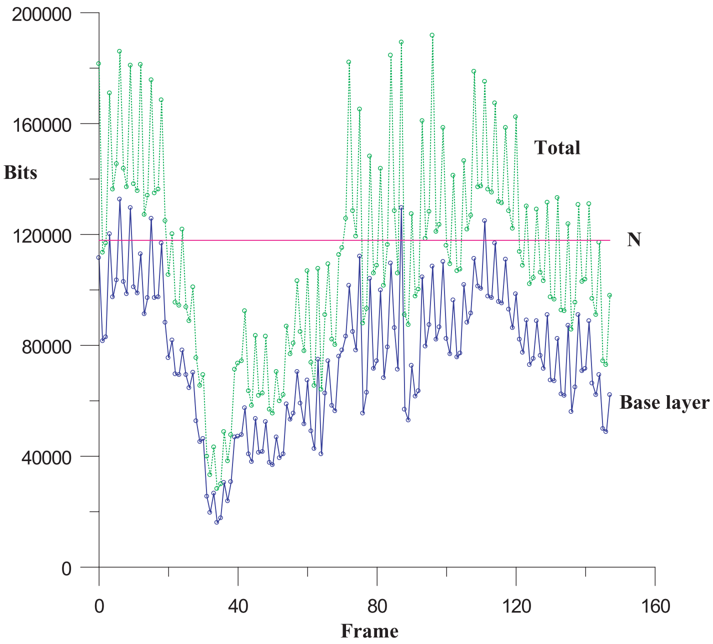


Fig. 7. Bit rate per frame of a typical two-layer VBR video.

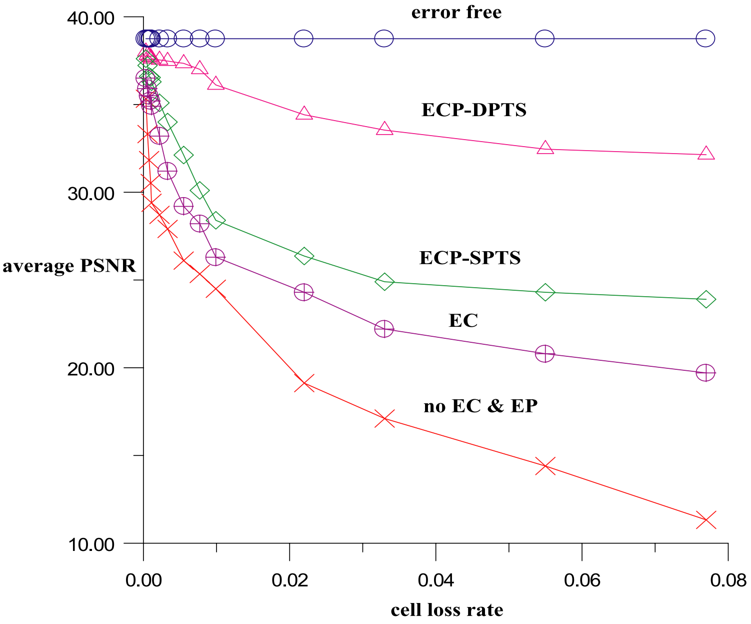


Fig. 8. The average PSNRs of the ‘Football’ video sequence with various techniques at random cell-loss rates 0.1–8%.

- *Frame-period:* T is 41.67 ms to match the frame rate of 24 fps.
- *Maximum delay jitter:* T_j is set to 7.6 ms to support real-time video transmission.
- *Token pool size:* A large buffer size may generate a smooth traffic but with the cost of large delay. In simulations, the maximum token pool size B is set at 35 cells to accommodate the delay jitter.
- *Maximum admitted number of cells:* $N = \gamma * T + B = 6511 * 1/24 + 35 = 307$, which is calculated based on Eq. (1).

Fig. 7 shows the 'Football' sequence, which is 150 frames in length and with VBR base layer and enhancement layer. The threshold of the bitrate per frame is N. Cells that have no token in the token pool will be tagged and may be lost when congestion happens in the network and the bitrate per frame exceeds the maximum admitted rate $307 \times 48 \times 8 = 117.890$ kbit. Although the average rate is below N, the bitrate of the base layer of several frames can even exceed N, and they are tagged, e.g., frame 3, frame 6, frame 9, frame 15, frame 87, and frame 111. Consequently, random cell loss can occur in both the base layer and the enhancement layer. The ECP–DPTS method in Fig. 1 was applied to prevent error propagation.

The average PSNR of the video sequence 'football' was computed to evaluate the performance of the ECP–DPTS method at various cell-loss rates. A sufficiently long test sequence was formed by concatenating the original sequence with itself by 100 times. Figs. 8 and 9 reveal the average PSNRs at the average cell-loss ratios 0.1–8% for comparing DPTS and SPTS with both the random and burst cases. In SPTS, all cells are with equal probability to be dropped. In DPTS, low priority cells are the first to be dropped and some high priority cells may also be dropped if the bitrate of

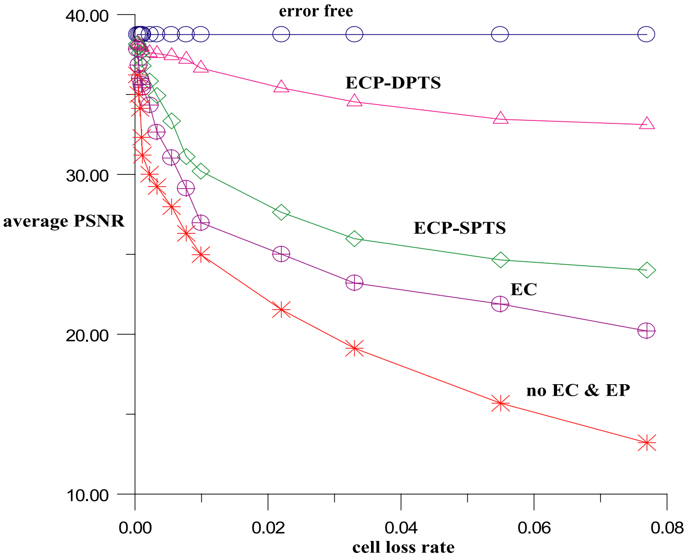


Fig. 9. The average PSNRs of the 'Football' video sequence with various techniques at burst cell-loss rates 0.1–8%.

the frame exceeds N. However, the results are all compared at the base of the same overall cell-loss rate. The average burst length is set to 4.68 cells in this simulation. The random case yields worse picture quality than the burst case. The ECP–DPTS technique outperforms other concealment techniques at all ranges of tested cell-loss rates.

5. Conclusion

The ATM network is effective for high-end real-time video transmission because it supports VBR video bitstream transmission and the connection of heterogeneous networks. Therefore, delivering scalable video over ATM is quite appropriate. It also allows dual-priority classes of cells through the setting of the cell-loss priority bit. The error effects will be restrained if the DPTS is properly operated. The two-layer video coding and DPTS method proposed herein confine cell loss to a low priority layer in case of collisions in the network to effectively reduce the error effects. In addition, the ECP–DPTS method stops temporal error propagation when long bursts in VBR video bitstream or unavoidable cell losses in base layer bitstream exist. Simulation results demonstrate that the ECP–DPTS with feedback can effectively isolate the error and conceal the damage to give satisfactory performance even when the cell-loss rate is higher than 1%.

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