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# Adaptive Spatial-Temporal Error Concealment with Embedded Side Information

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## Abstract

Error concealment (EC) is an important technique to recover the lost/damaged video data in transmitting video over error prone networks such as the Internet or wireless networks. Different EC strategies have their strength and weakness for different scenarios. Therefore an adaptive EC approach is desired. However, it is generally difficult for the decoder to figure out which strategy works the best for a specific case. This paper proposes to use data embedding to convey the necessary *high level* side information in a standard compliant way to help improve the decoder's EC performance. We show that the EC "mode" information (i.e.., whether spatial EC or temporal EC should be used) is critical for a lightweight adaptive spatial-temporal EC approach. Experiments show that with such side information embedded in the standard compressed bitstream, significant quality improvement can be achieved in recovering the lost video packets.

*Keywords: error concealment, adaptive error concealment, data embedding, data hiding, side information*

## 1 Introduction

The dramatic growth of the Internet and mobile wireless networks has allowed ubiquitous access to multimedia data. The unique characteristics of wireless networks such as limited and time-varying bandwidth, error prone nature, and low power wireless devices have imposed significant challenges to the transport of multimedia information. Compressed digital media is very vulnerable to error prone communication channels. The problem of recovering lost data in compressed video is thus of importance. Common techniques to combat error-prone networks include Forward Error Correcting (FEC), Automatic Repeat Request (ARQ), error resilient encoding, and error concealment (EC). Error concealment techniques aim to recover the lost image data by taking advantages of the spatial and/or temporal correlation of video data without incurring much overhead and delay. They compliment other error control techniques, and can be applied when there is still data loss after other potential error recovery techniques have been applied. This is usually the case because practical constraints (e.g., delay and bandwidth constraints) of a video communication system often prevent an extensive use of FEC and ARQ. For wireless video communications, the complexity of the error concealment techniques has to be taken seriously due to the low power nature of the wireless devices such as PDAs or video phones.

The effects of channel errors/loss on the reconstructed video sequence depend on the structure of the codecs as well as the transport mechanisms employed. Packetization is a common way to localize errors in the bitstream, and provides mechanisms for resynchronization in case error/loss occurs. In general, it is much difficult to conceal contiguous damaged blocks than isolated blocks. To facilitate loss recovery and to minimize the effect of packet loss, interleaved Group of Blocks (GOBs) or interleaved Macroblocks (MBs) based packetization techniques have been proposed. For example, in the RTP packetization scheme recommended in [1][2] for H.263 compressed video, all even GOBs of a frame is packed into one RTP packet, and all odd GOBs into another. In the latest video coding standard H.264 or MPEG-4 AVC [3], flexible macroblock ordering (FMO) is allowed, which assigns MBs to slices using a macroblock allocation map, not necessarily in the raster scan order. With FMO, one can packetize neighboring MBs into different slices/packets so that in the case of packet loss, the lost MBs will be isolated, and can thus be more effectively concealed.

Different EC strategies have their pros and cons for different scenarios [4]. An adaptive approach that aims to exploit the advantages of different EC strategies is thus desirable. However, it is generally difficult for the *decoder* to figure out which strategy works the best for a specific case. On the other hand, the relative performance of different EC strategies for a specific case can be easily evaluated at the *encoder* side, thanks to the availability of all original video data. If the relative performance information can be delivered to the decoder, then the decoder's EC module can choose the right EC strategy for each lost MB to improve the overall reconstructed video quality. In this paper, we propose to use data embedding to convey the necessary *high level* side information, as opposed to simply some redundant information, in a standard compliant way to help improve the decoder's error concealment performance. The advantage of using data embedding to convey the side information is that no explicit "out of band" mechanism/protocol is required to communicate the side information, and the resultant bitstream is standard compliant, thus can be decoded by a normal standard decoder that is not aware of the embedded side information; on the other hand, a decoder equipped with the proposed advanced EC capability will be able to extract and use the embedded side information to help improve the EC performance. Furthermore, the bit overhead or quality degradation introduced by data embedding is very limited, and the complexity associated with the proposed adaptive error concealment scheme is also very reasonable. We will show that the EC "mode" information, i.e., which strategy should be used for a particular lost MB, is critical for an adaptive spatial-temporal EC approach, and thus can be embedded into the compressed bitstream to significantly improve the decoder's EC performance.

This paper is organized as follows. Section 2 briefly reviews some of the common signal-processing based EC techniques. The general concept of exploiting data embedding to facilitate error concealment is discussed in Section 3. Section 4 proposes to use data embedding to convey the high level EC "mode" information for an adaptive lightweight spatial-temporal EC approach. Simulation results are presented in Section 5. Section 6 draws the conclusion.

# 2 Spatial-Temporal Error Concealment

In this section, we briefly review some general approaches for post-processing based error concealment. The post-processing based EC basically exploits the correlation between the damaged/missing block and its spatially and temporally adjacent blocks. It relies on the fact that there still exists some unexploited redundancy (between the lost data and the correctly received data) in the compressed bitstream to allow such exploitation by EC, which is usually true for most video coding techniques, especially those designed to work with error prone networks such as the Internet and wireless networks.

**Motion-compensated temporal prediction**

Temporal error concealment techniques use the temporally neighboring frames to conceal the loss of the current frame, based on the assumption that the video content is smooth and continuous in the time domain. A very simple scheme for temporal error concealment is to just copy the MB at the same spatial location in the previous frame to conceal the lost MB. This essentially assumes that the motion vector (MV) is zero. Thus it works only when there is no motion or very slow motion in the scene. If the motion vector is not damaged or lost, then the motion-compensated prediction from the reference frame can be used to conceal the damaged block. This can often produce good results, especially when there is little irregular motion in the scene. The problem, however, is that the MV and the coding-mode (intra/inter) of a MB may not be available when a packet is lost. One can try to estimate the lost MV, but the accuracy of the estimation may affect the results significantly. Even with the correct MV, the decoder in general does not know how close the motion-compensated prediction is to the original MB. A good measure to evaluate the accuracy of the estimation/prediction is the spatial smoothness of the pixel values around the boundary between the estimated MB and its neighboring correctly received MBs. In [5], it was proposed to choose one from a set of candidate MVs available from neighboring MBs that minimizes the boundary variation between the concealed MB using the candidate MV and its neighboring correctly received MBs. This approach, however, may not be applicable in some cases (e.g. scene change frames, or Intra MBs with large irregular motion).

### Spatial/frequency interpolation

The second class of techniques is to interpolate the lost region from its spatially neighboring available pixels or coefficients. They rely on the inherent spatial smoothness of the image data. These techniques could be very simple, but a general problem is that they may blur the edges, and may not be able to recover very complex structures. With some extra complexity, an edge-based directional interpolation can usually provide much better results than bilinear interpolation [6][7]. For example, a simple scheme was proposed in [6] where the edge direction is estimated by evaluating the pixel-wise difference between two sets of projection data available on the block boundary. Directional interpolation along the estimated edge direction is then applied to recover the lost block. Projection onto convex sets (POCS) based error concealment schemes have also been studied [8], which iteratively use the smoothness assumption and the pixel value range constraint. The performance of such an approach typically depends on the accuracy of the underlying assumptions/constraints.

### Hybrid spatial-temporal error concealment

There have been some attempts to combine both spatial and temporal error concealments to improve the performance. For example, the smoothness constraint can be applied to both temporally and spatially neighboring pixels to construct a maximally smooth concealed block [9]. A typical problem with such an approach is the potential loss of high frequency information, attributed to the imposed smoothness constraint. A hybrid temporal/spatial error concealment scheme is recently proposed in [10] by applying the “updating principal components (UPC)” statistical model to both motion vectors and spatial pixels in the region of interest (ROI). Under the assumption that video objects/ROIs can be extracted, and with proper training of the UPC models, the proposed scheme can achieve much better results than previous schemes that were designed mainly based on heuristics, at the cost of some extra computation. In general, however, there has been very limited success in this joint effort, mostly due to the lack of effective and simple mechanisms at the decoder to merge the results from both spatial and temporal error concealments. The complexity involved in the process is also of significant concern, especially for low power wireless devices.

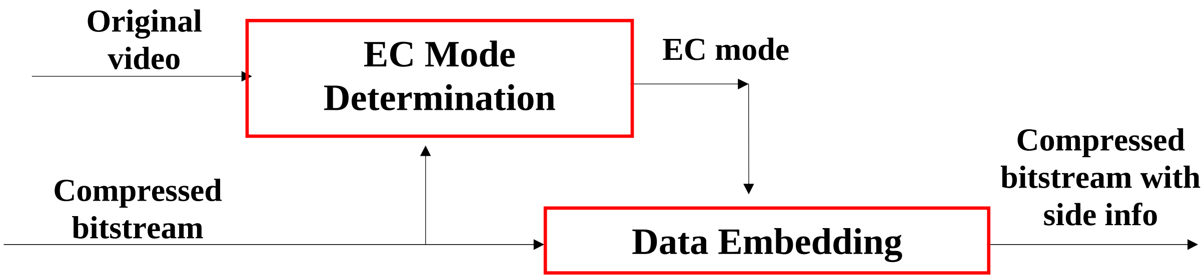
## 3 Data Embedding for Error Concealment

Data embedding provides an efficient way to convey side information that can be used to achieve better performance and additional functionalities for many different applications, e.g., in multimedia communication [11][12][13].

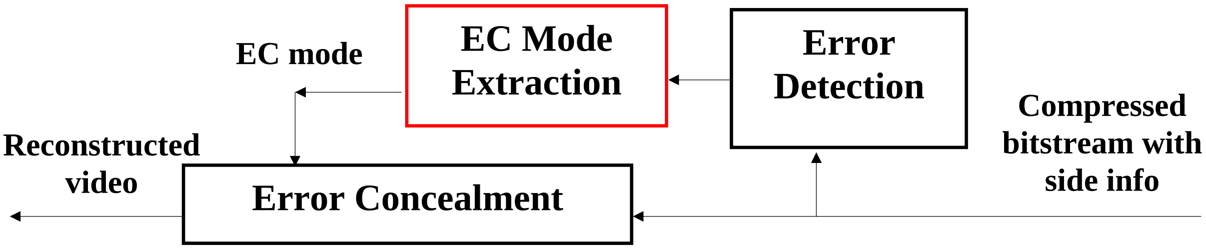
To our best knowledge, we are one of the firsts to suggest using data embedding for error concealment/resiliency purpose *in a standard compliant way*. In [11], we proposed to use data embedding to convey a rate-distortion based significance score associated with an image block that is used to signify the effectiveness that the associated block can be spatially interpolated based on its surrounding image data. The embedded significance score in the bitstream can later be extracted by the server or intermediate network nodes to assist real-time dynamic rate shaping by intelligently dropping some selective blocks in transmitting compressed video over time-varying channels. It has been shown in [11] that the bit-overhead introduced by data embedding can be made very low. In particular, it is possible to achieve fractional overhead-bit per embedded information bit. For example, it has been shown [11] that by embedding one bit to each 8x8 block using an *odd-even scheme* that enforces the sum of all the quantized DCT coefficient levels in a block to be even or odd, it incurs no bit overhead and no perceptual degradation of the video quality.

In a recent work [12], Yin et al proposed to use data embedding to facilitate spatial EC by embedding edge directional information of a block into a companion block prior to the transmission. This edge information can then be extracted at the receiver side for directional filtering to recover the lost blocks, thus reducing the computational load (used in inferring the edge directional information) at the decoder. Similar idea has also been used to embed some important redundant information such as the motion vector information in the compressed bitstream to facilitate motion-compensated error concealment at the decoder [13]. Parity check data is generated from the MV information of several GOBs and is embedded into companion GOBs so that the embedded data rate is reduced, at the expense of error resilience strength and some delay.

In general, data embedding may potentially introduce bit overhead or video quality degradation. Therefore, it is important to identify and extract highly summarized information that is critical to the performance improvement at the decoder. This will not only improve the EC performance, but also avoid the potential negative impact on the bit rate or video quality. In this paper, we propose to use data embedding to facilitate the adaptive employment of spatial or temporal error concealment at the decoder. As discussed in Section 1, it is generally very difficult for the decoder to figure out which one performs better than the other one for a particular MB, due to the lack of information about the original MB. But the encoder is capable of knowing exactly which one performs better. This EC "mode" information can thus be determined at the encoder and then embedded into the compressed bitstream as side information so that the decoder can take advantage of it when necessary.



(a) Encoder side



(b) Decoder side

Fig. 1: The general diagram of the proposed adaptive spatial-temporal error concealment scheme.

## 4 Adaptive Spatial-Temporal Error Concealment with Side Information

In this section, we describe an adaptive spatial-temporal error concealment scheme that utilizes some important side information embedded in the standard compressed bitstream to improve the EC performance. The basic idea is to determine the EC mode information at the encoder side, which is then embedded into the compressed bitstream and can be later extracted as necessary at the decoder side to facilitate the EC operation. Since typically more information (e.g., the original frames) is available at the encoder side, this side information is more accurate than what can be determined at the decoder side where the original frame is not available. It also reduces the computation load of the decoder, which is desirable for video communication to low power wireless devices.

Fig. 1 shows the general diagram of the proposed adaptive spatial-temporal error concealment scheme. Specifically, at the encoder side, we will compute the error concealed MBs using both spatial and temporal error concealment separately. Using the original video frame available at the encoder as the benchmark, we then identify which one reconstructs a better MB in terms of mean square error (MSE), with respect to the original MB. This one bit information, referred to as “EC mode” in the paper, is then embedded into the next row of MBs (GOB) using the even/odd data embedding approach as described below. At the decoder side, when a MB or a GOB is lost, this EC mode information can be extracted from the neighboring correctly received GOBs, and the appropriate EC operation (spatial or temporal) will be applied.

For the recovery of each lost MB, we will assume all other MBs in the same GOB are also lost. This is consistent with the packetization of most standard video codecs. Therefore only MBs in the previous GOB and/or the next GOB will be used in the concealment of the current MB. Note that in some cases, for example, when flexible macroblock ordering is used for H.264 codec [3], the neighboring MBs in the same row may also be available for concealment, which should generally provide better results for both spatial and temporal concealments. Although the general idea presented in this paper is equally applicable to such specific scenarios and should result in better error concealment performance, it is not the focus of the paper. The specific spatial error concealment and temporal error concealment schemes to be used are described as follows. They are chosen mainly because of their good performance and computational simplicity, which is critical for low power wireless devices. Other error concealment schemes [4][7][10] can also be used that may result in better performance at possibly the cost of increased computational complexity.

**Spatial error concealment**

We use spatial directional interpolation along the estimated edge direction for spatial error concealment. We only consider three candidate edge directions (135, 90, and 45 degrees), although allowing more candidate directions will provide better results at the cost of increased complexity. By slightly extending the scheme proposed in [6], we estimate the edge direction for a particular MB as the one that results in minimized pixel-wise absolute difference between two sets of projection data locating on, respectively, the top and bottom GOB boundaries associated with each missing/damaged MB, denoted as $P_k^{(1)}(i)$ and $P_k^{(2)}(i)$ where $k$ is the index for the edge directions and $i$ is the index for pixels within one projection data set. In other words, find k* such that

$$k* = \arg\min_k \tfrac{1}{N} \sum_{i=1}^{N} |P_k^{(2)}(i) - P_k^{(1)}(i)|\,.$$

where $N$ is the total number of pixels in each projection data set. For example, for the 45$^o$ direction (see Fig. 2), one set of projection data consists of the 16 boundary pixels in the MB above, and another 16 in the neighboring MB to the northeast. The other set of projection data consists of the 16 boundary pixels in the neighboring MB to the southwest, and another 16 in the MB below. Once the edge direction is determined, linear interpolation along that direction is applied to interpolate the pixels in the lost MB from the two projection data sets. The computation overhead of this error concealment scheme is about 4-5 operations (multiplication or addition) per missing pixel.

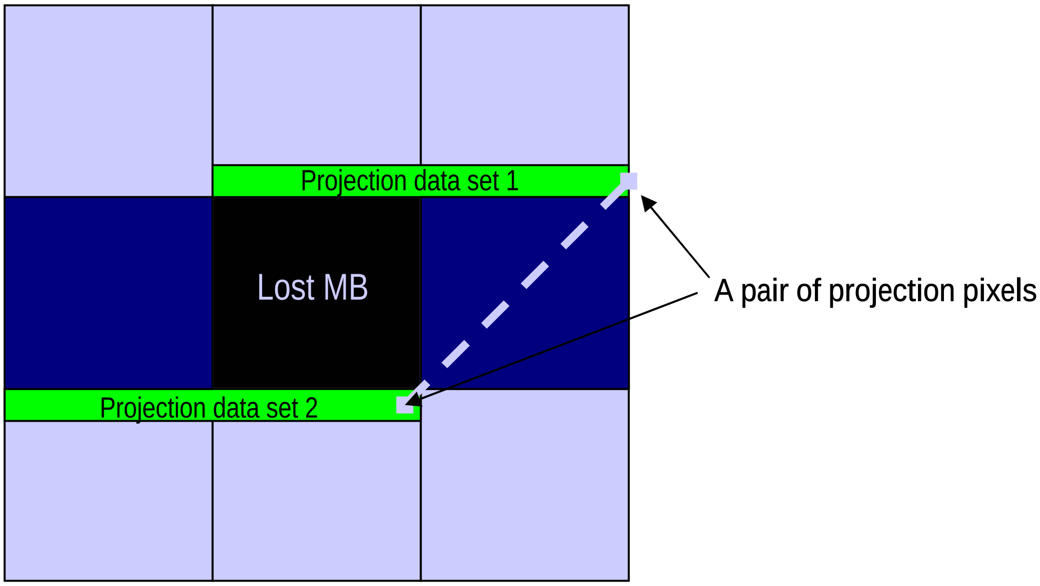


Fig. 2: Configuration for projection data sets for the 45$^o$ direction

**Temporal error concealment**

We first estimate the MV by choosing the one that results in minimal block boundary pixel variation [5] based on a set of candidates, including MVs of the top three, and the bottom three neighboring MBs, the MV of the MB located at the same spatial location in the previous frame, average of the above MVs, and the zero MV. For calculating the block boundary pixel variation, only pixels around the top boundary and bottom boundary of the lost MB are used. Motion-compensated error concealment using the estimated MV is then applied to conceal the lost MB. The complexity of this approach is about 3-4 operations per missing pixel.

**Data embedding method**

The even-odd embedding scheme is referred to as hiding one bit to one 8x8 block by forcing the sum of the quantized AC levels to be odd or even (by changing at most one DCT coefficient level to its nearby level, which is equivalent to quantizing the original coefficient to the second most nearby quantization level). On the average, about 50% of the embedding actually involves the change of one DCT coefficient level value, and the impact on the bit rate should be asymptotically zero if we assume an equal probability of even and odd and the coefficients are uniformly distributed within a quantization bin. To minimize the potential impact on the perceptual quality, one can exploit the visual masking effect by choosing the largest AC coefficient to change the level value (by one unit, if necessary) [11]. Typically a larger DCT coefficient can mask the quantization error introduced to it more effectively [14], or equivalently the quantization step size can be magnified by a factor that depends on the coefficient amplitude without introducing extra perceptual distortion. The perceptually optimized embedding method described above will ensure that the coefficient whose quantization level is changed for bit embedding maintains equal/close perceptual quality as other coefficients.

We will embed the EC mode bits of MBs in the even GOBs to the coded 8x8 blocks of the odd GOBs, and vice versa. For example, for a QCIF size frame, only 99 EC mode bits need to be embedded for each frame. In the rare case that there are less than 99 *coded* 8x8 blocks (the remaining 8x8 blocks are skipped in the encoding process due to small residue) in a frame, for example when there is very little motion in the scene, we will embed the side information sequentially until all *coded* 8x8 blocks have been used. The rest of the EC mode bits will not be embedded, and temporal EC will be used by the decoder for their associated lost MBs. Note that in such rare cases, typically there is little motion in the scene, and temporal EC can be very effective for those MBs whose EC mode bits are not embedded, and is thus preferred.

## 5 Simulation Results

Simulations have been done to test the effectiveness of the proposed adaptive spatial-temporal error concealment scheme on many different video sequences. The experimental setting is as follow. We consider a worse case scenario and assume that every other GOB is lost, i.e., a packet loss rate of 50%. This is consistent with the RTP packetization scheme recommended in [1][2] for H.263 compressed video, where all even GOBs of a frame is packed into one RTP packet, and all odd GOBs into another. When reconstructing a frame, the reference frame is assumed to be correctly received. This is to isolate the effect of temporal error propagation, and to signify the gain the proposed scheme can achieve over other prior solutions on a frame-by-frame basis. In other words, this setting tests the packet loss effect and the error concealment performance on every single frame, which allows us to examine the performance of the error concealment schemes on frames with many different characteristics. Our experiment shows that the bit overhead and perceptual quality degradation introduced by the data embedding process is negligible. For example, in one case where the video sequence (size 320x224) is coded at 256 kbps and 10 fps, with data embedding, the average PSNR value is reduced by 0.08 dB while the bit rate is also reduced by 0.002 bpp. This is because the side information we embed is highly concise, i.e., only one bit is embedded for each MB, and about half of the embedding actually do not introduce any extra distortion. In other words, only about 140 coefficients will be affected for each frame in the above example.

We compare the following six error concealment schemes:

- Use_ZeroMV: where the MB in the same spatial location in the previous frame is copied
- Use_EstimatedMV: where temporal error concealment based on estimated MV is used alone

- SP/TP_w/o_SideInfo: estimate the coding mode (inter/intra) based on the neighboring available coding mode information, using the method described in [4], and then use temporal error concealment for inter MBs and spatial error concealment for intra MBs. This approach provides some level of adaptation, but is very ad hoc.
- SP/TP_w_SideInfo: use adaptive temporal or spatial error concealment based on the "EC mode" bits extracted from the bitstream at the decoder
- Use_OriMV_SP4intra: assume the original MVs are available, and are used for motion-compensated EC. Spatial error concealment is used for intra MB
- Use_OriMV_0MV4intra: same as above, except the MB in the same spatial location in the previous frame is copied to conceal a lost intra MB

Fig. 3 shows the PSNR results of the reconstructed video frames for the movie trailer sequence "hangingup" (size 320x224) on a frame-by-frame basis. This movie trailer consists of several scenes with very different characteristics; some have slow regular motion (e.g., the first scene shown in Fig. 3) while others have intensive motion; the frame spatial complexity is also different from scene to scene. The sequence is encoded at 256 kbps and a frame rate of 10 fps. The average PSNR values for the cases of SP/TP_w_SideInfo, SP/TP_w/o_SideInfo, Use_EstimatedMV, and Use_ZeroMV are 30.2 dB, 28.2 dB, 26.9 dB and 25.8 dB, respectively. It is seen that the side information helps to significantly improve the EC performance, when compared to the heuristic based SP/TP_w/o_SideInfo scheme. The PSNR gain is up to 4-5 dB for some frames, while being relatively small for some other frames. In fact, the temporal EC scheme with estimated MV works out just fine for the first few frames shown in Fig. 3 that have little/slow motion (as usually observed in video conferencing sequence), but significantly underperforms for most other frames with medium to high motions. The Use_ZeroMV approach results in very poor performance for this complex sequence. For many cases such as the scene change or high motion frames, spatial error concealment is very important. Note that the sharp PSNR dips in Fig. 3 correspond to scene change frames where it is seen that spatial error concealment provides significantly higher PSNR than temporal error concealment.

Fig. 4 shows that with the EC mode information embedded, even with 50% packet loss, the decoder can reconstruct a frame with decent quality. The EC mode bit conveys some information that is very difficult, if not impossible, to infer at the decoder side. Without the embedded side information, the SP/TP_w/o_SideInfo scheme has difficulty choosing the correct error concealment strategy for some MBs, resulting in some annoying artifacts (see Fig. 4(c)). Note that the measure of block boundary smoothness can not be used to select spatial EC or temporal EC because the measure will most likely be biased toward spatial error concealment because the spatial linear interpolation, whether resulting in good or bad reconstructed MB, preserves the smoothness across the block boundary. Fig. 4(b) shows that using temporal error concealment alone does not work for a sequence with medium to high motions where many MBs will be intra-coded. On the other hand, spatial error concealment can faithfully reconstruct many MBs, including those that contain edge structures, e.g., most of the erroneous MBs shown in Fig. 4 (c) are reconstructed faithfully by directional spatial interpolation in Fig. 4(d).

Fig. 5 shows that, if we assume that the original MVs are available for error concealment (for example, they can also be embedded in the bitstream redundantly [13]), it provides much better results than using the estimated MVs for this particular test sequence that has high and irregular motion. However, with only one bit EC mode information embedded for each MB, the proposed SP/TP_w_SideInfo scheme can achieve close PSNR performance as using the original MVs, without introducing any meaningful delay and bit overhead. For some frames (e.g., the last few frames shown in Fig. 5), the proposed SP/TP_w_SideInfo scheme can actually achieve better PSNR, which suggests that some MBs can be better recovered using directional spatial interpolation than using original MV based temporal prediction. Note that the average PSNR values for the cases of SP/TP_w_SideInfo, SP/TP_w/o_SideInfo, Use_OriMV_SP4intra, and Use_OriMV_0MV4intra are 30.2 dB, 28.2 dB, 30.4 dB and 27.7 dB, respectively.

# 6 Conclusion

In this paper, we discuss the use of data embedding for achieving improved error concealment performance for video communications over error prone networks. We point out the importance of identifying some high level information as the side information, as opposed to simply using redundant information, in such an approach. With high level side information identified, the bit overhead and/or quality degradation introduced by the data embedding can be very limited. We propose and study a lightweight adaptive spatial-temporal error concealment scheme, and show that the EC mode, i.e., using spatial EC or temporal EC, is a piece of very important and concise side information. Experiments show that with such side information embedded in the standard compressed bitstream, significant quality improvement can be achieved in recovering the lost packets.

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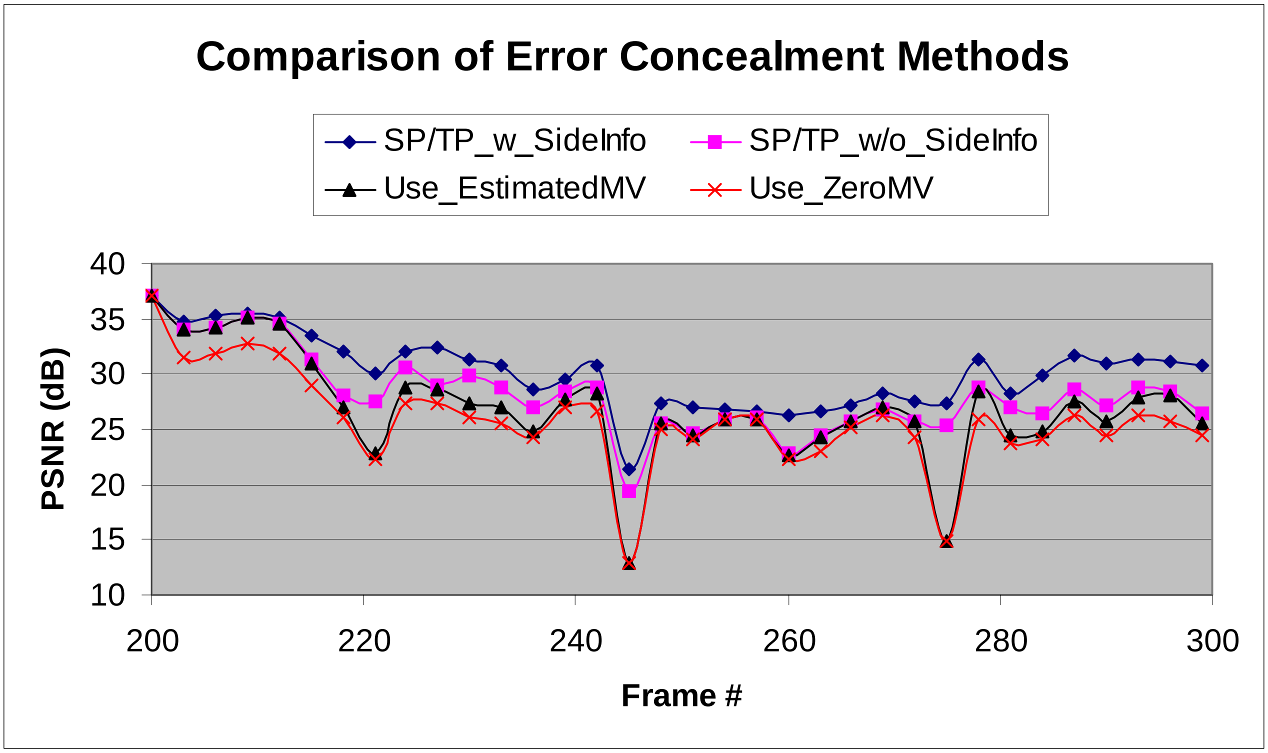
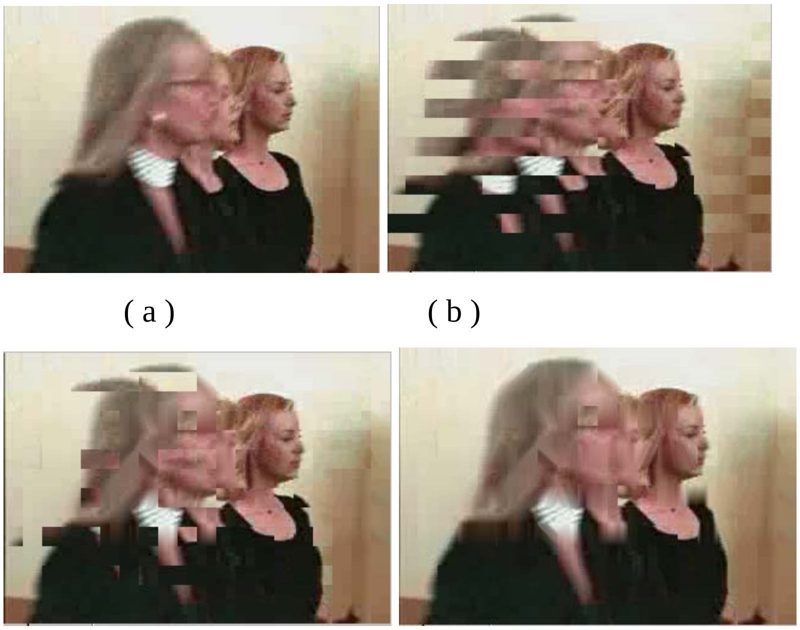


Fig. 3: PSNR comparison of different EC schemes for the “hangingup” sequence.



( a ) ( b )

( c ) ( d )

Fig. 4: Reconstructed frames using different EC schemes for the "hangingup" sequence, assuming every other GOB lost. (a): error free; (b): Use_estimatedMV; (c): SP/TP_w/o_SideInfo; (d): SP/TP_w_SideInfo

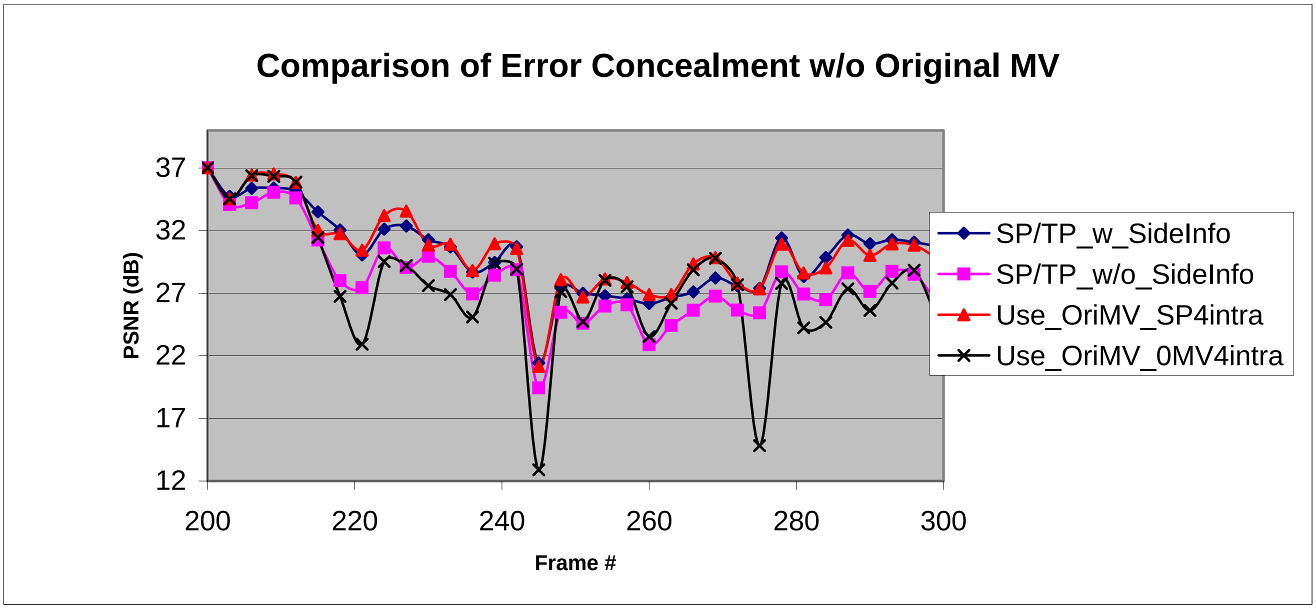


Fig. 5: Comparison of different EC schemes with or without original MV information.

## Biography:

**Wenjun Zeng** received his B.E., M.S., and Ph.D. degrees from Tsinghua University, China, in 1990, the University of Notre Dame in 1993, and Princeton University in 1997, respectively, all in electrical engineering.

He has been an Associate Professor with the Computer Science Department of University of Missouri, Columbia, MO since Aug. 2003. He was with PacketVideo Corporation, San Diego, from December 2000 to August 2003, where he was leading R&D projects on wireless multimedia streaming, encoder quality optimization, and digital rights management. From 1997 to 2000, he was with Sharp Labs of America, Camas, WA. Prior to that, he had work for Bell Laboratories, Murray Hill, NJ, and Matsushita Information Technology Lab, Panasonic Technologies Inc., Princeton. His current research interests include multimedia communications and networking, content and network security, and wireless multimedia. He was an active contributor to the MPEG4 Intellectual Property Management & Protection (IPMP) Extension standard and the JPEG 2000 image coding standard, where four of his proposals have been adopted. He has been awarded 9 patents.

Dr. Zeng has served as a Special Issue Guest Editor, Special Session and Panel Session Organizer, and Technical Program Committee Member for several IEEE international journals and conferences. He was the Lead Guest Editor of *IEEE Transactions on Multimedia's Special Issue on Streaming Media* published in April 2004. He is an Associate Editor of the *IEEE Transactions on Multimedia*, and is the Technical Program Co-Chair of the *Multimedia Communications and Home Networking Symposium, 2005 IEEE International Conference on Communications*, and the Chair of the *Workshop on Digital Rights Management Impact on Consumer Communications, 2005 IEEE Consumer Communications & Networking Conference*.