Hybrid Error Concealment Using Linear Interpolation

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ABSTRACT

In this paper a hybrid error concealment algorithm using linear interpolation is proposed. In the proposed hybrid algorithm, the selective motion field interpolation (SMFI) is employed to conceal the erroneous macroblock. The spatial and temporal boundary-matched errors are then used to check whether the SMFI conceals the erroneous macroblock properly. If the temporally recovered macroblock is reconstructed incorrectly, the spatial error concealment using linear interpolation is employed to conceal the damaged macroblock instead of SMFI.

It can achieve better performance subjectively as well as objectively over other error concealment techniques such as AMV, FBBM and MFI. Simulation was conducted on the H.263 codec and the experimental results reveal that the proposed algorithm significantly outperforms other concealment techniques.

Keywords: Hybrid error concealment, Selective motion field interpolation, Linear interpolation

1. INTRODUCTION

During image or video data transmission a bit error might cause the loss of single or multiple macroblocks in a coded image or video sequence because of the use of a compression algorithm in the coded sequence. The error propagation problem can be solved by error correcting codes (e.g., Reed Solomon codes), automatic retransmission request (ARQ) or error concealment technique [1]. Among them the error concealment is an effective technique since no overhead or redundancy is required. Error concealment can be performed in the temporal domain, spatial domain or frequency domain. The temporal error concealment attempts to use the data from the past frames to restore the lost data, while the spatial error concealment attempts to use the data in the present frame to restore the lost data.

To eliminate the effect of bit errors, many efficient error concealment algorithms have been proposed in recent years. The conventional temporal error concealment technique makes use of adjacent motion vectors of the erroneous macroblocks and the previously decoded frames to conceal the erroneous macroblock. The simplest and commonly used method is the Temporal Replacement (TR), which replaces the erroneous macroblock with its collocated macroblock in the previously decoded frame. Another scheme for reconstructing the motion vector of the erroneous macroblock attempts to employ a linear combination of motion vectors of surrounding macroblocks in the current or previous reference frames, such as using average of neighboring motion vectors (AMV), or using forward-backward block matching (FBBM) [2] or boundary matching [3]-[5] algorithm to search the best-matched macroblock in the previous decoded frames. Other algorithms employ the Lagrange or polynomial interpolation to recover the lost motion vectors from the neighboring motion vectors and reconstruct the erroneous macroblocks [6]-[7].

The previously mentioned temporal error concealment techniques usually use one estimated motion vector for the whole lost macroblock and then uses estimated displacement to conceal the erroneous macroblock. The disadvantage of such techniques is that incorrect estimation of the motion vector could lead to poor concealment of the whole macroblock. Al-Mualla et al. [8]-[9] suggested a technique referred to as Motion Field Interpolation (MFI) for temporal error concealment that estimates the motion vector of the erroneous macroblock using the motion vectors of the four neighboring macroblocks and then each pixel in the erroneous macroblock is concealed individually with bilinear interpolation of the neighboring motion vectors.

The conventional spatial error concealment technique usually uses the neighboring pixels of an erroneous macroblock to restore the lost data. There are some good approaches to recover the lost macroblock such as linear interpolation using corner or nearest pixels [10]-[11] and directional interpolation that preserves the edge [12]-[13]. Some papers use more complex approaches such as Markov random field (MRF) [14]-[15], orientation adaptive [16] or NURBS interpolation [17] to recover the lost pixels. In most image or video compression (e.g., JPEG, MPEG, H.263 and H.264 standards), the original pixel blocks in the spatial domain are transformed into the frequency do-

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main by discrete cosine transform (DCT). Since the DCT coefficients have similar characteristics in the neighboring blocks, the DC and AC coefficients of a lost macroblock can be restored from DCT coefficients of its neighboring macroblocks in this transform domain. This is referred to as the frequency error concealment, and some error concealment algorithms based upon DCT have been proposed [18]-[20].

Since the spatial error concealment technique uses spatial interpolation, it could cause the blurring effect. The effect introduced becomes severe for damaged macroblocks with edges. On other hand, the temporal error concealment technique attempts to recover the motion vectors of erroneous macroblocks. The incorrect estimation of the motion vector, however, could lead to visible artifacts at the boundaries with its neighbors. The incorrect motion vector usually occurs for the video sequences with fast motion or scene change. To achieve a better visible quality, some hybrid error concealments have been proposed [11], [21]-[23] which uses a combination of both techniques to conceal the erroneous macroblocks. In this paper, we present a hybrid error concealment that combines the advantages of each technique and can improve the quality of the corrupted video objectively as well as subjectively. In the proposed hybrid technique both spatial and temporal error concealments are based upon the linear interpolation that is reasonably simple and yet provide a level of quality comparable or better than existing techniques.

The paper is organized as follows. In Section 2, the linear interpolation using nearest pixels for spatial error concealment is briefly reviewed. Section 3 describes the linear interpolation based upon the selective Motion Field Interpolation (SMFI) for temporal error concealment. The performance of the SMFI is provided and compared with the Motion Field Interpolation (MFI) and other concealment techniques in both objective and subjective measures. The hybrid error concealment based upon spatial and temporal smoothness properties is presented in Section 4, and the experimental results of the hybrid technique are presented in Section 5. The simulation results reveal that the proposed algorithm outperforms other techniques. Section 6 gives conclusion.

2. SPATIAL ERROR CONCEALMENT

As described previously, there are many spatial error concealment techniques to reconstruct the erroneous macroblocks, and among them the linear interpolation using nearest pixels is the simplest method to restore the lost data. The linear interpolation employs nearest pixels from the four surrounding macroblocks to calculate the pixel value of the erroneous macroblock. The corresponding four nearest pixels are weighted according to the opposite distance and divided by the sum of the distances. The interpolated value of each pixel in the erroneous macroblock is calculated by

$$\tilde{g}_l(x,y) = \frac{1}{d_L + d_R + d_B + d_T}\{d_B.g_T(x,-1)+ d_T.g_B(x,N) + d_L.g_R(N,y) + d_R.g_L(-1,y)\} \quad (1)$$

that d_I represents the distance between $\tilde{g}_l(x,y)$ and the neighboring pixel $g_I(x,y)$. Although there exists many other advanced error concealment techniques, most of them are complicated and hard to implement in real-time processing. The linear interpolation is chosen in spatial error concealment for the hybrid technique due to its simplicity, and most importantly it can be implemented together with the selective motion field interpolation for temporal error concealment. If a nearest pixel is not available, it is assumed as 0; and for slice errors only pixels of both top and bottom neighboring macroblocks are considered.

3. SELECTIVE MOTION FIELD INTERPOLATION

Temporal error concealment techniques attempt to recover the lost data by exploiting the temporal redundancy of the video data. Motion vectors are estimated for the erroneous macroblocks and previously decoded frames are utilized to compensate for the erroneous macroblocks with the estimated motion vectors. This can be expressed as follows:

$$\tilde{G}_l(x,y) = G_r(x+d_x, y+d_y) \quad (2)$$

where G_r is a macroblock in the previous reference frame used to conceal the erroneous macroblock G_l, and $d = (d_x, d_y)$ is the estimated motion vector between G_l and G_r . The simplest method is the temporal replacement (TR) that the estimated motion vector $d = (d_x, d_y)$ is considered as a zero vector with assumption of no motion occurred between the current frame and the previous reference frame. More advanced techniques attempt to employ block matching or boundary-matching algorithm to search the best-matched macroblock from the previous decoded frames. All these techniques usually employ only one estimated motion vector to conceal the whole erroneous macroblock, and the main problem with such schemes is that incorrect estimation of the motion vector might cause obvious artifacts and lead to a poor concealment of the erroneous macroblock.

A. Motion Field Interpolation (MFI)

Al-Mualla et al. [8]-[9] suggested employing the Motion Field Interpolation (MFI) to provide a smoother motion field that reduces blocking artifacts. In the bilinear MFI the estimated motion vector $d = (d_x, d_y)$ for each pixel $g(x,y)$ within the lost macroblock is given by interpolating the neighboring motion vectors

$$d(d_x(x,y), d_y(x,y)) = \frac{1}{d_L + d_R + d_B + d_T}(d_B. V_T + d_T.V_B + d_L.V_R + d_R.V_L) \quad (3)$$

where V_T, V_B, V_L and V_R respectively represent the neighboring motion vectors of macroblocks to the above, below, left and right to the lost macroblock; d_T, d_{B,d_L} and d_R are the associated distances between $g(x,y)$ and the boundary. After normalization (i.e., with $d_T + d_B = 1$ and $d_L + d_R = 1$),$d = (d_x, d_y)$ can be expressed as

$$d(d_x(x,y), d_y(x,y)) = \frac{1}{2}(d_B.V_T + d_T.V_B + d_L.V_R + d_R.V_L) \quad (4)$$

Once the motion vector is estimated, the lost pixel is then concealed by

$$\tilde{g}_l(x,y) = g_r\left(x + d_x(x,y), y + d_y(x,y)\right) \quad (5)$$

The main advantage of MFI over the conventional concealment (i.e., the whole erroneous macroblock is concealed with only one estimated motion vector) is that block artifacts can be alleviated due to each pixel concealed individually. The problem with the MFI technique, however, is that all the four neighboring motion vectors for estimation might not be highly correlated with the lost motion vector and it cannot produce satisfactory results in areas with fast moving or sudden scene change. This is illustrated in Fig. 1 that shows the motion vector of each macroblock in two consecutive frames of the mobile video sequence. As shown in Fig 1, consider that the macroblock with motion vector $d = (0,1)$ in the area B, next to a fast motion area (A area) with large motion vectors, is contaminated with errors and lost. Then the lost motion vector will be estimated incorrectly using MFI that employs all the four neighboring motion vectors for pixel displacement estimation due to the fact that the motion vector of the top macroblock (with motion vector $d = (49,0)$) has a high dissimilarity with the erroneous macroblock. This causes artifacts and results in a high degradation of visual quality. Experiments show that most of macroblocks do not have a similar motion vector with all its neighboring macroblocks, especially for the area with slanting edges and rapid scene changes.

B. Similarity between macroblocks

To improve the performance of the MFI, in this work a selective MFI is proposed in which among the four neighboring motion vectors only two highly correlated motion vectors are selected to conceal the pixel of the erroneous macroblock using linear interpolation. The two motion vectors chosen for error concealment are based upon the difference or similarity of the neighboring motion vectors in both current and previous decoded frames. To describe the correlation between the macroblocks or motion vectors, we define the similarity on any two macroblocks as $S = |V_1 - V_2 = |x_1 - x_2| + |y_1 - y_2|$, that $V_1 = (x_1, y_1)$ and $V_2 = (x_2, y_2)$ are two motion vectors respectively. When $S \leq 2$, the two macroblocks or motion vectors are considered to be highly correlated or have high similarity. Otherwise, they are not similar or not correlated to each other.

The experiment on similarity was conducted on several video sequences of QCIF resolution (176x144 pixels). The H.263 codec was used to encode the video sequences. The results for some video sequences (*foreman, carphone* and *claire*), covering a wide range of motion contents, are tabulated in Table I. For *foreman* sequence, the average percentages of high similarity for these cases are 51.4%, 43.1% and 28.1% respectively, and the result reveals that most macroblocks have a higher similarity with 2 MBs on motion vectors than the other two. And a similar result can be obtained for the other two sequences.

C. Selective Motion Field Interpolation (SMFI)

Since the experimental result indicates that a linear MFI might achieve a better motion vector recovery than the conventional (bilinear) MFI, this work investigates a selective MFI (SMFI) for temporal error concealment in which only two neighboring motion vectors with highest similarity are selected and used in the estimation of the lost motion vector. The selection is based upon the similarity between neighboring motion vectors in the previous decoded frame and current frame. There are nine neighboring motion vectors around the erroneous macroblock: $(V_C^{i-1}, V_L^{i-1}, V_R^{i-1}, V_T^{i-1}, V_B^{i-1})$ in the previous frame and $(V_C^i, V_L^i, V_R^i, V_T^i, V_B^i)$ in the current frame, as depicted in Fig. 2. The temporal similarity between the central motion vector and it neighbors in the previous frame $i-1$ is given as

$$\begin{array}{ll} S_L^{i-1} \equiv \left|V_C^{i-1} - V_L^{i-1}\right| & S_T^{i-1} \equiv \left|V_C^{i-1} - V_T^{i-1}\right| \\ S_R^{i-1} \equiv \left|V_C^{i-1} - V_L^{i-1}\right| & S_B^{i-1} \equiv \left|V_C^{i-1} - V_B^{i-1}\right| \end{array} \quad (6)$$

The spatial similarity between the four neighboring motion vectors in the current frame i is given as

$$\begin{array}{ll} S_{LR}^i \equiv \left|V_L^i - V_R^i\right| & S_{LT}^i \equiv \left|V_L^i - V_T^i\right| \\ S_{LB}^i \equiv \left|V_L^i - V_B^i\right| & S_{RT}^i \equiv \left|V_R^i - V_T^i\right| \\ S_{RB}^i \equiv \left|V_L^i - V_B^i\right| & S_{TB}^i \equiv \left|V_T^i - V_B^i\right| \end{array} \quad (7)$$

The similarity between the erroneous macroblock and its four neighbors are respectively defined as

$$\begin{aligned} S_L &\equiv 3S_L^{i-1} + S_{LR}^i + S_{LT}^i + S_{LB}^i \\ S_R &\equiv 3S_R^{i-1} + S_{LR}^i + S_{RT}^i + S_{RB}^i \\ S_T &\equiv 3S_T^{i-1} + S_{LT}^i + S_{RT}^i + S_{TB}^i \\ S_B &\equiv 3S_L^{i-1} + S_{LB}^i + S_{RB}^i + S_{TB}^i \end{aligned} \tag{8}$$

In the selective MFI, the estimated motion vector $d = (d_x, d_y)$ for each pixel $g(x, y)$ within the erroneous macroblock is given by

$$d(d_x(x,y), d_y(x,y)) = \frac{1}{2}(x + d_B.V_T + d_T.V_B + d_L.V_R + d_R.V_L) \tag{9}$$

in which the two motion vectors that have highest similarity (i.e., smallest S) are selected for concealing each lost pixel of the erroneous macroblock, while the other two motion vectors with least similarity are assumed to be zeros. Each pixel $\tilde{g}_l(x, y)$ within the erroneous macroblock is then concealed by

$$\tilde{g}_l(x,y) = g_r(x + d_x(x,y), y + d_y(x,y)) \tag{10}$$

Note that if a neighboring motion vector is not available, it is assumed as 0; and if all three or four neighboring motion vectors are not available, the Temporal Replacement (TR) is employed for concealment instead.

4. HYBRID ERROR CONCEALMENT

As described previously, the spatial error concealment can hardly restore the details of the erroneous macroblock due to the blurring effect, while the temporal error concealment can completely reconstruct the erroneous macroblock if the motion vector is recovered correctly. The incorrect estimation of the motion vector, however, could lead to more severe degradation than the spatial error concealment. The incorrect estimation usually occurs in areas with fast/complex motion or sudden scene change.

Jo et al. [23] suggested a hybrid error concealment that adaptively combines the benefits of each error concealment technique. It makes use of the spatial smoothness property between adjacent pixels in the erroneous macroblock and its neighbors. The erroneous macroblock is firstly recovered using the temporal error concealment, then boundary-matching errors between the recovered macroblock and its neighbors are employed to determine whether the erroneous macroblock is concealed correctly or not. If the boundary-matching error is beyond a threshold, it means the temporal error concealment conceals the lost data improperly and the spatial error concealment is used to conceal the erroneous macroblock instead of the temporal error concealment.

The algorithm proposed in [23] was shown to outperform Sun's hybrid algorithm [22]. It, however, only utilizes the spatial smoothness property to determine the accuracy of recovered motion vector for the erroneous macroblock. As a matter of fact, most video sequences possess spatial and temporal smoothness properties in the adjacent areas, and the accuracy of temporal error concealment can be determined more accurately by examining the boundary-matching errors between the temporally recovered macroblock and its neighbors from both current and previous reference frames.

In the proposed hybrid algorithm, we improve Jo's algorithm by using both spatial and temporal boundary-matching errors to decide the accuracy of temporal error concealment. As depicted in Fig. 3, the spatial boundary-matching error between the temporally recovered macroblock G_R and its neighbors G_{TC} and G_{BC}, is given by

$$\begin{aligned} BME_r = &\frac{1}{2}\sum_{x=0}^{15}[g_R(x,0) - g_{TC}(x,-1)]^2 + \\ &\frac{1}{2}\sum_{x=0}^{15}[g_R(x,15) - g_{BC}(x,16)]^2 \end{aligned} \tag{11}$$

The index x and y of $g_R(x,y)$, $g_{TC}(x,y)$ and $g_{BC}(x,y)$ represents the relative distance from the uppermost and leftmost pixel of G_R, and $g_R(0,0)$ is the value of the uppermost and leftmost pixel. To check the spatial smoothness property, two average values of the boundary-matching errors between top macroblocks and between bottom macroblocks are respectively given as

$$\begin{aligned} BME_t = &\frac{1}{2}\sum_{y=1}^{16}[g_{TC}(0,-y) - g_{TL}(-1,-y)]^2 + \\ &\frac{1}{2}\sum_{y=1}^{16}[g_{TC}(x,15) - g_{TR}(16,-y)]^2 \end{aligned} \tag{12}$$

and

$$\begin{aligned} BME_b = &\frac{1}{2}\sum_{y=0}^{15}[g_{BC}(0,16+y) - g_{BL}(-1,16+y)]^2 + \\ &\frac{1}{2}\sum_{y=0}^{15}[g_{BC}(15,16+y) - g_{BR}(16,16+y)]^2 \end{aligned} \tag{13}$$

The ratio of spatial boundary-matching errors λ_{SBME}, defined as

$$\lambda_{SBME} = \frac{2BME_r}{BME_t + BME_b}, \tag{14}$$

is proposed in Jo's algorithm [23], and it is employed to check whether the temporal error concealment conceals the erroneous macroblock properly. In addition to λ_{SBME} , our proposed algorithm suggests another parameter, the ratio of temporal boundary-matching errors denoted as λ_{TBME} , to determine the accuracy of temporal error concealment. The ratio of temporal boundary-matching errors λ_{TBME} is defined as

$$\lambda_{TBME} = \frac{BME_r}{BME_{rl}}, \tag{15}$$

where

$$\begin{aligned} BME_{rl} = \frac{1}{2}\sum_{x=0}^{15}\left[g_{RL}(x,0) - g_{TCL}(x,-1)\right]^2 + \\ \frac{1}{2}\sum_{x=0}^{15}\left[g_{RL}(x,15) - g_{BCL}(x,16)\right]^2 \end{aligned} \tag{16}$$

indicates the boundary-matching error between its neighbors in the previous reference frame. Because of both spatial and temporal smoothness properties, λ_{SBME} and λ_{TBME} would be approximately equal to unity if the temporal error concealment conceals the damaged macroblock correctly. As both λ_{SBME} and λ_{TBME} exceed a threshold, it reveals that the SMFI conceals the damaged macroblock improperly, and the spatial error concealment is employed to reconstruct the erroneous macroblock. The proposed hybrid algorithm is summarized as follows:

Step 1: Find a lost macroblock.

Step 2: Use Selective Motion Field Interpolation (SMFI) to conceal the lost macroblock.

Step 2: Calculate BME_r, BME_t, BME_b and BME_{rl}, and compute both λ_{SBME} and λ_{TBME}.

Step 3: Compare λ_{SBME} and λ_{TBME} with threshold T_{SBME} and T_{TBME}.

If $\lambda_{SBME} \geq T_{SBME}$ and $\lambda_{TBME} \geq T_{TBME}$, go to Step 4.

Otherwise, go to Step 1.

Step 4: Use Linear interpolation with nearest pixels to reconstruct the lost macroblock.

5. EXPERIMENTAL RESULTS

The experiment was conducted on many video sequences to test and evaluate the performance of the hybrid error concealment algorithm. The selective motion field interpolation (SMFI) is first investigated and compared with motion field interpolation (MFI) as well as two widely used concealment techniques AMV and FBBM, which are shown to achieve better performance that the spatial error concealment technique except on the sequence with scene changes. The GOP structure is IPPPP..., i.e., all frames except the first frame are encoded as P frames, and the number of frames tested in a sequence is 101. The video sequences are contaminated with two types of errors (macroblock error and slice error respectively), starting from the fifth frame. A slice consisting of nine macroblocks is chosen to localize the errors, and if a slice error occurs resynchronization into the bit stream begins at the start of the next slice.

A. Experiments with Macroblock Error (ME)

Results for three QCIF sequences (*foreman, carphone,* and *claire*) and one CIF sequence (mobile) are given as follows. Table 2 displays the average PSNR performance over the first 101 frames, simulated on the foreman sequence that has relatively high motion activity with macroblock error rates (MER) 5%, 10% and 15% respectively. It is observed that the SMFI algorithm achieves a gain of approximately 2.5 dB on average over MFI and FBBM. The simulation result on the claire sequence that has low motion activity also reveals that the SMFI algorithm improves the FBBM and MFI by approximately 2 dB in average PSNR performance. A more detail PSNR performance in each frame simulated on foreman sequence is depicted in Fig. 4, in which each frame is contaminated with 10% MER, beginning with the fifth frames. As can be seen from the figure, the SMFI outperforms the other temporal error concealment techniques.

B. Experiments with Slice Error (SE)

The average PSNR over the first 101 frames simulated on several video sequences with various slice error rates (SER) was shown in Table 3, 4, 5, and 6 respectively. As shown, the MFI is able to achieve an average PSNR improvement of at least 1 dB over FBBM. Moreover, the SMFI averagely outperforms the MFI on all video sequences, and it has an average PSNR gain of 0.5 dB when the SER is 10%. Fig. 5 depicts the PSNR performance in each frame simulated on *foreman* sequence with 10% SER, which also shows the superiority of the SMFI. For subjective comparison, Fig. 6 demonstrates the concealed frame 50 of *foreman* sequence using the four different error concealment methods when the sequence was contaminated with 30% SER. As shown, the SMFI maintains a good visual quality as compared to other methods.

C. Performance of hybrid error concealment

Simulation results have demonstrated the superiority of the selective motion field interpolation (SMFI), and the SMFI is employed in the proposed hybrid error concealment algorithm for recovering the motion vector of the erroneous macroblock. The experiment was carried out on a MIX sequence that consists of *foreman* (20 frames), *highway* (40 frames) and *mobile* (40 frames) sequences, and has two scene changes respectively from the *foreman* sequence to the *highway* sequence, and from the *highway* sequence to the mobile sequence. The MIX sequence is contaminated with slice errors, starting from the fifth frame.

In the experiment, we assume $\lambda_{SBME} = \lambda_{TBME} =$

4 which gives good results. A comparison of PSNR performance is made in Fig. 7 with 20% SER that compares PSNR performance of the proposed hybrid algorithm and the one in [23]. Note that the hybrid algorithm in [23] employs the same spatial and temporal error concealment as that in our proposed algorithm (i.e., linear interpolation using nearest pixels and SMFI). The PSNR performance of using SMFI only is also displayed in the figure for comparison purpose. As shown, the proposed hybrid algorithm outperforms the algorithm in [23]. The hybrid algorithm in [23] can also detect the scene change correctly, and use spatial error concealment to conceal the erroneous macroblock instead of SMFI. As compared with the SMFI, however, it can be seen that the algorithm by [23] suffers from improperly concealing fast and complex motion areas in sequences that uses the spatial error concealment. And our proposed hybrid algorithm can significantly improve this degradation. Fig. 8 subjectively compares the decoded frame 16 of MIX sequence for both hybrid error concealments when the sequence was contaminated with 10% SER.

Table 7 shows the average PSNR performance for various slice errors. The simulation results show that the hybrid algorithm achieves average PSNR of 3 dB higher than that of using SMFI algorithm only. A subjective comparison is shown in Fig. 9 that demonstrates the damaged and the decoded frame 70 of the MIX sequence obtained by SMFI and our proposed hybrid algorithm.

6. CONCLUSION

This paper presented a hybrid error concealment algorithm using linear interpolation for error-prone video transmission channel. In the proposed hybrid algorithm, the temporal error concealment employing selective motion field interpolation (SMFI) is first used to conceal pixels in the erroneous macroblock. The spatial and temporal boundary-matched errors are then used to check whether the SMFI conceals the damaged macroblock correctly or not. If the temporally recovered macroblock is not concealed properly, the spatial error concealment using linear interpolation is employed instead of SMFI.

In the proposed SMFI, among the four neighboring motion vectors only two highly correlated motion vectors are selected to conceal each pixel of the erroneous macroblock using linear interpolation. Experimental results reveal that the proposed SMFI method achieves significant improvement on both PSNR performance and visual quality over other commonly used techniques. A gain of 2.5 dB on average over MFI and FBBM can be achieved with macroblock errors; and 0.5 dB and 1 dB over MFI and FBBM respectively with slice errors.

The proposed hybrid algorithm uses the linear interpolation on both spatial and temporal error concealment and it achieves better performance subjectively as well as objectively over other error concealment techniques.

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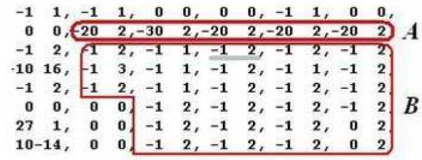
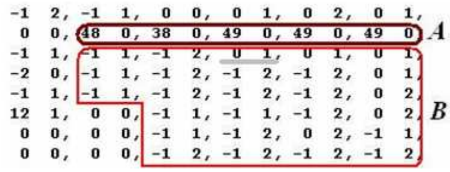


(a) Previous Decoded Frame



(b) Current Frame

Fig.1: *MVs (x,y) of two consecutive frames in MOBILE*

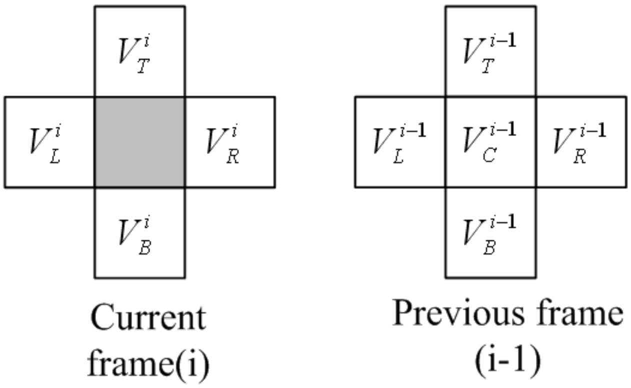


Fig.2: *2 Neighboring Motion Vectors around the Erroneous Macroblock*

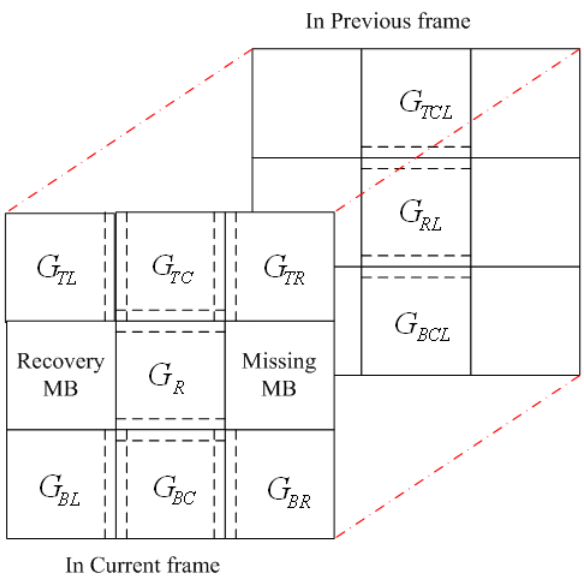


Fig.3: *Recovered Macroblock G_R and its Neighbors*

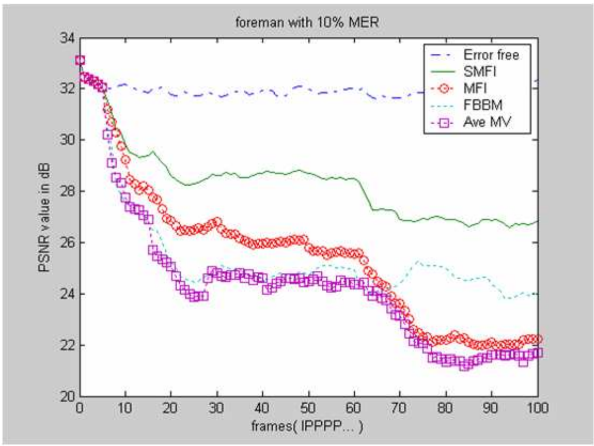


Fig.4: *4 PSNR Comparison of Different Methods for FOREMAN with 10% MER*

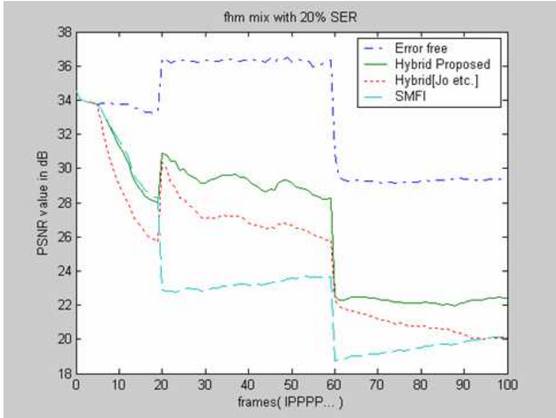


Fig.7: *PSNR Comparison for FOREMAN Sequence with 20% SER*

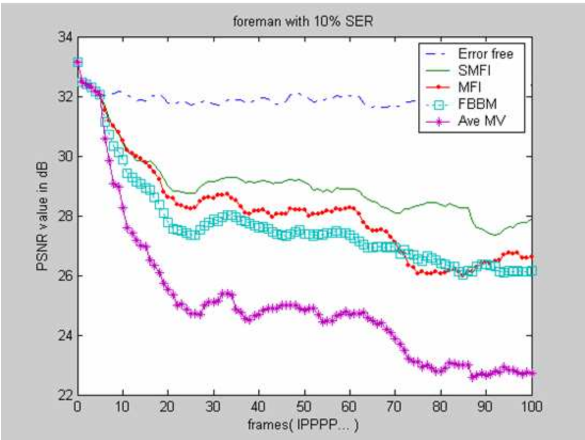
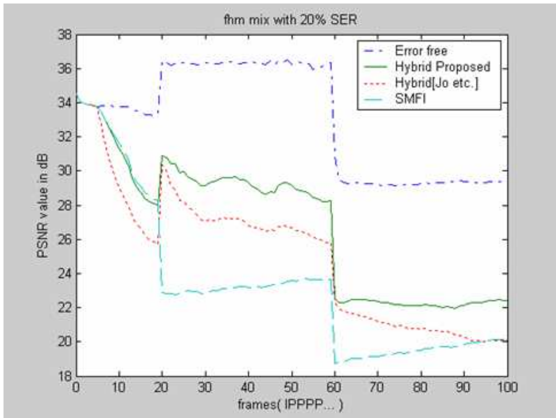
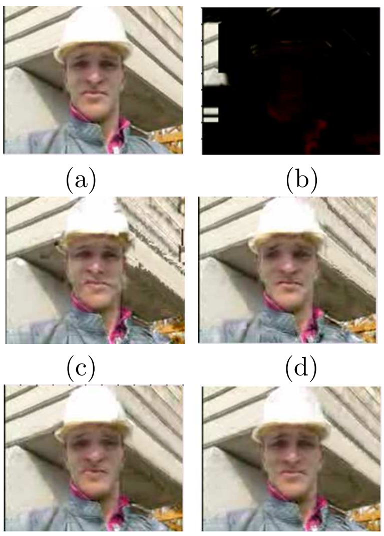


Fig.5: *PSNR Comparison of Different Methods for FOREMAN with 10% SER*



(a) Hybrid Algorithm by Jo (b) Proposed Hybrid Algorithm

Fig.8: *Decoded Frame 16 of FOREMAN Sequence*



(a) (b)

(c) (d)

(e) (f)

Fig.6: *Decoded frame 50 of FOREMAN sequence*

(a) Original Image (b) Damaged Image

(c) Decoded Image using SMFI (d) Decoded Image using Hybrid Algorithm

Fig.9: *Decoded Frame 70 of MIX Sequence*

Table 1: *PERCENTAGE OF HIGH SIMILARITY*

	Percentage of High Similarity		
Number of MB	2 MB	3MB	4MB
FOREMAN	51.4%	43.1%	28.1%
CARPHONE	55.9%	49.4%	33.5%
CLAIRE	62.8%	62.4%	59.1%

Table 2: *AVERAGE PSNR PERFORMANCE OVER 101 FRAMES OF FOREMAN SEQUENCE*

foreman	PSNR (Y) dB				
MER	Error free	AMV	FBBM	MFI	SMFI
5%	31.938	25.878	27.532	27.099	29.726
10%	31.938	24.430	25.483	25.531	28.339
15%	31.938	22.449	24.620	24.467	27.051

Table 3: *AVERAGE PSNR PERFORMANCE OVER 101 FRAMES OF FOREMAN SEQUENCE*

foreman	PSNR (Y) dB				
SER	Error free	AMV	FBBM	MFI	SMFI
10%	31.938	25.088	27.691	28.143	29.030
20%	31.938	23.024	25.091	26.091	26.788
30%	31.938	21.937	23.063	25.190	25.472
40%	31.938	20.690	22.653	23.768	23.814

Table 4: *AVERAGE PSNR PERFORMANCE OVER 101 FRAMES OF CARPHONE SEQUENCE*

CAR PHONE	PSNR (Y) dB				
SER	Error free	AMV	FBBM	MFI	SMFI
10%	33.259	25.732	29.452	28.925	30.153
20%	33.259	23.245	25.641	27.079	28.469
30%	33.259	21.466	24.704	26.323	26.591
40%	33.259	19.912	23.108	24.924	25.649

Table 5: *AVERAGE PSNR PERFORMANCE OVER 101 FRAMES OF CLAIRE SEQUENCE*

CLAIRE	PSNR (Y) dB				
SER	Error free	AMV	FBBM	MFI	SMFI
10%	36.211	31.351	32.023	34.707	34.841
20%	36.211	28.603	29.871	33.856	34.261
30%	36.211	26.894	28.926	33.469	33.750
40%	36.211	25.491	28.389	32.498	33.190

Table 6: *AVERAGE PSNR PERFORMANCE OVER 101 FRAMES, ON MOBILE SEQUENCE*

MOBILE (CIF)	PSNR (Y) dB				
SER	Error free	AMV	FBBM	MFI	SMFI
5%	29.229	24.582	24.237	26.591	26.903
10%	29.229	22.521	22.587	25.085	25.340
15%	29.229	21.334	21.319	23.819	23.845
20%	29.229	20.281	20.530	22.913	22.936

Table 7: *AVERAGE PSNR PERFORMANCE OVER 101 FRAMES ON MIX SEQUENCE*

MIX	PSNR(Y)dB		
SER	Error free	SMFI	Hybrid
5%	32.954	25.512	28.721
10%	32.954	23.358	26.124
15%	32.954	21.531	24.476

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