MPEG-2 Error Concealment based on Block Matching Principles

Sofia Tsekeridou and Ioannis Pitas

The authors are with the Department of Informatics, Aristotle University of Thessaloniki, Box 451, 54006 Thessaloniki, Greece (e-mail: {sofia,pitas}@zeus.csd.auth.gr)

Abstract

The MPEG-2 compression algorithm is very sensitive to channel disturbances due to the use of variable length coding. A single bit error during transmission leads to noticeable degradation of the decoded sequence quality in that part or entire slice information is lost until the next resynchronization point is reached. Error concealment (EC) methods, implemented at the decoder side, present one way of dealing with this problem. An error concealment scheme that is based on block matching principles and spatio-temporal video redundancy is presented in this paper. Spatial information (for the first frame of the sequence or the next scene) or temporal information (for the other frames) is used to reconstruct the corrupted regions. The concealment strategy is embedded in the MPEG-2 decoder model, in such a way that error concealment is applied after entire frame decoding. Its performance proves to be satisfactory for packet error rates (PER) ranging from 1% to 10% and for video sequences with different content and motion and surpasses that of other EC methods under study.

Keywords

Error concealment, MPEG-2 compression, block matching.

I. Introduction

In the prospect of digital TV (SDTV/HDTV) or multimedia applications, a wide range of video compression standards has emerged to satisfy their numerous requirements mainly for low bitrates and good quality. The MPEG-2 compression standard is one of them, developed mainly for digital TV/HDTV (high definition TV) broadcasting applications. Its applications further extend to video-on-demand (VOD), computer multimedia, video conferencing, electronic cinema, electronic news gathering, storage, direct broadcast satellite (DBS) or digital video broadcast (DVB). MPEG-2 [1]-[4] is a lossy algorithm that is based on motion-compensated DCT block transform and variable length coding allowing compressed bitstreams at rates close to 5 Mbps for NTSC/PAL quality. It exhibits a hierarchical structure: sequence, group of pictures (GOP), picture (I-, P- or B-frames), slice, macroblock (MB) and block. Transmission of MPEG-2 compressed bitstreams through various transmission media (satellite or terrestrial) involves tasks such as packet format specification, multiplexing, network transport and media synchronization [3]-[5]. A complete systems approach for digital video is presented in the MPEG-2 Systems standard, which, among other, defines the MPEG-2 Transport stream mainly intended for use in noisy channels [4]. Each MPEG-2 transport packet consists of 188 bytes, 4 of which are header information and the remaining are payload (parts of variable-length PES packets). The header contains a one-bit transport-error-indicator which indicates, if appropriately set by the system demultiplexer or an error detection/resilience mechanism [4], [6], [7], if the respective packet contains errors or not. An alternative systems approach is ATM transport used mainly in broadband ISDN (B-ISDN) networks [4]. ATM cells with optional ATM Adaptation Layer (AAL) protocol functionalities are 53 bytes long with a 5-byte header and a 48-byte payload, a byte of which is reserved for AAL. The MPEG-2 transport packet of 188 bytes can fit into 4 ATM/AAL cells, thus ensuring MPEG-2 and ATM interoperability.

Transmission through physical communication channels is liable to errors, being either packet/cell losses or bit errors (isolated or in bursts), referred to as *bitstream errors.* They frequently result in loss of the decoder synchronization, which becomes unable to decode until the next resynchronization point. Since resynchronization points are placed at the header of each slice by the MPEG-2 coder, unless otherwise specified, transmission errors may lead to partial or entire slice information loss and to severe degradation of the currently decoded frame quality, as well as of that of the subsequent decoded frames in a group of pictures (GOP) due to temporal error propagation. Error resilience may be achieved in three ways: (a) modifications to the encoding process to increase robustness to errors, (b) error detection and control, entropy-coding and robust packetization prior to or during transmission, (c) modifications to the decoding process and use of error concealment methods at the decoder. During encoding, use of smaller or adaptive [8] slice sizes to increase the number of synchronization points in the bitstream, fractal-based [9], hierarchical pyramidal-based [10] or wavelet-based [11] coding instead of the common DCT-based one, use of overlapped block motion compensation [11], combination of

VLC and FLC codes in the bitstream [12] or use of frequency scanning and MUVLC [13] instead of block scanning and VLC present methods that fall into the first error resilience category. This category further includes methods that implement a 9×9 with one pixel overlap block DCT [14], [15] or use layered coding (different scalability bitstreams) in combination with different prioritization transmission levels [5], [13], [16]-[21] in one or more channels. All these methods, however, result in significant overhead in the total bit rate or increased encoder complexity. Error control and detection schemes involve use of forward error correction (FEC) or Reed-Solomon (RS) coding/decoding [16]-[18], [22], [23] or use of the video specific AAL protocol [4], [5], [13] in ATM networks. Such error correction schemes, though, add redundancy to the bitstream. In order to reduce such redundancy, error resilient entropy coding (EREC) methods have been used instead [10], [16], [21], [24], [25]. At the transmission level, error resilience can also be accomplished by robust packetization such as interleaved packetization [16], [25] or use of different prioritization levels along with alternative packing schemes [15], [16], [26]. Even when either or both of the first error resilience methods are employed, some errors may still remain uncorrectable (commonly known as *residual errors*). In such cases, error resilience methods belonging to the third category are employed. Forcing the decoder to resynch [5]-[7], [18], [27]-[29] before the next resynchronization point in the bitstream might lead to correct decoding of part of otherwise lost frame area. Error concealment (EC) methods attempt to reconstruct lost areas by exploiting spatial and/or temporal redundancy. They are distinguished to spatial, temporal or spatio-temporal methods depending on the available information exploited for concealment. Spatial EC methods [5]-[7], [9], [14], [16], [20]-[22], [26]-[28], [30]-[42] are mainly targeted for intra-frame concealment ranging from simple bilinear interpolation ones to complex fuzzy reasoning based ones. Temporal methods [6], [7], [12], [16], [20]-[22], [26]-[28], [31], [33], [37], [38], [40], [43]-[48] can be used for both inter- and intra-coded concealment provided that temporal information is available. Spatio-temporal methods [5], [6], [15], [16], [22], [33], [49], [50] are based on measures of spatial and temporal activity for determining the type of concealment. The performance of these EC methods deteriorates for higher error rates. In such cases, layered coding combined with such methods [5], [20] gives better results with a possible increase in bit rate and complexity.

The present study focuses on the problem of error concealment assuming the existence of appropriate error detection. The presented EC scheme consists of a spatial method, called *split-match EC method*, for the first intra-frame concealment, since no temporal information is available for it, and a temporal one, called *forward-backward block matching EC method*, for concealing the other frames of an MPEG-2 coded video sequence. The EC scheme is embedded in the MPEG-2 decoder model and is based on block matching principles proving to be of improved performance compared to other ECs under study even for high packet error rates and sequences of varying content and motion. Care is taken to keep its complexity as low as possible for real-time capabilities. The structure of the paper is as follows. In Section II, the types of errors observable in a decoded video sequence are explained, for better problem understanding. Sections III and IV describe the two EC methods comprising the presented EC scheme. Alternative approaches to spatial EC based on anisotropic diffusion principles are also presented in Section III. A short description of some known EC methods that are compared with the presented ones is also given in Sections III and IV. Section V summarises the simulation results. Concluding remarks are outlined in Section VI.

II. Types of Errors

Transmission errors lead to two types of errors observable at the decoded video sequence:

- **Bitstream errors.** They result from direct bit errors or cell/packet loss in the transmitted bitstream and may lead to loss of the decoder synchronization.
- **Propagation errors.** They are caused due to predictive coding. Since temporal prediction is applied in P- and B-frames, such errors are observed only in these frames. Errors in previously decoded anchor frames (I- or P-frames) propagate to subsequent in coding order frames.

Appropriate transport structure (MPEG-2 transport packets) and error detection mechanisms (ATM/AAL, channel/source error detection) enable the decoder to decide on the spatio-temporal locations of corrupted by bitstream errors blocks. Assuming erroneous packets are discarded, the errors lie at the end of a damaged slice between the erroneously received packet and the next resynchronization point in the bitstream [27], [42]. The knowledge of the locations of bitstream error corrupted blocks in anchor frames and the fact that, at the locations of propagation errors, all MB information is available at the decoder (i.e. motion vectors, MB coding modes, prediction errors) enables the localization of propagation errors in predicted frames. In detail, if the motion vector and coding mode of a MB in a predicted frame are such that, for the decoding of this MB, information is obtained from a damaged MB in its reference frame, then the current MB is most probably partially or entirely corrupted due to propagation of the reference frame errors. It is worth noting that concealment of propagation errors is unnecessary if a good EC method is implemented in the decoder model. Even then, the knowledge of propagation error locations can prove useful in estimating and post-processing the propagation of errors due to imperfect concealment from previously reconstructed frames.

III. First Intra-Frame Error Concealment

The best possible concealment of an I-frame is most desirable since imperfect reconstruction of I-frames result in propagation of imperfect concealment errors to all frames of the respective GOP and finally in the degradation of the video sequence visual quality. Intra-frame concealment is performed by exploiting mere spatial information from retrieved neighbouring regions, since no temporal information is available. The use of *bilinear interpolation* between border pixels of neighbouring good MBs has been proposed in [22]. Since no left and right neighbours exist in our case, only the border pixels of the existing top (MB_T), and bottom (MB_B), MBs are used to conceal the currently lost one MB_C (spatial vertical interpolation, SVI EC). Concealment is achieved by evaluating the expression:

$$MB_T(i,j) = \frac{d_B}{d_{max}} MB_T(N,j) + \frac{d_T}{d_{max}} MB_B(1,j) \tag{1}$$

In the above equation, d_T and d_B represent distances in pixels of pixel (i,j) from its vertically neighbouring top and bottom border pixels respectively. d_{max} is the vertical size of the lost regions in pixels, which may be equal to N, the vertical dimension of a MB, if only one slice is lost. Such an interpolation scheme performs satisfactorily when little spatial detail exists or when vertical edges or lines are attempted to be reconstructed. In all other cases its performance deteriorates followed by noticeable blurring in the concealed regions.

More complicated interpolation methods or spatial techniques have also been proposed in the literature [9], [14], [16], [26], [30]-[32], [34]-[39], [41], [42] to deal with these drawbacks. They are, however, usually more computationally intensive than the bilinear interpolation approach. Novel methods for the concealment of lost MBs in the first I-frame of an MPEG-2 compressed sequence are investigated in this paper. They attempt to further reconstruct spatial details, textures, lines or edges in almost all directions in a smooth and continuous way with less artifacts and blurring. The first method, called *Spatial Anisotropic Diffusion EC method*, applies a form of anisotropic diffusion [51], in such a way that neighbouring image content is diffused into the lost region when respective gradients are of great values. A second method, called *Spatial Split-Match EC method*, an initial version of which was introduced in [40], attempts to spatially match top and bottom neighbouring regions and conceals the region in the direction of the match by either copying, interpolating, or diffusing the content of the matched regions. It is noted that concealment is performed on a MB basis. A more detailed description of these methods follows.

A. Spatial Anisotropic Diffusion EC Method

Motivated by the work of [51] which used anisotropic diffusion principles for edge preservation purposes, the inverse problem is examined for concealment applications. Since the gradients between lost areas and surrounding good areas have large values, “diffusion” of the surrounding image content to the lost areas must be implementable when gradients increase and must diminish when the latter decrease. The image intensity $I_{i,j}$ at pixel (i,j) of a lost MB is determined by iteratively employing the expression [51]:

$$I_{i,j}^{t+1} = I_{i,j}^{t} + \lambda[c_T \nabla_T I + c_B \nabla_B I]_{i,j}^{t} \qquad (2)$$

where $\nabla_T I_{i,j}$ and $\nabla_B I_{i,j}$ are the intensity differences between the considered pixel (i,j) and the respective border one from the existing top and bottom MBs respectively. Initial conditions $I^0_{i,j}$, for (i,j) inside the lost MB region, are set to 0 (no image content is assumed available in this region). Parameter λ controls the stability of the numerical presentation (2) of the diffusion equation and is set equal to 0.15. Based on our latter remark, the conduction coefficients c_T and c_B are chosen such that they are proportional to the gradient values (intensity differences) and inversely proportional to the distance of the pixel (i,j) from its top or bottom estimator. Thus, the conduction coefficients are determined by:

$$c_{T/B} = 1 - \frac{d_{T/B}}{d_{max}} e^{-\nabla_{T/B} I_{i,j}/K} \tag{3}$$

$d_{T/B}$ (i.e., d_T or d_B) and d_{max} are similar to the ones already defined in equation (1). Constant K is used to reduce the effect of large intensity differences and to ensure smooth intensity diffusion. A value of 10.0 has been employed in our simulations. Total concealment is achieved with only a few iterations (in the order of 10). Thus, no additional delays are introduced in the concealment scheme, except for a slice delay, since the next slice should be decoded before the current can be concealed.

Anisotropic diffusion reduces the blurring effect of the spatial interpolation method, although it still fails to reconstruct areas with many details or edges and lines other than vertical ones. Its use in combination with the subsequently described EC method diminishes these drawbacks, as it is explained later on.

B. Spatial Split-Match EC Method

In order to deal with the problem of reconstructing lost regions with high spatial detail, texture or edges (other than vertical ones), spatial region similarity principles have been applied in existing neighbouring regions and concealment has been performed in the direction defined by the detected similar regions. These concepts have been incorporated in the *Split-Match* EC method. The flow chart of its algorithm is shown in Figure 1. Apart from the region similarity evaluation and concealment tasks, a *split-match* process is embedded in the algorithm, which decreases the size of the top and bottom neighbouring regions to be matched when region matching in the previous step has failed. An overview of the implementation principles of each incorporated task is given subsequently.

Two approaches are adopted for neighbouring *region similarity* evaluation. In the first approach, the mean absolute difference (MAD) between neighbouring blocks B_T and B_B of size $b_x \times b_y$ is estimated:

$$MAD = \frac{1}{b_x \times b_y} \sum_{x=0}^{b_x} \sum_{y=0}^{b_y} |B_T(x,y) - B_B(x,y)| \tag{4}$$

The combination of blocks (referred to as the “best match”) that leads to either a MAD value smaller than a predefined threshold (use of constant thresholds) or to the minimum MAD compared to respective values obtained by matching equal-sized blocks located in a predefined search region is used to recover the image content of the lost image part in the direction of the match. Constant thresholds are employed in the first steps of the split-match process (large blocks - splitting occurs), whereas search regions are defined in its last steps (smallest block - no splitting occurs, see Figure 2c and d), as will be explained later on. In the second approach, the statistical behaviour of these blocks is evaluated by means of their mean (m_T (top), m_B (bottom)) and variance (σ_T^2, σ_B^2) values. Similarity decisions are based on the validity of the expression:

$$(|m_T - m_B| < Q * \sigma_T) \;\; AND \;\; (|m_T - m_B| < Q * \sigma_B) \tag{5}$$

In (5), Q is a constant factor, set to 0.5 in our simulations, that controls the strictness of the similarity rule. Despite its simplicity, this decision rule combined with the split-match task leads to remarkably good results. Furthermore, it alleviates the disadvantage of constant thresholds of the first approach, since region “adaptive-like” thresholds are set by this method.

The *split-match* process has four steps as shown in Figure 2, where MB_C denotes the macroblock to be concealed and MB_T, MB_{TL}, MB_{TR}, MB_B, MB_{BL} and MB_{BR} represent the available top, top-left, top-right, bottom, bottom-left and bottom-right neighbouring macroblocks to MB_C, respectively. In the first two steps, large neighbouring blocks are defined for matching, whereas, at the last two steps, the minimum sized block (4×4) is used and different search regions are defined. Such an approach is adopted to ensure smallest processing time and best possible concealment. The initialization of this process with large block matching ensures that big homogeneous or textured regions will be reconstructed directly, thus avoiding processing delays or computational effort. On the other hand, the satisfactory reconstruction of smaller homogeneous or textured regions, regions with small details, lines and edges, requires the matching of smaller blocks. A brief description of the four steps of the algorithm follows:

- *Step 1: Initialization - Maximum Block Size*

  Initialization is performed by attempting to match the largest vertically neighbouring blocks b_1 and t_1 of size 16×8 pixels, as shown in Figure 2a. If these regions are considered similar, entire MB concealment follows by copying, as shown later on. Otherwise, the algorithm proceeds to the second step.

- *Step 2: First Splitting - Vertical Directions only*

  The initial blocks of the 1st step are split into two smaller ones, b_1, b_2 and t_1, t_2, respectively, of size 8×8 (horizontal splitting) and matching is performed in the vertical direction only for each pair separately, i.e. b_1 with t_1 and b_2 with t_2 (see Figure 2b). Thus, concealment of smaller flat or textured regions (or regions at the borders of high spatial activity areas) is directly performed.

- *Step 3: Second Splitting - Definition of Initial Search Region - Smaller set of directions*

  The blocks of step 2 are further split to the smallest allowable ones of size 4×4, denoted by b_i and t_i. Now though, an initial horizontal search region is additionally defined as shown in Figure 2c. The smallest blocks to be matched (b_i with t_i) slide inside the search regions and all their combinations are considered for "best match" determination based on similarity decisions introduced previously. This step is performed iteratively until the next best combination of blocks mismatches or entire MB concealment is achieved. The concept of sliding windows ensures edge or line reconstruction at any direction.

- *Step 4: No Splitting - Enlargement of Search Region - Larger set of directions*

The search regions of step 3 are further enlarged, as shown in Figure 2d, to allow the possibility of a larger set of reconstructed directions extending to neighbouring left and right top or bottom MBs. The block size remains the same and matching is performed between b_k and t_k shown in Figure 2d. This step is performed iteratively until entire MB concealment. It is noted that reconstruction of horizontal or almost horizontal lines or edges is impossible when using information from only top and bottom available MBs, especially in cases where several consecutive slices are lost.

As soon as a "best match" has been found, *concealment* is performed by one of the following three methods: (a) copying, (b) diffusion or (c) interpolation of the image content of the best matched blocks into the lost region in the direction of the match. Copying is performed in the way shown in Figure 2. The image content of the top/bottom neighbouring block of the "best match" is copied to the top/bottom part of the lost region in the direction of the match, respectively (e.g. in case that blocks b_1 and t_1 of the 1st step match, the image content of b_1 is copied into the top equally sized region of MB_C represented by a light grey color and the image content of t_1 is copied into the bottom part of MB_C represented by a darker grey color). In the first two steps of the split-match process, concealment is directly performed without the involvement of any iterative process. In its last steps, though, an iterative procedure is necessary to conceal the regions left unconcealed in the previous steps or iteration. For this purpose, concealed areas of the lost MB are labelled to enable unconcealed area identification and they are not re-concealed when, in a next step or iteration, they lie in the direction of the best match. Concealment by copying leads to blocking artifacts in the concealed areas. In order to smooth this blocking effect, the post-processing technique of [52] is used. This method is performed only on the concealed areas. The algorithm of [52] decides whether the current pixel belongs to a monotone or edge MB and adjusts its behaviour accordingly. The decision is made on a bigger region than the size of a MB. However, only the MB considered is affected. For the monotone MBs, smoothing is accomplished by filtering with a separable $2D$ 3×3 FIR filter with identical responses in the horizontal and vertical dimensions equal to $\{0.227, 0.547, 0.227\}$. For the edge MBs, first the direction of the edge is estimated and then the blockiness is reduced by $1D$ FIR filtering in the edge direction with an impulse response of $\{0.036, 0.282, 0.363, 0.282, 0.036\}$.

Concealment by anisotropic diffusion is performed in the way described in Section III-A between border pixels of the best matched blocks. The determination of the pixels to be concealed located in the direction of the best match is performed in the way illustrated in Figure 3. Those pixels, for which the inequality: $x_{min} \leq x \leq x_{max}$ is valid, are concealed by employing anisotropic diffusion between them and the border pixels of the best match. In more detail, concealment is applied to those pixels whose distance from the $(0, 0)$ point in Figure 3, when it is projected on the line perpendicular to the direction of the best match (thus producing value x), lies between the smallest, x_{min}, and largest, x_{max}, such distances. The latter are evaluated with respect to the location of the best matched blocks. This type of concealment is introduced to eliminate the need of employing a post processing technique for block artifact reduction, since diffusion does not introduce many significantly visible blocking artifacts.

Concealment by bilinear interpolation is performed as in the case of anisotropic diffusion, with the difference that image content in the lost region is restored by interpolating the image content of the border pixels of the best match using a formula similar to (1). Such kind of concealment is introduced for comparison purposes. Because blocking artifacts introduced by copying are more noticeable in the third and fourth steps of the split-match process, concealment by diffusion or interpolation is employed only in these steps, whereas concealment in the first two steps is achieved always by copying.

IV. Intra-/Inter-frame Error Concealment

Temporal information is available at the decoder for all but the first frame in a single scene of an MPEG-2 coded sequence. This is true even for intra-coded frames (I-frames), since previously decoded P-frames already exist in the decoder frame buffer for the decoding of the subsequent in coding order B-frames. Consequently, temporal EC methods can be used for their concealment, which, in contrast to spatial ones, result in nearly perfect concealment in areas of no or little motion.

Temporal EC methods exploit previously decoded temporal information to conceal lost regions in current frames. Simple temporal EC methods are temporal replacement [22], motion compensated concealment [22] and adaptive temporal concealment [5], [50]. Temporal replacement replaces the lost MB with that in the same location of the previously decoded frame, stored in the decoder buffer. No motion information is exploited, which results in noticeable shifts in strong motion areas. This method is also known as zero motion EC (ZM EC). Better results are obtained if motion information is exploited for concealment. The motion compensated concealment (MC EC) estimates motion for the lost MB by averaging available motion vectors from neighbouring MBs based on the assumption of uniform motion between all neighbouring MBs. For intra-coded neighbours, however, no motion vectors are available, thus leading to similar defects as the zero motion EC. A solution to this problem is the transmission of concealment motion vectors for intra-coded MBs. These, however, lead to an overhead of about 0.7% of the total bit rate (for bitrates of 6-7 Mbps) [5], [12] and transmission errors might lead to their loss as well. Furthermore, the assumption of smooth motion does not always apply for all neighbouring MBs. Adaptive temporal concealment (Adaptive EC) is based on local measures of spatial and temporal activity. When spatial activity is high, motion compensated temporal concealment is applied. When temporal activity is high, spatial interpolation is used. The method is applied to I-frames, while P- and B-frames are concealed by MC EC. Its performance is usually better than the other two, judging mainly from the perceived visual quality of the concealed sequences, with a small increase in complexity.

When motion uniformity does not apply for all neighbours of the lost MB or motion information is not available due to their intra-coding, none of the above mentioned methods performs satisfactorily. The *temporal forward-backward block matching EC method* attempts to alleviate these drawbacks by selecting the neighbour that leads to the best possible concealment of the lost MB based on block matching principles. The concealment scheme is embedded in the decoder model as shown in Figure 4, in such a way that concealment is performed after the entire frame decoding has been completed. If the concealed frame is a reference one, it is stored in the previous or future picture buffer of the decoder to be used for decoding and concealing the frames which are next in the coding order, otherwise it is displayed. Thus, only the concealment of damaged by bitstream error blocks is necessary.

The temporal forward-backward block matching EC method exploits the temporal redundancy of an image sequence. The assumption of a smooth and uniform motion for at least some adjacent blocks is adopted. Temporal block matching is performed between the top and/or bottom macroblocks, MB_T and MB_B respectively, of the lost macroblock MB_C, and equally sized blocks located in a predefined search region in the reference frame/frames, its centre being MB_C, as shown in Figure 5. Neighbouring candidates for block matching are either the available top neighbour, MB_T (case A in Figure 5), the available bottom one, MB_B (case B), or the combination of both (case C). In the latter case, their vertical distance is restricted to 16 pixels (a MB's vertical dimension) and the movement of MB_T and MB_B in the search region is identical. Temporal matching is performed for all neighbouring candidates in a predefined search region of size $N \times M$ and the one that leads to MAD minimization is used to estimate the lost MB image content. Concealment is performed by copying into the lost MB area the image content of the appropriate neighbour of the temporal "best match". For example, if the case A candidate minimizes the respective matching error at a certain location inside the search region, the immediately bottom 16×16 neighbouring region of the temporal best match is copied into the lost area of equal size. The definition and separate matching of different neighbouring candidates aims at dealing with cases where the smoothness of motion applies for some but not all neighbouring blocks. Temporal matching proves also useful when no motion vectors are available for adjacent MBs due to their intra coding. In order to reduce the computational complexity and processing time, the search region, initialized in the reference frame/frames, is set bigger if temporal matching is performed between far distant frames and decreases if they are closer in time. Furthermore, a logarithmic search rather than a full search may be employed. For I- and P-frames, the matching is performed between the current and the past reference frames, while for B-frames, matching is performed between the current and the past as well as the future reference frames. The best match, in the latter case may be a part of either the past or the future reference frame. The reference frames are already decoded and stored in the decoder buffers, even when I-frames require concealment. Consequently, no additional memory requirements are introduced.

An alternative approach is also considered for further processing time reduction, mainly for P- and B-frames, for which adjacent motion information is available at the decoder. Specifically, much smaller search regions of size $K \times L$ are initialized around their motion compensated ones in the reference frame/frames for the candidates of cases A and B in Figure 5. Motion compensation is performed using the available motion vectors of adjacent blocks, as shown in Figure 5. Motion vectors are used only if they exist. Motion vectors for I-frames may be obtained by the respective ones of the previously decoded P-frames.

V. Simulation Results

In order to evaluate the performance of the presented concealment scheme, three different 4:2:0 CCIR 601 sequences have been used, namely the Flower Garden (125 frames, large uniform motion, movement of background), the Mobile & Calendar (40 frames, moderate irregular motion, movement of background) and the Tunnel (100 frames, large irregular motion, static background) sequence. These have been coded by an MPEG-2 encoder at 5 Mbps at 25 fps (PAL) using slice sizes equal to an entire row of MBs, $N = 12$ (number of frames in a GOP) and $M = 3$ (number of frames between successive I- and P- or P- and P- frames). Layered coding (scalable profiles) has not been used. Motion compensation has been performed on a MB basis. MPEG-2 transport packets are considered, which are 188 bytes long composed by 4 bytes header information and 184 bytes payload [4]. Errors may result from either isolated bit errors or packet loss. Appropriate error detection is assumed to be performed prior to concealment. Erroneous packets are discarded by the decoder until it regains synchronization. Two different packet error rates (PER) are considered: 0.01 and 0.1, corresponding to medium and high error rate cases. For higher PER values, none of the ECs under study performs satisfactorily without the additional use of error control, coder modifications or layered coding.

Performance evaluation of both methods of the concealment scheme has been performed based on $PSNR$ values and perceived visual quality of the concealed sequence. Results from luminance concealment were exploited for further chrominance concealment. The Split-Match EC (S-M EC) method is compared with SVI EC proposed in [22]. Constant and adaptive thresholds for region similarity decisions have been considered. "Optimal" constant thresholds have been experimentally estimated for the Flower Garden sequence, by evaluating the perceived visual quality of the concealed frame, and have been applied to the other two sequences as well. Results are presented in Table I for all test sequences measured on the first I-frame. Table I additionally includes results obtained by the spatial diffusion EC (SD EC). Although SVI EC and SD EC result in similar $PSNR$ values, which are generally better than the ones achieved by the S-M EC method, they also lead to significant blurring in the concealed areas, thus producing an inferior visual quality of the concealed frame. The use of constant thresholds by the S-M EC achieves better $PSNR$ values, than when adaptive ones are employed, but they have the disadvantage of their manual estimation. However, it is seen that use of "optimal" constant thresholds for the Flower Garden in the concealment of the other sequences leads to satisfactory results. Small variations in $PSNR$ values are observed for different types of concealment employed by the S-M EC for almost all cases listed in Table I. However, diffusion does not require post-processing of block artifacts as copying does, although the latter is simpler. Judging from the perceived visual quality of the concealed frames (Figure 6), the S-M EC method achieves to reconstruct spatial edges at various directions and results in smooth continuation of the image content in the lost areas, when spatial information is sufficient for their retrieval. It is also observed that, although the use of adaptive thresholds might not lead to the best $PSNR$ values, the subjective quality of the concealed frames is much better than that achieved using constant ones.

Average $PSNR$ values evaluated on the test sequences concealed by the temporal Forward-Backward Block Matching (F-B BM) EC method and the temporal methods presented in Section IV are tabulated in Table II. The F-B BM EC method surpasses all the other temporal ECs under study in almost all cases examined (different PER values and test sequences). This is further supported by the $PSNR$ plots versus frame indices shown in Figure 7 and the achieved visual quality of the concealed frames, examples of which are illustrated in Figures 8-10. This significant improvement results from the fact that concealment in I-frames is much better performed when taking into account temporal information as well. It is generally agreed that the an MPEG-2 coded video sequence quality is greatly affected by the visual quality of its I-frames, since they serve as anchor frames for the decoding of P and B ones. The fact that they are coded independently from other frames aids in delimiting the propagation of decoding errors from frames in a previous GOP to frames in the next one. Therefore, their best possible concealment, which implies use of motion information as the F-B BM EC method does, results in a remarkable improvement of the visual quality of the decoded sequence. Furthermore, the capability of the F-B BM EC method to deal with cases for which the assumption of smooth motion for all neighbours of a lost MB is not valid, or when intra-coding of adjacent MBs leaves the decoder with no details about their motion, enhances its performance compared to the other temporal ECs under study, since it attempts to locate the best possible candidate from the neighbouring regions for concealment. Even if the Adaptive EC decides on spatial concealment for such occasions, such concealment is worse than temporal one. The control of the search region size and the use of motion information, when available, assist in reducing the processing time of the F-B BM EC method. Block artifacts caused mainly in occluded regions, where mere past information is not sufficient (observed in I- or P-frames), are less visible for smaller PER values and become noticeable if PER values become greater than 10%. The F-B BM EC proves tolerant for PER values as high as 10%, while the other temporal ECs under study cause more artifacts, which become noticeable even at frame rates of 25fps.

VI. Conclusions

An error concealment scheme based on block matching principles for MPEG-2 non layered coded video sequences is presented. It applies the *spatial Split-Match error concealment method* to the first I-frame of a sequence or a scene and uses the *temporal Forward-Backward Block Matching error concealment method* to the other frames. The concealment scheme is embedded in the decoder model in such a way that concealment is performed after entire frame decoding. It is robust for packet error rates as high as 10%, when other error concealment methods usually fail. The Split-Match error concealment method is based on spatial block similarity principles. When spatial information is adequate for lost region retrieval, it succeeds in reconstructing edges or lines of various orientations, textures and other spatial details in a smooth and continuous way. The Forward-Backward Block Matching error concealment method is based on temporal block similarity principles and performs well when motion uniformity is not valid for all adjacent MBs or when no motion information exists for adjacent MBs (due to their intra-coding), cases where the other temporal error concealment methods under study may fail.

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TABLE I

$PSNR$ VALUES MEASURED ON THE FIRST I-FRAME OF THE THREE TEST SEQUENCES, ACHIEVED BY THE SPATIAL CONCEALMENT METHODS UNDER STUDY.

$PSNR$ - Y Component - Different PER values							
EC Method	Type of Concealment	Flower Garden		Mobile & Cal.		Tunnel	
		1%	10%	1%	10%	1%	10%
Error Free		32.21	32.21	35.30	35.30	36.54	36.54
S-M EC (Adaptive Thr.)	Copying-Post Pr.	28.82	23.55	31.41	26.54	33.10	34.65
	Interpolation	28.55	23.21	31.65	26.38	32.60	34.95
	Diffusion	28.57	23.23	31.64	26.37	32.60	34.89
S-M EC (Constant Thr.)	Copying-Post Pr.	29.17	23.75	31.44	26.64	33.14	34.70
	Interpolation	29.31	23.75	31.62	26.59	34.95	35.06
	Diffusion	29.37	23.80	31.57	26.57	34.89	35.00
SD EC		29.41	23.47	32.28	27.23	33.39	34.99
SVI EC		29.37	23.62	32.36	27.42	33.76	35.21
Erroneous		22.76	12.02	22.68	16.50	22.76	28.47

TABLE II

AVERAGE $PSNR$ VALUES FOR THE THREE TEST SEQUENCES ACHIEVED BY THE TEMPORAL CONCEALMENT METHODS UNDER STUDY FOR DIFFERENT PERs. THE FIRST FRAME IS CONCEALED BY THE SPLIT-MATCH EC METHOD, USING ADAPTIVE THRESHOLDS AND ANISOTROPIC DIFFUSION.

Average $PSNR$ - Y Component - Different PER values						
EC Method	Flower Garden		Mobile & Cal.		Tunnel	
	1%	10%	1%	10%	1%	10%
Error Free	27.95	27.95	35.51	35.51	36.03	36.03
F-B BM EC	**27.42**	**25.15**	**33.78**	**30.23**	33.94	**30.74**
Adaptive EC	26.52	23.27	33.24	28.83	34.00	29.94
MC EC	26.63	23.29	33.38	28.75	**34.13**	30.04
ZM EC	26.12	21.51	32.94	26.41	33.94	29.72
Erroneous	18.76	11.16	23.52	14.31	24.57	16.59

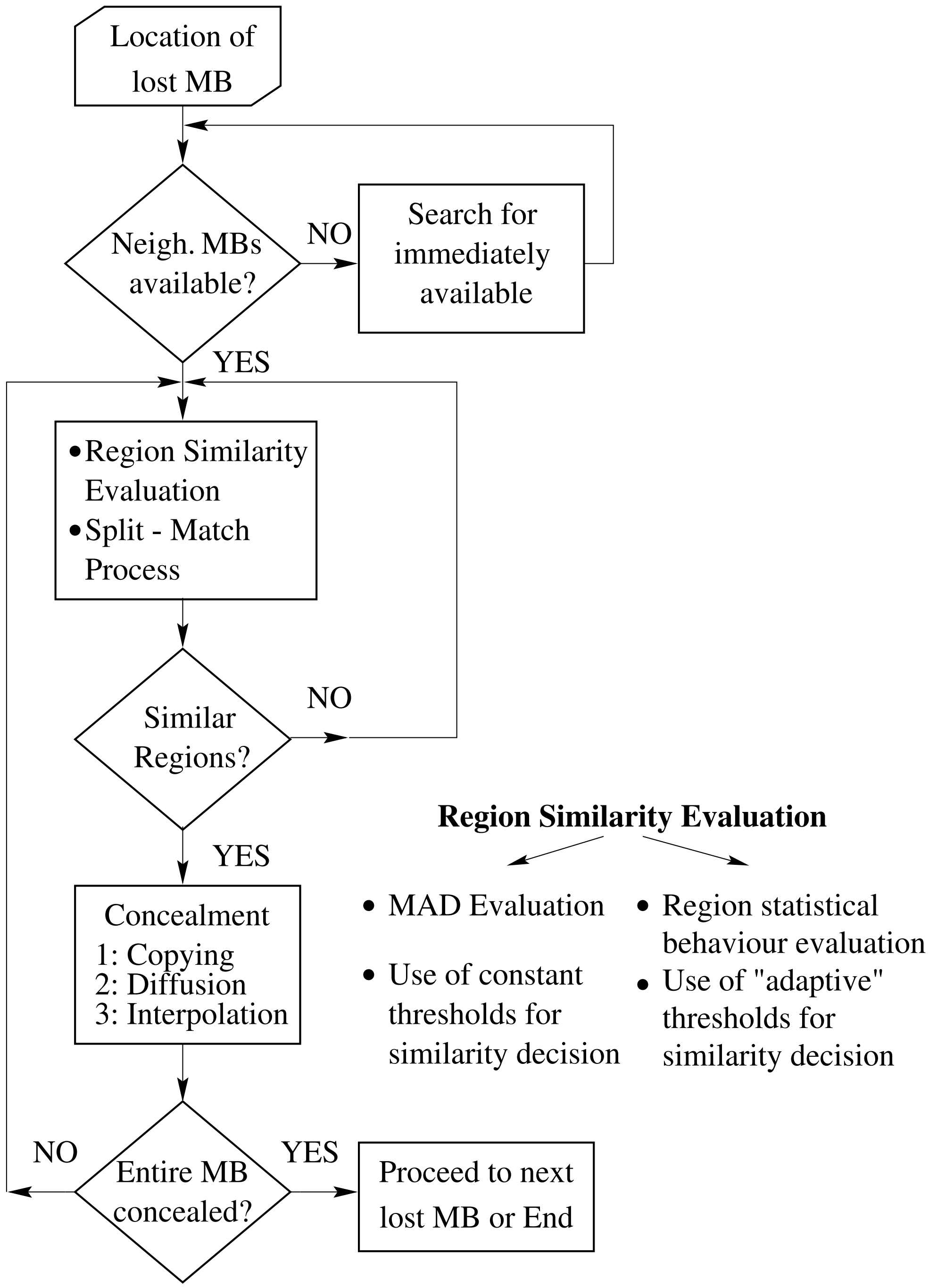


Fig. 1. Flow chart of the Split - Match EC algorithm.

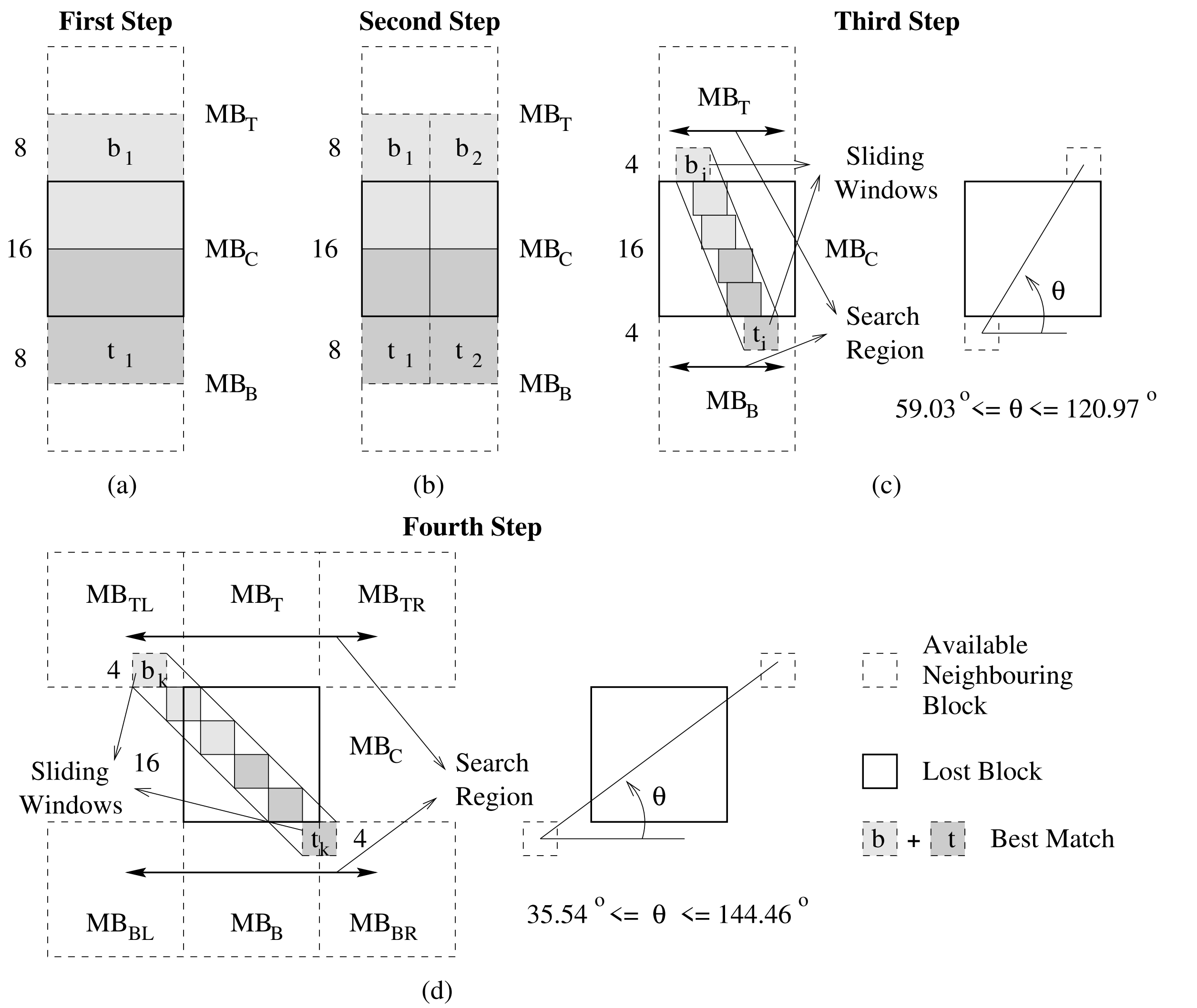


Fig. 2. Schematic presentation of the Split - Match algorithm. MB_T, MB_B, MB_{TL}, MB_{TR}, MB_{BL}, MB_{BR} are adjacent to the lost one, MB_C, MBs.

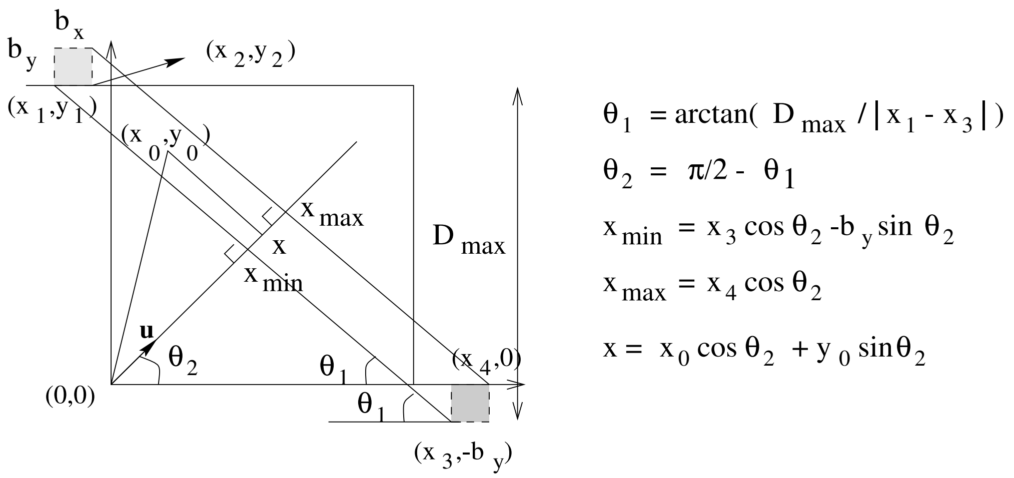


Fig. 3. Graphical presentation of how pixels located in the direction of the best matched blocks are determined for further concealment.

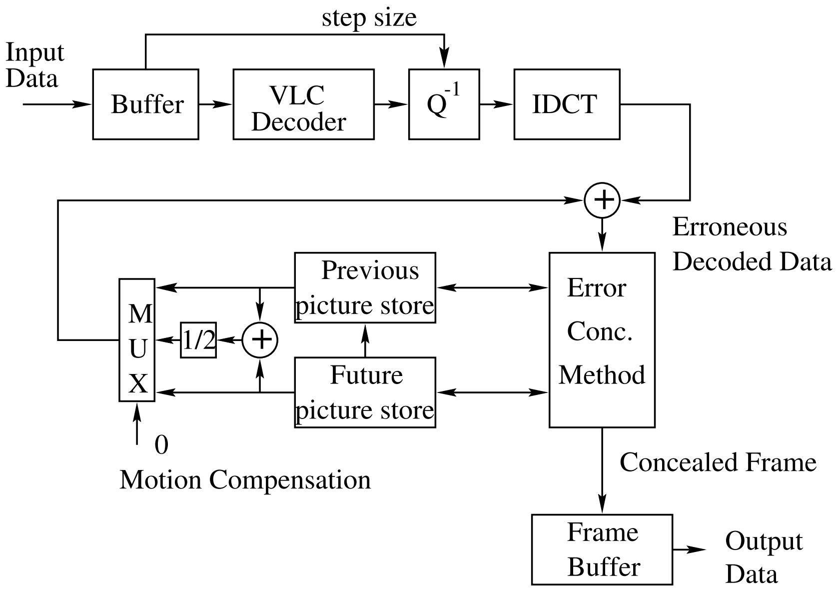


Fig. 4. Introduction of the error concealment method in the MPEG-2 decoder model.

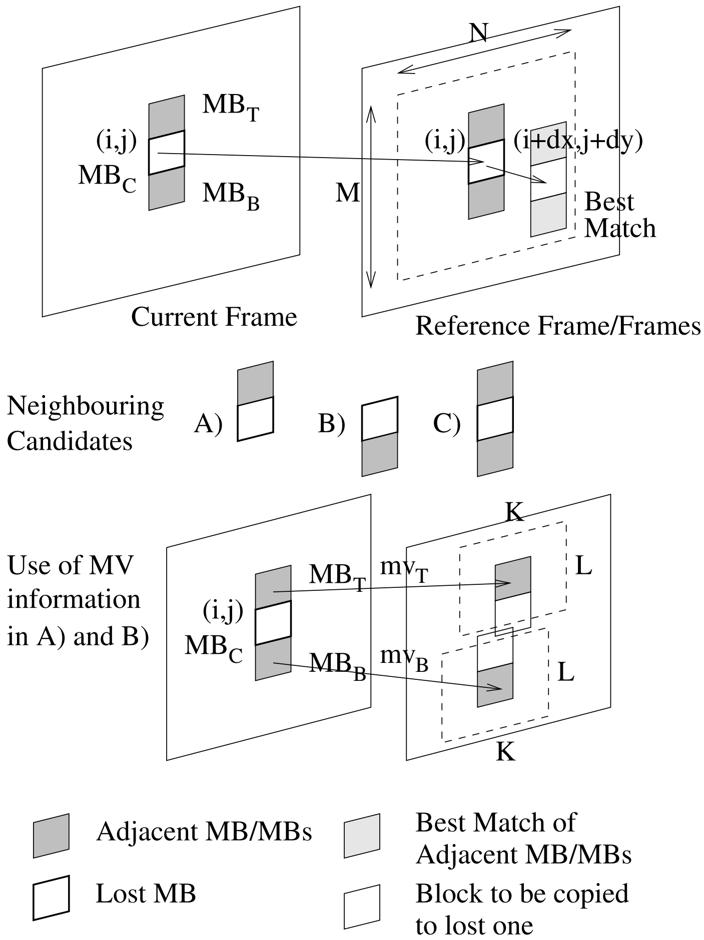


Fig. 5. Temporal Matching of top and/or bottom available MBs (MB_T, MB_B) between current and reference frame/frames. Neighbouring candidates are either existing top, or bottom or combined top and bottom MBs.

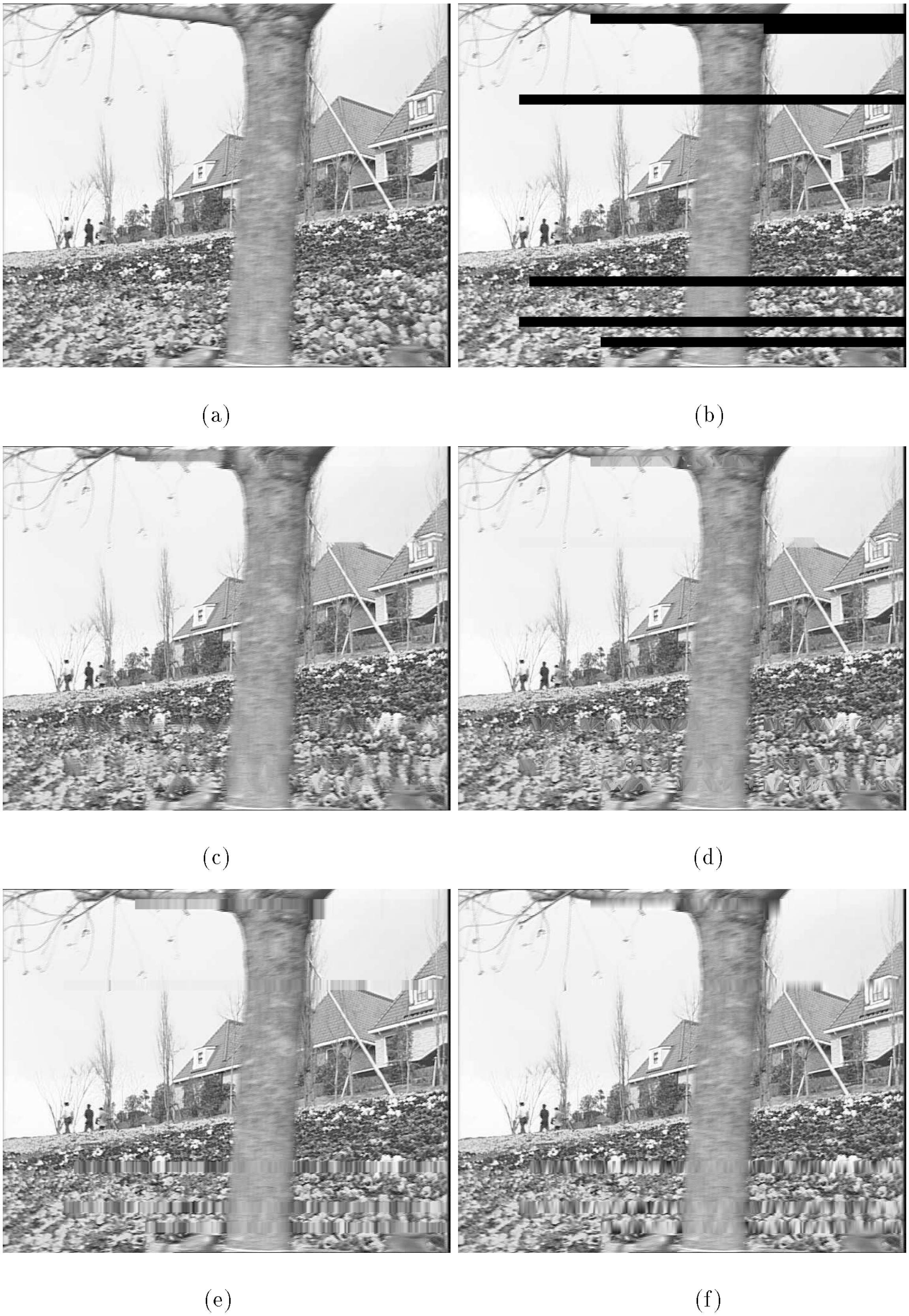


Fig. 6. First frame of the Flower Garden sequence: (a) Error Free, (b) Erroneous, $PER = 0.1$, Concealed by: (c) S-M EC using adaptive thresholds and copying, (d) S-M EC using adaptive thresholds and anisotropic diffusion, (e) SD EC, and (f) SVI EC.

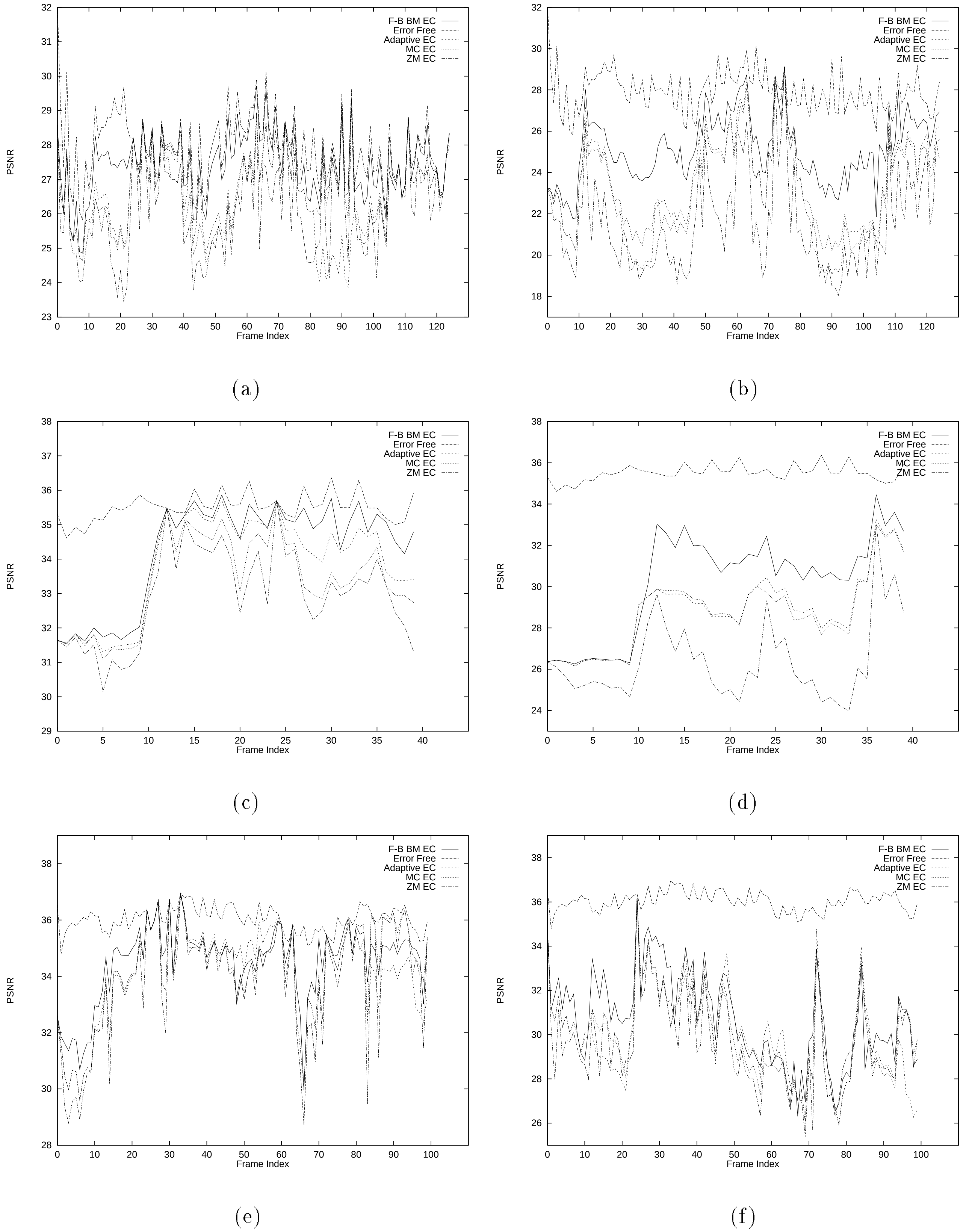


Fig. 7. $PSNR$ values against frame indices achieved by the temporal EC methods: F-B BM EC, Adaptive EC, MC EC and ZM EC. Evaluation has been performed on the Flower Garden (plots (a) $PER = 0.01$ and (b) $PER = 0.1$), the Mobile & Calendar (plots (c) $PER = 0.01$ and (d) $PER = 0.1$) and the Tunnel (plots (e) $PER = 0.01$ and (f) $PER = 0.1$) sequences.


(a) (b)


(c) (d)

(e)

Fig. 8. Frame 14 (B-frame) of the Flower Garden sequence: (a) Error free, (b) Erroneous, $PER = 0.1$, Concealed by: (c) F-B BM EC, (d) Adaptive EC and (e) MC EC.

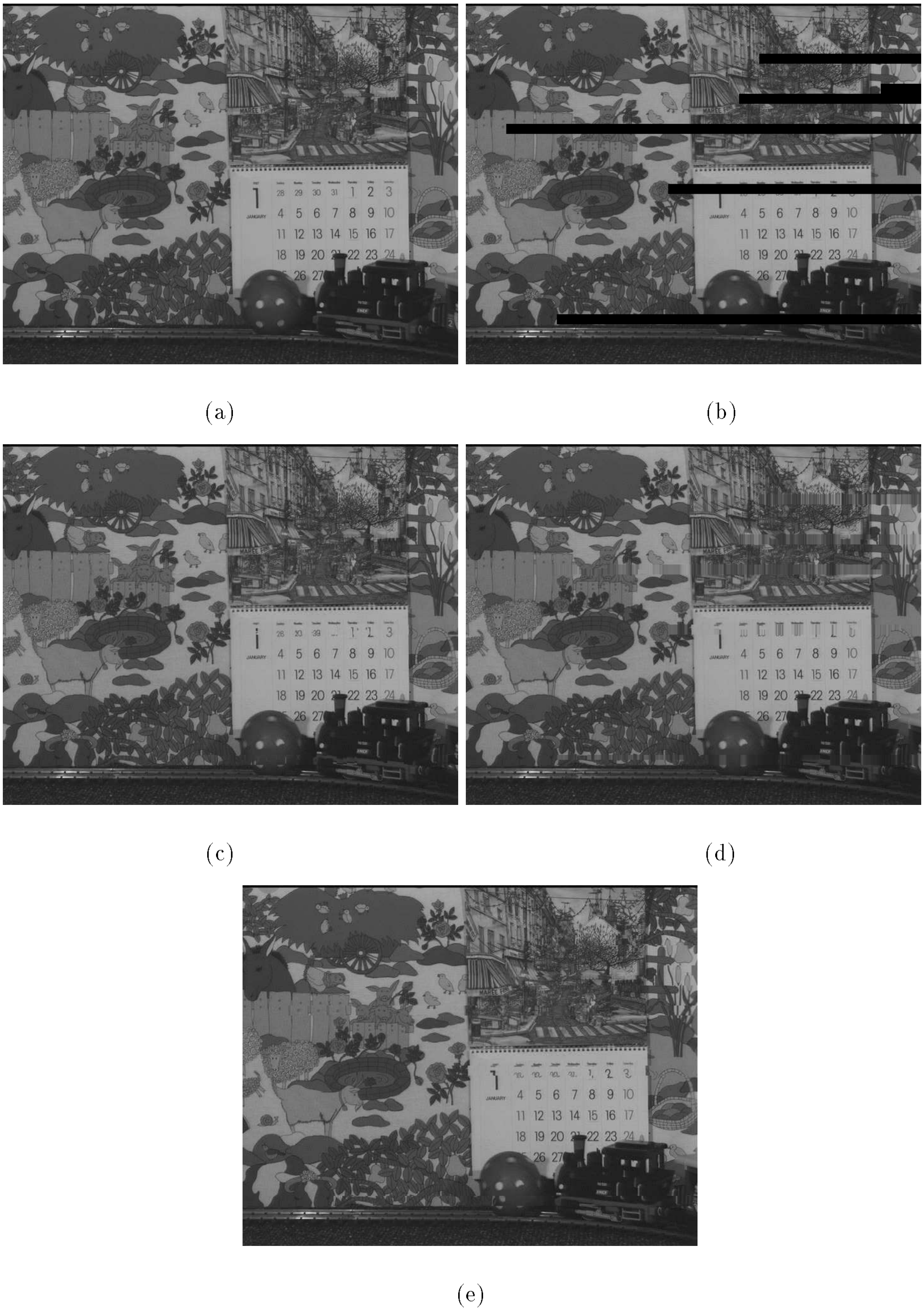
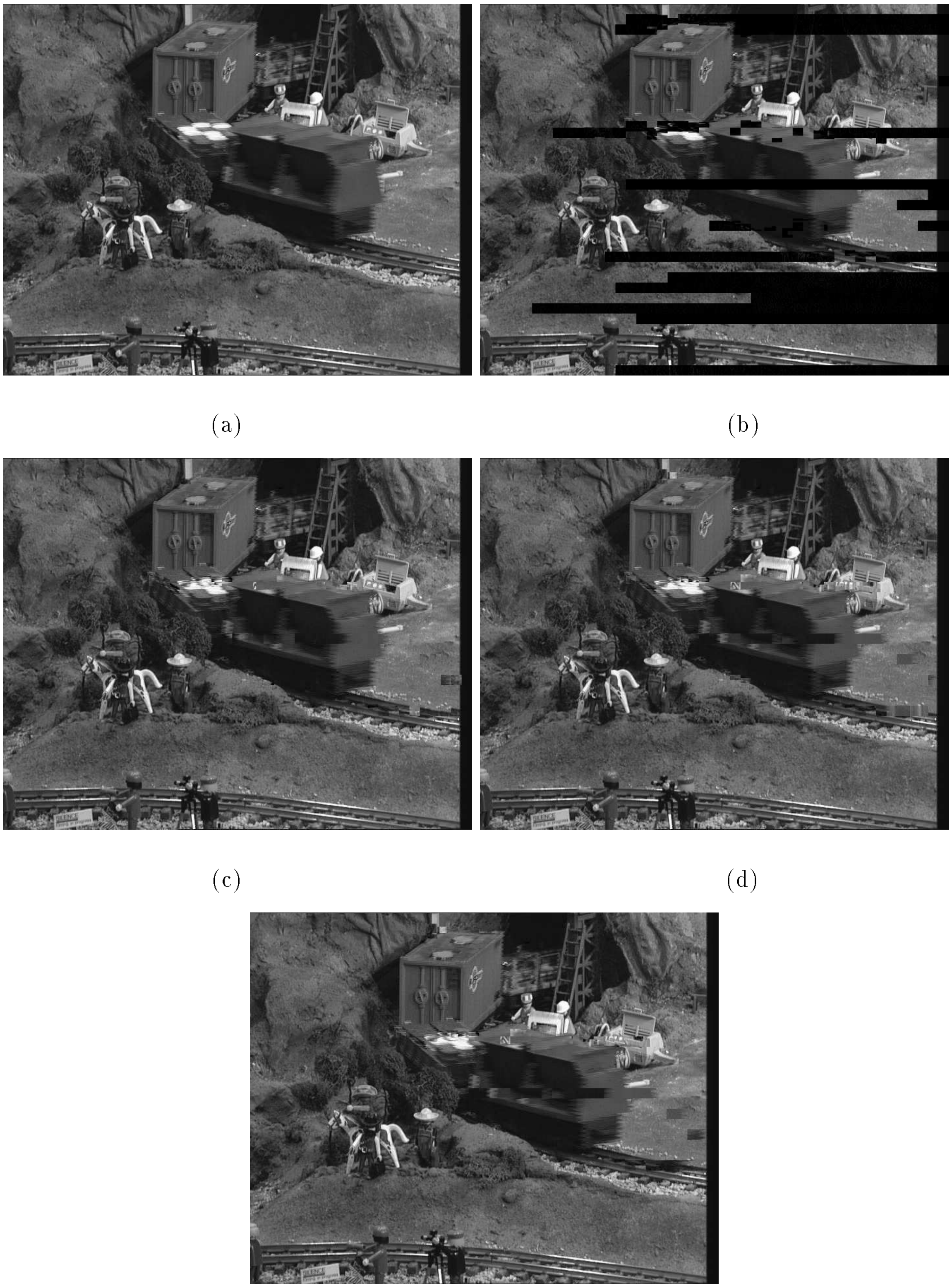


Fig. 9. Frame 12 (I-frame) of the Mobile & Calendar sequence: (a) Error free, (b) Erroneous, $PER = 0.1$, Concealed by: (c) F-B BM EC, (d) Adaptive EC and (e) MC EC.



(a) (b) (c) (d) (e)

Fig. 10. Frame 90 (P-frame) of the Tunnel sequence: (a) Error free, (b) Erroneous, $PER = 0.1$, Concealed by: (c) F-B BM EC, (d) Adaptive EC and (e) MC EC.