Temporal & Spatial Error Concealment Techniques for Hierarchical MPEG-2 Video Codec

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Abstract

The MPEG-2 source coding algorithm is very sensitive to the channel disturbances. For instance a single bit error in the bitstream will cause a high degradation of picture quality due to error propagation. Hence, for picture replenishment error concealment techniques (ECT's) may be required at the receiver.

The aim of this article is to study different ECT's for MPEG-2 hierarchical coded pictures applied for terrestrial broadcasting. For the base layer different temporal and spatial ECT's are investigated. Two temporal ECT's are considered: a simple temporal error concealment (EC) and a temporal EC with motion compensation. The latter method provides the best results in inter coded pictures (where motion vectors exist). For the intra coded pictures, where no motion information exists, two spatial interpolation techniques are considered. The main problem for spatial EC in MPEG-2 coded pictures is that only the top and the bottom macroblock can be used for interpolation, since one error in the bitstream causes one damaged horizontal stripe of macroblocks in the picture. Different ECT's for the upper layer of hierarchical coded pictures are also investigated. The possibility of upsampling the base layer for concealing the upper layer made by spatial scalability gives best results.

1 Introduction

The future terrestrial digital TV/HDTV signal will be a highly compressed signal due to the restricted bandwidth of the channels in Europe (UHF and VHF). The TV/HDTV source coding algorithms used for this applications will be based on MPEG-2 [1], where motion compensated, hybrid DCT, variable length coding (VLC) and adaptive quantization are performed.

The MPEG-2 source coding algorithm is very sensitive to the channel disturbances. Therefore, for broadcast applications in order to assume graceful degradation as in analogue systems, MPEG-2 hierarchical coding profiles will be needed.

The future digital TV/HDTV should also support a compatibility with the standard definition TV (SDTV), where the SDTV-image quality will be expected for portable receivers. However, HDTV image quality will be demanded for stationary receivers with a roof-top antenna. Both, system compatibility and some step-wise graceful degradation can be achieved by using the MPEG-2 hierarchical source coding profiles with matched channel coding [2, 3]. Up to two/three layers can be obtained with the so called SNR and/or spatial-scalability specified in the MPEG-2 hierarchical profiles.

In order to achieve graceful degradation, the two (TV1, TV2) or three (TV, HD1, HD2) layers require different protection. This will be done with a combination of Unequal Error Protection (UEP) Codes and modulation [3]. The base layer (TV or TV1) should be highly protected. However, at very long distances or at worst reception conditions, i.e. deep fades or impulsive noise, the portable receiver, which suffers from the non existence of a graceful degradation, may risk to receive nothing (the threshold effect). Even for a fixed receiver the graceful degradation with three different protection layers may not be sufficient. To avoid this or to enhance the picture quality, one may apply the ECT's at the receiver. For instance for the most critical layer, EC may help to obtain an appropriate picture quality, even if there are many residual errors in the bitstream after channel decoding. ECT's in the upper layers give also a better quality comparing to use only the lower layer(s).

It should be noted that MPEG-2 has its own multiplexing format. The video, audio and auxiliary data after multiplexing and forming the MPEG-2 Transport Packet Stream, are submitted to channel coding and modulation.

The aim of this article is to study different temporal and spatial ECT's for MPEG-2 hierarchical coded pictures, taking into account a real transmission medium [3, 4].

The paper is organized as follows: in order to understand the problem and the mechanism of EC the hierarchical MPEG-2 source coding is briefly described in section 2. Section 3 examines the different error detection techniques. In section 4 different temporal and spatial EC algorithms for the base and the upper layers are analyzed. Simulation results are given in section 5 and section 6 is devoted to some conclusions.

2 MPEG-2 Video Codec

The MPEG-2 video international standard [1] specifies the coded representation of the video data. The video source coding is based on motion compensated hybrid DCT coding. There are three different types of pictures defined: the intra coded (I-), the predictive coded (P-) and the bidirectionally predictive coded (B-) pictures. The pictures are divided into slices. One slice consists of several macroblocks. One macroblock is divided into four blocks, where each block contains 8×8 pixels. This block is submitted to the 8×8 DCT (Discrete Cosine Transform).

In I-pictures after the DCT operation a zig-zag-scanning followed by quantization and variable length encoding (VLC) are performed. The inter coded pictures (P and B) use motion compensated prediction from a previous picture (or a following picture or both (in B-pictures)). Additionally to the motion vectors the prediction error will be sent in the bitstream. This prediction error will be coded like the intra coded macroblocks. Since the prediction error will be very small or sometimes zero, the compression in inter coded pictures is very high.

In a two or three layer hierarchical system the base layer (TV1 or TV) will be encoded and decoded in the same way

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as described before (MPEG-2 MainProfile@MainLevel). The layers TV2 or HD1 and HD2 are made with the tools for hierarchical source coding: SNR scalability and spatial scalability. The SNR Scalable Profile at Main Level ("SNRP@ML") provides two layers called TV1 and TV2 of the same spatial resolution but of different quality. Here, the quantization error of the base layer will be computed and this error will be sent in the upper layer. However, the Spatially Scalable Profile at High 1440 Level ("SSP@H14L") provides three layers called TV, HD1 and HD2 with different spatial resolution (TV/HD, made by spatial scalability) and of different quality (HD1/HD2, made by SNR scalability). With spatial scalability, the base layer will be upsampled and additionally to the motion vectors, the upsampled picture will be used for prediction. The spatial scalability provides the link between the SDTV and the HDTV formats.

In this article we consider a TV picture of 4 : 2 : 0 format with 720×576 pixels and a HDTV picture of 4 : 2 : 0 format with 1440×1152 pixels. One slice will consist of 44 (HDTV: 88) macroblocks. The choice of the length of slices may have an influence on EC because synchronization is only possible after one slice. Therefore, shorter slices could be better, but they will cause a higher bit rate.

3 Error Detection Techniques

For EC measures, proper error detection is needed. Errors may be detected by both source and channel coding.

The channel decoder can detect errors in the received Transport Packets with high reliability [4]. A wrong packet will be indicated in the Transport Header. If the source decoder knows the errors in packets, the slices where the packet errors are, will be concealed until the next synchronization point. Synchronization words are only given at the beginning of each slice, so that the next access in the bitstream will be at the beginning of the next slice.

Another way for error detection is the detection capability of the source decoder. The source decoder can detect errors, if for instance some codeword in the bitstream cannot be mapped into the table of the variable length code. But if one codeword is mapped into another codeword, the video source decoder cannot detect it and this error will propagate.

Error detection in the channel decoder gives better results than error detection in the source decoder [4] (with the assumption that the EC method is very good), because visible errors, which comes from the non-detected errors in the source decoder, will be concealed.

4 Error Concealment Techniques

The two main ECT's described here are the temporal and the spatial EC. Temporal EC makes use of the temporal redundancy in one sequence. It is devoted to inter coded pictures, because there exists some motion information. Temporal ECT's are easier to implement and the complexity is less than some spatial recovering algorithm. The spatial EC exploits the spatial redundancy in one picture. This technique is proposed for intra coded pictures, where no motion information exist. In this section different temporal and spatial ECT's and the combination of the two algorithm are analyzed. For the upper layers of a hierarchical MPEG-2 coded sequence other possibilities for EC like using the upsampled TV-picture are also investigated.

4.1 Temporal Error Concealment

Different temporal ECT's for inter coded pictures (P- and B-pictures) are investigated in [4]. The first one is a simple temporal EC. In this method the previous anchor picture is copied into the current picture where errors were detected. With this method shifts will be visible, if there is motion.

The second method uses in addition the motion-vectors from one nearest macroblock in the current picture. This method is called motion compensated temporal EC. Because a detected error results in one damaged horizontally oriented stripe of the decoded image, the nearest macroblocks are the two macroblocks above and below the current macroblock.

The second method usually is the best one [4], since high motion becomes not visible. But if the motion from the current macroblock is a motion with another direction than the surrounding macroblocks, this error becomes visible.

4.2 Spatial Error Concealment

Spatial ECT's are devoted to I-pictures where no motion information exist. Two different methods based on simple interpolation are considered in this article. The first technique interpolates each single block in one macroblock. The $N \times N$ block will be interpolated with the pixels of two neighboured blocks (Figure 1 with $N = 4$).

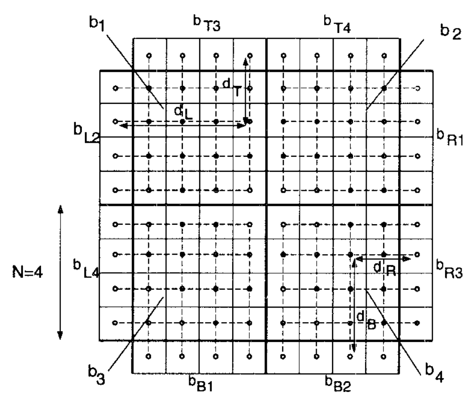

Figure 1: Spatial interpolation of each single block

This interpolation can be described as follows:

$$
\begin{aligned}
b_1(i,k) &= \frac{d_T b_{L2}(i,N) + d_L b_{T3}(N,k)}{d_L + d_T} \\
b_2(i,k) &= \frac{d_T b_{R1}(i,1) + d_R b_{T4}(N,k)}{d_R + d_T} \\
b_3(i,k) &= \frac{d_B b_{L4}(i,N) + d_L b_{B1}(1,k)}{d_L + d_B} \\
b_4(i,k) &= \frac{d_B b_{R3}(i,1) + d_R b_{B2}(1,k)}{d_R + d_B}
\end{aligned}
\qquad i,k = 1 \dots N, \qquad (1)
$$

where $b_l, l = 1 \dots 4$ is the l^{th} block of the current macroblock, $b_{Xl}, l = 1 \dots 4$ with $X = L, R, T, B$ is the l^{th} block of the neighboured macroblock (Left, Right, Top, Bottom) and d_X with $X = L, R, T, B$ is the distance from the respective pixel of the block b_{Xl} to the current pixel $b_l(i,k)$. This technique gives good results if the four surrounding macroblocks exist. In MPEG-2 the synchronization point is at the start of the next slice, therefore, one horizontal stripe of macroblocks must be concealed. The left and the right macroblocks cannot be used for concealment because they do not exist. Therefore, another technique is considered for concealing the horizontal stripes of macroblocks.

The second technique interpolates each pixel of the whole macroblock with the adjacent pixels of the four neighbouring macroblocks. Figure 2 shows the macroblock with the boundary pixels of the neighbouring macroblocks.

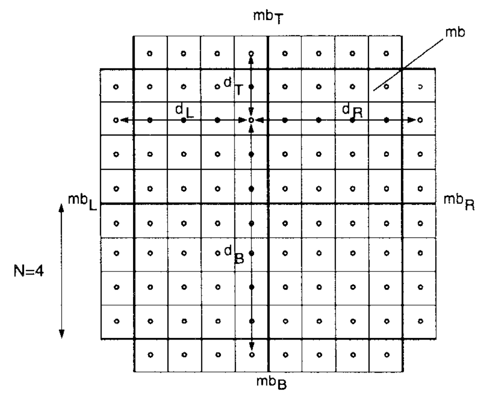

Figure 2: Spatial interpolation of the whole macroblock

Each pixel of the current macroblock with the size $2N \times 2N$ will be concealed by simple interpolation of the four pixels of the surrounding macroblocks. The equation for this is:

$$mb(i,k) = \frac{1}{d_L + d_R + d_T + d_B}(d_R mb_L(i,2N) + d_L mb_R(i,1) + d_B mb_T(2N,k) + d_T mb_B(1,k)) \quad (2)$$

$$i,k = 1 \ldots 2N,$$

where mb is the current macroblock, mb_X with $X = L, R, T, B$ is the respective neighboured macroblock (Left, Right, Top, Bottom) and d_X with $X = L, R, T, B$ is the distance from the respective pixel of the macroblock mb_X to the current pixel $mb(i,k)$. This technique works better if the surrounding macroblocks exist. If some of the macroblocks do not exist for interpolation (if one whole stripe of macroblocks is damaged) the corresponding distance will be set to zero (for instance if mb_L do not exist d_R will be set to zero).

With only two available macroblocks mb_T and mb_B the equation 2 reduces to:

$$mb(i,k) = \frac{d_B mb_T(2N,k) + d_T mb_B(1,k)}{d_T + d_B} \quad i,k = 1 \ldots 2N. \quad (3)$$

This spatial interpolation can be used for MPEG-2 coded pictures where the next synchronization point is at the start of the next slice.

With the first method there will be some 'block-effect': some of the reconstructed blocks are correct (for instance if the two neighboured blocks have the same colour) and some of the blocks become blurred. This block-effect in one macroblock vanishes, if one uses the second technique. No abrupt transition occurs in one macroblock. The whole macroblock becomes blurred if there are edges in one macroblock. Then this will be also a visible block-effect in terms of macroblocks. In MPEG-2 coded pictures, where some stripes of macroblocks are damaged, only the interpolation with the second method is possible. The interpolation is then in one direction: in the vertical direction. Therefore, edges in the vertical direction will be concealed correctly, whereas edges in the horizontal direction will become blurred.

Other possibilities for spatial EC are for instance the multi-directional interpolation [5] and the signal loss recovering by imposing smoothing constraints [6]. For MPEG-2 coded pictures the multi-directional filtering will be reduced to a nearly one-directional filtering, because the left and right macroblocks can't be used for multi-directional interpolation. Also for the second method the four surrounding macroblocks and additional the undamaged DCT-coefficients (which are not given in a whole damaged stripe of macroblocks) are needed otherwise the complexity will be increased.

For I-pictures, MPEG-2 has the possibility of transmitting additional EC motion vectors in the bitstream. This would result in a noticeably better quality and is not so difficult to implement like the spatial concealment algorithms or combinations of spatial and temporal concealment techniques [6, 7]. With the additional transmission of frame motion vectors the overhead will be less than 0.7 % of the total bit-rate [8].

4.3 Combination of Spatial and Temporal Error Concealment Techniques

One way of combining the two concealment techniques in a video sequence is to conceal the I-pictures with spatial EC (if there are no concealment motion vectors) and to conceal the P- and B-pictures with temporal EC with motion compensation. Additionally to this a method, which is based on adaptive spatio-temporal replacement of missing data [7], may be applied in the I-pictures. The criterion for the decision spatial/temporal is the measurement of the image activity. With this adaptive spatio-temporal method the picture replenishment mainly for I-pictures will be enhanced, because with high motion a simple temporal EC and with high spatial detail the spatial EC will fail.

4.4 Error Concealment in MPEG-2 Spatial Scalable Profile

The MPEG-2 spatial scalability provides the link between the TV and the HDTV resolutions. The base layer bitstream TV contains all data for TV quality (MP@ML). The upper layer HD1 contains all additional data for obtaining HDTV resolution. Additionally to the motion vectors, the upsampled TV picture is used for prediction. The error between the original HDTV-picture and the predicted picture is sent in the upper layer. In I-pictures the prediction is only made with the upsampled TV-picture. In P-pictures also the forward motion vectors and in B-pictures also the forward and backward motion vectors are used for prediction.

Because the TV layer is the highest protected layer, the TV-layer may be received without errors at bad reception conditions, but the HD1 layer will contain packet errors. If one has a stationary receiver with HDTV quality, it seems worthwhile to conceal the wrong packets of the upper layer instead of using only the base layer.

Three different concealment methods for the upper layer are considered in this article. The first method is simple temporal EC. In this case the previous anchor picture is copied into the current picture where errors are detected. This method will cause shifts if there is motion. The second method uses additionally the prediction technique from one nearest macroblock. The choice of the nearest macroblock will be done like in [4]. The prediction technique varies from macroblock to macroblock: motion vectors only or motion vectors with the upsampled TV-picture can be used for prediction. This technique provides better results than the first technique, because the motion is compensated. Only if the prediction technique chosen is not appropriate for the current macroblock, errors in the picture domain will be visible. This technique cannot be applied to the I-pictures since I-pictures will be concealed without motion compensation.

The third technique avoids such errors in the picture domain: the erroneous parts of the picture will be simply concealed with the upsampled TV-picture. With this technique, the picture quality will be decreased (the sharpness), but no shift and no wrong macroblock occur. This technique gives also good results by applying it to the intra coded pictures.

4.5 Error Concealment in MPEG-2 SNR Scalable Profile

If there are errors in the upper layer made by SNR-scalability it will be better to take at the erroneous part only the base layer information, because the upper layer contains only the quantization error (without motion information). If one try to reproduce the quantization error, it may happen, that the estimated error is wrong and this wrong estimated error will result in a bad picture quality. Therefore, at the place where a wrong packet is detected, it is better to take only the base layer information.

5 Simulation Results

The simulations are carried out under the following conditions: the bitrate of the non-hierarchical coded TV-sequence was 5 Mbit/sec and the bitrate of the MPEG-2 hierarchical coded HDTV-sequence was $6 + 9 + 9 = 24$ Mbit/sec (TV+HD1+HD2), which seems to be a good compromise between the TV and the HDTV quality. 20 I-, P- or B-pictures were disturbed with the packet error rate $PER = 10^{-1}$ in the respective layer and the mean of the PSNR-values is given in the tables. The errors were simulated with the Channel Model [4], which reproduces the errors after the channel decoder (Rayleigh fading channel for the base layer and Rice fading channel for the upper layers). The burst errors of the inner Viterbi-Decoder were simulated.

For the I-pictures of the non hierarchical TV-sequence different spatial ECT's are investigated. The PSNR-values for the two interpolation techniques (blockwise interpolation 'spatial_block' and macroblockwise interpolation 'spatial_mb') and simple temporal EC ('simple') for the TV-sequence 'Flower' and 'Mobile' are depicted in Table 1 for one disturbed I-picture, where every second macroblock is disturbed and where it is assumed to have synchronization points at every macroblock (to show the interpolation technique, when the four surrounding macroblocks exist). For comparison Figure 3 shows the I-picture without errors, Figure 4 the disturbed I-picture without EC, Figure 5-7 the I-picture with the different ECT's.

The two concealment techniques 'spatial_block' and 'spatial_mb' give very good results if the four surrounding macroblocks exist. The difference between the two algorithms is very small and depends on the spatial activity of the picture: for some macroblocks the first method and for other macroblocks the second method is appropriate. The second technique causes blurring whereas the first technique causes some block-effect. The two techniques outperform the simple temporal ECT especially for the sequence 'Flower', where the motion is high.

PSNR Comparison 'Flower'				
	simple	spatial_ block	spatial_ mb	without errors
Y	18.515	22.661	23.291	30.717
I : U	26.823	30.363	30.504	33.321
V	31.888	33.768	33.885	35.305
PSNR Comparison 'Mobile'				
Y	21.001	22.296	22.678	28.938
I : U	31.188	31.480	31.465	34.601
V	31.817	32.145	32.134	35.888

Table 1: PSNR values for 'Flower' and 'Mobile' (I-picture)

For the MPEG-2 coded pictures, where horizontal stripes of macroblocks are damaged, only two neighbouring macroblocks exist for the spatial interpolation. The mean PSNR-values for the different ECT's are depicted in Table 2. Figure 8 shows a picture disturbed with $PER = 10^{-1}$. For this case only the macroblockwise spatial ECT is useful, because with the other technique only one neighbouring block can be used for interpolation. For comparison the simple temporal ECT is shown in Figure 9. Figure 10 shows the I-picture concealed with the technique 'spatial_mb'. For some parts, where two neighboured stripes of macroblocks were disturbed, the ECT is very bad, because only one neighbouring macroblock can be used for interpolation. To enhance this technique one may also use the concealed macroblocks for the interpolation of the next macroblock ('spatial_mb_enhanced'). This is shown in Figure 11.

PSNR Comparison 'Flower'				
	simple	spatial_ mb	spatial_ mb_enhanced	without errors
Y	19.412	20.180	20.431	30.717
I : U	27.767	28.207	28.348	33.321
V	32.486	32.548	32.620	35.305
PSNR Comparison 'Mobile'				
Y	20.289	20.135	20.339	28.938
I : U	30.533	28.924	28.086	34.601
V	31.713	29.418	28.916	35.888

Table 2: PSNR values for 'Flower' and 'Mobile' (I-picture), $PER = 10^{-1}$

The results show that the spatial ECT's 'spatial_mb' and 'spatial_mb_enhanced' in MPEG-2 coded I-pictures outperform the simple temporal EC if there is high motion. Only for the parts, where two neighboured slices are damaged, the spatial ECT is bad. In I-pictures with slow motion the simple temporal EC is best especially for the parts, where only one neighboured macroblock can be used for interpolation. Therefore it seems worthwhile to measure the motion and the spatial activity to decide whether the simple temporal or the spatial ECT will be applied (adaptive-spatio EC [7]).

Simulation results for different ECT's in P- and B-pictures of MPEG-2 spatial scalable profile are given in Table 3 for the sequences 'Edin_Street' and 'Ski' respectively. The layer HD1 of a MPEG-2 hierarchical coded sequence is achieved with spatial scalability. Therefore, this layer is disturbed with $PER = 10^{-1}$ for the investigations. The HD2-layer is assumed to be not received. The different temporal ECT's are simple temporal EC (simple copying from one previous picture, 'simple'), temporal EC with motion compensation (with the prediction method (motion compensation and/or combining the prediction with the upsampled picture) from one nearest macroblock of the current picture, 'motion') and EC with the upsampled TV-picture ('upsampled_tv'). For comparison the PSNR-value is also given for both layers TV and HD1 without errors and for only the base layer (TV, the HD1 layer is not decoded).

PSNR Comparison 'Edin_Street'					
	base layer	simple	motion	upsamp._tv	without errors
P : Y	27.560	27.990	31.186	31.363	32.237
P : U	35.908	29.077	36.856	36.777	36.937
P : V	34.598	35.041	35.620	35.544	35.753
B : Y	27.394	30.419	30.764	30.797	31.389
B : U	35.878	36.650	36.694	36.613	36.740
B : V	34.647	35.468	35.531	35.434	35.583
PSNR Comparison 'Ski'					
P: Y	24.804	20.295	30.376	31.078	32.217
P: U	36.383	33.564	38.394	38.151	38.624
P: V	33.663	29.781	35.993	35.904	36.520
B: Y	24.807	22.882	29.406	30.440	31.301
B: U	36.222	35.467	37.738	37.603	37.848
B: V	33.445	31.911	35.198	35.122	35.463

Table 3: PSNR values for 'Edin_Street' and 'Ski' (P- and B-pictures, disturbed HD1-layer)

The two concealment techniques 'upsampled_tv' and 'motion' give best results, where for the luminance component 'upsampled_tv' outperforms 'motion', because in the picture concealed with 'motion' there can occur wrong macroblocks if the motion vector is not appropriate for the concealed macroblock. In contrast to this the method 'upsampled_tv' will cause loss in sharpness, but this will be better than some wrong macroblock. For the sequence 'Ski' the simple temporal ECT is very bad because there is high motion. In this case it is better to use only the base layer. The results show, that it is better to conceal the wrong parts of a picture with the technique 'upsampled_tv' (or 'motion') than to use only the base layer at all. For I-pictures the results will be similar except that the concealment technique 'motion' cannot be used. Therefore, for I-pictures the technique 'upsampled_tv' will give best results.

Simulation results for picture replenishment in P- and B-pictures of MPEG-2 SNR scalable profile are given in Table 4 for the sequences 'Edin_Street' and 'Ski' respectively.

	PSNR Comparison 'Edin_Street'			PSNR Comparison 'Ski'		
	only low. layers	err. upp. layer	without errors	only low. layers	err. upp. layer	without errors
P : Y	32.237	33.238	33.168	32.217	33.221	33.347
P : U	36.937	37.497	37.583	38.624	39.551	39.602
P : V	35.753	36.345	36.385	36.520	37.647	37.741
B : Y	31.389	32.164	32.195	31.301	32.708	32.773
B : U	36.740	37.456	37.448	37.848	39.034	39.077
B : V	35.583	36.216	36.216	35.463	36.935	37.002

Table 4: PSNR values for 'Edin_Street' and 'Ski' (P- and B-pictures, disturbed HD2-layer)

The HD2-layer of a MPEG-2 hierarchical coded sequence is achieved with SNR scalability. Therefore, this layer is disturbed with $PER = 10^{-1}$ for the investigations. The technique for picture replenishment is to use only the TV and HD1 layer where errors were detected. For comparison the PSNR-value is given for the three layers TV, HD1 and HD2 without errors and for only the lower layers (TV and HD1, the HD2 layer is not decoded). The results show, that it is worthwhile to use also the correct received information of the disturbed upper layer (HD2) than to use only the lower layers TV and HD1. For I-pictures similar results are expected.

6 Conclusions

In this paper different ECT's for the different layers of MPEG-2 hierarchical coded video sequences are studied. For the I-pictures of the baser layer, where no motion information exist, spatial ECT's are investigated. The problem of spatial interpolation in a MPEG-2 coded picture is that only the top and the bottom macroblock can be used for the spatial interpolation. It is shown that the spatial ECT is better than simple temporal concealment in a picture with high motion. Otherwise the simple temporal ECT will be better. Therefore, it seems worthwhile to investigate the spatial activity and the temporal activity for the decision of which concealment technique should be applied.

For the upper layers in a hierarchical coded sequence different concealment techniques are studied and it is shown, that it is worthwhile to use the erroneous upper layer than to turn it off.

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Figure 3: I-picture of 'Flower' without errors

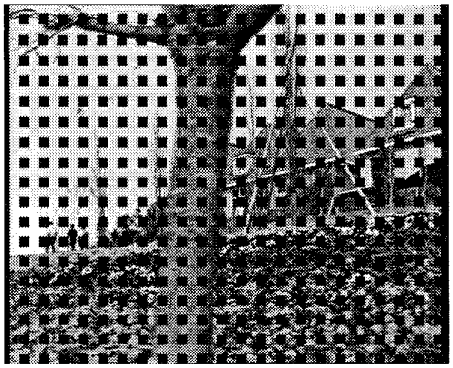

Figure 4: I-picture, no EC

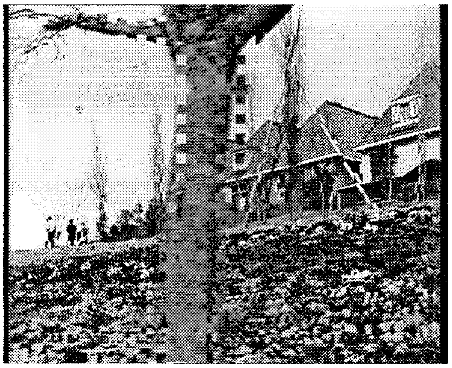

Figure 5: I-picture, EC 'simple'

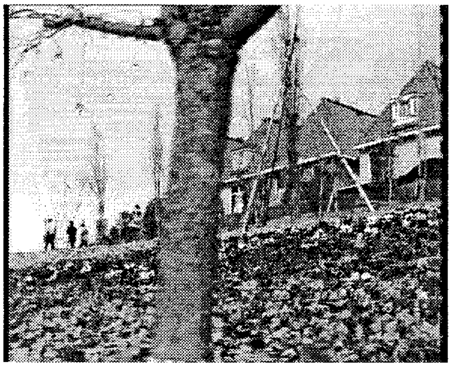

Figure 6: I-picture, EC 'spatial_block'

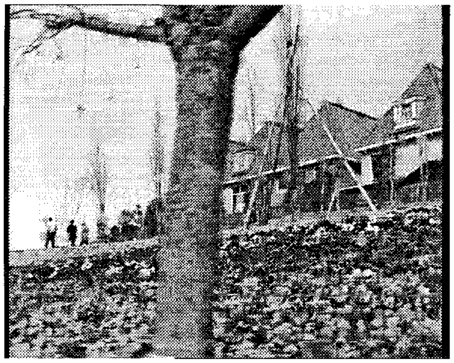

Figure 7: I-picture, EC 'spatial_mb'

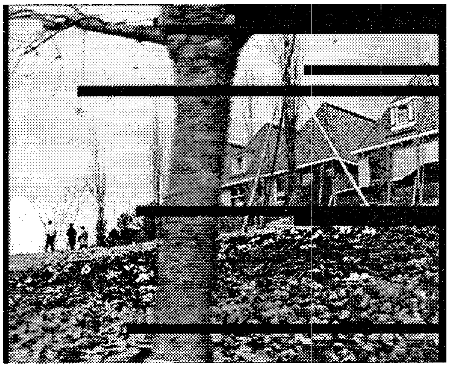

Figure 8: I-picture, no EC, $PER = 10^{-1}$

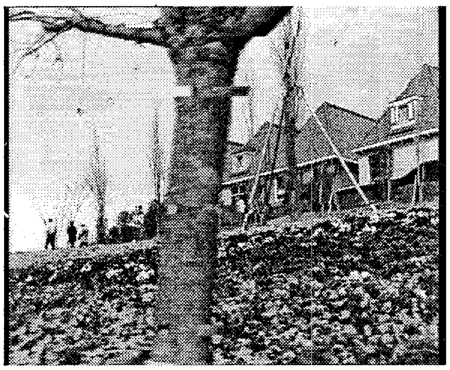

Figure 9: I-picture, EC 'simple'

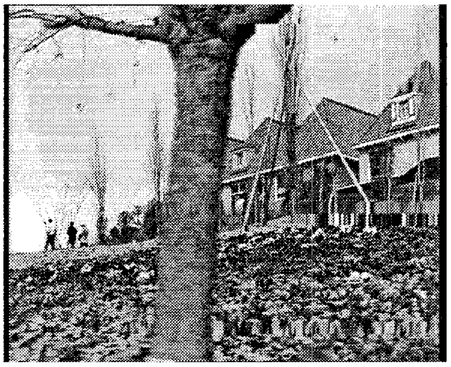

Figure 10: I-picture, EC 'spatial_mb'

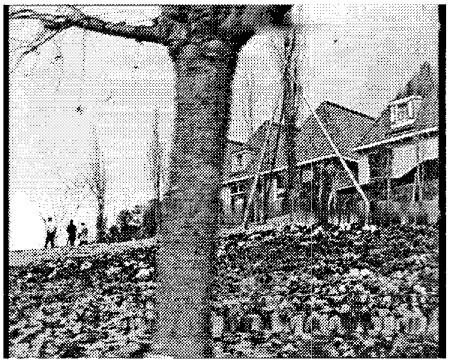

Figure 11: I-picture, EC 'spatial_mb_enhanced'