

Video error concealment with outer and inner boundary matching algorithms

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ABSTRACT

Low-complexity error concealment techniques for missing macroblock (MB) recovery in mobile video delivery based on the boundary matching principle is extensively studied and evaluated in this work. We first examine the boundary matching algorithm (BMA) and the outer boundary matching algorithm (OBMA) due to their excellent trade-off in complexity and visual quality. Their good performance is explained, and additional experiments are given to identify their strengths and weaknesses. Then, two more extensions of OBMA are presented. One is obtained by extending the search pattern for performance improvement at the cost of additional complexity. The other is based on the use of multiple overlapped outer boundary layers.

Keywords: Error concealment, wireless video, mobile video, boundary matching algorithm, outer boundary matching algorithm, H.264

1. INTRODUCTION

For visual communications over unreliable channels in a mobile and/or wireless environment, the received video quality is one of top priorities to users. Techniques for combating transmission errors can be classified into three categories [7] based on the role of the encoder and the decoder. Only the encoder is used to handle transmission errors in forward error prevention. Error concealment is a post-processing technique conducted at the decoder. When the encoder and the decoder work together in error handling, it is called interactive error control. Among these three categories, error concealment has the least restriction in implementation. The recent trend in error concealment is to utilize unique features offered by newer video standards such as the variable block-size, multiple reference frame, and quarter-pixel precision in H.264/AVC, inter-layer correlation in H.264/SVC and inter-view correlation in H.264 multi-view extension. However, the complexity of the resultant methods is often quite high for a mobile terminal. It is challenging to keep good balance between complexity and visual quality in mobile applications due to the limited resource available in the decoder of a mobile user.

One critical job in error concealment is to recover the lost macroblock (MB) information. Among low-complexity error concealment algorithms for MB recovery, the boundary matching principle and its derived algorithms attract a lot of attention due to the excellent trade-off in complexity and visual quality. Actually, the boundary matching algorithm (BMA) is recommended as a non-normative part of H.264 standard for temporal error concealment [3]. The outer boundary matching algorithm (OBMA), which was originally proposed in [1] and called the decoder motion vector estimation (DMVE) method therein, is a variant of BMA. OBMA offers significantly better error concealment performance than BMA while maintaining the same level of complexity. Despite this fact, it appears that the importance of OBMA (especially in mobile visual communication) has been buried in numerous error concealment techniques in the literature. In this work, we attempt to offer more insights into BMA and OBMA, and point out their strengths and weaknesses. Furthermore, extensions of OBMA are presented to give a comprehensive treatment on this subject.

The rest of this paper is organized as follows. BMA and OBMA algorithms are reviewed in Sec. 2. The performance of several low complexity MB concealment techniques is evaluated by computer simulation in Sec. 3. The performance of BMA and OBMA is analyzed in Sec. 4. More experiments are designed to support our analysis in Sec. 5. Two extensions

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of OBMA and the associated experimental results are presented in Sec. 6. Finally, concluding remarks are given in Sec. 7.

2. BMA AND OBMA ALGORITHMS

BMA relies on the boundary smoothness assumption to conceal the lost MB information. The candidate motion vector (MV) set consists of its eight neighboring MVs denoted by MV0, MV1, ..., MV7, and the zero motion vector (ZMV) denoted by MV8, as shown in Fig. 1. For each MV candidate, BMA constructs a candidate MB in the reference frame by backward tracing. To recover the lost MB, the mean of absolute differences (MAD) between the boundary of candidate MBs in the reference frame and the neighboring MBs of the lost MB in the current frame is computed as

$$D_n^{BMA} = \frac{1}{N} \left| \sum_{\forall i \in I} P_i^N - \sum_{\forall j \in J} P_j^C \right| \quad (1)$$

$$n_{opt} = \arg \min_n (D_n^{BMA}) \quad (2)$$

where D_n^{BMA} is the MAD of the n^{th} candidate MB with $n=0,1,\dots,8$, P_i^N and P_j^C denote boundary pixel values of neighboring MB i and candidate MB j , and I and J are sets of corresponding boundary pixel pairs as shown in Fig. 1 and N is the total number of boundary pixels. For example, N is $16 \times 4 = 64$ for a MB of size 16×16 . Then, the candidate MB that yields the smallest distortion is selected as the best candidate (n_{opt}) and used to conceal the lost MB.

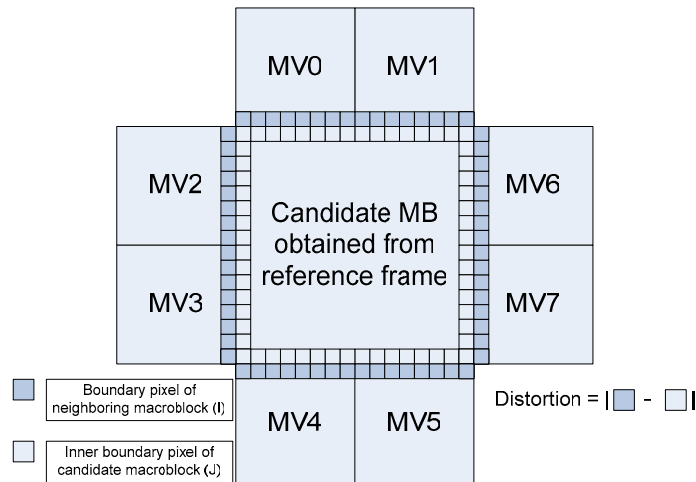


Figure 1: Distortion calculation in BMA.

Instead of using adjacent pixel values for distortion computation as done in BMA, OBMA utilizes a linear translational model to conceal a lost MB as shown in Fig. 2 by assuming that the lost MB can be reconstructed from the reference frame with constant motion in both magnitude and direction. OBMA adopts the same candidate set $\{MV0, MV1, \dots, MV7, MV8\}$, where MV8 is the ZMV, but a different distortion computation criterion as

$$D_n^{OBMA} = \frac{1}{N} \left| \sum_{\forall i \in I} P_i^N - \sum_{\forall k \in K} P_k^O \right| \quad (3)$$

$$n_{opt} = \arg \min_n (D_n^{OBMA}) \quad (4)$$

where D_n^{OBMA} is the MAD of the n^{th} OBMA candidate MB, P_k^O is the pixel value of the outer boundary of candidate MB k and I and K are sets of corresponding boundary pixel pairs as shown in Fig. 2. The candidate MB that has the

smallest distortion is selected as the best candidate. A concept similar to OBMA, called DMVE, was first proposed in [1]. Unlike DMVE, OBMA employs only one layer of the outer boundary and uses all adjacent neighboring MBs in the matching process.

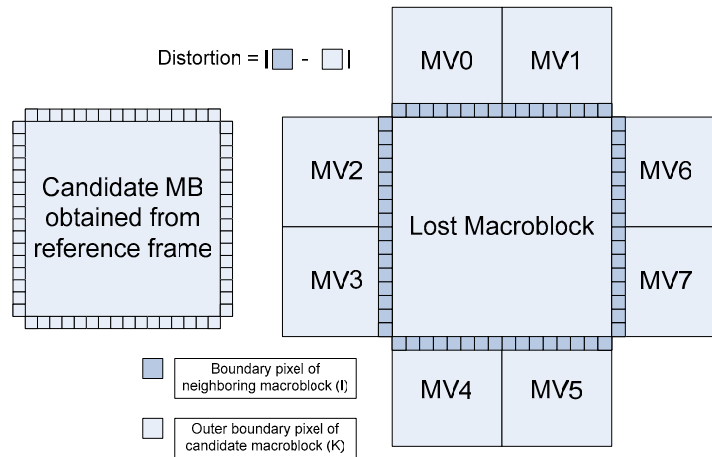


Figure 2: Distortion calculation in OBMA.

3. BMA AND OBMA PERFORMANCE EVALUATION

BMA and OBMA are very similar to each other and have exactly the same complexity. However, according to the experimental results given in Fig. 3, OBMA outperforms BMA by a large margin. (They correspond to the 4th and the 3rd bars in the chart for a given error rate.) In the experiment, six different error concealment algorithms are tested for three video sequences (carphone, foreman and mobile) under three error conditions (10%, 20% and 30% MB loss rate). Each video sequence has 10 frames and the frame size is 176x144 (QCIF). They are encoded in IPPP format with 15 fps. For each case, different uniformly distributed random error patterns are used and the average performance is reported.

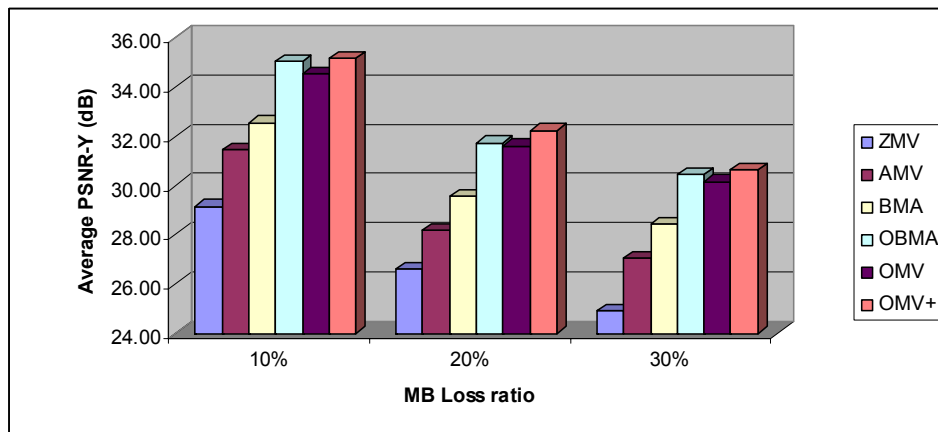


Figure 3: Performance evaluation of low-complexity error concealment techniques

Beside BMA and OBMA, we have tested three other error concealment techniques, *i.e.* the zero motion vector (ZMV), the average motion vector (AMV) and the overlapped motion vector (OMV). ZMV conceals the lost MB by using the corresponding MB from the reference frame (*i.e.* the MV is set to zero) while AMV uses the MB obtained from the average MV of neighboring MBs. OMV was originally proposed in [4] using a weighted combination of three predicted subblocks obtained from the side match criterion and MVs of neighboring subblocks along the vertical and horizontal directions. Here, for simplicity, we use a simple averaging instead of the weighted sum. The side match criterion used in OMV is essentially the BMA criterion function. Due to the similarity between BMA and OBMA, we can change OMV's

side match criterion to the OBMA criterion function and this resultant technique is referred to as OMV+. OBMA performs very well in all test conditions. Its performance is much better than ZMV, AMV and BMA. In fact, it yields more than 1 dB improvement when compared to BMA. In addition, OBMA also enhances the performance of OMV by an average of 0.6 dB. Based on this result, OBMA is very suitable for practical applications since it has an excellent performance while demanding a low complexity. In the next section, we explain the concepts behind performance of BMA and OBMA as well as the reasons why OBMA performs much better than BMA despite its similarity.

4. BMA AND OBMA PERFORMANCE ANALYSIS

The difference between BMA and OBMA comes from the different boundary layer of candidate MB used in their criterion function. OBMA exploits the outer boundary for matching while the inner boundary is used in BMA. To explain their significant performance difference, we will examine the criterion functions more carefully. As shown in Fig. 4, BMA's criterion function is similar to the gradient-based horizontal and vertical edge detectors with simple differences.

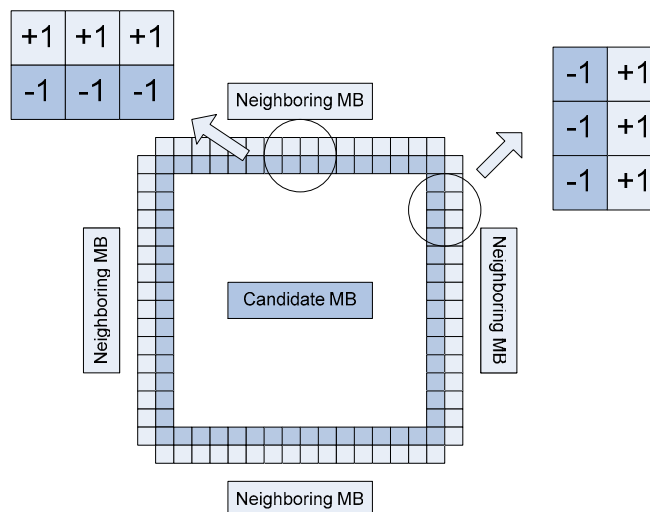


Figure 4: The criterion function of BMA which resembles the gradient-based horizontal and vertical edge detectors

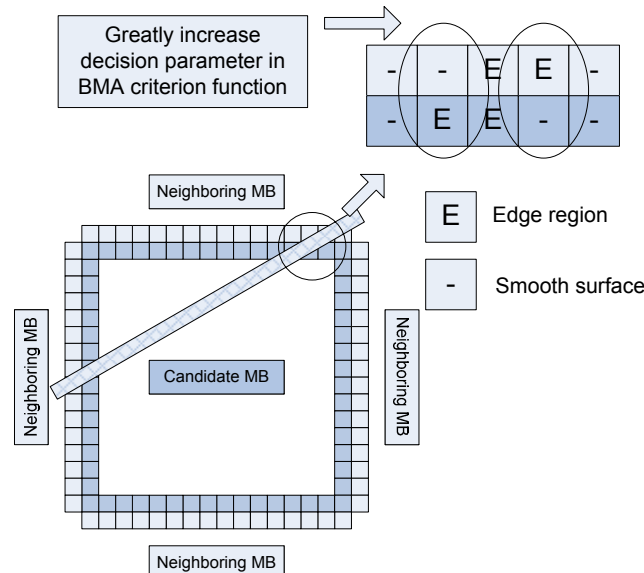


Figure 5: The edge in the vicinity of the block boundary is penalized by BMA.

Due to this resemblance, BMA’s criterion function actually penalizes an edge located in a block boundary. As shown in Fig. 5, when an edge lies across a block boundary, it results in an uneven surface between the outer and the inner boundaries, which leads to an increased MAD value. As a result, the block of ground truth is less likely to be selected. Except edges that are perpendicular to the boundary, all others across the block boundary tend to hurt the BMA performance. By using the outer boundary, OBMA’s criterion function incorporates the edge information in the vicinity of a block boundary into its matching decision accurately. Consider an example given in Fig. 6, which has three matching candidates. Since the 2nd and the 3rd candidates have inconsistent edge information with the neighboring MB, their MAD calculated by OBMA’s criterion function is higher. The original lost MB will give zero value if it is in the candidate set. In other words, the edge in the vicinity of a block boundary helps select the right MB by OBMA.

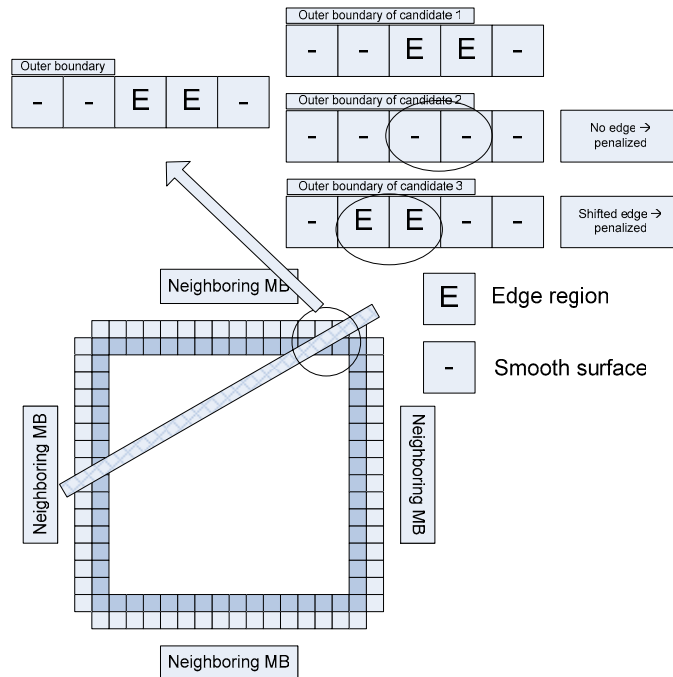


Figure 6: The edge in the vicinity of a block boundary helps select the right MB by OBMA.

5. FURTHER INSIGHTS INTO OBMA PERFORMANCE

The superior performance of OBMA can be explained by the block-based motion estimation concept as well. That is, OBMA can be viewed as a special type of block matching. In video encoding, each MB is compared with all possible candidate MBs in the search range of the reference frame to determine the best motion vector that yields the minimum residual. The traditional motion estimation is to find the closest match to a block of size 16x16 using the spatial information of all pixels inside the block. In contrast, OBMA performs a search to find the best match to a block of size 18x18 using the spatial information of all pixels located at the outmost layer.

5.1 Effect of Error Types

The results shown in Fig. 7 are obtained from testing BMA and OBMA over ten different video sequences. The experiment setting is identical to the one presented in Fig. 3. In most video sequences, OBMA outperforms BMA by a large margin. There are however three cases (*i.e.* Football, Ice and Soccer) that they offer about the same level of quality. This can be explained as follows. In the encoder, the motion estimation algorithm may yield an inaccurate motion vector (MV) when dealing with fast motion sequences and result in a larger residual. Consequently, the performance of OBMA is also limited by fast motion sequences such as the above three image sequences. On the other hand, OBMA can handle sequences of moderate motion with strong edges and textures since it can use this information to enhance the matching decision. This phenomenon has been observed from sequences such as mobile, bus and city.

To confirm the strengths and weaknesses of OBMA, we test BMA and OBMA with selective error patterns instead of uniformly distributed random errors. The purpose is to observe the performance of each error concealment technique under various error conditions. In particular, we manually assign erroneous MBs to different regions. These two error assignment methods are describe below

1. **Type I errors:** Missing MBs are located in regions consisting of strong edges, textures and smooth areas. Examples of this type include background, static objects, slow moving objects, clear object contours, etc
2. **Type II errors:** Missing MBs are located in regions of fast motion objects, highly deformed regions such as mouths, eyes, etc.

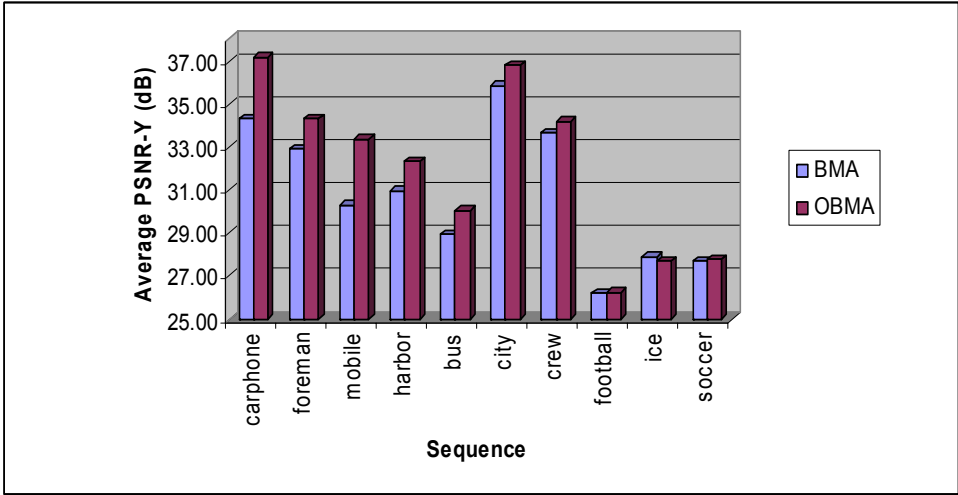


Figure 7: BMA and OBMA performance comparison for different video sequences with 10% MB loss rate.

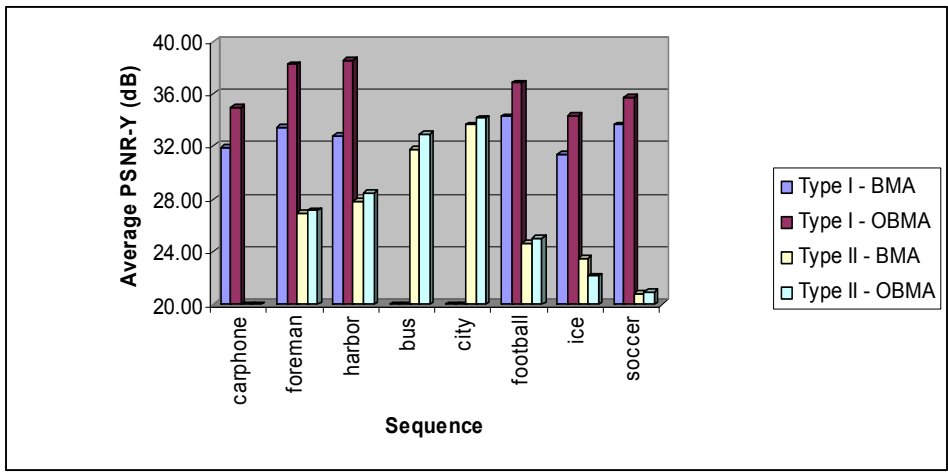


Figure 8: Performance comparison of BMA and OBMA against two error types.

Based on the arguments given above, we expect OBMA to perform well for type I errors but not for type II errors due to the poor performance of motion search in the latter case. This conjecture is confirmed by experimental results shown in Fig. 8. The experiment setting is the same as that given in Fig. 7 except that only 5% MB loss is tested due to a limited number of classified MBs. We see clearly that the performance gap between OBMA and BMA is quite large for type I errors but narrows significantly for type II errors. Although OBMA yields mediocre quality in the Football, Ice and Soccer sequences in Fig. 7, it performs very well in the same three sequences when only type I errors are considered in Fig. 8. On the other hand, the performance of OBMA degrades significantly for type II errors for the Foreman and Harbor sequences, even though the overall results were good in Fig. 7. Please also note that there are no sufficient classified MBs to synthesize type II errors for the Carphone sequence and type I errors for the Bus and the City

sequences. Thus, their results are skipped in Fig. 8. To conclude, OBMA will significantly outperform BMA if the motion vector provides an effective temporal prediction.

5.2 Effect of Video Spatial Resolutions

Only QCIF sequences were considered in all experimental results reported above. In the following, we evaluate the performance of BMA and OBMA with respect to video of higher spatial resolutions, *e.g.* CIF (352x288) and 4CIF (704x576). Sequences City and Ice were used in this test. For each sequence, we used 100 frames and encoded them with the IPPP format. The error is chosen to be uniformly distributed random error and the MB loss rate is set to 10%. The City sequence has moderate motion with strong edges and textures while the ice sequence has fast motion with little texture and detail. As expected, the performance gap between BMA and OBMA is larger for the City sequence as shown in Fig. 9. Furthermore, the performance gap between OBMA and BMA is getting larger when applied to the City sequence of higher spatial resolutions.

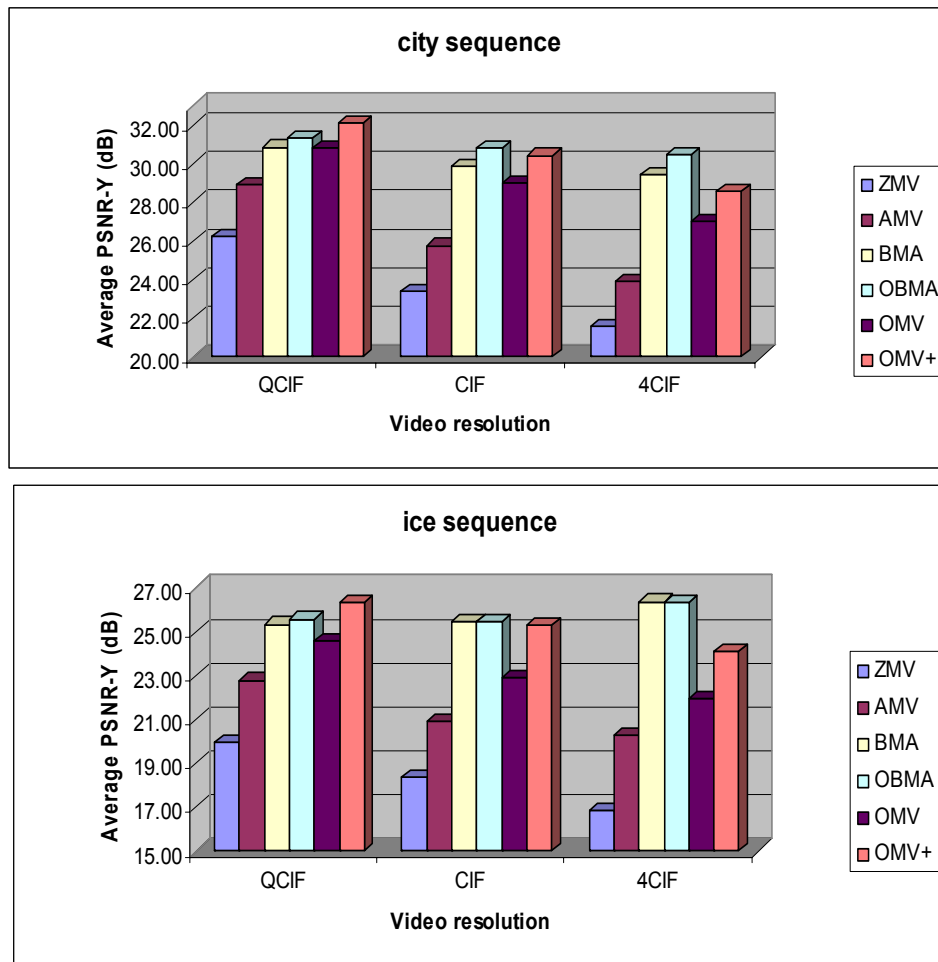


Figure 9: The performance of several error concealment algorithms under different resolution

Another interesting observation from Fig. 9 is that OMV+ is slightly better than OBMA for the QCIF case but OBMA outperforms OMV+ by approximately 0.5 and 2.0 dB for CIF and 4CIF City sequences, respectively. This is due to better contrast and detail information available in higher resolution video. All boundary matching algorithms rely heavily on the spatial neighboring information. With higher spatial resolutions, they tend to have better features in the matching process. To conclude, these results further demonstrate the advantages of OBMA over other low-complexity error concealment algorithms for video of higher resolution.

6. EXTENSIONS OF OBMA

Two extensions of OBMA are considered in this section. The first one is the search pattern extension. With this technique, OBMA can trade additional complexity for improved performance. Another extension is to use multiple overlapped layers, which is an extended version to an idea described in [1].

6.1 OBMA with Refined Local Search

OBMA in its original form only searches the reference frames with a small set of neighboring motion vectors (MVs). The overall performance of OBMA can be improved by increasing the number of MV candidates at the cost of higher computational complexity. To evaluate the trade-off between the concealed video quality and the complexity, we compare the PSNR results as well as the complexity for the following three search patterns. Four variations are examined in each case.

Table 1: Comparison of complexity and quality of various modified OBMA algorithms
(Note that the index is used in Fig. 10)

Error concealment technique		Average PSNR-Y	Complexity	Index	
BMA		32.04	8	1	
OBMA		33.54	8	2	
OBMA-FS	FS5	34.74	83205	14	
	FS1	R16	34.52	16641	13
		R8	34.46	4225	12
		R4	34.13	1089	10
OBMA-RS	RS2	34.36	2312	11	
	RS1	QP	34.36	648	9
		HP	34.36	200	7
		FP	34.17	72	5
OBMA-SS	SS2	34.27	297	8	
	SS1	QP	34.29	90	6
		HP	33.96	33	4
		FP	33.86	17	3

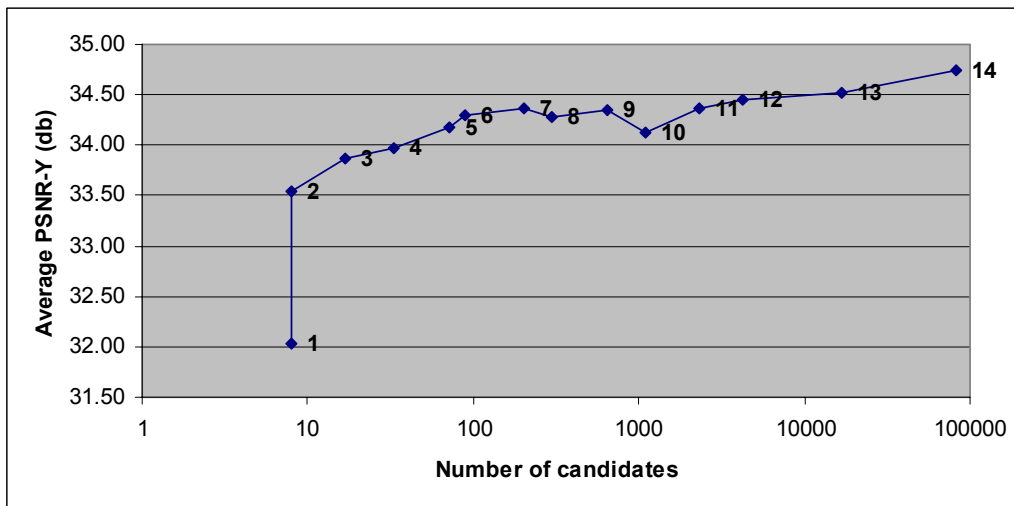


Figure 10: The comparison between the quality and the complexity of various search pattern extensions

1. OBMA with full search (OBMA-FS). OBMA-FS uses all possible candidates in a large search area pointed by the estimated MV of the lost MB. The search is performed with a quarter-pel resolution and can be extended to multiple reference frames.

- OBMA-FS5. We set the number of reference frames to 5 and the search range to 16x16. It includes all possible candidates.
- OBMA-FS1-R16, OBMA-FS1-R8 and OBMA-FS1-R4. We use only 1 reference frame and set the search range to 16x16, 8x8 or 4x4, respectively

The complexity of OBMA-FS can be computed by

$$N_C = N_R * (2 * R_F * 4 + 1) * (2 * R_F * 4 + 1) \quad (5)$$

where N_C and N_R are the numbers of candidates and reference frames, respectively and R_F is the search range in pixels.

2. OBMA with refined local search (OBMA-RS). OBMA obtains matching candidates from a small search region pointed by the MV of neighboring MBs. The complexity is drastically reduced from the previous case since the search region is much smaller.

- OBMA-RS2. It uses a search range of 2x2 with the quarter-pel resolution.
- OBMA-RS1-QP, OBMA-RS1-HP and OBMA-RS1-FP: They use search range of 1x1 with quarter-pel, half-pel and full-pel resolutions, respectively.

The complexity of OBMA-RS is give by

$$N_C = 8 * (2 * R_S * R_Q + 1) * (2 * R_S * R_Q + 1) \quad (6)$$

where R_S is the search range of a small search region, R_Q is the search resolution equal to 4, 2 and 1 for quarter-pel, half-pel and full-pel resolution, respectively

3. OBMA with selective search (OBMA-SS). OBMA-SS is similar to OBMA-RS except that it only considers a small search region pointed by the MV of neighboring MBs that gives the minimal MAD. It can be viewed as a two-stage operation.

- OBMA-SS2. It uses a search range of 2x2 with the quarter-pel resolution.
- OBMA-SS1-QP, OBMA-SS1-HP and OBMA-SS1-FP. They use a search range of 1x1 with quarter-pel, half-pel and full-pel resolutions, respectively.

The complexity of OBMA-SS can be calculated via

$$N_C = (2 * R_S * R_Q + 1) * (2 * R_S * R_Q + 1) + 8 \quad (7)$$

The original BMA and OBMA use a set of eight neighboring MBs for matching. Thus, their complexity is equal to 8 candidates. The complexity of all techniques and their performance are shown in Table 1. The plot of quality versus complexity is given in Fig. 10. The experimental setting is similar to that in Fig. 3 with MB loss rate equal to 10%. OBMA-FS5 outperforms OBMA by 1.3 dB at the cost of 83,205 matching candidates. This is not suitable in mobile video applications. In refined and selective search cases, the performance of OBMA is not affected by the reduction in the search range from 2x2 to 1x1. Besides, the reduction of search resolution from quarter-pel to half-pel slightly decreases the overall performance. In general, to increase the number of matching candidates gives rise to quality improvement as observed in Fig. 10 as shown by the positive slopes between two adjacent points. However, there are some segments that have a negative slope such as the transition from OBMA-RS1-QP (9) to OBMA-FS1-R4 (10) and from OBMA-RS1-HP (7) to OBMA-SS2 (8). Overall, we see that OBMA with a selective search pattern offers an excellent trade-off between quality and complexity.

6.2 Multiple Boundary Layers

In this extension, we may increase the number of boundary layers from one to multiple layers. The outer boundary layer number ranges from 1 to 8 in Fig. 11 and three different resolutions (QCIF, CIF and 4CIF) of the City sequence was tested. The sequence consists of 100 frames and it is encoded in the IPPP format. The MB loss rate is 10%. It turns out that the single-layer OBMA yields the best results for all three video resolutions. Its performance is decreasing when more outer layers are used in the criterion function. To explain this, we interpret OBMA from the motion estimation viewpoint. The original OBMA is equivalent to performing a search similar to motion estimation with a block of size 18x18 using the spatial information of all pixels located at the outmost boundary. When N overlapped layers is used, the size of searching block becomes (2N+16)x(2N+16) and this corresponds to motion estimation with a larger block size.

When the block size is too large, the accuracy of block-based motion estimation can be hurt. As discussed before, a larger residual is equivalent to higher distortion in a restored MB. Actually, we may reduce the block size to achieve better quality. This can be done by performing OBMA in the subblock level (block size of 8x8) as suggested in [5] and [8], which is called the refined estimation with a smaller block size. (RBMA) and proven to be better than OBMA with block size 16x16.

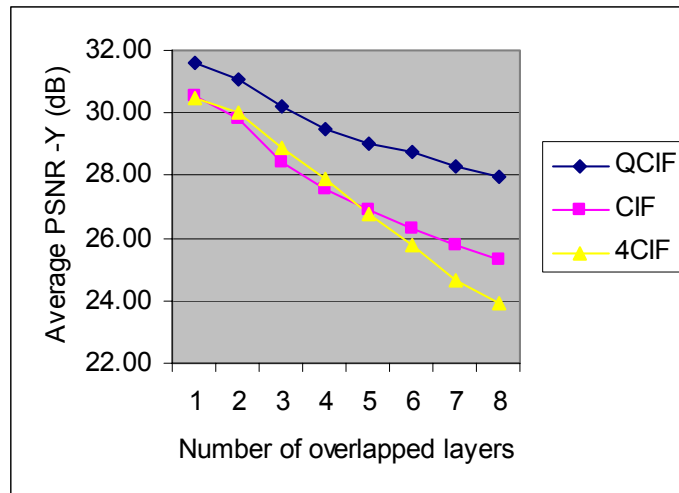


Figure 11: The performance of OBMA with a different number of outer boundary layers used in the matching process.

7. CONCLUSION AND FUTURE WORK

Several low-complexity error concealment techniques based on the boundary matching criteria were studied extensively in this work. The large performance difference between BMA and OBMA was analyzed. Extensive experiment results were conducted to support our analysis. We would like to integrate OBMA with some new features in H.264 such as flexible macroblock ordering (FMO) to have a full low-complexity error concealment system that is suitable for low complexity mobile video applications.

8. ACKNOWLEDGEMENTS

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