New Half-Pixel Accuracy Motion Estimation Algorithms for Low Bitrate Video Communications

H. Mahdavi-Nasab and Shohreh Kasaei

Abstract

Fractional-pixel accuracy *motion estimation* (ME) has shown to result in higher quality reconstructed image sequences in hybrid video coding systems. However, the higher quality is achieved by notably increased *motion field* (MF) bitrate and more complex computations. In this paper, new half-pixel block matching ME algorithms are proposed to improve the rate-distortion characteristics of low bitrate video communications. The proposed methods tend to decrease the required video bandwidth, while improving the motion compensation quality. The key idea is to put a deeper focus on the search origin of the ME process, based on center-bias characteristics of low bitrate video MFs. To employ the benefits *of mesh-based ME* (MME), the introduced algorithms are also examined in the framework of a fast MME scheme. Experimental results show the efficiency of the proposed schemes, especially when employed in the MME approach so that a reduction of more than 20% in the MF bitrate is achieved when employing typical QCIF formatted image sequences.

Keywords: Motion estimation (ME), Block matching, Mesh-based ME, Half-pixel accuracy ME, Low bitrate communications, Video coding.

1. Introduction

Motion estimation, as one of the main stages of conventional video coding systems, is an efficient tool in removing temporal redundancy between adjacent video frames. *Block matching algorithm* (BMA) is the most widely used method for ME purposes, due to its simplicity [1, 2, 3]. In this method, each frame is divided into non-overlapping blocks, and a single motion is considered for all pixels within each block (or *macroblock*, as called in MPEG and H.26X standards). *Motion vector* (MV) of a block (in the target frame) is found by searching for the most similar block in the reference frame. The search is carried out in a predetermined limited area (search area), based on a likelihood measurement criterion such as *sum of absolute differences* (SAD) or *sum of squared differences* (SSD). Since the displacement of an object in two subsequent frames does not necessarily appear at integer grid points, the modern coding standards (*e.g.,* MPEG-4, H.264/AVC), have adopted fractional-pixel (1/2-, 1/4-, and 1/8-pixel) accuracy ME approaches to improve the decoded video quality [2, 3].

In these methods, the MV may point to blocks placed at half-pixel (or fractional-pixel) locations. The pixel values in these candidate blocks are obtained by interpolating the nearest pixels at integer locations. The up-sampling interpolation scheme may be simply bilinear, taking into account only the nearest four pixels, or more sophisticated anti-aliasing 6- or 8-tap modified Wiener filters that consider further pixels [3, 4].

One of the main problems of sub-pixel accuracy ME approaches are their high computational load. The increased complexity is due to the required interpolation process and the increased number of candidate blocks to be searched. To decrease the computation burden, conventional encoders generally perform half-pixel ME in two steps. First, they search for the location in which the minimum of used criterion is occurred at integer-pixel displacements. Then, the eight nearest half-pixel candidate blocks to the selected integer MV are examined to refine the result. Some fast methods have been investigated (precisely or with negligible degradation) to further decrease the computational burden (of integer- and half-pixel BMA) [5, 6, 7, 8, 9, 10, 11]. However, none of the reported fast methods tends to reduce the expanded bandwidth of sub-pixel *motion field*s (MF), which is a direct result of the increased number of motion levels to be coded, and their near center distribution. Moreover, none of them has employed the Wiener anti-aliasing filters, due to their high complexity.

A promising more recent block-based ME technique is the *mesh-based ME* (MME); also called warping, or control grid interpolation. In this approach, the matching blocks in the reference frame are non-overlapping deformable blocks that cover the whole frame. The MME approach is able to realize non-translational movements such as rotation, zooming, and moving away or towards the camera; and thus produces high quality frames with no blocking artifacts. In addition, it has been shown that the MME leads to lower prediction errors in many cases, especially at low bitrates [12, 13, 14, 15, 16]. Figure 1 illustrates an example of the mentioned MME and BM methods.

In the MME method a mesh (grid of polygons, usually triangles or quadrangles) is overlaid on the current frame, and corresponding points of its nodes (mesh vertices) are determined in the reference frame by some ME techniques (such as BMA). To obtain the MVs of the interior pixels of the mesh elements, the MVs of the vertices are linearly interpolated. In the next step, the MVs of the vertices are refined iteratively by perturbing the location of the reference frame nodes and computing the resulting PSNRs of the jointed patches. While in the BMA, the MVs are independent, in the MME they are related to each other through the interpolation process. Due to this interdependence, which implies a large set of possibilities and interpolation processes, the refinement step imposes a high computational load that makes the MME very hard or even impossible (for real time applications) to implement [16]. In some recent researches, the refinement step is discarded and some adaptive interpolation schemes are proposed to compensate for the resulted degradation [16, 17, 18].

In this paper, we propose new methods for half-pixel accuracy BMA that are capable of reducing the MF bitrate significantly (even near to its integer-pixel counterpart), while preserving (or even improving) the quality of motion compensated frames (*e.g.*, in terms of PSNR). Since at low bitrate video communications the ratio of the MF bitrate to the total video bitrate increases [3, 12, 19], the achieved bitrate reduction would be crucial for applications such as video-conferencing and (especially) video-phone. The proposed half-pixel accuracy ME algorithms are also applied in the framework of a *fast MME* (FMME) scheme. The MME approach uses the BMA to find MVs of the mesh nodes and the iterative refinement step is eliminated to simplify the computations. The applied mesh is a regular quadrilateral patch. It will be shown that the proposed algorithms lead to similar and even improved characteristics in the MME scheme compared to the BMA.

The rest of this paper is organized as follows. In Section 2, the distinct motion characteristics of low bitrate image sequences are discussed and the proposed ME algorithms are presented. In Section 3, the experimental results are shown to evaluate the proposed algorithms when applied on some typical image sequences. Finally, Section 4 concludes the paper.

2. *Proposed Half-Pixel Accuracy Motion Estimation Algorithms*

The conventional two-step half-pixel search does not consider many possible half-pixel located candidate blocks. The only examined half-pixel locations are those around the selected block of the first step (the integer-pixel accuracy search). However, the first step might lead the search to an incorrect position (*i.e.*, a local minimum). From the computational point of view, it might be very difficult to perform a full half-pixel search. Nevertheless, with the mentioned current progresses in fast computations of integer- and half-pixel BMA, it seems quite possible to slightly expand the half-pixel search area. In addition, in low and very low bitrate applications (generally with lower frame rates), there will be more time available for the encoder to perform (slightly) more complicated computations.

In designing our half-pixel search strategies, the following facts about the motion characteristics of low bitrate video applications (such as video-phone and video-conferencing) are considered.

I. "MV distribution of most *head and shoulder* type sequences is strongly center-biased". Analyzing some typical sequences with low to moderate motion activities, has shown that more than 95% of the MVs, generated by full search BMA with ±16 pixel search area, have Euclidian magnitudes of less than five pixels [11].

II. "Many half-pixel accuracy searches might be practically unnecessary". *Yu et al*. [7] applied conventional half-pixel BMA search method (two-step search) on various MPEG QCIF[1] test sequences (with 16X16 macroblocks) to investigate the effectiveness of the half-pixel searches. As the result, for most sequences, the majority of final motion vectors point on integer-pixels. For relatively low motion scenes (such as *Akiyo*, *Salesman*, *News* and *Miss America* sequences), the practically wasted half-pixel searches are more than or about 90% of the total searches. Even for the *Carphone* and *Foreman* sequences, which possess larger motions, about 60% of macroblocks have integer valued MVs.

III. "Higher PSNR of sub-pixel ME is gained at the expense of remarkable increment in MF bitrate". This is a natural result of the increased number of motion levels (the

[1] Quarter Common Intermediate Format

symbols in the VLC process of hybrid video coding) to be coded, and their near center distribution.

Table 1 shows the results of coding the MFs of some test image sequences, generated by integer- and half-pixel BMA, and the related motion compensation PSNRs. In these experiments, we have used full search BMA, conventional half-pixel method using a bilinear interpolation filter, and ±7 pixels search range. The arithmetic coding is then applied to compress the MFs. The image sequences are in QCIF format, with 25 frames per second and 16X16 blocks. The first 80 frames are examined for each sequence.

Table 1: Motion field bitrate (Kbps) and PSNR (dB, in parenthesis) of some image sequences with integer- and half-pixel accuracy BMA.

ME \ Sequence	*Foreman*	*Carphone*	*M & D*[1]	*Suzie*
Integer-pixel	7.92 (32.90)	6.72 (34.03)	4.29 (41.19)	6.49 (35.60)
Half-pixel	11.87 (34.50)	10.15 (35.56)	6.31 (41.89)	10.05 (36.92)

Based on the above facts and observations we have designed two improved ME algorithms, which impose a greater emphasis on the search origin and possibly skip some less important information to reduce the required bitrate. These are discussed below.

2.1. Proposed Center-Biased Half-Pixel BMA

Considering the computation constraints, we propose to perform a full half-pixel search on a quite restricted ±1.5 pixels search area. This results in adding at most 40 half-pixel points

[1] *Mother & Daughter*

adjacent to the search origin, to the already examined 8 half-pixel candidate blocks. To make the implementation practically easier for real-time encoders, this extra search is only done for non-zero MVs found in the first step. Note that in low bitrate applications often the majority of the first step found MVs have zero magnitudes (*i.e.*, belong to background or stationary parts).

Figure 2 shows a schematic flowchart of the proposed algorithm, called *center-biased half-pixel BMA* (CH-BMA). The CH-BMA mainly aims at improving the motion compensated frame quality by preventing from being trapped in the possible local minima and reducing the required bandwidth. The latter is because the distribution of MVs is expected to get transformed to a more center concentrated shape.

2.2. Proposed Selective-Accuracy Half-Pixel BMA

One solution to bitrate reduction problem may be decreasing the number of motion levels (magnitudes) in the MF; which are passed to the entropy coding block of the hybrid video coding system. Restricting the search area while employing a full search sub-pixel ME or decreasing the search accuracy when applying large search ranges, both would accomplish this idea. A proper selection between these two (for the purpose of motion compensation of each frame) is the duty of a ME method which combines them into a single framework; to achieve lower bitrates with negligible degradation in reconstructed video quality. Fortunately, as discussed above, the motion of objects in our interested range of applications is often quite limited, and a majority of half-pixel searches can be avoided. Clearly, the lost information in the first case (small search area) can be negligible if large MVs do not constitute a significant part of the MF. On the other hand, in some rare high motion activity cases with significant large MVs a larger search area, with lower ME accuracy (*e.g.*, integer-pixel) maight be preferred.

To perform this selection more appropriately (accuracy or search range), a direct computation of motion compensation error for both cases (for each frame) may be cumbersome. Thus, determining a measurement factor to estimate the amount of motion activity contained in the sequence is crucial. The measurement should be done as a preprocessing step before estimating the MF of each new frame. If the result, which we call *motion measure* (MMES), is greater than a predetermined threshold then a flag is set and an integer-pixel ME with a sufficiently large search area is performed. Otherwise, the half-pixel accuracy ME is carried out in a full search manner within a very small search range. Finally, the flag is sent along with the produced MF to inform the decoder to how to interpret the received information. Figure 3 schematically shows the proposed *selective-accuracy ME algorithm* (SA-BMA), where A and B denote the large and small search ranges.

In this work, we have used the *principle component analysis* (PCA) [20, 21], to measure the amount of motion activity between two frames. As our experiments have shown, performing the PCA in the frequency domain produces more robust results (than applying it in the spatial domain) in many cases. To simplify the computations and also to suppress noise, down-sampled versions of the two frames and their differences are used in a multi-resolution framework. Specifically, to determine the MMES the following steps are applied (see Figure 4):

1- Down-sample the low-pass filtered successive frames by two in each direction.

2- Perform the FFT on the results.

3- Determine the absolute difference of the magnitudes of the FFTs.

4- Down-sample the difference by two in each direction.

5- Apply the PCA.

6- Select the greatest variance of the components as the MMES.

Although the preprocessing step may seem to be computationally costly, it is much less costly than a full search integer-pixel BMA (*e.g.,* about 15% for QCIF formatted sequences, with 16X16 blocks and ±7 pixels search range) and even less than recently introduced fast full search schemes [9, 10, 11], on average.

2.3. Required Computational Cost

In cases where the MVs found by the conventional two-step search are not zero, the CH-BMA performs a full half-pixel search on a quite restricted search area. Assuming a search area of 1.5 pixels for the half-pixel search, this leads to at most 40 additional candidate blocks (if the found MV is greater than two pixels) located at half-pixel positions to be tested. If the non-zero MVs are about 50% of the MF (although in most cases of low bitrate video applications it is less), this requires 40 X P X Q extra additions (with the SAD criterion and P X Q pixels frames). Compared to the 450 X P X Q additions required for the exhaustive BMA (with 7 pixels search range), this is less than 10% of extra additions. Considering the 16 X P X Q additions for the two-step half-pixel BMA search, the additional needed computations are only about 8%. Applying fast algorithms for performing integer- and half-pixel accuracy BMA decreases the above numbers effectively with similar proportions.

Regarding the SA-BMA, if B is sufficiently less than A (see Figure 3}), the computational burden for the two search accuracies is about the same. For instance, if A and B are respectively set to 7 and 3, the number of candidate blocks at integer- and half-pixel accuracy searches are 225 and 161, respectively. Consequently, considering the interpolation process required for half-pixel search the amount of computations are about the same. The computational cost for determining the MMES is also much less than performing a full BMA. Considering the processes shown in Figure 4, this computational cost is about 15% of the exhaustive BMA for QCIF formatted sequences with 7 pixels search range. Therefore, assuming a sufficiently small B, the computational cost of the SA-BMA is only about 20% more than the BMA.

2.4. Proposed High Accuracy Fast Mesh-Based Motion Estimation

Applying the proposed half-pixel accuracy BMA schemes to determine the MVs of the nodes of an overlaid mesh leads to higher accuracy MME algorithms. To achieve a better compromise between the MME and the BMA, we propose to apply the mesh structure shown in Figure 5-b. Here, the mesh nodes are the centers of the elements of the conventional mesh (Figure 5-a), which may be considered as the macroblocks in a counterpart BMA approach. With such a mesh structure, the number of the mesh nodes is notably reduced (about 20% for QCIF image sequences) and the estimation of the MVs of the outermost mesh nodes is more precise and reliable. Moreover, as the only transmitted MVs of MME-based video communication systems are the MVs of the nodes, the MF bitrate would be the same as its BMA counterpart.

Specifically, the fast two-step CH- and SA-MME schemes are proposed as follows:

1- Determine the MVs of the mesh nodes of Figure 5-b, using the two-step half-pixel, CH-BMA or the SA-BMA schemes.

2- Determine the MVs of the pixels inside each mesh element applying a bilinear interpolation scheme [12, 13, 15], based on the MVs of the element nodes.

3. Experimental Results

In this section, we evaluate the performance of the mentioned ME methods when using some typical image sequences. Specifically, the first 80 frames of *Foreman*, *Carphone*, *Mother and Daughter*, *Suzie*, and *Miss America* QCIF formatted sequences (144X176, 25 frames per second) are used. The blocks are 16X16, the matching criterion is the *sum of absolute* *differences* (SAD), and the search range is ±7 pixels. In addition to the center-biased and selective-accuracy half-pixel BMA algorithms, their FMME counterparts are also examined.

Table 2 lists the performance of the ME methods in terms of PSNR. In addition, for using the simple bilinear filter (to determine the pixel values at half-pixel locations), the results of applying a 6-tap Wiener interpolation filter (employed in H.264/AVC) are also presented. For SA-X algorithms, the parameters A, B, and T (see Figures 3 and 4) are selected to be 7, 3, and 170, respectively. Table 3 shows the required bitrates of the produced MFs when compressed by arithmetic coding. No MV prediction preprocessing is performed.

The PSNR results confirm the problem of being trapped in the local minima in the two-step search scheme. Performing a more precise search around the origin has resulted in finding more accurate matching blocks that improve the PSNR. In addition, as these newfound MVs are shorter, the entropy coded new MF is also more compact. Applying the CH-BMA (with the Wiener filter) leads to about 0.3 dB PSNR improvement for *Foreman* and *Carphone* sequences in addition to 1.32 Kbps and 0.6 Kbps reduction in the required bitrates, respectively. The average PSNR improvements for the tested sequences, shown in Table 2, when using the bilinear and Wiener filters, were 0.07 dB and 0.13 dB, respectively. As shown in Figures 6 to 9, the PSNR improvement in the ME quality is more than 0.5 dB for many frames of the examined sequences. Also, applying the CH-X algorithms on *Miss America*, although not so efficient in terms of PSNR, results in 10% and 11% reduction in required MF bitrate, for bilinear and Wiener interpolation filters, respectively. For the mesh-based counterparts (the CH-MME compared with the two-step half-pixel MME) the resulting PSNRs have improved. These improvements for the bilinear and Wiener filters were 0.16 dB and 0.17 dB, respectively, on average. This can be explained by noting that the main problem of the MME is its error propagation (due to the bilinear interpolation used to determine the MVs of the inner pixels of each mesh element). Therefore, as the CH-X schemes prevent some incorrect MEs, they can suppress the error propagation problem. In other words, the CH-MME benefits from a double advantage: preventing from getting trapped in local minima of the BMA and also suppressing the error propagation problem of the MME.

Note that higher PSNRs, or lower error levels for the motion compensated frames, in turn generally lead to lower bitrates needed for coding the residual errors. Reducing the required bitrates, while improving the ME quality, justifies the improvement of the rate-distortion characteristics for the proposed CH-X schemes.

The CH-X algorithms are the most robust schemes against changes in the video contents and motion activities. The obtained results are always better than (or at least equal to) their conventional counterparts. The best results are achieved in sequences with moderate motion activity, such as *Foreman* and *Carphone* (and *M & D* for the CH-MME). On the other hand, the SA-X schemes, in some cases lead to slightly weaker results regarding to mean PSNR (*e.g.*, *Suzie* sequence). In Figures 6 to 9, several cases of lower estimation quality in the SA-BMA approach are observed (*e.g.*, frames 21, 22 and especially 31 in Figure 6, and frames 13-15 of Figures 8 and 9). This may be discussed as follows. While in the CH-X schemes some specific efficient searches are added, in the SA-X algorithms we have intentionally ignored some less significant information (*i.e.*, skipping the half-pixel search in cases with high motion activities), to reduce the required bandwidth.

The average PSNR for SA-BMA is only about 0.02 dB less, or 0.05 dB more (without or with the Wiener filter, respectively) than the conventional method. The gained or lost PSNR is practically not significant. On the contrary, the reduction in the MF bitrate is approximately 22% on average (for both filters). For some cases (*e.g.*, *M &* D and *Suzie*), the reduction is more than 25% of the total MF bitrate. For SA-MME, a superior performance is observed. The PSNR is about 0.15 dB higher than its two-step counterpart on average. Applying the

SA-MME on *Carphone*, for instance, leads to PSNR improvement of more than 0.3 dB. However, the bitrate is again more than 20% less.

The rate-distortion curves of Figures 10 and 11 confirm the stated results. To obtain these curves, the half-pixel schemes are performed on *Foreman* and *Carphone* sequences using different frame rates (*e.g.*, 25, 12.5 and 8.33 frame rates). The presented curves reveal the superiority of the proposed schemes more clearly. As seen in these curves, considering the rate-distortion criterion for the ME methods, generally the best results belong to the SA-X schemes. Thus, it is reasonable to consider the SA-X algorithms as efficient high accuracy ME schemes for low and very low bitrate applications, especially when applied in the MME framework.

In addition, the SA-X schemes generally show similar advantages when applied on different kinds of sequences (*e.g.*, *Coastguard* or *Container*). As an example, applying the CH-X to *Coastguard* sequence leads to similar results as the two-step schemes (with negligible superiority in the PSNR). On the other hand, applying the SA-X on this sequence leads to about 20% reduction in the MF bitrate (specifically, it is 5.95 Kbps for the two-step and CH-X schemes and 4.72 Kbps for the SA-X). The resulting PSNRs are nearly the same (33.64, 33.68, and 33.61 dB for the two-step, CH- BMA, and SA-BMA schemes with the Wiener filter, respectively).

Regarding the basic ME methods (BMA and FMME), the overall results can be summarized as:

1- The FMME generally leads to higher motion compensated frame qualities when using the proposed algorithms.

2- The sensitivity of the FMME method to the type of up-sampling interpolation filter is much less than BMA. While in half-pixel BMA schemes, applying the Wiener filter generally produces significant better results, for FMME the difference in PSNR is less than 0.01 dB. It is notable that fast full search algorithms designed recently are based on simple bilinear filters [6, 8] which are as efficient as the Wiener filters for half-pixel FMME schemes.

4. Conclusion

In this paper, new schemes for half-pixel accuracy motion estimation were proposed. The main ideas were enhancing the search precision around the search origin, and adaptively combining the half- and integer-pixel ME schemes. Applying the recent improvements in fast computation of the integer- and fractional-pixel accuracy motion estimation in the framework of the proposed methods makes these methods practically considerable even for real-time applications.

The simulation results show the efficiency of the proposed algorithms. The SA-X schemes are able to reduce the MF bitrate more than 20%, which is remarkable for low bitrate applications. In CH-X algorithms, there is a simultaneous improvement in motion compensation quality and motion field bitrate, which is significant especially for moderate motion activity image sequences.

The achieved superiority of the proposed schemes is more notable in the fast MME framework. This emphasizes the advantageous performance of MME schemes at low bitrates.

The proposed schemes can simply be extended to cover 1/4- and 1/8-pixel accuracy ME. For instance in SA-X, a quarter-pixel search in a very restricted (*e.g.*, one pixel) search area around the origin can be added for the frames with very low motion activity to obtain more precise results.

Table 2: Mean PSNR (in dB) of various half-pixel accuracy ME algorithms for some QCIF test sequences, with bilinear and Wiener (in parenthesis) up-sampling filters and 16×16 blocks.

ME \ Sequence	*Foreman*	*Carphone*	*M & D*	*Suzie*	*Miss America*
Two-step BMA	34.50 (34.72)	35.56 (35.83)	41.89 (41.93)	36.92 (37.10)	42.84 (43.11)
CH-BMA	34.65 (34.99)	35.69 (36.11)	41.90 (41.93)	36.96 (37.13)	42.87 (43.16)
SA-BMA	34.48 (34.82)	35.62 (36.07)	41.87 (41.92)	36.76 (36.97)	42.86 (43.17)
Two-step FMME	34.72 (34.64)	35.57 (35.59)	41.73 (41.78)	37.14 (37.15)	43.23 (43.25)
CH-MME	35.00 (34.92)	35.78 (35.84)	41.96 (42.02)	37.15 (37.17)	43.30 (43.30)
SA-MME	34.91 (34.81)	35.89 (35.90)	41.99 (42.04)	37.05 (37.07)	43.32 (43.34)

Table 3: Motion Field Bitrate (in Kbps) of various ME algorithms for some QCIF test sequences, with bilinear and Wiener (in parenthesis) up-sampling filters and 16×16 blocks, compressed by arithmetic coding.

ME \ Sequence	*Foreman*	*Carphone*	*M & D*	*Suzie*	*Miss America*
Two-step BMA	11.87 (12.00)	10.15 (10.17)	6.31 (6.56)	10.05 (10.11)	7.96 (8.29)
CH-BMA	10.83 (10.68)	9.69 (9.57)	5.96 (6.10)	9.94 (9.98)	7.09 (7.46)
SA-BMA	9.42 (9.30)	8.35 (8.29)	4.73 (4.84)	7.90 (7.90)	5.87 (6.26)

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Figure 1:

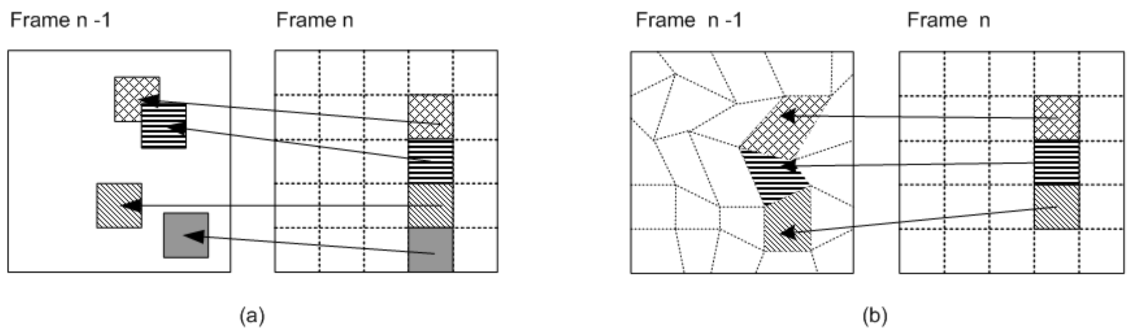
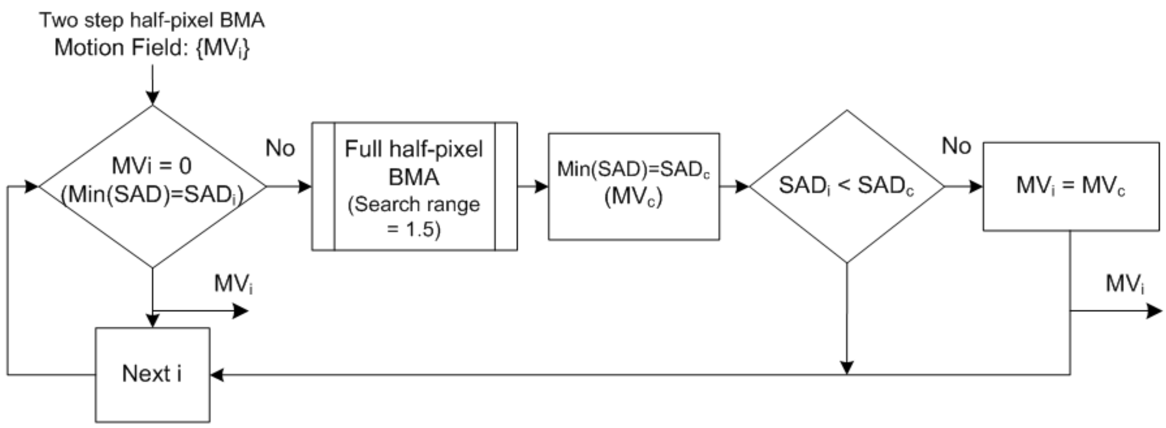


Figure 2:



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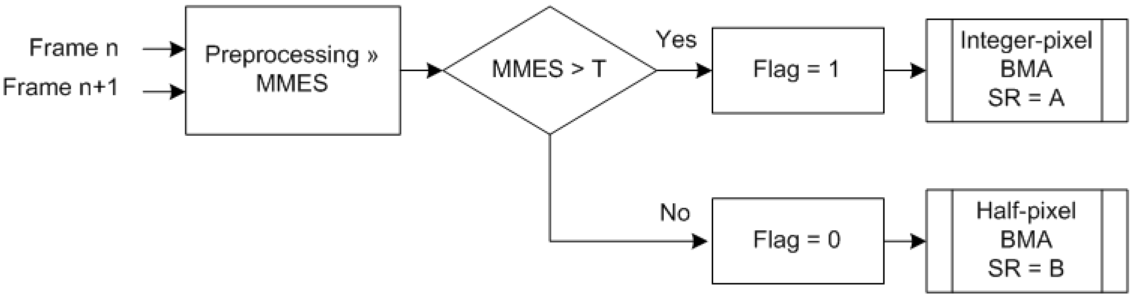

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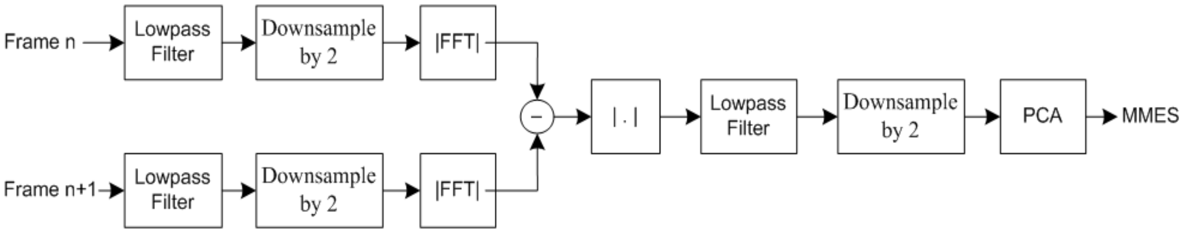
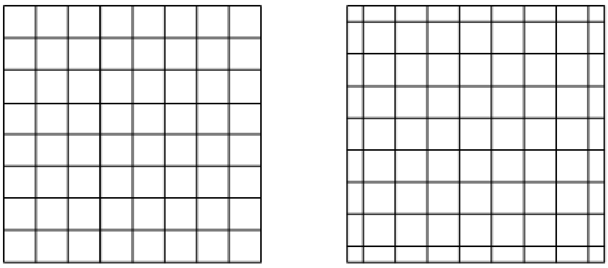


Figure 5:



(a) (b)

Figure 6:

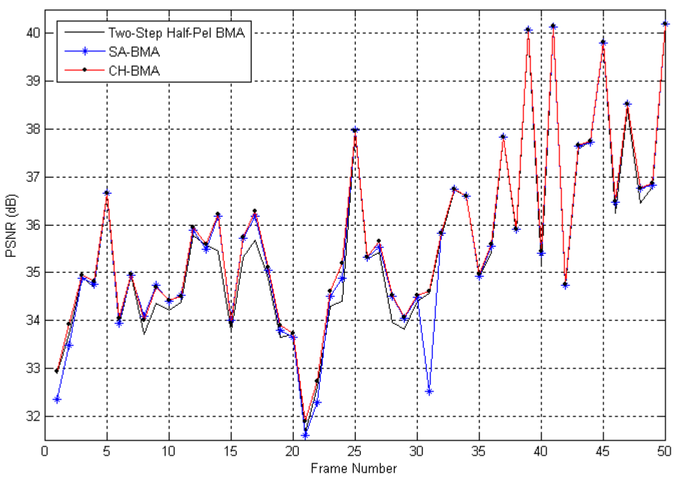


Figure 7:

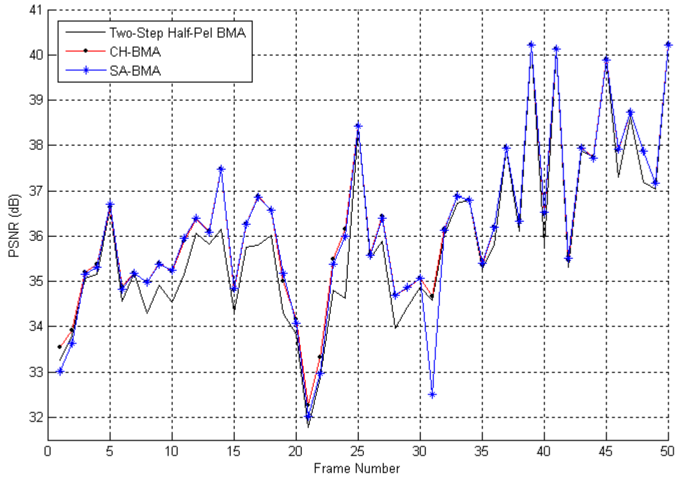


Figure 8:

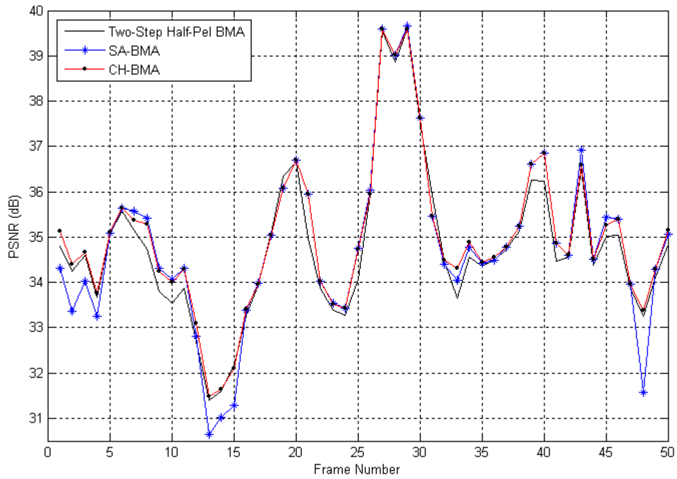


Figure 9:

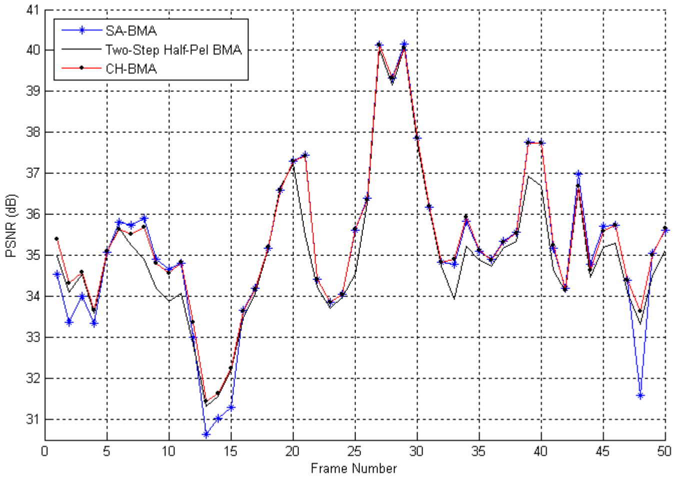


Figure 10:

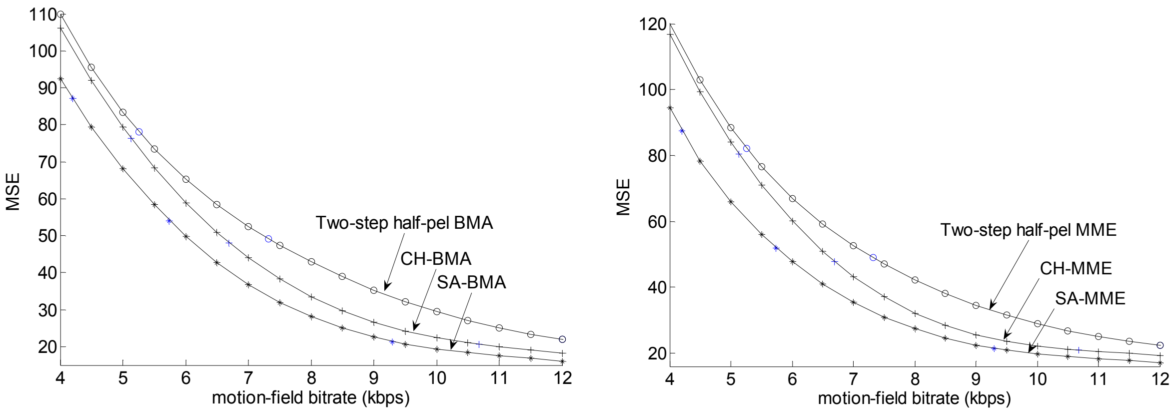


Figure 11:

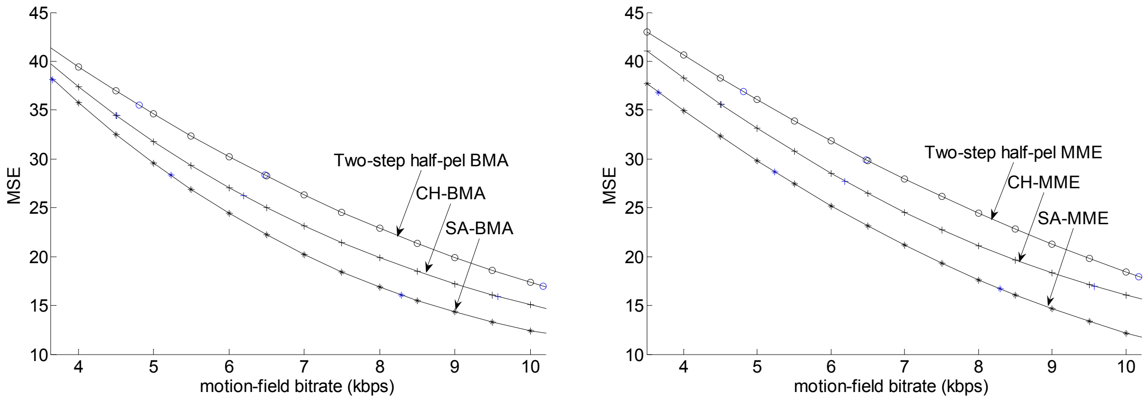


Figure Captions:

Figure 1: An example of two block-based ME methods: (a) BMA, (b) MME.

Figure 2: Schematic flow chart of the proposed CH-BMA algorithm.

Figure 3: Schematic flowchart of the proposed SA-BMA, A > B.

Figure 4: Structure of the proposed preprocessing step of the SA-BMA.

Figure 5: Quadrilateral mesh structures: (a) Conventional. (b) Proposed.

Figure 6: Performance of various half-pixel block matching methods applied on QCIF image sequence *Carphone*, with bilinear up-sampling filter.

Figure 7: Performance of various half-pixel block matching methods applied on QCIF image sequence *Carphone*, with 6-tap Wiener up-sampling filter.

Figure 8: Performance of various half-pixel block matching methods applied on QCIF image sequence *Foreman*, with bilinear up-sampling filter.

Figure 9: Performance of various half-pixel block matching methods applied on QCIF image sequence *Foreman*, with 6-tap Wiener up-sampling filter.

Figure 10: Rate-distortion curves of different half-pixel accuracy schemes performed on QCIF *Foreman* sequence: (a) BMA, (b) MME.

Figure 11: Rate-distortion curves of different half-pixel accuracy schemes performed on QCIF *Carphone* sequence: (a) BMA, (b) MME.