國立交通大學

資訊科學與工程研究所

碩 士 論 文

基於空間可變之動作補償預測的動向不確定性之分析

Motion Uncertainty Analysis for Spatially-Variant Temporal Prediction

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摘　要

這份論文中提出了如何利用空間可變之動作補償濾波器來增加動作補償估測之效率。一些近年來的研究指出原本為了解決鋸齒(aliasing)現象而設計的小數點像素精度之插補濾波器，也能在某種程度上解決動向不確定性問題。實驗結果甚至指出這些濾波器某些情況在超高清晰度(UHD)的影片的編碼效率比低解析度的來得好。基於一個為了減輕動向不確定性之編碼工具，當前的作法卻有兩個主要的問題：(1)濾波器的設計仍然是為了移除鋸齒現象，(2)對於擁有不同程度動向不確定性之像素所使用之濾波器都是故定的。在這份論文中我們對於動向不確定性進行了一些實驗來提供細部的分析，同時經由實驗結果，一些重要的發現被提出，並且我們利用這些發現來提出空間可變之動作補償濾波器之設計原則。

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ABSTRACT

This thesis addresses the problem of improving temporal prediction efficiency through a spatially-variant motion-compensated filtering. A few recent studies pointed out that the sub-pel interpolation filters, originally designed to address aliasing effects, can overcome the problem of motion uncertainty to some extent. Experimental results even indicated that in terms of coding efficiency, they can improve more in UHD videos than in low-resolution ones in some cases. As a coding tool for alleviating motion uncertainty, current approach however poses two major problems: (1) the filter design is still aimed at removing aliasing effects, and (2) pixels having motion uncertainty of different degrees are forced to use the same filter. In this thesis, we carried out a few experiments to provide a detailed analysis on motion uncertainty. Also, from the experimental results, some important observations were made to form guidelines for designing a spatially-variant temporal prediction filter.

誌　　謝

回顧兩年的研究所生涯，首先，我要感謝我的指導教授—彭文孝 博士，給予我於學問研究上的指導。彭老師實事求是的精神，與深入剖析問題的態度，其追根究柢與契而不捨的指導方式，已經成為我在學習與研究路上的典範與楷模。其次，我要感謝我的學弟王澤瑋，不辭辛勞的與我討論，給予許多珍貴的意見，並且能適時從旁給予建議修正我已偏差的研究方向，使我在這兩年的碩士生涯，不再舉步維艱。謹此對兩人致上由衷的謝意。

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Motion Uncertainty Analysis for Spatially-Variant Temporal Prediction

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Abstract

This thesis addresses the problem of improving temporal prediction efficiency through a spatially-variant motion-compensated filtering. A few recent studies pointed out that the sub-pel interpolation filters, originally designed to address aliasing effects, can overcome the problem of motion uncertainty to some extent. Experimental results even indicated that in terms of coding efficiency, they can improve more in UHD videos than in low-resolution ones in some cases. As a coding tool for alleviating motion uncertainty, current approach however poses two major problems: (1) the filter design is still aimed at removing aliasing effects, and (2) pixels having motion uncertainty of different degrees are forced to use the same filter. In this thesis, we carried out a few experiments to provide a detailed analysis on motion uncertainty. Also, from the experimental results, some important observations were made to form guidelines for designing a spatially-variant temporal prediction filter.

CHAPTER 1

Research Overview

1.1 Introduction

Technology evolution in both capture and display devices will soon make possible the creation and presentation of Ultra High Definition (UHD) videos. The video bit-rate is expected to go up faster than the transmission bandwidth. Although H.264/AVC [2][9] has been a successful video coding standard, it was reported to have poor efficiency in coding UHD videos. Part of the reason is the lack of coding tools for dealing with motion uncertainty. It is thus necessary to design a video codec that is specifically optimized for UHD applications.

A few recent studies pointed out that the sub-pel interpolation filters, mainly designed to address aliasing effects, can overcome the problem of motion uncertainty to some extent. Experimental results even indicated that in terms of coding efficiency, they can improve more in UHD videos than in low-resolution ones in some cases. The result may appear to contradict our intuitive notion since the aliasing effects are supposedly to be less severe when a higher sampling rate is in use. But, when viewed from the perspective of reducing motion uncertainty, it can indeed justify the observation.

1.2 Problem Statement

As a coding tool for alleviating motion uncertainty, current approach however poses two major problems:

1. The filter design is still aimed at removing aliasing effects.
2. Pixels having motion uncertainty of different degrees are forced to use the same filter.

The former can be solved by using the least-squares method to update the filter on a frame-by-frame basis, whereas the latter requires to adapt the filter in a spatially-variant manner. This thesis aims to design a spatially-variant temporal prediction filter. In the course of the design process, we carried out a few experiments to understand

1. how the level of motion uncertainty may vary with the pixel location within a macroblock,
2. how the distribution of motion uncertainty may vary with video content,
3. what contexts may be useful in predicting the distribution of motion uncertainty,
4. how the filter should be adapted in response to the varying distribution of motion uncertainty.

1.3 Contributions and Organization

The main contributions of this thesis include the following:

1. A detailed analysis on motion uncertainty.
2. A number of guidelines for designing spatially-variant temporal prediction filters.

The remainder of this thesis is organized as follows: Chapter 2 contains a review of known prediction filter designs and several issues that relate to prediction efficiency. Chapter 3 introduces the concept of motion uncertainty and contains a number of experiments for discovering motion uncertainty characteristics. In Chapter 4 a spatially-variant Wiener prediction filter is designed and its performance is tested in comparison with well-known filter designs. Chapter 5 concludes our study with a summary of this work and provides a list of future works.

CHAPTER 2

Background

2.1 H.264/AVC Interpolation Filter

The interpolation process in H.264/AVC is shown in figure 2.1. $A1, A2...F6$ represent inter-pel pixels. Each half-pel pixels $(b, h, j, aa, bb...jj = b, h, j, aa, bb, ...jj)$ is interpolated by specific inter-pell pixels with a fixed filter. For example,

$$b = (C1 - 5 * C2 + 20 * C3 + 20 * C4 - 5 * C5 - C6 + 16)/32$$
$$h = (A3 - 5 * B3 + 20 * C3 + 20 * D3 - 5 * E3 - F3 + 16)/32$$

And each quarter-pel pixel is interpolated by applying a bilinear filter on two neighbor half-pel or interger-pel pixels.

During the sub-pel motion compensation process, each motion vector(MV) will be refined in sub-pel precision for a certain range. Finally the refined MV points one sub-pel position, and sub-pel pixel in related position will be gethered to be the predictor.

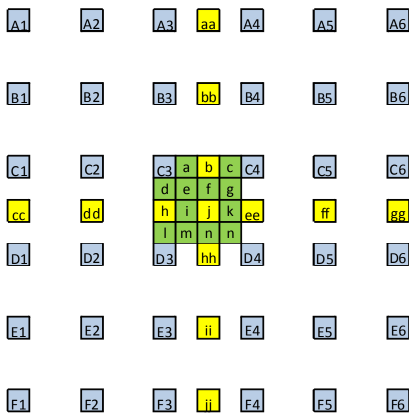

Figure 2.1: Average residual signal energy calculated from Football sequence using block size of 16x16.

2.2 Related Works

2.2.1 Motion- and Aliasing-Compensated Prediction

Experimental results of motion compensation show that even with translational motion, no perfect motion compensation is achieved for images. In addition to camera noise, Werner [8] supposes aliasing also cause the prediction error.

T. Wedi *et al.*[7] formulate the motion-compensated prediction process between sampled discrete image and natural continuous image, and derive the prediction error of these two types of image. The derivation results prove that aliasing did exist in the discrete motion-compensated predction process. Moreover, the results indicate two main feature of prediction error caused by aliasing:

1. the impact of aliasing on the prediction error vanishes at integer-pel motion displacements;
2. the impact of aliasing on the prediction error maximizes at half-pel motion displacements.

In order to reduce the impact of aliasing, T. Wedi *et al.*[7] suggest that inperpolation filter should be applied during motion-compensated prediction process. The proposed Weiner interpolation filter design is as Figure 2.2.

At first original image S is filtered by a low-pass filter, resulting in S_{LP}. Then S_{LP} is downsampled into smaller image S_d. By using S and S_d as training set, Weiner filter h_w can be obtained by solving Wiener-Hopf equation. Finally, Weiner filter h_w will be

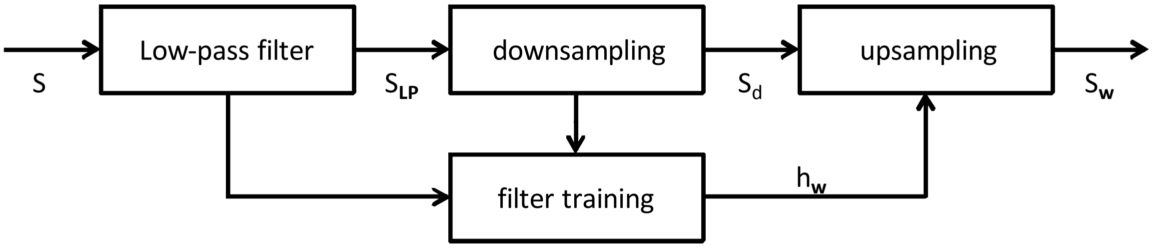

Figure 2.2: The filter design flow suggested by T.Wedi et al.

used to upsample S_d to obtain interpolated image S_w.

For interpolation filter dealing with higher downsampling rate images, T. Wedi *et al.* [7] suggest a top-down filter design. Instead of directly design filter for higher downsampling rate images, the interpolation fitler for lower downsampling rate is obtained first. Next the filter for higher downsampling rate image is obtained by using image resulting from lower downsampling rate filter and original image as training set. This design principle is which sub-pel Interpolation filter in H.264/AVC Standard mentioned in Chapter 2.1 is used.

2.2.2 AIF

To improve the motion-compensated prediction efficiency, the concept of AIF was introduced. Instead of a fixed interpolation filter as in H.264/AVC standard [2] [9], interpolation filters adaptively trained for each frame were suggested. Y. Vatis *et al.[6]* proposed a 2-D non-separable adaptive Weiner interpolation filter that has 5.77% of bit-rate saving on average.

Later Y. Ye *et al.[10]* proposed an Enhanced-AIF(E-AIF) that achieved averaging 12.53% of bit-rate saving on HD(720p, 1080p) sequences.

2.2.3 OBMC

M.T. Orchard *et al.[5]* presented an estimation-theoretic analysis of motion compensation. The result indicates that in block-based motion compensation, residual variance gets higher when pixel position moving from block center. Figure 2.3 shows the residual variance of sequence football.

To improve the prediction accuracy, OBMC was also proposed in [5]. The concept of OBMC is to utilize the predictors indicating by neighboring MBs. For example, in

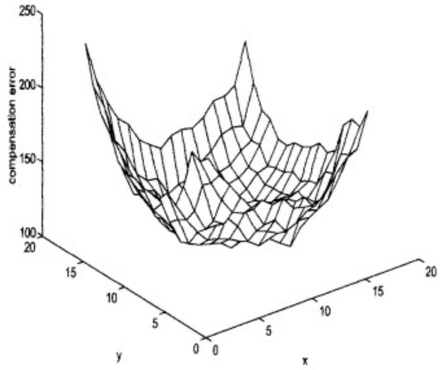

Figure 2.3: Average residual signal energy calculated from Football sequence using block size of 16x16.

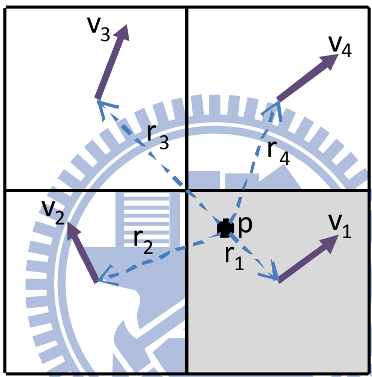

Figure 2.4: One example of OBMC. The shaded block is the current MB. Pixel p's distance to block MV (v1, v2, v3, v4) is (r1, r2, r3, r4).

figure 2.4, v_2, v_3, v_4 represent neighboring block's MVs. The current block apply the linear combination of the predictors indicated by $v_{1,}v_2, v_3, v_4$ as its final predictor.

Initially OBMC is only implemented in to H.263 [1]. Y.W. Chen *et al.[4]* proposed an A parametric window design for OBMC and extended H.264/AVC with proposed algorithm under quad-tree MB partiton coding framework. Average of 5% bit-rate saving is acquired.

2.2.4 Extended Macro Block Sizes

Since the high resolution video content is the trend for next generation video coding, their characteristics are analyzed. Extended MB sizes [3] were proposed to improve the coding efficiency for one of the characteristics that smooth area are enlarged. Extended

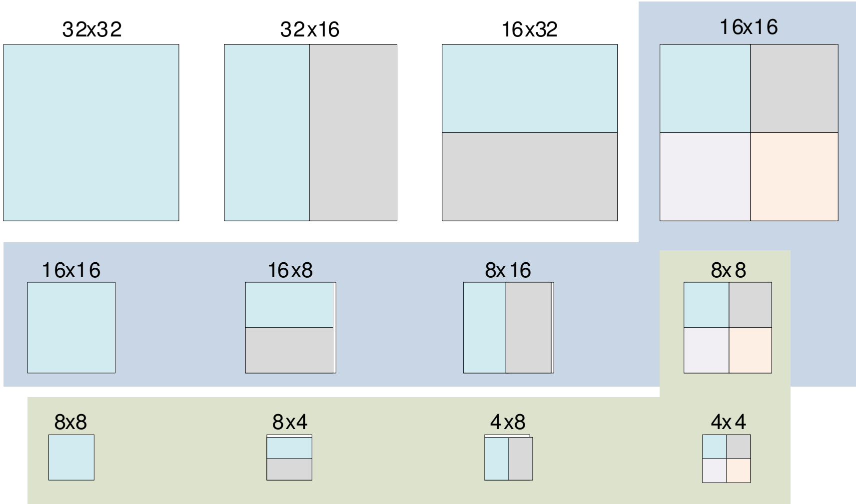

Figure 2.5: MB partition in 32x32 MBs.

macro block sizes allow MB partition to be 32x32 or even 64x64, quad-tree based partition exists in the same time as shown in figure 2.5. On average 15.10% of bit-rate saving is obtained on HD sequences.

2.3 Comparison of Well-Known Prediction Filter Designs

H.264/AVC interpolation filter seems to solve aliasing problem. OBMC utilizes MVs from neighboring MB to generate the motion-compensated predictor, somehow dealing with motion uncertainty problem. However, the coding gain of OBMC is not as high as expected. AIF offers impressive coding gain upon H.264/AVC interpolation filter as well as OBMC, however its design principle still follows H.264/AVC interpolation filter.

CHAPTER 3

Analysis of Motion Uncertainty

3.1 Motion Uncertainty

According to one of the conclusion in [5], a block MV found by block motion estimation aims to be the MV of block center. Thus for pixels away from block center, the block MV may not be its true motion vector. The phenomenon is called "motion uncertainty." Two element related to motion uncertainty can be came up with immediately: (1) pixel distance from block center and (2) motion compensation block size. In the following sections we try to analyze motion uncertainty through the observation of true motion vector(TMV) distribution. Then true motion indicated by OBMC is compared with the TMV distribution, in order to verify how OBMC compensates motion uncertainty. We also perform a simple experiment by applying Wiener filters with different filter tap lengh to support our conclusions on motion uncertainty characteristics.

3.2 Observation of Motion Uncertainty

To analyze motion uncertainty, the following experiments are performed:

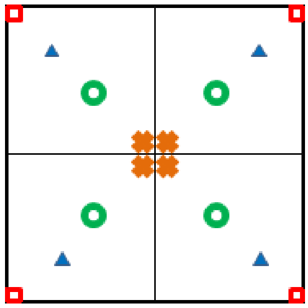

Figure 3.1: The 4 distinct pixel position goups to be analyzed. These groups are marked as "corner," "near-corner," "near-center" and "center" related to their distance to block center.

1. For pixels at different positions compared to block center, find out their true motion vector characteristics.
2. For pixels at related positions, observe their motion uncertainty range.

3.2.1 Experiment Setting

Here are the experiment settings:

- CIF, 720p and 2560x1600 sequences with first 200 frames are tested.
- Only one previous original frame are referenced for MC, in order to avoid other encoding effects such as quantization noise.
- Fixed MB size of 16x16, 32x32 and 64x64 with search range 128 are applied for MC.
- Sum of square difference(SSD) minimization are used as MC criterion.
- MBs with SSD magnitude between only first 5%~60% are picked out as analysis candidates, since MBs with too large and too small SSD will confuse the experiment result.
- For simplicity, 4 distinct pixel position groups are analyzed. As shown in Figure 3.1.

The reason that the first 5% MBs are excluded is that MBs with large SSD are likely to be occlusion. In this case usually spatial prediction is preferred. In additon, on average there are 50% of MBs to be encoded as skip mode for each sequence under H.264/AVC framework. In skip mode the MV is generated by neightboring MBs and the residual is set to zero. Also there are some non-skip mode MBs with no residual. In both cases the motion compensated prediction is good enough. So the first 60% SSD magnitude is an acceptable lower threshold. Additionally, the candidates MBs occupies more than 70% of tatal SSE in each sequence.

3.2.2 True Motion Distribution

To find out the true motion vector(TMV) of each pixel group, experiment settings as described above are applied with following detailed settings:

- MC criterion is changed to be weighted SSD.
- ME is modified to MB size of 9x9 with search range 17.
- TMV search starts from the block motion.

The weighted SSD is realized by applying an Gaussian weighting kernel. The reason of using weighted SSD is that the pixel TMV is desired instead of block TMV. In the same way, the smaller MB size as well as search range are also optimized for finding TMV.

3.2.3 OMBC Motion Distribution

OBMC mentioned in Ch. 2.2.3 utilizes neighboring MVs as current MB MVs to generate the predictor. Somehow OBMC compensates motion uncertainty problem. To visualize its behavior, the true motion distributions indicating by OBMC are also acquired.

For achieving a fair comparison between OBMC and true motion search in Chapter 3.2.2, the true motion probability measures are modified. Each MB will utilizes 3 neighboring block MVs as well as the MV itself, as shown in figure 2.4.

For each pixel position, specific weighting w_i is computed and normalized by

$$w_i = \frac{r_i^{-2}}{\sum_{i=1}^{4}(r_i^{-2})}$$

Where r_i is denoted for the distance between the target pixel and the center of related neighboring block. For exmaple, at corner pixels the distances to the 4 intereted MVs are about to be the same, the weightings are computed as (0.25, 0.25, 0.25, 0.25).

The weightings are nomalized to be summed as 1 because OBMC references 4 MVs as its TMV, while the true motion search in Chapter 3.2.1 find only one MV to be TMV for one pixel.

3.2.4 Experiment Results of True Motion Distribution

Following the above experiment settings, first the true motion distribution is tested for different pixel positions.

Figure 3.2 shows the true motion distribution for different sequences. Immediate obsevations are:

1. True motion spreading only depends on sequence.
2. The probability of block motion indicating TMV is always showed as peak.
3. The peak probability is hardly exceeds 0.5.

Figure 3.3 shows the true motion distribution for different pixel positions. The obsevations are:

1. Most of the TMVs appear mostly within 1 to 2 pixels away from block motion
2. TMV spreading becomes wider while target pixel moving from corner to block center.
3. For OBMC, the peak value is much higher compared to TMV results. In the same time the spreading for OBMC is narrower, too.
4. The shape of spreading is alike for TMV as well as OBMC. The peak value also get larger as the target pixel moving from corner to center.
5. OBMC is sensitive to pixel positions where TMV are not.
6. From TMV cruves, concentration speed disparity is not obvious for different positions.

Next the true motion distribution is tested for different MB sizes.

Figure 3.4 shows the true motion distribution for different sequences for different MB sizes. The obsevations are:

1. True motion spreading shape and characteristics of peak value are the same as above.
2. Most of the TMVs still appear within 1 to 2 pixels away from block motion
3. TMV spreading becomes wider when MB size increases.
4. OBMC is not sensitive to MB sizes where TMV is.

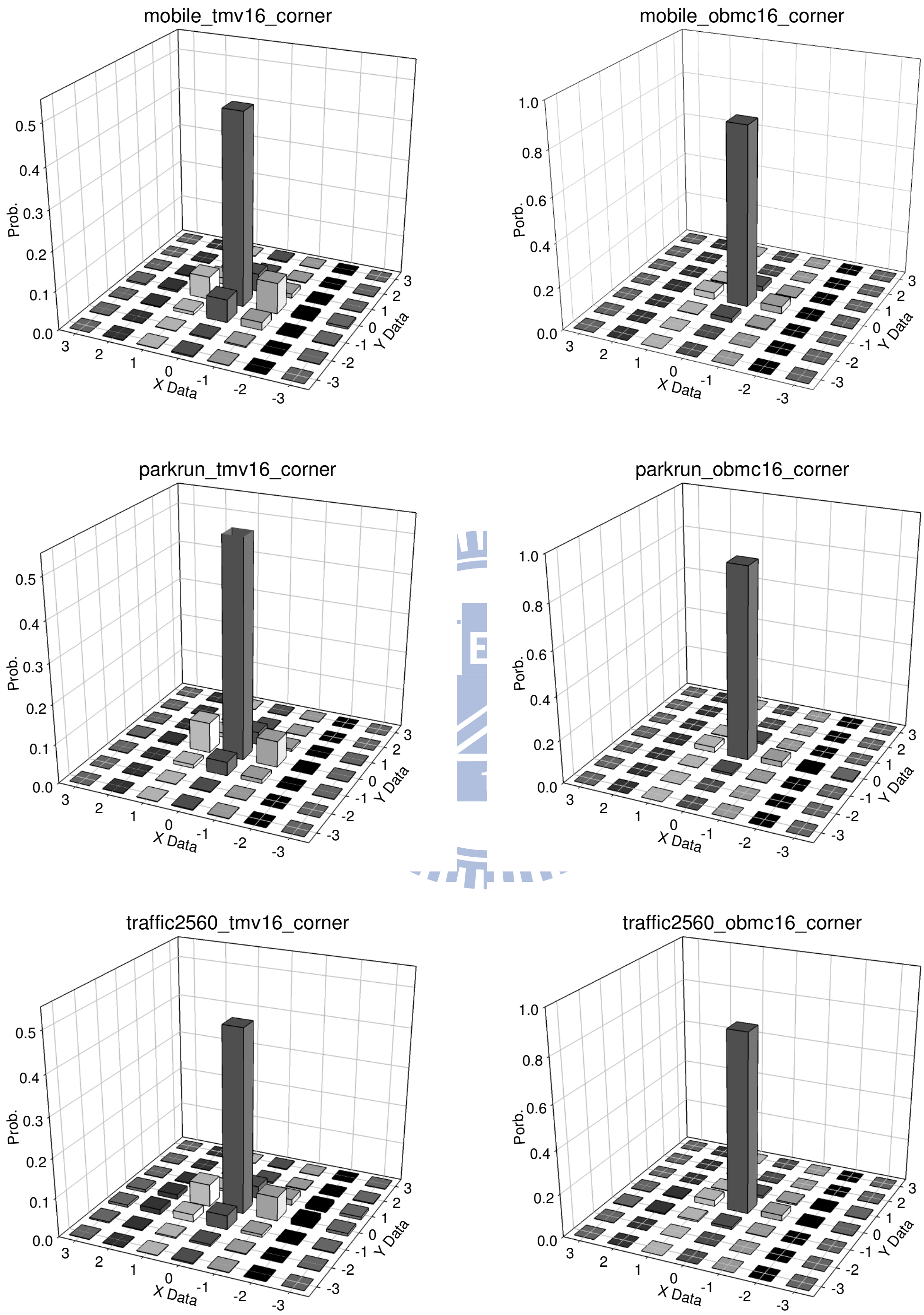

Figure 3.2: Example of how true motion indicated by TMV search and OBMC distributes for different sequences.

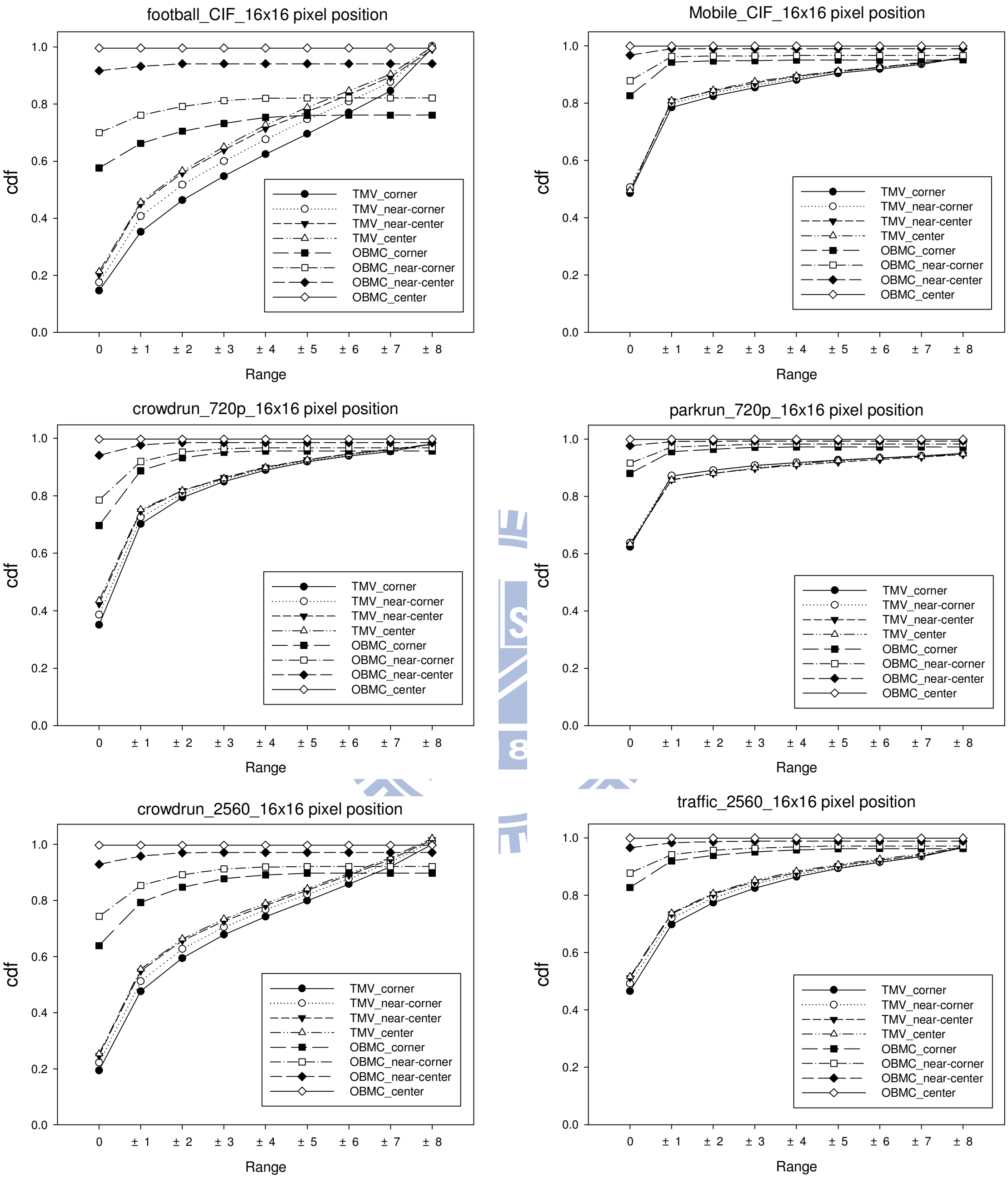

Figure 3.3: True motion distributions for different pixel positions indicated by TMV search and OBMC. The axis marked "Range" is the distance started from block MV. The axis marked "cdf" is the cumulative distribution function for the probability of true motion occurance.

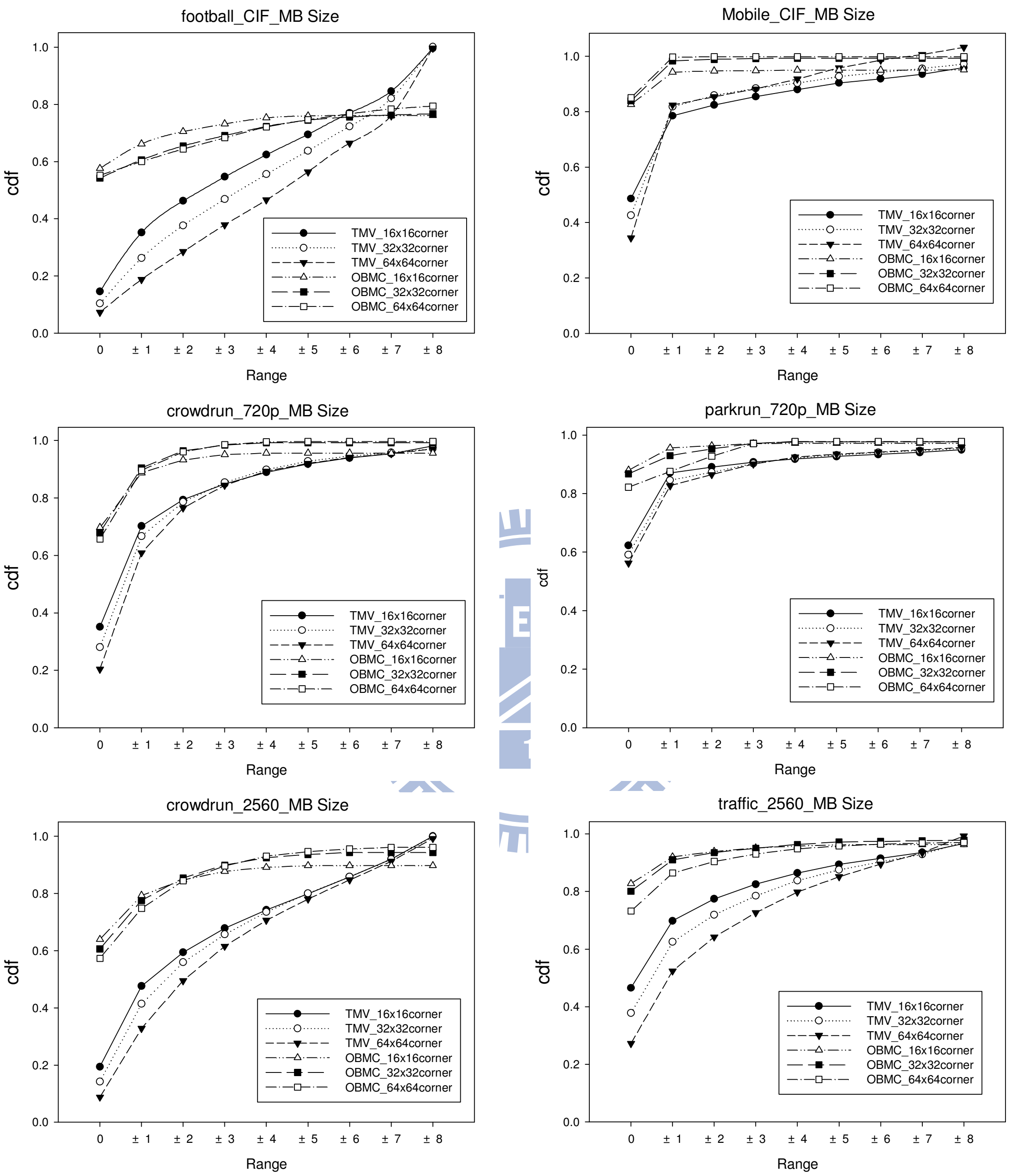

Figure 3.4: True motion distributions for different MB sizes indicated by TMV search and OBMC. The axis marked "Range" is the distance started from block MV. The axis marked "cdf" is the cumulative distribution function for the probability of true motion occurance.

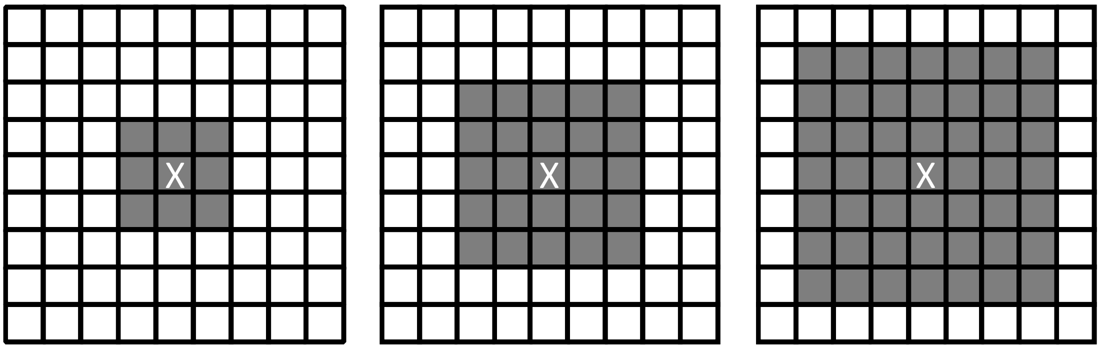

Figure 3.5: Weiner filter with: (a) 9 taps, (b) 25 taps and (c) 49 taps. The shaded blocks indicate filter supports and the block marked "X" indicates the pixel pointed by block MV.

3.3 First Experiment

After observing the true motion distribution, the following experiment is executed to investigate the influence of motion uncertainty spreading range on prediction efficiency. For each position in candidate MBs, three Weiner filters as in Figure 3.5 are generated for each sequence. The difference between those filters are only filter tap length.

Figure 3.6 shows the experiment results. By applying the filter with 9 taps, an obvious sum of square error(SSE) decline is achieved. However applying filters with 25 taps and 49 taps acquires merely advanced SSE decline than 9 taps filter. In reality there are up to 2% and 1% of additionally SSE decline for 25 taps and 49 taps filters. This experiment shows that increasing filter tap length over a certain magnitude cannot contribute desirable prediction efficiency. Moreover the simular filter supports will encounter averaging effect when the training sets for filter are not carefully classified.

3.4 Motion Uncertianty Characteristics

From the experiments above, the motion uncertainty phenomenon exists and is observed. Its characteristics are summerized as following.

1. Most-likely TMV for a pixel is its block MV.
2. Motion uncertainty could happen to every pixel in a MB.
3. The distribution of motion uncertainty occurrence depends on sequence.
4. Motion uncertainty occurs mostly within 1 or 2 pixels away from block MV.

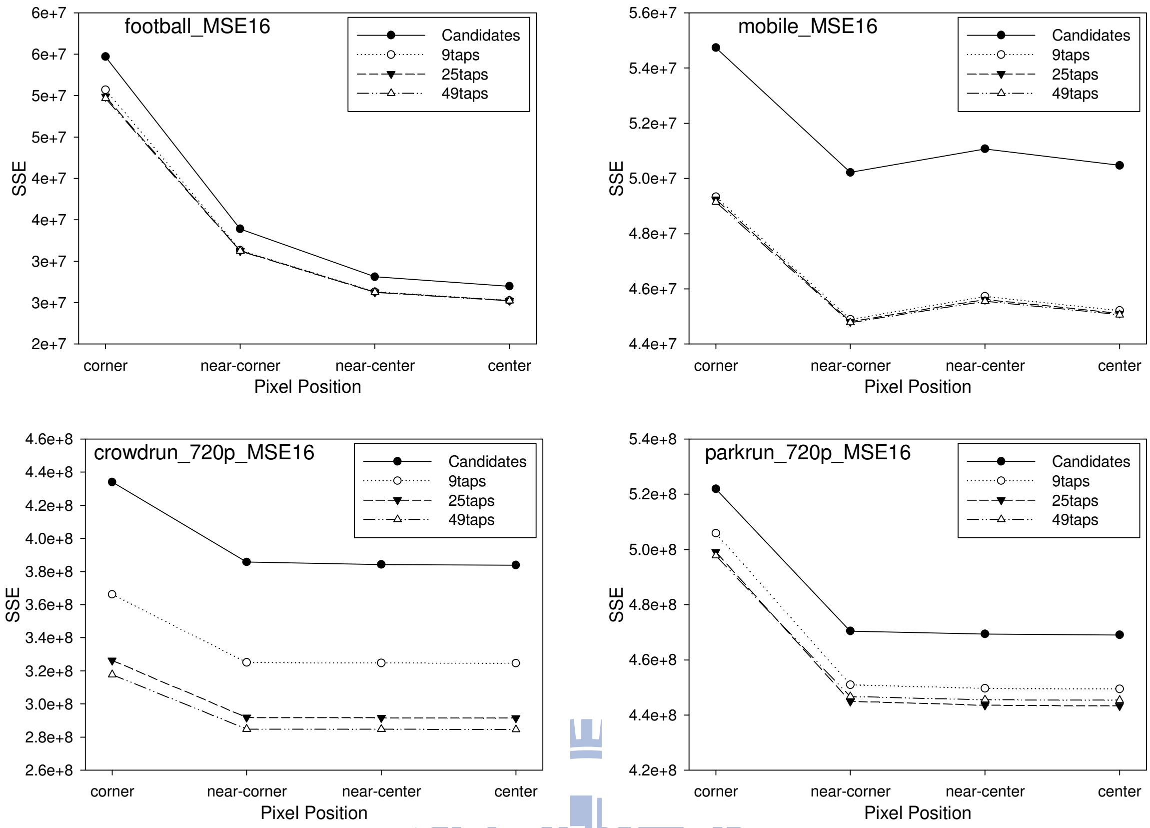

Figure 3.6: SSE for sequences at MB size 16x16.

5. Motion uncertainty becomes smaller for pixels near block center compared to distant pixels.
6. Motion uncertainty becomes stronger when MB size increases.
7. The true motion distribution indicated by OMBC also fits the motion uncertainty distribution, however the magnitude is not exact.

CHAPTER 4

Design of Spatially-Variant Weiner Prediction Filter

In Chapter 3, the phenomenon of motion uncertainty is investgated and its characteristics are analyzed. Based on these characeristics, the author makes some assumptions and tries to develop a set of filters in order to decrease the prediction error. And finally the design principle of spatially-varaint weiner prediction filter is introduced.

4.1 Proposed Filters

Weiner filters with the same shape but different length are tested in Chapter 3.3. However, the reduction of SSE is gentle while filter tap increases. One reason is that motion uncertainty mostly happens within 1 or 2 pixels away. Moreover, there is a blind spot that Weiner filter is acquired by training. Therefore the seletion of training set is important.

In order to choose the proper training set to avoid averaging problem during computation, a set of filters are designed with different filter supports. Total of 14 Weiner filters are shown in Figure 4.1.

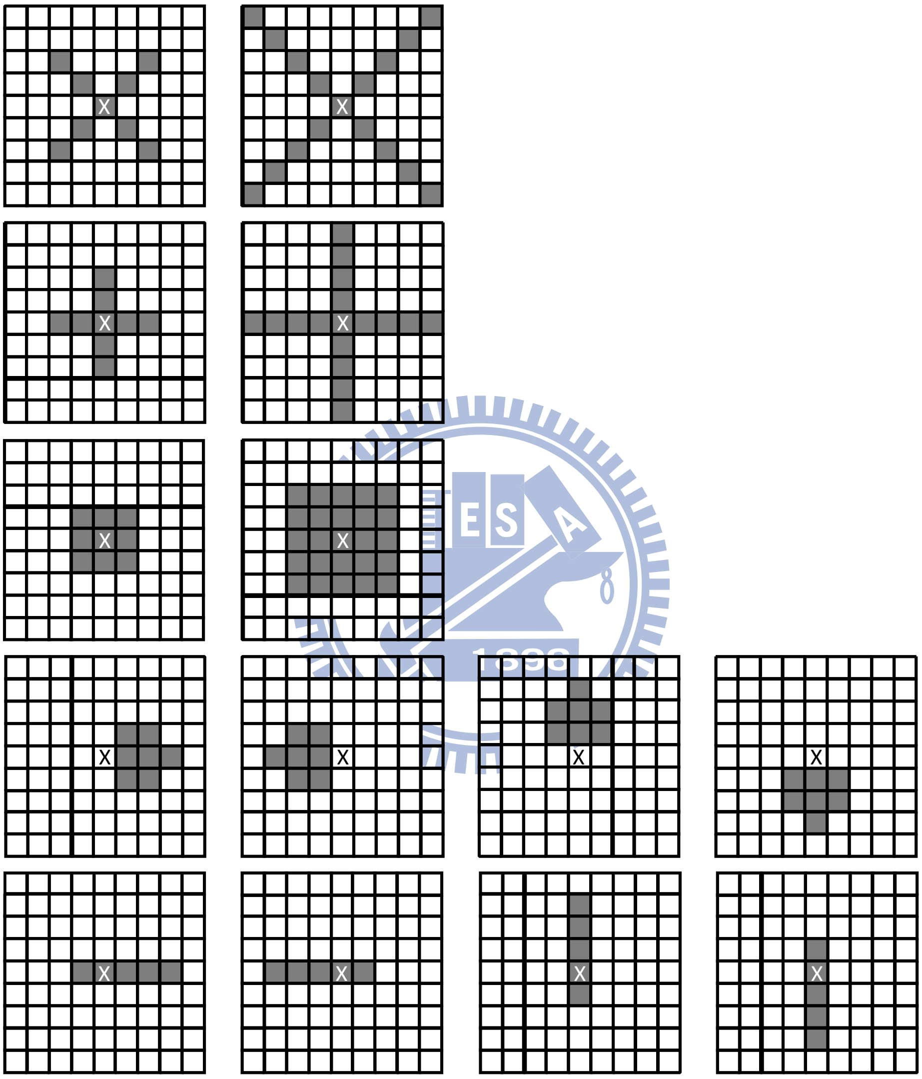

Figure 4.1: Proposed 14 Weiner filter supports.

Each filter is trained seperately for 4 pixel positions as in Chapter 3.2.1. Each pixel can freely choose one among 14 filters as well as original motion compensated pixel to obtain mininal prediction error. Although the overhead of signaling is huge considering implementation in real application, this experiment is worth investing the efficeincy of proposed filter design.

4.2 Performance Comparison

Several well-known prediction filter design is compared to the proposed filter in this section. The experiment results for different MB sizes are shown in Figure 4.2, 4.3 and 4.4.

The line marked "Candidates" is the SSE of candidate MBs at each pixel position under the selectin criterion in Chapter 3.2.1. "AVC" indicates the H.264/AVC standard[] interpolation filter with quarter-pel precision(totally 16 refinement selections). "AVC(position free)" indicates H.264/AVC interpolation filter with quarter-pel precision, but each pixel position in a MB can freely choose the quarter-pel interpolation minimizing prediction error. In "AVC(all free)" there is no limitation of sub-pel selection, every pixel can freely choose the best quarter-pel location in totally 16 selections. The standard H.264/AVC interpolation filter offers great decreasing of SSE. More SSE decreasing can be obtain by loosen the quarter-pel selection limits.

The line marked "OBMC" indicates the SSE generates by OBMC algorithm in Chapter 3.2.3. "OBMC Adaptive" indicates the SSE generated by the same algorithm, but each MB can choose the one between OBMC and original motion compensation predictor.

OBMC does a good job at decreasing the SSE of corner pixels. Unfortunately the OBMC algorithm implemented in this experiment does not acquire good performance since only integer-pel precision MVs are utilized. OBMC is expected to perfrom better if combined with sub-pel precision MVs.

The proposed filter design, the line marked "proposed," alway performs best for every sequence at every MB size. Although the overhead is high since the filter choice need to be signalled for each pixel, the proposed filter still outperforms H.264/AVC interpoation filter with the same overhead(the line marked "AVC(all free)").

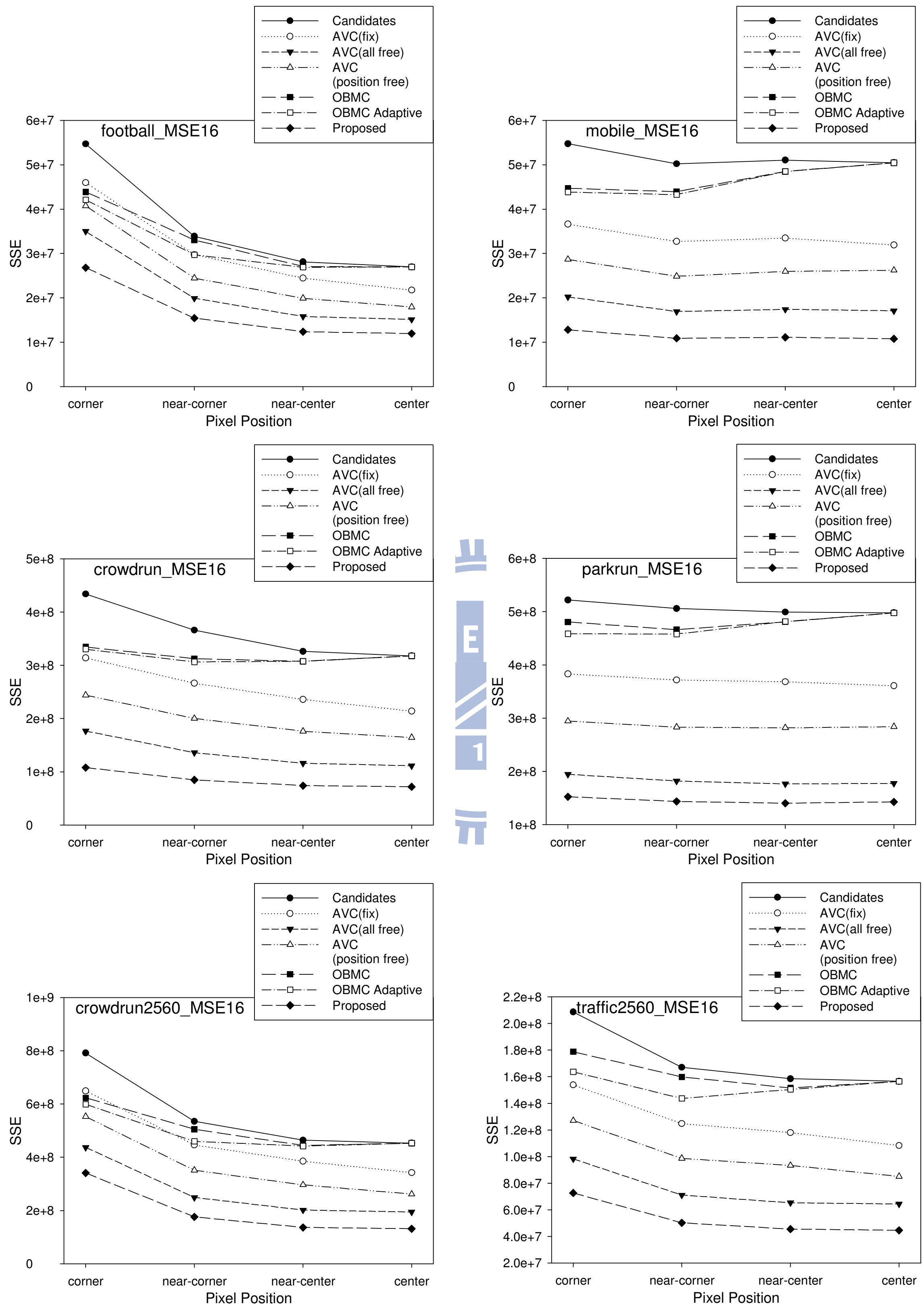

Figure 4.2: SSE Comparison for MB size 16x16.

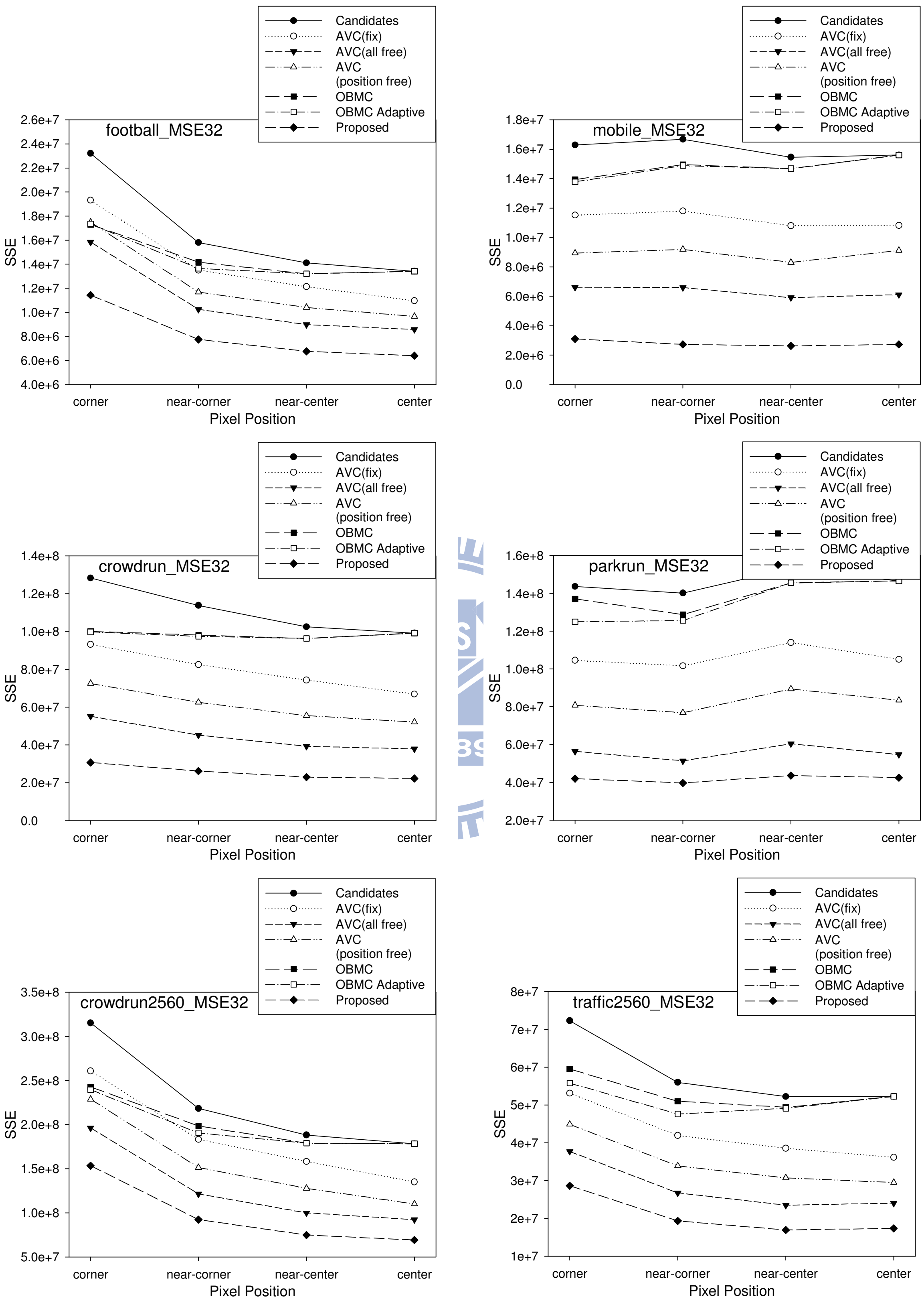

Figure 4.3: SSE Comparison for MB size 32x32.

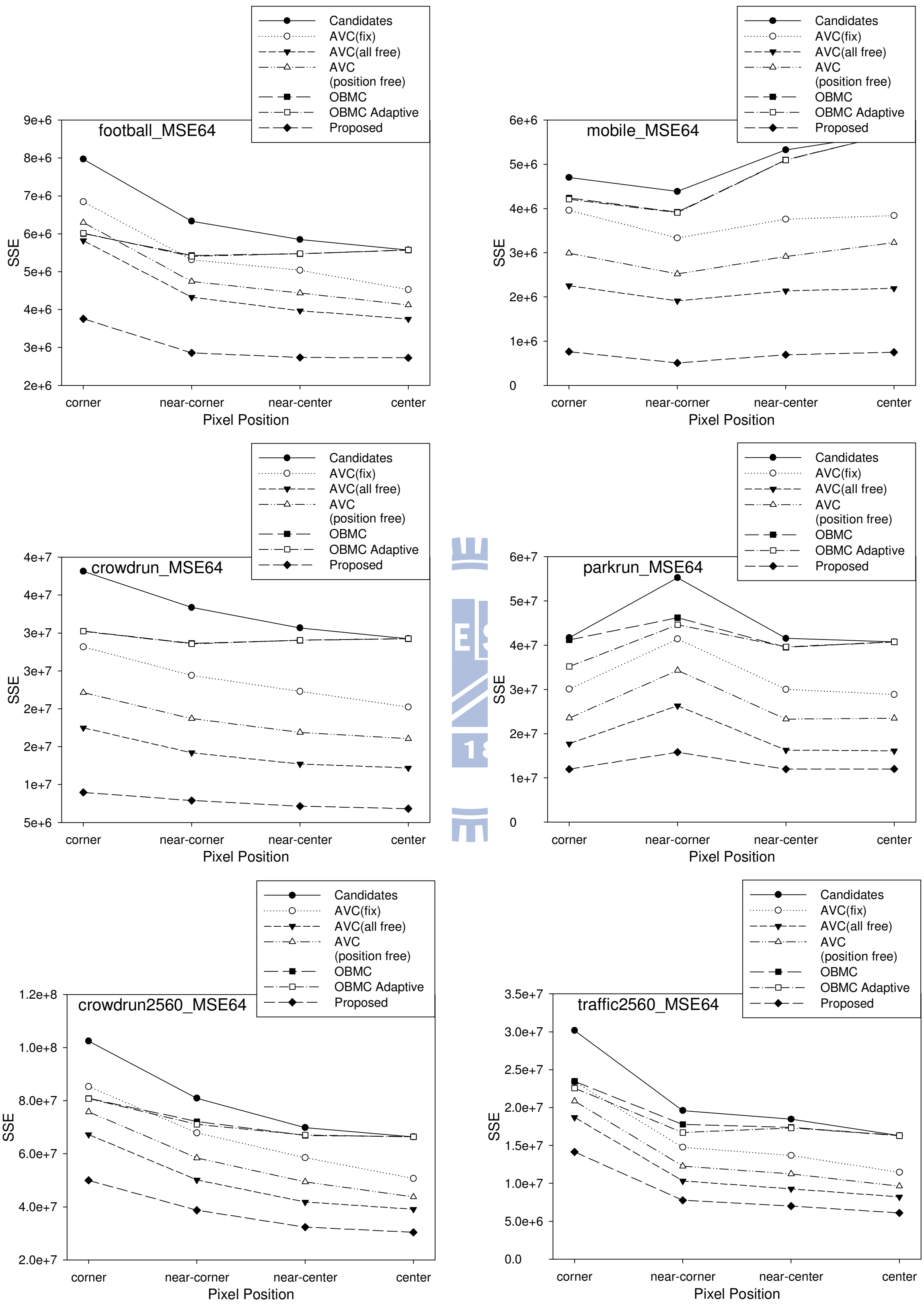

Figure 4.4: SSE Comparison for MB size 64x64.

Besides the performance comparison, the trend of SSE also needs to be addressed. The SSE shows a slope in a decreasing manner form corner to center pixels in candidates blocks. OBMC reduce the SSE most at corner pixels, producing a flatter lline. H.264/AVC filters with different constrains offer significant SSE reduction but keeps the slope. The proposed filter still keeps the slope but the slope becomes gentle in some sequences such as foreman, crowdrun and parkjoy. It can be explained that motion uncertainty within one pixel is also an aliasing problem, thus the H.264/AVC interpolation compensates this problem. However the proposed filter design deals with motion uncertainty for more than 1 pixel, thus provides better performance.

Finally the slope of SSE indicates one more fact: as there is no perfect motion compensation, there maybe no perfect compensation for motion uncertainty can be achieved. However by designing proper filter, the effect of motion uncertainty is expected to be reduced.

4.3 Design Pinciple of Spatially-Variant Prediction Filter

In last section the proposed filter shows outstanding performance beyond those well-known filter design. After summarizing the experiment results in Chapter 3 and last section, the design principles of spatially-variant prediction filter in order to improve prediction efficiency are suggested.

- Filters for different pixels should be unequally related to their distance to block center.
- Filter supports with pixels within 3 pixels from its block MV are sufficient.
- Training set selection is important for Weiner filter design.
- Context information can be introduced to reduce the amount of signaling overhead.

CHAPTER 5

Conclusions

In this work, we attempt to analyze the motion uncertainty problem resulting from block-based motion compensation. We first design a number of experiments to analyze the distribution of motion uncertainty and its characteristics. Based on the experimental results, some important observations were made to help to develop a spatially-variant temporal prediction filter. Preliminary experiments show that such an approach can more effectively overcome the problem of motion uncertainty in temporal prediction, as compared with the existing filter designs. Again we summarize our observation of motion uncertainty here:

1. Most-likely TMV for a pixel is its block MV.
2. Motion uncertainty could happen to every pixel in a MB.
3. The distribution of motion uncertainty occurrence depends on sequence.
4. Motion uncertainty occurs mostly within 1 or 2 pixels away from block MV.
5. Motion uncertainty becomes smaller for pixels near block center compared to distant pixels.
6. Motion uncertainty becomes stronger when MB size increases.
7. The true motion distribution indicated by OMBC also fits the motion uncertainty distribution, however the magnitude is not exact.

Our work is still in its early stage. We plan to extend our investigation in several directions: (1) tradeoff between performance of spatially-variant prediction filter and signaling overhead, (2) implementation of spatially-variant prediction filter into H.264/AVC framework, and (3) The relationship between motion uncertainty and context information such as neighboring MVs.

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