

One-Dimensional Processing for Efficient Optimal Post-Process/In-Loop Filtering in Video Coding

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Abstract — *In this paper, efficient optimal post-process/in-loop filtering in video coding is presented by applying two separate one-dimensional filters to significantly decrease the computational load of the optimal filtering process at the expense of only a slight quality loss. Furthermore, the compression of filter coefficients is evaluated using a Golomb-Rice (GR) coding approach together with differential encoding. Experimental results show that the proposed one-dimensional processing approach reduces the computational complexity by at least 4 times compared to the formerly proposed two-dimensional optimal filtering case and enables real-time implementation. It is furthermore shown that, the filter coefficients can be compressed by up to 40% if GR coding is used together with differential encoding¹.*

Index Terms — Video compression, optimal filtering, Golomb-Rice coding

I. INTRODUCTION

Video coding or compression is used for storage and transmission of image sequences in consumer electronic products. From the storage point of view efficient video coding enables storing more data into limited storage media such as CD, DVD, or Blue-ray disc [1]. In the case of transmission, video coding is a necessity to meet limited bandwidth constraints. Therefore, video coding is mostly inevitable for video storage and transmission.

Almost all video compression techniques make use of spatial or temporal redundancy to reduce the data amount. H.264/AVC [2] is the latest video coding standard that outperforms all former standards in terms of the visual quality obtained for a certain bit-rate. Because motion estimation has the highest computational complexity, some fast motion estimation (ME) methods [3, 4] are used in H.264/AVC to speed-up the process. It is furthermore possible to accelerate the motion estimation process using specific ME approaches such as 1BT [5], 2BT [6], MF-1BT [7], C-1BT [8], or MC-

1BT [9] which are particularly suitable for dedicated hardware implementations, especially for consumer electronics devices that have limited CPU processing and power capabilities.

A different direction of research is concerned with increasing video compression performance or the reconstructed video quality at a certain bit-rate, possibly at the cost of higher computational load. For this purpose it is possible to introduce modifications into different parts of the video encoder. For example improved ME approaches with higher computational complexity are presented in [10-12] to further improve the compression efficiency of the video coder. A de-blocking filter (DBF) is proposed in [13] to be used within H.264/AVC to further improve the visual quality of compressed video at the expense of additional computational load. The basic idea of the DBF used in [13] is to provide enhanced visual quality by means of reducing blocking artifacts existing at block boundaries. Several approaches have been proposed to reduce the complexity of the DBF or to improve its performance. In [14], the influence of the DBF on coding efficiency from low to high bit-rates is examined. A fast two-dimensional DBF has been proposed in [15] to enable easier implementation of the filtering process. In [16] it is proposed to use a hybrid filtering scheme to reduce the number of processing cycles of the filtering process. In [17] it is proposed to compute boundary strength not for all pixels at the block boundaries but only at alternating pixels. The boundary strength is determined with a reduced complexity approach in [18]. In [19], a fuzzy de-blocking filter is presented and it is shown that the performance is generally better than [13] at the expense of additional computational load.

Recently, a new optimal-filtering based approach is proposed in [20] which is based on the idea to minimize the difference between the reconstructed compressed video frame and the original frame in least squares (LS) sense. For this purpose the filter coefficients of an optimal linear filter are obtained at the encoder in LS sense and these coefficients are multiplexed into the bit-stream so that the decoder can use them to filter the reconstructed frame. A two-dimensional filter is used in [20] and as the filter coefficients have to be computed for each frame the complexity introduced at the encoder is relatively high. It is important to note that this filter is not an alternative to DBF and can be used in conjunction with DBF to further improve visual quality. The optimal filtering concept is utilized for image compression in [21].

In this paper, the computational complexity of the approach presented in [20] is reduced using one-dimensional filters that are applied successively in the horizontal and vertical

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directions. Therefore the computational load of optimal filtering is decreased significantly compared to the formerly proposed two-dimensional filtering, at the expense of only a slight drop in reconstruction performance. Furthermore, compression of filter coefficients is investigated in this paper and it is shown that the video coding performance can be improved in rate-distortion sense by compressing filter coefficients using a simple entropy encoding scheme, which is particularly useful at low bit-rates.

II. ONE-DIMENSIONAL POST-PROCESS/IN-LOOP OPTIMAL FILTERING

Approaches used for filtering of video frames for quality enhancement can be classified into two main categories, namely post-filtering and in-loop filtering based approaches. Post-filtering is used outside the coding loop, so that video frames are filtered at the final step after reconstructed. On the other hand, in-loop filtering is utilized inside the coding loop and in-loop filtered frames are used as reference for the prediction of subsequent frames. In [20] an optimal filtering concept is proposed for in-loop filtering or post-filtering. These two cases are referred to as in-loop optimal filtering (ILOF) and optimal post-filtering (OPF).

The optimal filtering approach proposed in [20] aims to obtain a filter which minimizes the difference between the reconstructed encoded frame (\hat{I}) after filtering and the original image frame (I) with an optimum two-dimensional filter kernel \mathbf{G} of size $k \times k$. This kernel is obtained such as to minimize the difference between the reconstructed frame and the original frame. Therefore an enhanced reconstructed video frame can be obtained by filtering in the form of:

$$\hat{I}_{F-2D}(i, j) = \hat{I}(i, j) * \mathbf{G} \quad (1)$$

where \hat{I}_{F-2D} is used to represent the filtered video frame using a two-dimensional filter. The optimal filter \mathbf{G} can be computed as

$$\min_{\mathbf{G}} \|I(i, j) - \hat{I}(i, j) * \mathbf{G}\|_2^2 \quad (2)$$

in LS sense. In [20], (2) is solved in LS sense using an unrolled implementation of the iteratively preconditioned conjugate gradients (IPCG) approach of which details are given in [22].

The method presented in [20] is shown to improve the compression performance when used in H.263 as well as H.264/AVC. However its computational load is relatively high because of the LS solution of the two-dimensional filtering process.

In this paper it is proposed to use two one-dimensional filters instead of the two-dimensional filter, in order to reduce the computational complexity of the optimal filtering process. A further contribution of this paper is that it is considered in this paper to compress the filter coefficient so as to reduce the overhead resulting from the coefficients being multiplexed into the bit-stream to further improve the performance of the proposed approach.

In the proposed one-dimensional filtering approach, the reconstructed image \hat{I} is initially filtered using a vertical kernel of size $k \times 1$ in the form of

$$\hat{I}_{Fv} = \min_{\mathbf{G}_v} \|I(i, j) - \hat{I}(i, j) * \mathbf{G}_v\|_2^2 \quad (3)$$

where \mathbf{G}_v is the optimal vertical filter kernel which is applied in the vertical direction that minimizes the difference between the original and filtered video frame. In the next step, a second filter that performs the filtering operation in the horizontal direction is used in the form of

$$\hat{I}_{F-1D} = \min_{\mathbf{G}_h} \|I(i, j) - \hat{I}_{Fv}(i, j) * \mathbf{G}_h\|_2^2 \quad (4)$$

where \mathbf{G}_h represents the optimal horizontal filter kernel of size $1 \times k$. Note that, this computation is carried out using the output of the previous stage, i.e. after the optimal filtering with \mathbf{G}_v . The output of the proposed one-dimensional filtering based approach is denoted as \hat{I}_{F-1D} . It is expected that there will be a difference between \hat{I}_{F-1D} and \hat{I}_{F-2D} since applying the vertical and horizontal one-dimensional filters can be regarded as constraining the two-dimensional filters to be separable, and therefore it is expected that there will be a small drop in reconstructed image quality. On the other hand, less filter coefficients have to be multiplexed into the bit-stream for the one-dimensional filtering approach, resulting in a reduction in the total bit-rate. The method in [20] requires k^2 coefficients for each frame, whereas the proposed one-dimensional method needs only $2k$ coefficients. It is important to note that the total coefficient overhead for the proposed method increases linearly with respect to the filter size. In order to evaluate the decrease in quality against the gain obtained by reduced bit-rate it is required to assess the rate-distortion performance. Nonetheless, the aim of the proposed approach is to reduce the computational complexity of the optimal filtering process, so a small drop in performance compared to two-dimensional optimal filtering is acceptable.

III. COMPRESSION OF FILTER COEFFICIENTS USING GOLOMB-RICE CODING

One of the most important parts of video coding schemes is entropy coding. Entropy coding is particularly used for lossless encoding after quantization, in video coding systems. Variable length coding (VLC) [23] and context-adaptive binary arithmetic coding (CABAC) [24] are well-known entropy coding techniques used in various video coding applications.

Golomb coding [25] is an entropy coding method that is particularly effective for encoding small values; such as motion vectors obtained from the motion estimation process. The Golomb-Rice (GR) code [26] is a Golomb code where the

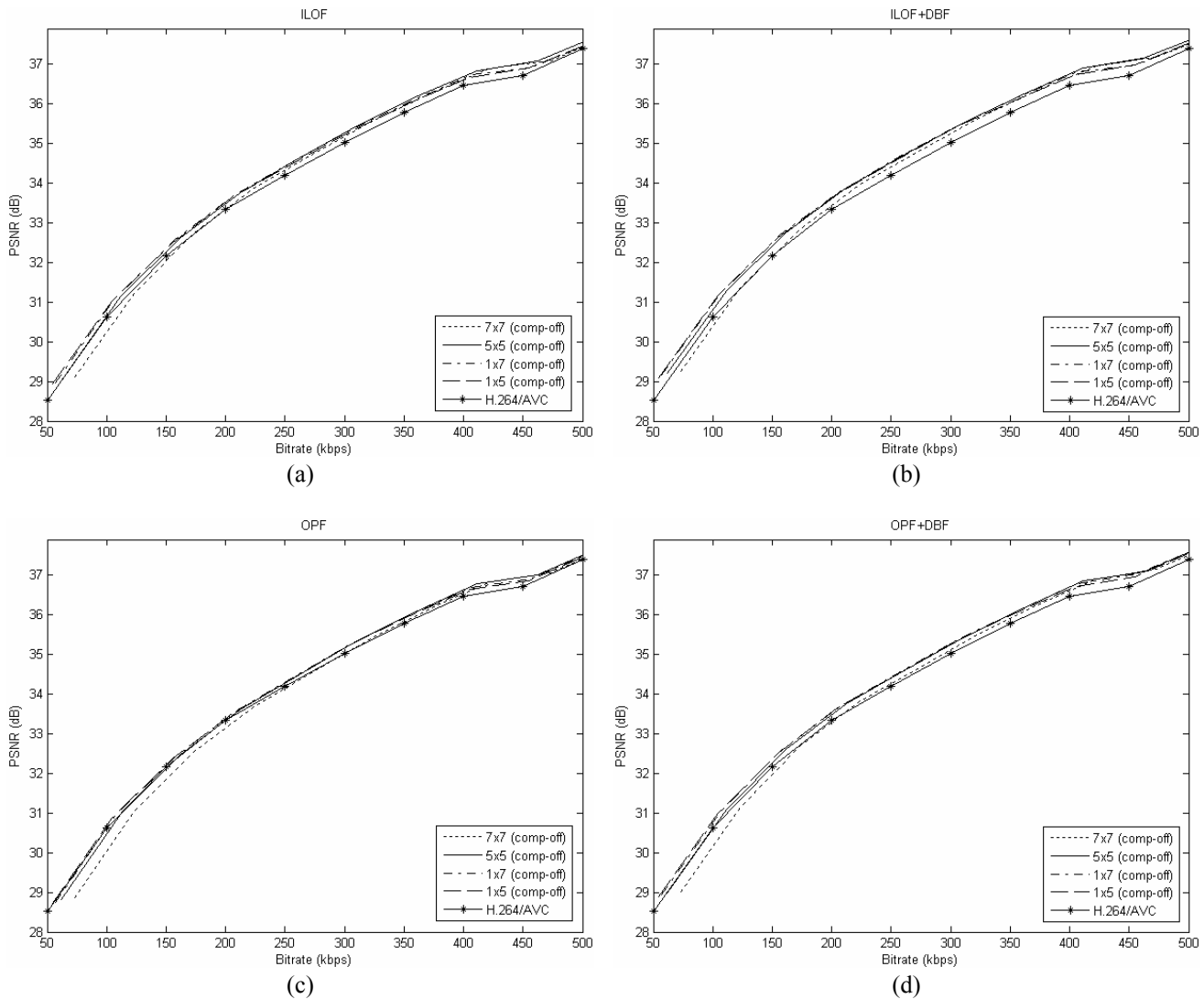


Fig. 1. Rate-Distortion performance comparison without filter coefficient compression for the Coastguard sequence (a) ILOF, (b) ILOF+DBF, (c) OPF, (d) OPF+DBF.

divisor is a power of two, enabling an efficient implementation using shifts and masks rather than division and modulo.

Table I shows the general structure of GR coding. In Table I, N refers to the data to be encoded by GR, and M represents the GR divisor which is a constant that enables efficient encoding for a specific data distribution. In results presented in this paper, the GR divisor is empirically determined and set to $M = 4$ based on experimental evaluation of optimal filtering coefficients. GR coding consists of two parts: the first part is a division code which is obtained by writing Q times the 0-bit and adding one 1-bit as suffix. The second part is the remainder code which is obtained by encoding the remainder R in binary format.

In the optimal filtering approach, the filter coefficients between succeeding frames are observed to have high correlation. Because of the spatial similarities between successive video frames, optimal filter coefficients of

succeeding frames also show high similarity. Therefore it is proposed to encode filter coefficients differentially in order to reduce the dynamic range of coefficients. Therefore, differential pulse code modulation (DPCM) is used. For each filter coefficient, the corresponding filter coefficient of the previous frame is used as prediction. After DPCM, GR coding of filter coefficients is carried out. Because filter coefficients (and also DPCM results) can also take negative values, one extra sign-bit is used.

**TABLE I
GENERAL STRUCTURE OF GOLOMB-RICE CODING**

N, M	N =input number M =constant of GR -divisor
Division	$Q = \text{int}[N/M]$
Remainder	$R = [N \% M]$
Code format	<division code><remainder code>
Division code	<0-bit array of size Q , one 1 bit >
Remain. code	Binary encoding of remainder

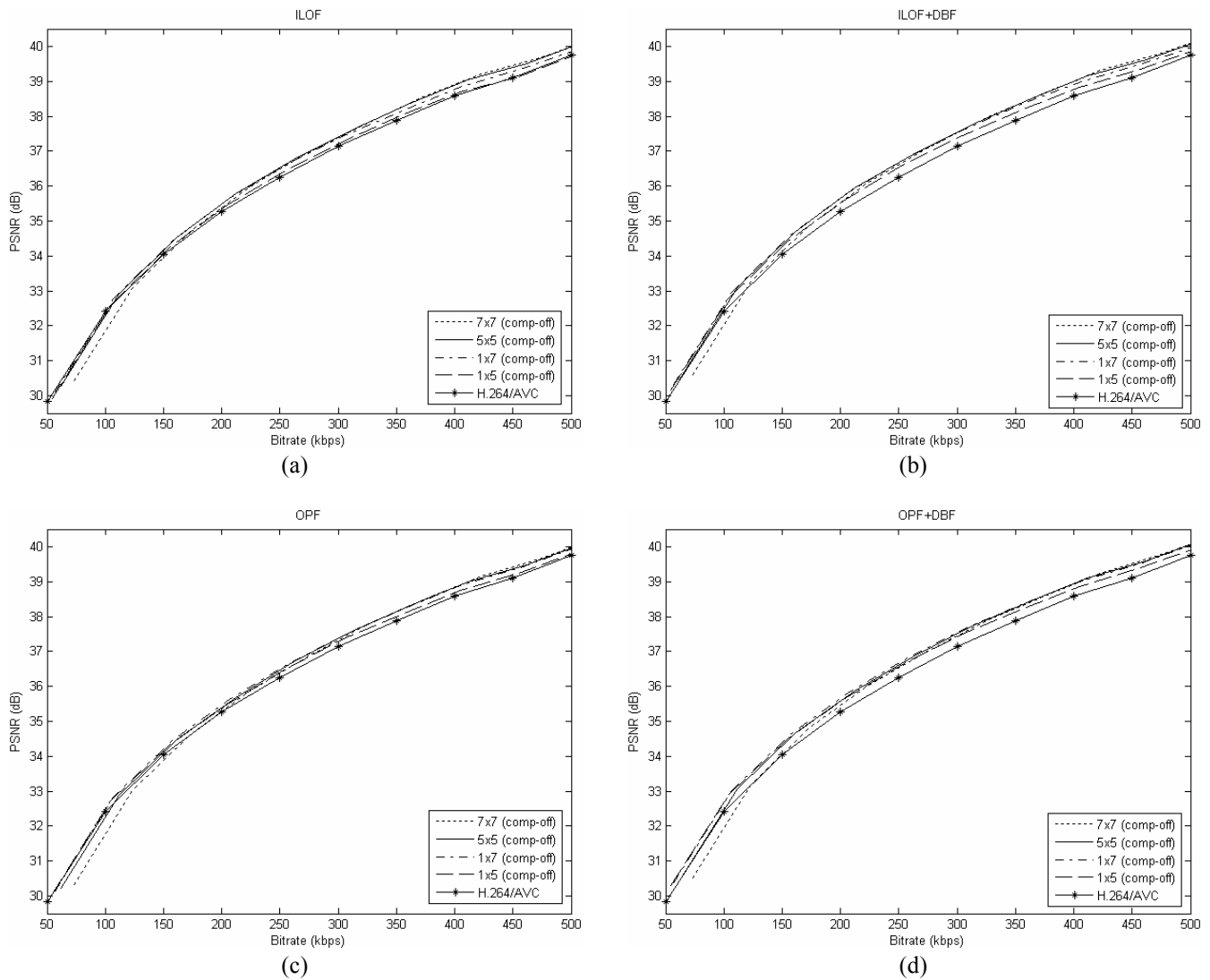


Fig. 2. Rate-Distortion performance comparison without filter coefficient compression for the Foreman sequence (a) ILOF, (b) ILOF+DBF, (c) OPF, (d) OPF+DBF.

IV. EXPERIMENTAL RESULTS

The “Foreman” and “Coastguard” video sequences are used to demonstrate the performance of the proposed approach. H.264/AVC reference software JM version-11 [27] is employed in the experiments.

Note that in all results provided, the frame rate is set to 30 frames/sec. Initially, it is aimed to evaluate the rate-distortion performance of one-dimensional versus two-dimensional optimal filtering, without filter coefficient compression. Rate-distortion (R-D) results for the Coastguard (QCIF) sequence are given in Fig. 1 for this case. ILOF+DBF and OPF+DBF are used to denote the cases where optimal filtering is used together with the standard deblocking filter of H.264/AVC. Note that in all H.264/AVC standard results (without optimal filtering) the deblocking filter is always active (i.e. ON), to provide comparative evaluation with optimal filtering results. Note that in this case optimal filter coefficients are not compressed, and each filter coefficient is represented in 16-bit

raw format. It is seen that, one-dimensional optimal filters provide better results compared to two-dimensional filters at lower bit-rates, because of the smaller overhead. On the other hand, two dimensional kernels enable better performance for high bit-rates since the ratio of overhead to total available bit budget is decreased at higher bit-rate range. It is seen from this figure that one-dimensional optimal filtering proposed in this paper, improves the reconstruction performance of standard H.264/AVC. Result show that only the two-dimensional optimal filter of size 7×7 gives worse results compared to standard H.264/AVC at low bit-rates because of the relatively high overhead. Similar results are obtained for the Foreman (QCIF) sequence as shown in Fig. 2. Comparing the overall performance, it is observed that ILOF+DBF provides the best results for two-dimensional kernels. On the other hand, for the one-dimensional case, OPF+DBF provides the highest PSNR values. It is important to note that the performance of ILOF+DBF and OPF+DBF is quite similar and it is seen that deblocking has in both cases

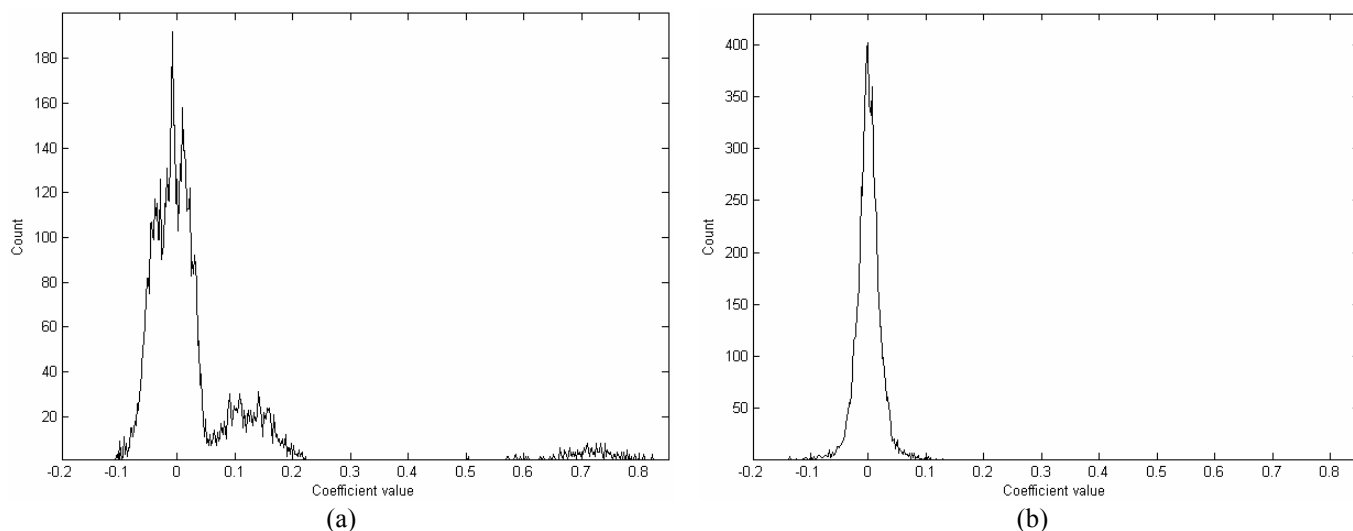


Fig. 3. Histogram of filter coefficients for the Foreman sequence using OPF+DBF with a two-dimensional filter kernel of size 5x5 (a) Original (b) DPCM values.

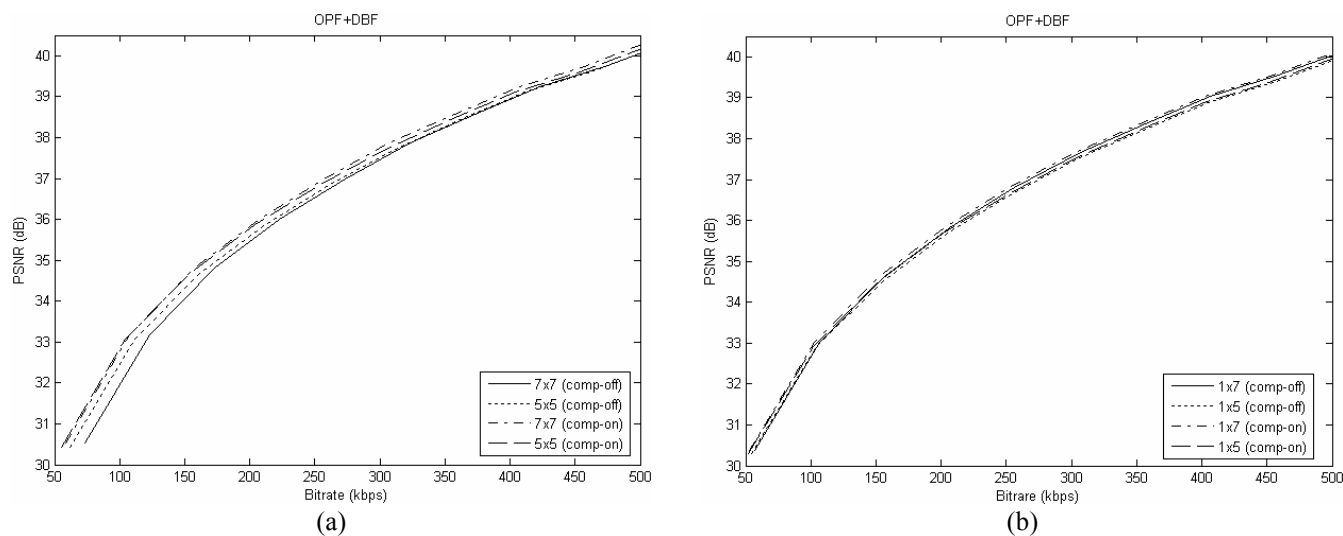


Fig. 4. Effect of filter coefficient compression on R-D performance for Foreman sequence using OPF+DBF (a) Two-dimensional optimal filtering (b) One-dimensional optimal filtering

TABLE II. AVERAGE COMPRESSION RATIOS (%) OF DPCM FILTER COEFFICIENTS FOR THE FOREMAN AND COASTGUARD SEQUENCES

		Bit rate									
		50 kbps	100 kbps	150 kbps	200 kbps	250 kbps	300 kbps	350 kbps	400 kbps	450 kbps	500 kbps
Foreman	ILOF	1.62	17.22	24.32	29.45	33.42	36.23	38.41	40.44	41.33	42.90
	ILOF+DBF	1.60	17.83	24.27	29.05	32.87	35.94	38.37	40.83	41.34	43.01
	OPF	34.51	37.83	40.32	40.66	42.59	43.59	44.23	45.26	45.28	46.35
	OPF+DBF	30.59	36.44	38.83	40.63	41.94	42.81	44.10	45.19	45.33	46.43
Coastguard	ILOF	13.22	23.65	29.19	32.13	34.24	36.70	38.49	40.42	39.88	41.39
	ILOF+DBF	14.70	24.23	29.26	32.29	34.50	36.43	38.60	40.18	39.75	41.67
	OPF	41.05	42.20	43.27	43.98	44.47	45.32	46.28	46.84	46.93	47.49
	OPF+DBF	39.17	40.55	42.26	43.12	44.01	45.06	45.93	46.44	46.59	47.30

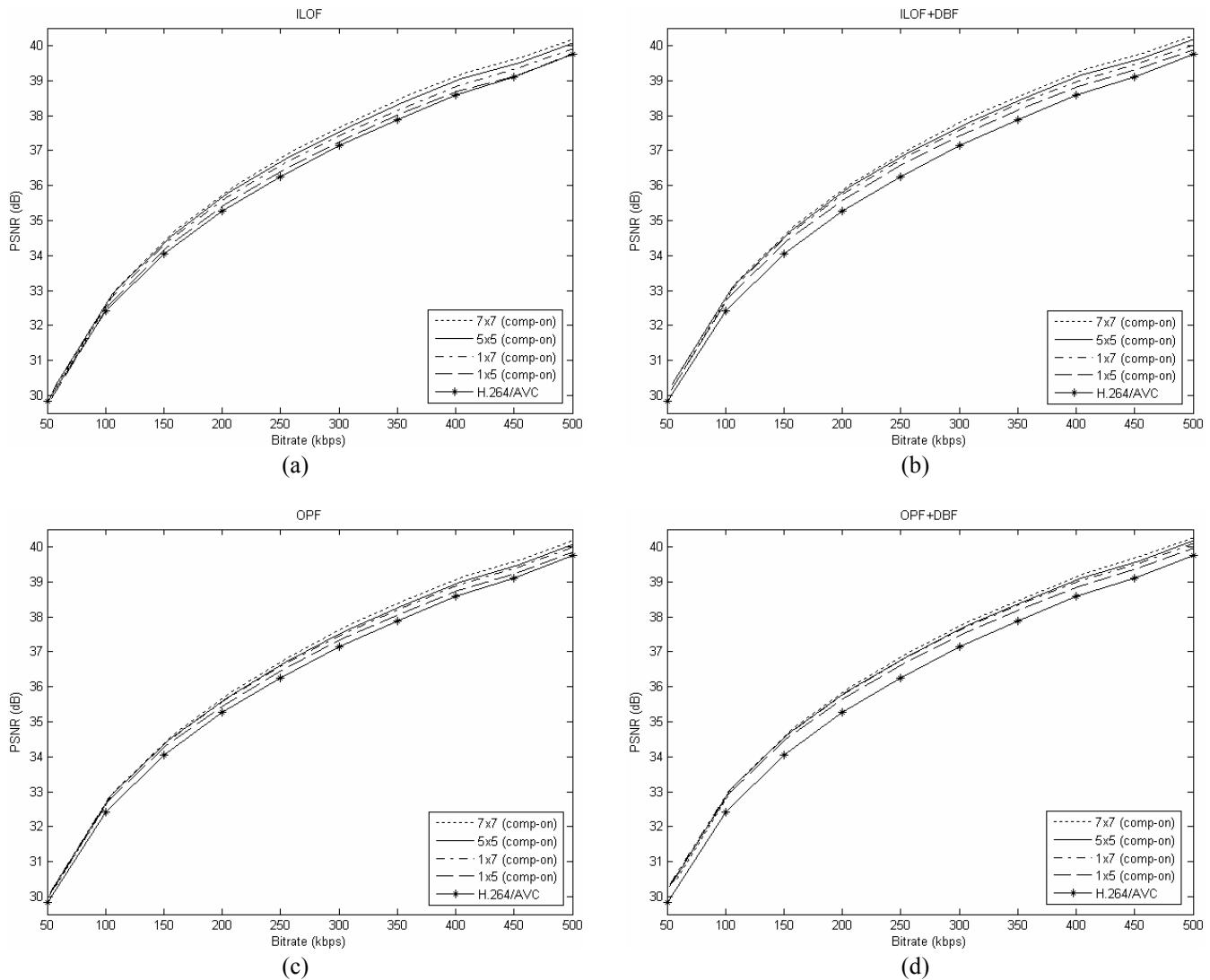


Fig. 5. Optimal filtering R-D performance for the Foreman sequence (a) ILOF, (b) ILOF+DBF, (c) OPF, (d) OPF+DBF.

(ILOF and OPF) a positive effect on PSNR. Comparing ILOF and OPF cases, it is seen that these also provide similar results for both sequences.

In order to evaluate the influence of entropy encoding of filter coefficients, GR encoding of DPCM coefficients is utilized. In order to facilitate efficient encoding, initially, filter coefficients are quantized into a 10-bit range including the sign bit. 10 bit quantization is used, as experiments have shown that quantization with 10 bits results in virtually no performance loss. In order to assess the gain of DPCM, Fig. 3 shows the histograms of the original filter coefficients as well as values obtained after DPCM, for the 300 frames of the Foreman sequence using OPF+DBF with a two-dimensional filter kernel of size 5×5 . It is clearly seen that DPCM is very effective in reducing the dynamic range. Since the dynamic range of the values that need to be entropy encoded is reduced, these values will be compressed more effectively. The effect of filter coefficient compression on R-D performance for the Foreman sequence is depicted in Fig. 4. It is seen in Fig. 4(a) that the performance of optimal filtering for the two-dimensional case shows an important

improvement compared with results presented in [20], if the coefficient compression approach proposed in this paper is utilized. This is actually an expected situation since less of the bit-rate is consumed for multiplexed optimal filter coefficients. If the coefficient compression performance for one-dimensional filtering is evaluated, it is again obvious that the proposed compression approach provides better results. It should be noted that similar improvements are obtained for ILOF, ILOF+DBF, and OPF; which are not displayed in this paper to save space.

Table II shows the average compression ratios of filter coefficients for the Foreman and Coastguard sequences in the case of a 5×5 filter kernel, for different bit-rates. As seen from this table, compression ratios are relatively low for ILOF and ILOF+DBF at low bit-rates. The performance of ILOF at low bit-rates changes frame by frame and therefore corresponding filter coefficients have a relatively higher dynamic range which is less compressible compared to OPF. It is also seen that the utilized compression approach adopted in this paper can compress filter coefficients by up to 40%.

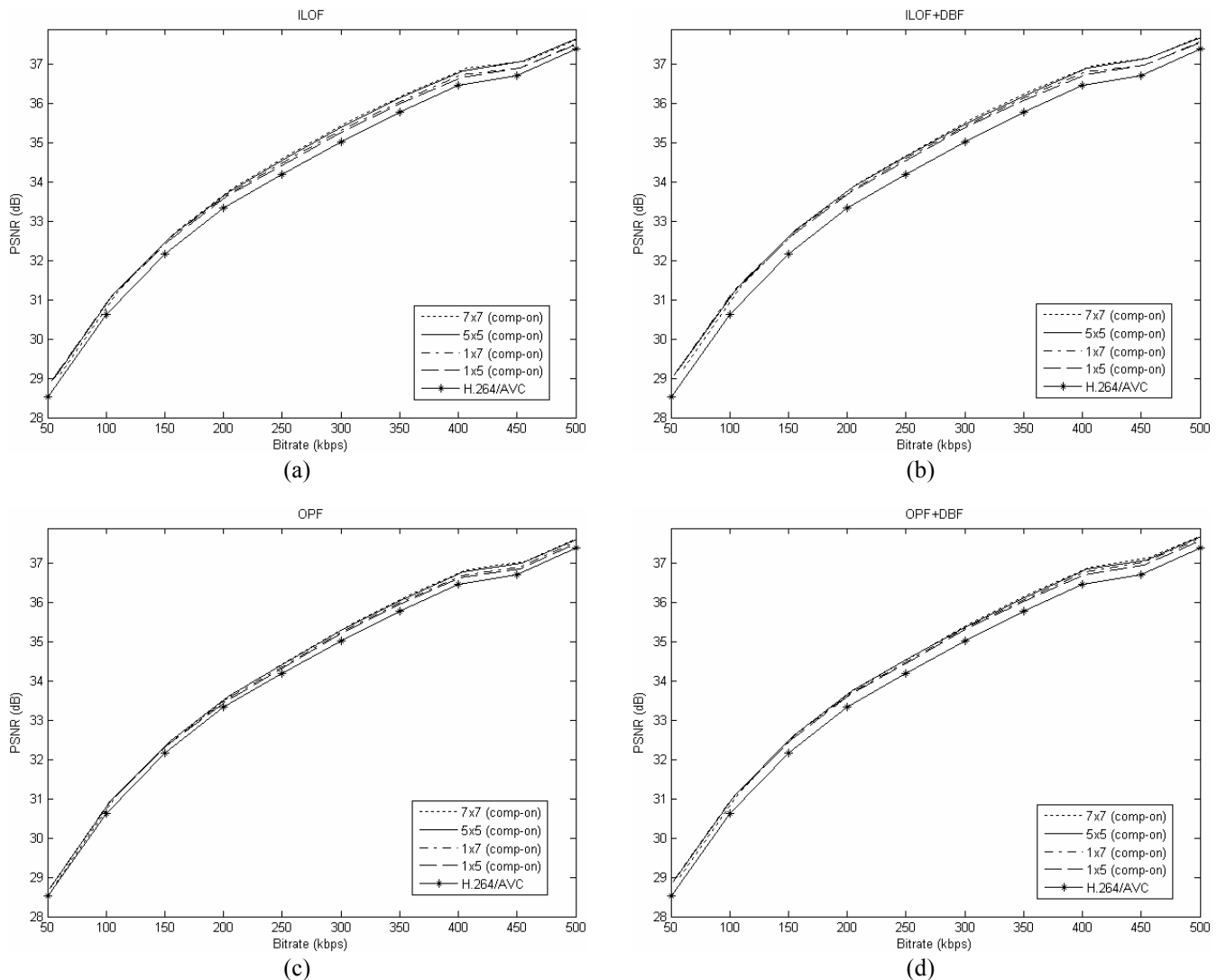


Fig. 6. Optimal filtering R-D performance for the Coastguard sequence (a) ILOF, (b) ILOF+DBF, (c) OPF, (d) OPF+DBF.

In the next stage of experiments, the proposed one-dimensional optimal filtering approach is compared to two-dimensional optimal filtering, with filter coefficient compression enabled. These results are given in Fig. 5 and Fig. 6 for the Foreman and Coastguard sequences, respectively. It is observed in these experiments that 1-D optimal filtering performs close to 2-D optimal filtering for low and medium bit-rates and always better than H.264/AVC with standard DBF only. For higher bit-rates, two-dimensional optimal filtering is observed to slightly outperform one-dimensional optimal filtering but it is seen that in this case an optimal filter of size 5×5 performs just as well as a filter of size 7×7 . These results are important to show that the one-dimensional optimal filtering performs similar to two-dimensional optimal filtering at low and medium bit-rates.

The methods presented in [17] and [18] are also tested for comparison. Table III shows PSNR differences compared to the H.264/AVC DBF ON case (H.264/AVC with standard DBF) for the Foreman sequence. It seen from these results that the method presented in [17] does not change the

performance of H.264/AVC. On the other hand, the method in [18] results in a slight degradation with respect to the original deblocking filter. Note that the proposed one-dimensional filtering approach provides up to 0.5dB improvement in quality.

The main motivation for one-dimensional optimal filtering is to reduce the high computational complexity of two-dimensional optimal filtering. Table-IV shows the average computational timings for one-dimensional and two-dimensional optimal filtering for a single frame using a computer with 2.8 GHz P4 processor with 2GB RAM. It is clearly seen that the one-dimensional filtering proposed in this paper significantly reduces the required time for optimal filter coefficient computation compared to the two-dimensional optimal filtering case presented in [20]. For example, 188.1 ms is required for the computation of an optimal filter for a filter of size 7×7 which is too high for real-time video communications. On the other hand, the computation speed of the 1×7 filter is fast enough to enable 30fps real-time implementation. It is furthermore possible to use a filter size of 1×5 filter, to further speed-up the computation.

TABLE III.
PSNR DIFFERENCES (DB) COMPARED TO H.264/AVC DBF ON FOR THE “FOREMAN” SEQUENCE.

Method	QP		22	24	26	28	30	32	34	36	38	40
	Filter Size											
ILOF	7x7		0.49	0.52	0.53	0.54	0.55	0.54	0.55	0.52	0.48	0.47
	5x5		0.36	0.38	0.39	0.41	0.41	0.41	0.41	0.36	0.32	0.25
	1x7		0.2	0.25	0.28	0.29	0.27	0.30	0.26	0.18	0.13	0.07
	1x5		0.06	0.11	0.14	0.16	0.16	0.15	0.12	0.04	-0.02	-0.04
ILOF + DBF	7x7		0.56	0.60	0.60	0.64	0.66	0.68	0.68	0.61	0.59	0.61
	5x5		0.42	0.46	0.49	0.53	0.55	0.53	0.55	0.50	0.45	0.46
	1x7		0.29	0.37	0.41	0.42	0.45	0.43	0.42	0.37	0.34	0.28
	1x5		0.14	0.22	0.27	0.31	0.31	0.29	0.27	0.22	0.18	0.15
OPF	7x7		0.59	0.63	0.64	0.67	0.70	0.71	0.70	0.66	0.62	0.57
	5x5		0.43	0.47	0.48	0.52	0.56	0.58	0.58	0.54	0.52	0.47
	1x7		0.33	0.41	0.43	0.46	0.51	0.52	0.51	0.46	0.44	0.39
	1x5		0.15	0.23	0.27	0.32	0.37	0.41	0.44	0.41	0.41	0.37
OPF + DBF	7x7		0.64	0.70	0.72	0.76	0.79	0.77	0.74	0.70	0.65	0.60
	5x5		0.49	0.55	0.58	0.63	0.66	0.65	0.62	0.59	0.56	0.51
	1x7		0.39	0.48	0.52	0.57	0.61	0.60	0.56	0.53	0.48	0.44
	1x5		0.22	0.32	0.37	0.43	0.48	0.50	0.48	0.47	0.45	0.43
[17]	N/A		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
[18]	N/A		-0.21	-0.13	-0.09	-0.06	-0.03	-0.02	0.00	0.01	-0.03	-0.04
H.264/AVC DBF off	N/A		-0.08	-0.13	-0.19	-0.23	-0.24	-0.24	-0.23	-0.27	-0.27	-0.31

TABLE IV.
AVERAGE ELAPSED COMPUTATION TIME PER FRAME FOR DIFFERENT FILTER SIZES

Method	Filter Size	Computation of Filter Coefficients (ms)	Filtering Operation (ms)
H.264/AVC	N/A	N/A	1.9
[17]	N/A	N/A	1.2
[18]	N/A	N/A	2.5
[20]	7x7	188.1	7.3
[20]	5x5	55.8	6.3
Proposed	1x7	17.2	1.3
Proposed	1x5	12.1	1.1

Note that in case of optimal filtering the encoder performs optimal filter coefficient computation (and filtering in case of ILOF) whereas the decoder performs only linear filtering with the filter coefficients multiplexed into the bit-stream by the encoder. Therefore, the computational load at the decoder is considerably lower. The computational performance of the methods presented in [17] and [18] are also assessed by running these algorithms for different QP values and taking average timings. As seen from the table the method in [17] reduces required time for deblocking whereas the method presented in [18] causes a slight increase in timing. The method in [18] is evaluated with respect to an older JM version in [18] where it is shown to reduce the complexity but it did not reduce the complexity compared to the DBF used in JM version 11.

V. CONCLUSIONS

In this paper a one-dimensional optimal filtering approach is presented to speed-up the recently proposed two-dimensional optimal filtering based video compression enhancement scheme. The optimal filtering can be used with

or without the standard deblocking filter (DBF). It is shown that the performance improves if optimal filtering is used in conjunction with the standard DBF. In this paper, furthermore, the compression of filter coefficients is investigated. Experimental results demonstrate that the proposed one-dimensional optimal filtering approach provides a slightly decreased reconstructed video quality compared to two-dimensional optimal filtering, that is an acceptable tradeoff compared to the significant speed improvement which is very important particularly for real time encoder implementations that find many applications in consumer electronics products.

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