Improved Method for the Macroblock-Level Deblocking Scheme

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This paper presents a deblocking method for video compression in which the blocking artifacts are effectively extracted and eliminated based on both spatial and frequency domain operations. Firstly, we use a probabilistic approach to analyze the performance of the conventional macroblock-level deblocking scheme. Then, based on the results of the analysis, an algorithm to reduce the computational complexity is introduced. Experimental results show that the proposed algorithm outperforms the conventional video coding methods in terms of computation complexity while coding efficiency is maintained.

Keywords: H.264/AVC, blocking artifact, deblocking filter, computational complexity.

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I. Introduction

The discontinuity between adjacent blocks, known as blocking artifacts, is the main drawback in block-based video coding. These artifacts deteriorate both visual quality and coding efficiency. The main reason for the problem results from the independent processing of video blocks with coarse quantization and motion compensated prediction. In recent years, a variety of efforts have been made to alleviate the blocking artifacts. The blocking artifacts can be suppressed in the spatial domain [1]-[7] or in discrete cosine transform (DCT) domain [8]-[12]. In the recent video coding standards H.264/AVC [13], the spatial deblocking filters are applied to the reconstructed images obtained after the frame encoding. In other words, the blocking artifacts remain at the signal to be encoded and deteriorate the coding efficiency. This problem can be solved if the deblocking filter is used in DCT domain since the blockiness can be alleviated before the image is encoded. However, the block shifting technique used in these methods only operates between blocks with the same size of DCT matrix. Therefore, it is difficult to apply these methods to H.264/AVC in which different sizes of DCT matrices are used.

We proposed a deblocking method operating in both spatial and transform domains in [14]. In order to estimate the amount of blocking artifacts to be removed, the process of extraction and reduction of the blocking artifacts are repeated by a brute-force search and the optimal amount of the blocking artifacts is found with respect to the rate-distortion cost. In this manner, the blocking artifacts are removed out of the bitstream and the bitrate reduction is obtained without the reconstruction quality loss. However, the computational overhead of the repeated deblocking process makes it difficult to apply the algorithm to the real-time video encoding.

In this paper, we analytically investigate our previous work and design a probabilistic model to estimate the performance of the deblocking procedure. In the model, the performance is determined by the quantization parameter (QP) and a statistical property of the blocking artifacts. Then, the computation complexity is reduced by limiting the number of deblocking processes according to the modeling results.

The rest of this paper is organized as follows: The details of our previous work are explained in section II. Section III presents the analysis of the method and its application to the computational complexity reduction. The simulation results are provided in section IV. Finally, section V summarizes and concludes the paper.

II. MB Deblocking Method

1. Adaptive Deblocking Filter

The spatial filter operation used in our work is the adaptive deblocking filter [5] in which the blocking artifacts on coded block boundaries are detected and suppressed by an *n*-tap filter. This adaptive deblocking filter mainly operates in two parts: boundary analysis and 4×4 block filtering.

In the boundary analysis, in order to determine the strength of the filtering, an integer-valued boundary strength (BS) parameter is assigned to each edge. The maximum value of BS, 4, indicates the strongest filtering operation, whereas the minimum value of BS, 0, indicates no filtering operation on the edge. In addition, since genuine horizontal or vertical edges of the image can appear at the edges of blocks, a pair of quantization-dependent parameters is used to distinguish the blocking artifacts from the true edges of the image. If the average QP of the two blocks is small, the parameters decrease to preserve the image sharpness. Otherwise, the parameters increase to suppress the blocking artifacts. In the decoder, these parameters are calculated in the same manner in order to decode exactly.

The filtering is applied to left vertical and top horizontal boundaries of 4×4 blocks for both luminance and chrominance components in the macroblock (MB). Filtering operation affects up to three pixels on either side of the boundary. Based on the value of BS, the parameter pair, and the differences among the pixels, a set of *n*-tap filters is implemented and applied to the pixels. More details can be found in [5].

2. MB-Level Deblocking Scheme

In recent video coding standards, such as H.264/AVC, the deblocking filter is applied to the reconstructed images and the filtered images are used as references. Thus, the coded bitstream contains the information to be eliminated by deblocking filtering. The main purpose of this method is to improve the coding efficiency by removing the information.

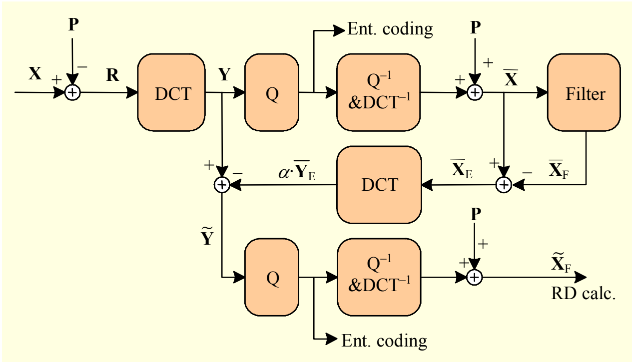

Fig. 1. Block diagram for encoding the block.

Figure 1 shows the block diagram of the MB-level deblocking scheme (MBDS) [14]. After the conventional encoding loop, the reconstructed block $\bar{\mathbf{X}}$ containing the blocking artifact is obtained. Here, the filter coefficients are determined based on the BS and pixel values across the block edges as explained in the previous subsection. It is possible to extract the blocking artifact $\bar{\mathbf{X}}_E$ by subtracting the filtered block $\bar{\mathbf{X}}_F$ from $\bar{\mathbf{X}}$. In order to remove $\bar{\mathbf{X}}_E$ from the original DCT coefficients, the DCT is applied to $\bar{\mathbf{X}}_E$ to obtain $\bar{\mathbf{Y}}_E$. Then, we subtract $\bar{\mathbf{Y}}_E$ from the original coefficient block $\mathbf{Y}$ with a weight parameter α to give the refined coefficient block $\tilde{\mathbf{Y}}$:

$$\tilde{\mathbf{Y}} = \mathbf{Y} - \alpha \cdot \bar{\mathbf{Y}}_E, \tag{1}$$

where the real-valued weight α is in the range [0,1]. Finally, $\tilde{\mathbf{Y}}$ is quantized, scaled, and added to the prediction block. $\tilde{\mathbf{X}}_F$ is used as a reference for motion compensation in the next frames.

It can be seen that the coding bitrate would be increased or decreased because there are some residual coefficients subtracted from the second DCT/IDCT process. Therefore, this subtraction should be applied only when the bitrate reduction is guaranteed. In other words, the value of the weight α should be carefully selected so that the coding efficiency does not deteriorate. To this end, the optimal weight parameter is chosen to minimize the Lagrangian RD function:

$$J = \tilde{D} + \lambda \cdot \tilde{R}, \tag{2}$$

where $\tilde{D}$ is the sum of the absolute difference between $\mathbf{X}$ and $\tilde{\mathbf{X}}_F$. $\tilde{R}$ is the bitrate required for coding the quantized coefficients of $\tilde{\mathbf{Y}}$, and λ defined in the standard [13] is the Lagrange multiplier associated with the rate. The best value of α is searched in a predefined set [14] which is constructed depending on the picture types and color planes. However, the

Table 1. Terminology definition.

$\mathbf{Y}$	Coefficient block
$\overline{\mathbf{Y}}_{\mathrm{E}}$	Blocking artifact coefficient block
Y	Random variable (RV) representing DCT coefficients of $\mathbf{Y}$
$\overline{Y}_{\mathrm{E}}$	RV representing DCT coefficients of $\overline{\mathbf{Y}}_{\mathrm{E}}$
b_A	Scale parameter of Laplace distribution of $\overline{Y}_{\mathrm{E}}$
y	Input coefficient
z	Quantized value of y
P_V	Subtraction effectiveness probability
$\overline{P}_V$	Average of subtraction effectiveness probability
$\overline{\mathrm{Y}}_{\mathrm{E}i,j}$	Coefficient value at position (i,j) of $\overline{\mathbf{Y}}_{\mathrm{E}}$
$\overline{P}_{\mathrm{B}}$	Average of subtraction effectiveness probability for a block

brute-force search to find the best value of α requires huge computational resources.

III. Analysis of the MB-Level Deblocking Method

In MBDS, the quantization operator compresses a range of input values of $\mathbf{Y}$ and $\tilde{\mathbf{Y}}$ to a single quantum value. However, when the blocking artifacts are too small or the quantization parameters are too large, the quantized values of $\mathbf{Y}$ and $\tilde{\mathbf{Y}}$ are the same. As a result, the subtraction in (1) is not valid after the quantization process. In this section, we mathematically analyze the relationship among the blocking artifacts, quantization parameters, and weight parameters in concerning with the validity of the subtraction. The results of the analysis are used to reduce the computational complexity of MBDS by reducing the searching range of α. For easier reading, refer to Table 1 which summarizes the notations used in this section.

1. Formulation of Subtraction Validity

Let Y be the random variable (RV) representing DCT coefficients of the block $\mathbf{Y}$, and $\overline{Y}_{\mathrm{E}}$ be the RV representing DCT coefficients of the blocking artifact $\overline{\mathbf{Y}}_{\mathrm{E}}$. $\overline{Y}_{\mathrm{E}}$ can be modeled by a zero mean Laplace distribution [15] with the probability density function (PDF)

$$f_{\overline{Y}_{\mathrm{E}}}(y)=\frac{1}{2b_A}e^{-|y|/b_A}, \tag{3}$$

where b_A>0 is a scale parameter. Its cumulative distribution function (CDF) is

$$F_{\overline{Y}_{\mathrm{E}}}(y)=\begin{cases}0.5\cdot e^{y/b_A} & \text{if } y<0,\\ 1-0.5\cdot e^{-y/b_A} & \text{if } y\ge 0.\end{cases} \tag{4}$$

Notice that the original coefficients are subtracted by the α-scaled version of $\overline{Y}_{\mathrm{E}}$ in (1). However, this subtraction is valid only when the quantized value of original coefficient differs from that of the subtracted value. In other words, the subtraction is effective when

$$QP(Y\,|\,qp)\neq QP(Y-\alpha\cdot\overline{Y}_{\mathrm{E}}\,|\,qp) \tag{5}$$

holds, where $QP(y\,|\,qp)=round(y/qp)$ is the basic forward quantizer operation [16] returning the quantized value of y, and qp is the quantization parameter scale.

Let $y\in[z-qp/2, z+qp/2]$, in which z is the quantized value of y. Then the probability of valid subtraction (PVS) is defined as

$$\begin{aligned}P_V(y)&=\Pr\left[QP(y\,|\,qp)\neq QP(y-\alpha\cdot\overline{Y}_{\mathrm{E}}\,|\,qp)\right]\\&=1-\Pr\left[z-qp/2\le y-\alpha\cdot\overline{Y}_{\mathrm{E}}<z+qp/2\right].\end{aligned} \tag{6}$$

Let

$$P_1(y)=\Pr\left[z-qp/2\le y-\alpha\cdot\overline{Y}_E\right], \tag{7}$$

and

$$P_2(y)=\Pr\left[y-\alpha\cdot\overline{Y}_E<z+qp/2\right]. \tag{8}$$

Then, the PVS can be rewritten as

$$P_V(y)=2-P_1(y)-P_2(y). \tag{9}$$

The average of the PVS in the range $[z-qp/2,\ z+qp/2]$ can be obtained by

$$\overline{P}_V=\frac{\int_{z-qp/2}^{z+qp/2} f_Y(y)\cdot\left(2-P_1(y)-P_2(y)\right)dy}{\int_{z-qp/2}^{z+qp/2} f_Y(y)dy}. \tag{10}$$

The distribution of Y can be modeled as a zero-mean Laplacian distribution [15] with the PDF is $f_Y(y)=\frac{1}{2b}e^{-|y|/b}$, where b>0 is a scale parameter. Since both this PDF and the quantization operation are symmetric to zero, we can assume that z>0 without the loss of generality. We also have $\Pr\left[\overline{Y}_{\mathrm{E}}\ge 0\right]=\Pr\left[\overline{Y}_{\mathrm{E}}<0\right]=1/2$ since $\overline{Y}_{\mathrm{E}}$ has a zero-mean Laplacian distribution. Then, we obtain

$$P_1(y)=1-\frac{1}{2}e^{-\frac{y-z+qp/2}{\alpha\cdot b_A}}, \tag{11}$$

$$P_2(y)=1-\frac{1}{2}e^{\frac{y-z-qp/2}{\alpha\cdot b_A}}. \tag{12}$$

Substituting $P_1(y)$ and $P_2(y)$ into (9) results in

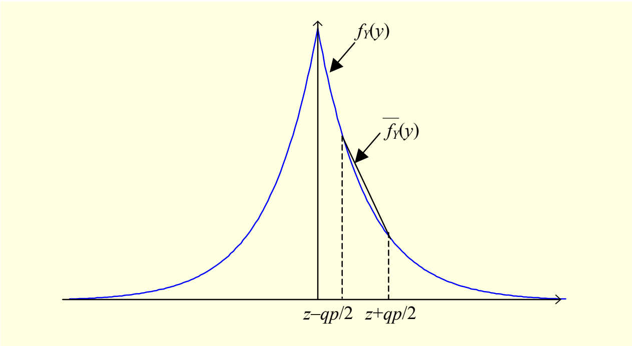

Fig. 2. Approximation for Laplacian distribution.

$$P_V(y)=\frac{1}{2}e^{-\frac{qp/2}{\alpha\cdot b_A}}\cdot\left(e^{-\frac{y-z}{\alpha\cdot b_A}}+e^{\frac{y-z}{\alpha\cdot b_A}}\right). \tag{13}$$

For simplicity, we assume that $f_Y(y)$ can be approximated as a line $\bar{f}_Y(y)$ in range $[z-qp/2,\ z+qp/2]$ as shown in Fig. 2. Then, from (3) and (13), $\bar{P}_V$ can be given by

$$\bar{P}_V=\frac{\int_{z-qp/2}^{z+qp/2}\bar{f}_Y(y)\cdot\left(2-P_1(y)-P_2(y)\right)dy}{\int_{z-qp/2}^{z+qp/2}\bar{f}_Y(y)dy}$$
$$=\frac{\alpha\cdot b_A}{qp}\cdot\left(1-e^{-\frac{qp}{\alpha\cdot b_A}}\right). \tag{14}$$

For a block of size n, the coefficient subtraction for the whole block is valid if at least one coefficient subtraction among the total n^2 coefficients is valid. Assuming that coefficients in the block are independent and identically-distributed RVs, we obtain the PVS for the $n\times n$ block as follows:

$$\bar{P}_B=1-\left(1-\bar{P}_{\mathrm{SEP}}\right)^{n^2}. \tag{15}$$

2. Application of Probability of Valid Subtraction

Since the computational complexity overhead of the MBDS mainly comes from the α searching procedure, skipping the searching at the blocks whose PVS value is lower than a certain value can reduce the processing time without deteriorating the coding efficiency. To this end, the scale parameter b_A and the PVS for each encoding block must be calculated. Firstly, using the maximum-likelihood method in [17], the scale parameter b_A is estimated as

$$b_A=\frac{1}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n}\left|\bar{\mathrm{Y}}_{\mathrm{E}i,j}\right|, \tag{16}$$

where $\bar{\mathrm{Y}}_{\mathrm{E}i,j}$ is the coefficient value at position (i, j) of the blocking artifact block. Then, the PVS of the block $\bar{P}_B$ can be directly calculated based on the the scale parameter b_A by using (15). However, the direct calculation of $\bar{P}_B$ requires huge computation since many exponential operations need to be performed. This problem can be solved by analyzing (14) and (15) in detail.

We can easily see that $\bar{P}_B$ in (15) is increasing in $\bar{P}_V$ because its first derivative

$$\frac{\partial\bar{P}_B}{\partial\bar{P}_V}=n^2\cdot\bar{P}_V\cdot\left(1-\bar{P}_V\right)^{n^2-1}\geq 0, \tag{17}$$

when $\bar{P}_V\in[0,1]$. In addition, $\bar{P}_V$ in (14) increases in $t=\alpha\cdot b_A/qp$.

Proof. Because the second derivative of $\bar{P}_V$

$$\frac{\partial^2\bar{P}_V}{\partial t^2}=-\frac{e^{-1/t}}{t^3}<0, \tag{18}$$

when $t>0$, the first derivative of $\bar{P}_V$

$$\frac{\partial\bar{P}_V}{\partial t}=1-e^{-1/t}-\frac{e^{-1/t}}{t} \tag{19}$$

decreases in $t>0$. In addition, we have

$$\lim_{t\to+\infty}\frac{\partial\bar{P}_V}{\partial t}=\lim_{t\to+\infty}\left(1-e^{-1/t}-\frac{e^{-1/t}}{t}\right)=0, \tag{20}$$

and

$$\lim_{t\to+0}\frac{\partial\bar{P}_V}{\partial t}=\lim_{t\to+0}\left(1-e^{-1/t}-\frac{e^{-1/t}}{t}\right)=1. \tag{21}$$

From (19), (20), and (21), we conclude that the first derivative of $\bar{P}_V$ is above zero when $t\geq 0$. As a result, $\bar{P}_V$ is increasing in $t\geq 0$. □

Because $\bar{P}_B$ increases in $\bar{P}_V$ which increases in t, $\bar{P}_B$ increases in t. Therefore, the lower bound of $\bar{P}_B$ discarding α searching procedure can be replaced by a lower bound of t. In other words, the α searching procedure for the block can be skipped if the following inequality satisfies:

$$t<\theta_n\Rightarrow\alpha\cdot b_A<\theta_n\cdot qp, \tag{22}$$

where θ_n is the threshold and n is the block size. According to the target application, θ_n can be selected to trade-off the computational complexity overhead and the coding efficiency. The larger the value of θ_n is, the larger the number of the skipped α searching procedures are. In this paper, we empirically use the same value θ_n=0.2 for all blocks.

IV. Experimental Results

The simulation conditions are given in Table 2. Several sequences with various resolution, frame rate, and number of encoded frames were tested. In our simulations, group of picture (GOP) structure of IPPP is used, CABAC is used for entropy coding, and all intra/inter encoding modes are enabled to evaluate the performance of the proposed methods.

Table 2. Simulation conditions.

Reference software	KTA 2.0 [18]
Spatial resolution	QCIF, CIF, 720p
Number of frames	100 (QCIF, CIF), 150 (720p)
Frame rate	30 (QCIF, CIF), 60 (720p)
Number of references	4
MV search range	64
GOP structure	IPPPP…
Entropy coding method	CABAC
QP	12/17/22/27 for I slices
	13/18/23/28 for P slices

In order to evaluate the coding efficiency performance, the Bjøntegaard delta bitrate (ΔBR) and Bjøntegaard delta PSNR (ΔPSNR) [19] between our proposed method and the conventional H.264/AVC are used. The computational complexity overheads (ΔT) of MBDS and proposed method are provided in forms of the proportion of the increased encoding time of those methods to conventional H.264/AVC.

The experimental results for various sequences are presented in Table 3. Two candidate sets, set 1 and set 2, which are predefined depending on the picture types and color planes to search for the optimum value of α, are used [14]. It can be seen that the proposed method reduces the processing time with both set 1 and set 2 of α, while the coding efficiency is slightly reduced. For set 1, computational complexity overhead is reduced about 75% with 0.88% loss of ΔBR in average. For set 2, the average encoding time decreases about 20%, and the average ΔBR is achieved by –3.38% as compared with the conventional H.264/AVC.

Table 3. Experimental results.

Sequence	Set 1						Set 2					
	MBDS			Proposed method			MBDS			Proposed method		
	ΔBR (%)	ΔPSNR (dB)	ΔT	ΔBR (%)	ΔPSNR (dB)	ΔT	ΔBR (%)	ΔPSNR (dB)	ΔT	ΔBR (%)	ΔPSNR (dB)	ΔT
QCIF												
Claire	–4.730	0.221	5.98	–4.518	0.212	1.35	–4.685	0.218	2.11	–4.439	0.206	0.22
Deadline	–4.622	0.272	4.86	–4.170	0.244	1.65	–4.131	0.241	1.51	–4.075	0.238	0.22
M&daughter	–5.407	0.259	5.16	–4.789	0.229	1.81	–5.259	0.255	1.59	–4.950	0.236	0.24
News	–5.699	0.347	5.35	–5.290	0.317	1.74	–5.493	0.331	1.65	–5.175	0.311	0.24
Students	–5.102	0.285	5.77	–4.961	0.276	1.91	–4.918	0.275	2.06	–4.777	0.266	0.27
CIF												
Highway	–3.331	0.068	5.14	–3.026	0.055	1.62	–3.058	0.059	1.85	–2.759	0.054	0.18
M&daughter	–3.846	0.133	4.98	–3.423	0.119	1.47	–3.365	0.117	1.80	–3.206	0.113	0.14
News	–5.381	0.240	5.12	–4.763	0.213	1.25	–4.986	0.223	1.90	–4.479	0.200	0.15
Paris	–4.500	0.271	6.13	–4.183	0.251	1.49	–4.352	0.261	2.17	–4.108	0.246	0.17
Silent	–4.945	0.247	5.43	–4.513	0.225	1.34	–4.306	0.214	1.94	–4.299	0.214	0.15
720p												
Crew	–2.198	0.077	5.81	–1.548	0.053	1.25	–1.621	0.056	1.91	–0.981	0.032	0.20
Cyclists	–2.310	0.074	4.92	–1.736	0.056	1.44	–1.613	0.052	1.71	–1.295	0.042	0.22
Jets	–5.164	0.083	5.33	–4.493	0.061	0.91	–4.482	0.065	1.37	–3.551	0.047	0.12
Raven	–2.119	0.070	5.19	–1.454	0.048	1.86	–1.392	0.047	1.87	–1.051	0.035	0.28
Shuttle start	–2.802	0.062	4.75	–2.025	0.046	0.96	–2.166	0.049	1.72	–1.521	0.035	0.16
Average												
Average	–4.144	0.181	5.33	–3.659	0.160	1.47	–3.722	0.164	1.81	–3.378	0.152	0.20

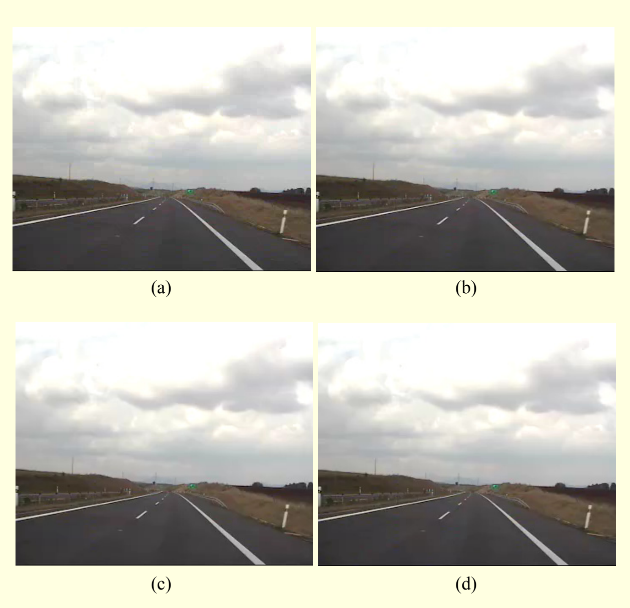

Fig. 3. Deblocked images for first frame of highway CIF sequence: (a) original H.264 without ADF (bitrate: 998.16 kbps, PSNR: 39.82 dB), (b) original H.264 with ADF (bitrate: 998.16 kbps, PSNR: 40.01 dB), (c) MBDS (bitrate: 919.92 kbps, PSNR: 39.96 dB), and (d) proposed (bitrate: 936.24 kbps, PSNR: 39.98 dB).

Figure 3 shows examples of decoded images of the first frame in the *highway* CIF sequence. There are visible blocking artifacts in Fig. 3(a) when the deblocking filter ADF [5] is not applied. By applying the ADF, these blocking artifacts are removed as shown in Figs. 3(b), 3(c), and 3(d). However, the bitrate of Fig. 3(b) is the same as that of Fig. 3(a) because the blocking artifact information is not removed out of bit stream. The bitrates of the MBDS and the proposed method, shown in Figs. 3(c) and 3(d), respectively, are much reduced.

V. Conclusion

In this paper, a detailed analysis for the conventional MBDS was performed. The analysis results showed that both blocking artifact magnitude and quantization parameter scale play vital role in the effectiveness of the MBDS. Based on the relationship between blocking artifact and quantization parameter, the fast algorithm of MBDS was designed to reduce the computational complexity of the conventional method. Experimental results exhibited a significant reduction of computational complexity without deteriorating coding efficiency.

References

[1] C.J. Kuo and R.J. Hsieh, "Adaptive Postprocessor for Block Encoded Images," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 5, no. 4, Aug. 1995, pp. 298-304.

[2] Y.L. Lee, H.C. Kim, and H.W. Park, "Blocking Effect Reduction of JPEG Images by Signal Adaptive Filtering," *IEEE Trans. Image Process.*, vol. 7, no. 2, Feb. 1998, pp. 229-234.

[3] J.G. Apostolopoulos and N.S. Jayant, "Postprocessing for Very Low Bit-Rate Video Compression," *IEEE Trans. Image Process.*, vol. 8, no. 8, Aug. 1999, pp. 1125-1129.

[4] A.S. Al-Fohoum and A.M. Reza, "Combined Edge Crispiness and Statistical Differencing for Deblocking JPEG Compressed Images," *IEEE Trans. Image Process.*, vol. 10, no. 9, Sept. 2001, pp. 1288-1298.

[5] P. List et al., "Adaptive Deblocking Filter," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 13, no. 7, July 2003, pp. 614-619.

[6] Y. Chiu and L. Xu, "Adaptive (Wiener) Filter for Video Compression," ITU-T SG16 Q.6 Document, VCEG-AI14, Berlin, July 2008.

[7] Y. Huang et al., "Adaptive Quadtree-based Multi-reference Loop Filter," ITU-T SG16 Q.6, VCEG-AK24, Japan, Apr. 2009.

[8] B. Zeng, "Reduction of Blocking Effect in DCT-Coded Images Using Zero-Masking Techniques," *Signal Process.*, vol. 79, no. 2, Dec. 1999, pp. 205-211.

[9] T. Chen, H.R. Wu, and B. Qiu, "Adaptive Postfiltering of Transform Coefficients for the Reduction of Blocking Artifacts," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 11, no. 5, May 2001, pp. 594-602.

[10] L. Shizhong and A.C. Bovik, "Efficient DCT-Domain Blind Measurement and Reduction of Blocking Artifacts," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 12, no. 12, Dec. 2002, pp. 1139-1149.

[11] L. Ying and R.K. Ward, "Removing the Blocking Artifacts of Block-based DCT Compressed Images," *IEEE Trans. Image Process.*, vol. 12, no. 7, July 2003, pp. 838-842.

[12] G. Zhai et al., "Efficient Deblocking With Coefficient Regularization, Shape-Adaptive Filtering, and Quantization Constraint," *IEEE Trans. Multimedia*, vol. 10, no. 5, Aug. 2008, pp. 735-745.

[13] Joint Video Team (JVT) of ISO/IEC MPEG\ITU-T VCEG, "Draft ITU-T Recommendation and Final Draft International Standard of Joint Video Specification (ITU-T rec. H.264-ISO/IEF 14496-10 AVC)," JVT-G050, Mar. 2003.

[14] T.H. Le et al., "Macroblock-Level Deblocking Method to Improve Coding Efficiency for H.264/AVC," *ETRI J.*, vol. 32, no. 2, Apr. 2010, pp. 336-338.

[15] S.R. Smoot and L.A. Rowe, "Study of DCT Coefficient Distribution," *Proc. SPIE Symp. Electronic Imaging*, vol. 2657, San Jose, CA, Jan. 1996.

[16] A. Hallapuro et al., "Low Complexity Transform and Quantization – Part I: Basic Implementation," JVT document JVT-B038, Geneva, Feb. 2002.

[17] N. Balakfishnan and C.D. Cutler, "Maximum Likelihood Estimation of the Laplace Parameters Based on Type-II Censored Samples," Statistical Theory and Applications: Papers in Honor of Herbert A. David, Eds. H.N. Nagaraja, P.K. Sen, and D.F. Morrison, 1995, pp. 145-151.

[18] Joint Video Team (JVT), KTA Reference Software. Available: http://iphome.hhi.de/suehring/tml/kta/.

[19] G. Bjøntegaard, "Calculation of Average PSNR Differences between RD-Curves," ITU-T SG16 Q.6 Document, VCEG-M33, Austin, Apr. 2001.

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