REDUCTION OF BLOCKING ARTIFACTS FOR LOW BIT-RATE VIDEO CODING USING REGULARIZED DEQUANTIZATION

S. Moon-Ho Song, Gunho Lee, Sanghoon Sull and Sung-Jea Ko

School of Electrical Engineering, Korea University
Seoul, Korea

ABSTRACT

Most discrete cosine transform (DCT) based video coding suffer from blocking artifacts where boundaries of 8×8 DCT blocks become visible on decoded images. The blocking artifacts become more prominent as the bit rate is lowered. In this paper, we present a new dequantization technique for discrete cosine transform (DCT) based encoding to sharply reduce the blocking artifacts. Our proposed dequantization scheme, through regularization, sharply reduces blocking artifacts in decoded images. The performance the proposed algorithm is compared to that of the currently specified H.263+ Annex J deblocking filter. The comparison will show visual improvements as well as numerical improvements in terms of the peak-signal-to-noise ratio (PSNR) and the blockiness measure (BM) to be defined.

1. INTRODUCTION

Several investigators have recently reported algorithms dealing with the quantization matrix and the associated dequantization scheme. In [1], Prost, *et al.* proposes a technique that modifies the quantization matrix to be used by the decoder. This new quantization matrix, used during decoding, is computed (by the encoder) using an approach similar to Miller's least squares solution [2] for image restoration applications [3]. The solution proposed in [1], and later corrected by Philips [4], offers a dequantization scheme different from the standard method.

Konstantinides, *et al.* [5] propose yet another technique for computing a modified quantization matrix for image sharpening applications directly in DCT domain. However, neither approaches [1,5] guarantee that the dequantization process will map the quantized DCT coefficients to its value ± (quantizer spacing/2) in DCT domain.

In contrast, we propose a regularization based dequantizer which will guarantee the mapping of quantized DCT coefficients to within ± (quantizer spacing/2). This is guaranteed through a built-in non-linearity in our proposed iterative algorithm.

2. FORMULATION

2.1 A Model of DCT-based Transform Coding

Before dealing with details of the regularized dequantization, the conventional DCT-based transform coding currently specified in standards such JPEG, H.261, H.263, and MPEG is reviewed to establish the notation.

In conventional DCT-based transform coding, the image is first divided into 8×8 blocks and the individual blocks are transformed by the discrete cosine transform (DCT). We denote the output of this operation by $\mathbf{Df}$, where $\mathbf{f}$ is the lexicographically ordered image and the operator $\mathbf{D}$ is the appropriately defined 2-D DCT matrix. The DCT coefficients are then quantized with or without a dead-zone. Since the quantization process includes a division (or a multiplication by its inverse) step by elements of the quantization matrix, the quantization operator Q can be mathematically expressed as follows:

$$\begin{aligned} Q\{\mathbf{Df}\} &= \mathrm{round}\{\mathbf{M}^{-1}\mathbf{Df} - \mathrm{sgn}(\mathbf{Df})\delta/2\} \\ &= \mathbf{M}^{-1}\mathbf{Df} - \mathrm{sgn}\{\mathbf{Df}\}\delta/2 + 1/2 \\ &\quad - \mathrm{rem}\{\mathbf{M}^{-1}\mathbf{Df} - \mathrm{sgn}(\mathbf{Df})\delta/2 + 1/2\} \end{aligned} \tag{1}$$

where round{} and rem{} operators indicate the usual rounding and remainder operations, respectively; and sgn{} is the signum function that maps positive, zero and negative valued reals to 1, 0 and −1, respectively. Furthermore, $\mathbf{M}$ is a diagonal matrix whose elements consist of appropriately ordered elements of the quantization matrix. Note that $\delta = 1$ for quantization with a dead-zone. If we let $\delta = 0$, Eq. (1) then represents quantization without a dead-zone. Lastly, we have also used the identity:

$$\mathrm{round}\{x\} = x + 1/2 - \mathrm{rem}\{x + 1/2\}. \tag{2}$$

The quantized DCT coefficients are then encoded losslessly.

Upon receipt of losslessly encoded quantized DCT coefficients, the decoder first reverses the lossless encoding process to obtain quantized DCT coefficients. The lossless encoding and decoding steps together form a mathematical identity and thus, we neglect this part in the current development. In any case, the decoder has access to quantized DCT coefficients $Q\{\mathbf{Df}\}$ as computed by the encoder. The dequantization operation P can simply be modeled by a multiplication by $\mathbf{M}$, quantization scales followed by a correction for dead-zones. That is,

$$\begin{aligned} P\{Q\{\mathbf{Df}\}\} &= \mathbf{M}(Q\{\mathbf{Df}\} + \mathrm{sgn}\{\mathbf{Df}\}\delta/2) \\ &= \mathbf{Df} + \mathbf{M}(1/2 - \mathrm{rem}\{\mathbf{M}^{-1}\mathbf{Df} - \mathrm{sgn}\{\mathbf{Df}\}\delta/2 + 1/2\}) \end{aligned} \tag{3}$$

Again, in the above, $\delta = 1$ indicates quantization with a dead-zone and $\delta = 0$ without a dead-zone.

The conventional decoder then takes the dequantized DCT coefficients and performs the 2-D inverse discrete cosine transform (IDCT) as follows:

$$\begin{aligned}\mathbf{g} &= \mathbf{D}^{-1} PQ\{\mathbf{Df}\} \\ &= \mathbf{f} + \mathbf{D}^{-1}\mathbf{M}(1/2 - \mathrm{rem}\{\mathbf{M}^{-1}\mathbf{Df} - \mathrm{sgn}(\mathbf{Df})\delta/2 + 1/2\})\end{aligned} \tag{4}$$

Note that what is desired is the original image $\mathbf{f}$; however, the image as determined by the conventional decoder is $\mathbf{g}$. This conventionally decoded image includes the quantization error which precisely is the second term of Eq. (4):

$$\text{error} = \mathbf{D}^{-1}\mathbf{M}(1/2 - \mathrm{rem}\{\mathbf{M}^{-1}\mathbf{Df} - \mathrm{sgn}(\mathbf{Df})\delta/2 + 1/2\}) \tag{5}$$

The error term above is due to the quantization Q followed by the conventional dequantization described by Eq. (3). The natural question to ask is whether there exists a better dequantizer. Without any further information regarding the image, and because the error term above depends on the original image $\mathbf{f}$, using the conventional dequantizer (3) appears to be the only choice. However, through regularization, with the assumption that the image $\mathbf{f}$ is smooth, we have developed a different dequantization procedure.

In view of the inequality

$$-1/2 < 1/2 - \mathrm{rem}(x + 1/2) \le 1/2. \tag{6}$$

The error in the DCT coefficients (just before the IDCT step) also obey

$$\begin{aligned}&\left|\mathbf{e}_n^T\mathbf{M}\{1/2 - \mathrm{rem}(\mathbf{M}^{-1}\mathbf{Df} - \mathrm{sgn}(\mathbf{Df})\delta/2 + 1/2)\}\right| \\ &\qquad \le \frac{\mathbf{e}_n^T\mathbf{M}\mathbf{e}_n}{2}, \quad \text{for all } n\end{aligned} \tag{7}$$

where T indicates transpose and $\mathbf{e}_n$ is the Euclidean basis vector with a "1" in the nth row and zeros in other rows. Although Eq. (7) appears to be cumbersome, what it states is simply that, the error introduced (in DCT domain) by the quantizer is limited between $\pm$ (quantizer spacing/2) for nth DCT coefficient. This observation allows a slightly different relationship between $\mathbf{g}$ and $\mathbf{f}$. For this purpose, define:

$$c_{ij} = \text{2D - IDCT of} \left\{ \begin{bmatrix} 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \\ \vdots & & \vdots & \vdots & \vdots & & \vdots \\ \vdots & & 0 & 0 & 0 & & \vdots \\ 0 & \cdots & 0 & q_{ij} & 0 & \cdots & 0 \\ \vdots & & 0 & 0 & 0 & & \vdots \\ \vdots & & \vdots & \vdots & \vdots & & \vdots \\ 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \end{bmatrix} \right\} \tag{8}$$

where q_{ij} is the ijth element of the quantization matrix. Furthermore, let $\mathbf{c}_{ij}$ be lexicographically ordered version of c_{ij}. Then,

$$\mathbf{g}(k) = \mathbf{f}(k) + \sum_{0 \le i,j \le 7} \alpha_{ij}(k)\mathbf{c}_{ij} \tag{9}$$

where the argument (k) indicates the extraction of the corresponding kth 8×8 block. Thus, all vectors in Eq. (9) are of the size 64×1. Furthermore, due to the inequality as shown by Eq. (7), the coefficients $\alpha_{ij}(k)$ are restricted to lie within the interval $(-1/2, 1/2]$. Note that Eq. (9) is satisfied for all 8×8 blocks of the image. This is true whether or not the dead-zone is used by the quantizer.

2.2 Regularization

In view of the previous analysis, the question that we pose is: find $\alpha_{ij}(k)$ to minimize $\| \mathbf{f} - \mathbf{g} \|_2$, the L_2-norm, using Eq. (9). The problem as stated is an *ill-posed problem* [6], and a unique solution cannot be obtained. The remedy is to regularize the problem. By assuming that the original image $f(x, y)$ is "smooth", we solve: find f that minimizes:

$$\| f - g \|_2^2 + \lambda \| \nabla f \|_2^2 \tag{10}$$

The minimizer of the functional in Eq. (10) obeys the following Euler-Lagrange Equation [7]:

$$F_f - \frac{\partial}{\partial x} F_{f_x} - \frac{\partial}{\partial y} F_{f_y} = 0 \tag{11}$$

where $F = (f - g)^2 + \lambda(f_x{}^2 + f_y{}^2)$ and subscripts indicate partial differentiation along the direction of the subscripting variable. Substitution of appropriate variables into the Euler-Lagrange Equation (11) results in the following Poisson Equation:

$$\nabla^2 f = \frac{1}{\lambda}(f - g) \tag{12}$$

with an appropriate boundary condition (Dirichlet or Neumann) depending on the particular application. Although for a different application, see [8] for a detailed description of the boundary condition in relation to the Euler-Lagrange Equation.

2.3 Image Decoding by Regularized Dequantizer

The decoded image must still be based on the received quantized DCT coefficients and thus must satisfy Eq. (9). Therefore, Eq. (12) cannot be used by itself. Because we are only interested in a dequantizer that modifies quantized DCT coefficients by $\pm$ (quantizer spacing/2), Eq. (12) must be used together with Eq. (9).

The substitution of Eq. (9) into a lexicographically ordered version of Eq. (12) yields:

$$\sum_{0\le i,j\le 7} \alpha_{ij}(k)\,(L\mathbf{c}_{ij} - \frac{1}{\lambda}\mathbf{c}_{ij}) = L\mathbf{g}(k) \tag{13}$$

where L is the matrix representation of the Laplacian operator for lexicographically ordered operands (*i.e.*, vectors). Note that the original image $\mathbf{f}$ has been completely eliminated in Eq. (13). In fact, all terms that appear in Eq. (13) are known except for the coefficients $\alpha_{ij}(k)$. Therefore, the problem at hand is to determine $\alpha_{ij}(k)$, using Eq. (13). For this purpose, Eq. (13) may be written in matrix-vector form as follows:

$$\left[L\mathbf{c}_{00} - \frac{1}{\lambda}\mathbf{c}_{00} \quad | \quad \cdots \quad | \quad L\mathbf{c}_{77} - \frac{1}{\lambda}\mathbf{c}_{77} \right] \mathbf{a}(k) = L\mathbf{g}(k) \tag{14}$$

where $\mathbf{a}(k)$ is the lexicographically ordered version of the coefficients $\alpha_{ij}(k)$. It can be shown that the system of equations above is invertible and it may be solved exactly and $\mathbf{a}(k)$ can be found simply by inverting Eq. (14). Certain fast FFT-like approaches may also be used. Note that Eq. (14) must be satisfied for all 8×8 blocks. Once $\mathbf{a}(k)$ has been determined for all blocks, the desired image can be obtained by Eq. (9) for all 8×8 blocks. However, because the coefficients $\alpha_{ij}(k)$ must be limited to lie in the interval $(-1/2, 1/2]$, we must resort to an iterative approach. In other words, if any of the computed coefficients $\alpha_{ij}(k)$ lies outside the interval $(-1/2, 1/2]$, those coefficients must be clipped. The algorithm then recomputes the coefficients based on the currently available data. The proposed iterative decompression algorithm including the regularized dequantizer is summarized below:

- Initialize image with the conventionally decoded image: $\mathbf{f}^{(0)} = \mathbf{g}$
- Initialize coefficients for all 8×8 blocks: $\alpha_{ij}(k) = 0$
- Loop for $m = 0, 1, 2, 3, \ldots$
  - Find the incremental coefficient $\alpha_{ij}^{(m)}(k)$: Solve Eq. (14) with $\mathbf{g} = \mathbf{f}^{(m)}$.
  - Update and clip the effective coefficient: $\alpha_{ij}(k) = \min(\max(\alpha_{ij}(k) + \alpha_{ij}^{(m)}(k), -1/2), 1/2)$
  - Update the current image (for all 8×8 blocks): $\mathbf{f}^{(m)}(k) = \mathbf{g}(k) - \sum_{0\le i,j\le 7} \alpha_{ij}(k)\mathbf{c}_{ij}$

The end result or the decoded image, is in effect, the IDCT of the regularized dequantizer output. In practice, the coefficients $\alpha_{ij}(k)$ corresponding to low frequency components rapidly grow to values outside the interval $(-1/2, 1/2]$, which is then clipped within the iteration loop. This clipping allows coefficients corresponding to higher frequency components to rise. In any case, because the final decoded image is based on Eq. (13) the proposed technique guarantees the updating of received DCT coefficients to within $\pm$ (quantizer spacing/2) for all DCT coefficients.

3. RESULTS

The performance of the proposed regularized dequantizer is evaluated and compared to the standard H.263+ with its standard quantization table with and without the deblocking filter (Annex J). The blockiness measure (BM) defined by the following is used to compare the two approaches.

$$\mathrm{BM} = 10\log_{10}\left\{ \frac{\sum_{\text{vertial}} \| \frac{\partial}{\partial x}(f-\hat{f}) \|_2^2 + \sum_{\text{horizontal}} \| \frac{\partial}{\partial y}(f-\hat{f}) \|_2^2}{N_{pix}} \right\} \tag{15}$$

where N_{pix} is the total number of pixels summed. In the above, f is the original image and $\hat{f}$ is the decompressed image by one of (*i*) H.263+ decompression, (*ii*) H.263+ with its deblocking filter and (*iii*) the proposed regularized dequantizer. Note that the differences in the derivatives across the 8×8 block boundary are summed only along vertical and horizontal block boundaries. Higher BM indicates more severe blocking artifact.

Figure 1 shows plots of the PSNR (a) and the BM (b) values as functions of the quantization scale factor (QUANT of H.263+) using the standard Lenna image. The proposed algorithm consistently provides higher PSNR and lower BM values for all values of QUANT. The readily recognizable trend is that larger the quantization step size (QUANT) and thus lower the bit-rate, higher the performance gain of the regularized dequantizer over the conventional dequantizer. All images were obtained (for the regularized approach) in just three or less iterations.

Although improvements in actual PSNR values appear to be small (less than 1 dB), the visual improvement offered by the proposed regularized dequantizer becomes apparent upon viewing the zoomed images. In Figure 2, (a) shows the image as decoded by H.263+, (b) shows the H.263+ decompression followed by the deblocking filter (H.263+ Annex J), and (c) shows the decoded image by the proposed regularized dequantizer. All images are zoomed by a factor three. The visual improvement offered by the regularized dequantization is self-evident upon a quick comparison of these images.

4. CONCLUSION

We have presented a new technique for decompressing DCT encoded images based on our proposed regularized dequantizer. The superiority of the proposed technique has been demonstrated over the existing H.263+ method with and without its deblocking filter. As simulations have indicated, the proposed technique would be particularly appropriate for low-bit rate videos. Lastly, the technique is also suitable for other DCT based standards such as MPEG and JPEG.

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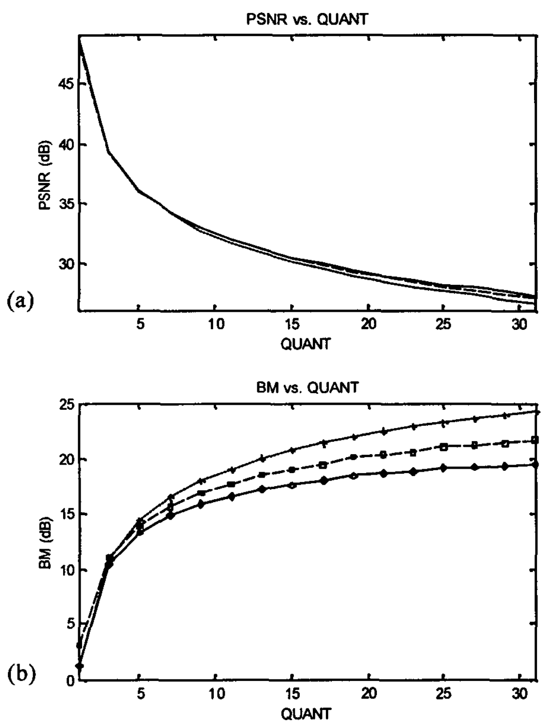

Figure 1: The PSNR (a) and BM (blockiness measure) (b) as functions of QUANT (quantizer scale) for decompression using the conventional H.263+ decoder (dotted), H.263+ decoding followed by the deblocking filter of H.263+ Annex J (dashed), and by the proposed regularized dequantizer (solid).

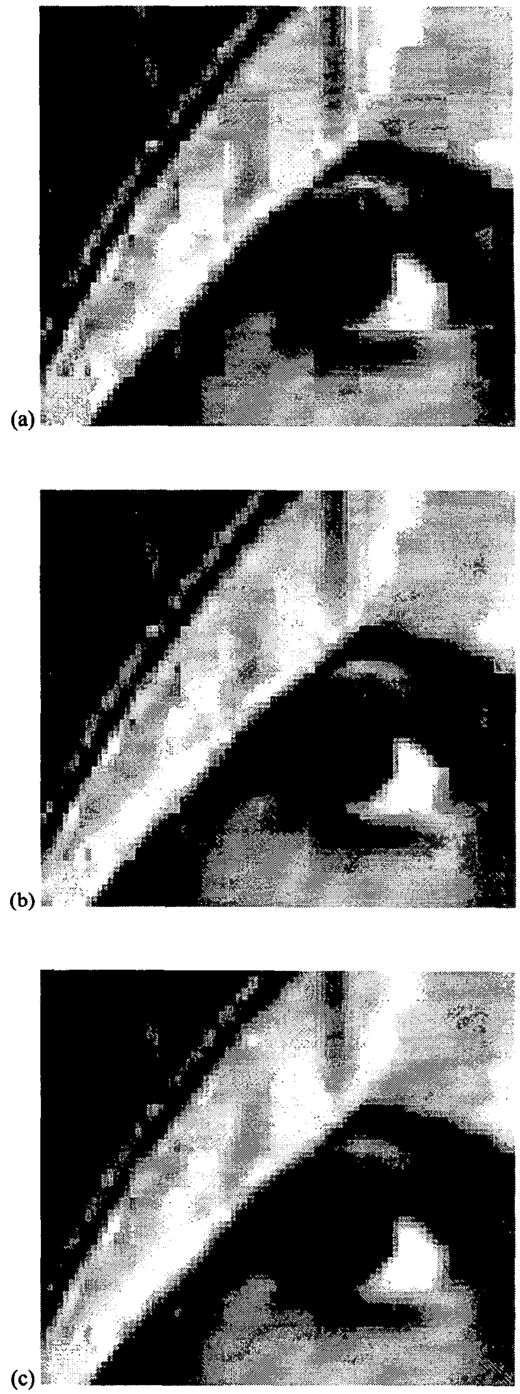

Figure 2: Demonstration of the proposed regularized dequantizer. (a) shows H.263+ decompressed image, (b) shows H.263+ decompression followed by the deblocking filter (Annex J) and (c) shows the decompressed image by the proposed regularized dequantizer.