AN ITERATIVE DEBLOCKING METHOD USING 2-D DIRECTIONAL FIR FILTERS

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ABSTRACT

An iterative deblocking algorithm for DCT-compressed images using two-dimensional FIR filters adapted for local directionality of each block, is proposed. First, we introduce a set of simple lowpass filters, which are adapted for edges of different angles. In conventional deblocking methods based on lowpass-filtering and convex projections, a single filter is applied to a whole image. In the proposed method, on the other hand, a suitable filter is chosen out of the directional filters designed previously in every subimage (typically 8×8 block). Experimental results indicate that adaptive filtering improves PSNR at each iteration.

1. INTRODUCTION

Transform coding is widely used for image compression. In particular, the discrete cosine transform (DCT) is employed in international standards such as JPEG and MPEG [1]. However, transform coding systems have problems in very low bit rate applications. The major drawback is the "blocking effect" that arises due to dividing an image into subimages (blocks) prior to coding.

To reduce the blocking effect, a straightforward way is the filtering method, where a lowpass filter is applied at pixels directly adjacent to block boundaries [2]. Several improvements on the filtering method have been made. Zakhor has proposed an iterative deblocking algorithm based on the band-limitation and the quantization constraint [3]. In the band-limitation step of each iteration, a lowpass filter of size 3×3 is applied to the decoded image. In the next step, each block is transformed with the DCT, and the quantization constraint is applied. This iteration is guaranteed to converge to a solution of the constrained minimization problem regardless of the cutoff frequency of the lowpass filter [4]. Narita *et al.* have improved the quantization constraint step [5].

These methods use a single filter for image deblocking. However, the numbers of iterations of the algorithm increases the mean square error (MSE) between the original and the deblocked images due to lowpass filtering. In a typical image, image characteristics differ considerably from one region to another. It is reasonable, then, to adapt the processing to the changing characteristics of the image and degradation.

In this paper, we propose an approach of *block-by-block* adaptive filtering. In the filtering step of the iterative algorithm, for each decoded block, we choose one suitable lowpass filter from a set of filters. Filters to be designed are adapted for local directionality of each block. Experimental results describe that the proposed approach has the advantage over a non-adaptive filtering method in the MSE sense.

2. DIRECTIONAL ADAPTIVE FILTERING FOR IMAGE ENHANCEMENT

Consider blocks which contain strong edges or lines. We call such block that contains directionality the *directional block* (DB). We can assume that if the block size is small enough such as 8×8 in the JPEG [1], strong edges or lines will fit with a straight line heading toward the direction ϕ. In general, the luminance along a parallel direction ϕ with the straight line varies smoothly, whereas the one along a perpendicular direction does sharply. The DB is therefore characterized by an angle of the direction ϕ and denoted by $\mathcal{B}^{\phi}$.

What lowpass filters are appropriate for the DB $\mathcal{B}^{\phi}$? As a straightforward way to solve the problem, we introduce filters with rectangle-shaped passband spectral regions as shown in Fig. 1, where the long sides of the rectangle are in the angle of

$$\theta = \phi - \pi/2. \tag{1}$$

This type of filter is called the *directional adaptive lowpass filter* (DALPF). Let $\mathcal{P}$ and $\mathcal{S}$ be the passband and the stopband regions, respectively. The 2-D DALPF for θ, which is denoted by $H_T^{\theta}(\omega_1, \omega_2)$, to be designed is defined as a rectangle-shaped lowpass filter with the following specifications:

$$|H_T^{\theta}(\omega_1, \omega_2)| = \begin{cases} 1 & (\omega_1, \omega_2) \in \mathcal{P} \\ 0 & (\omega_1, \omega_2) \in \mathcal{S} \end{cases}, \tag{2}$$

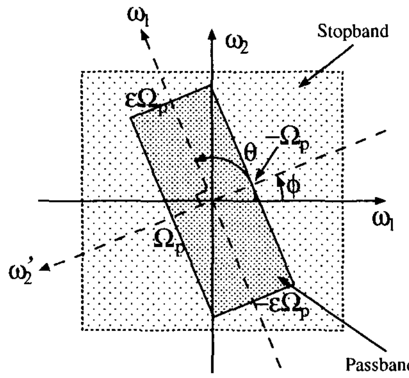

Figure 1: Frequency response of the DALPF for the DB $\mathcal{B}^{\phi}$

$$\mathcal{P} = \left\{(\omega_1,\omega_2)\big||\omega_1'| < \epsilon\Omega_p, \text{and } |\omega_2'| < \Omega_p\right\}, \quad (3)$$
$$\mathcal{S} = \left\{(\omega_1,\omega_2)\big||\omega_1'| > \epsilon\Omega_s, \text{or } |\omega_2'| > \Omega_s\right\}, \quad (4)$$

where

$$\begin{bmatrix}\omega_1'\\ \omega_2'\end{bmatrix} = \begin{bmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{bmatrix}\begin{bmatrix}\omega_1\\ \omega_2\end{bmatrix}. \quad (5)$$

Assume that the resulting filter is a zero-phase FIR filter with odd length. Using linear programming, we find an optimal approximation $|H^{\theta}(\omega_1,\omega_2)|$ to the desired amplitude response $|H_T^{\theta}(\omega_1,\omega_2)|$ by minimizing the Chebyshev (L_∞) norm

$$J = \max_{(\omega_1,\omega_2)} |H_T^{\theta}(\omega_1,\omega_2) - H^{\theta}(\omega_1,\omega_2)| \quad (6)$$

at a dense set of points in both the passband and the stopband [6]. When the angle θ is uniformly quantized into K levels between $-\pi/2$ and $-\pi/2$, a set of K DALPF's

$$\left\{H^{\theta_k}(\omega_1,\omega_2)\,\Big|\,\theta_k = -\frac{\pi}{2} + \frac{\pi}{K}k, k = 0,\ldots,K-1\right\} \quad (7)$$

is obtained. Frequency response of the resulting DALPF $H^{\pi/4}(\omega_1,\omega_2)$ is illustrated in Fig. 2.

Similarly, a *non-directional lowpass filter* (NDLPF) is defined as a filter when $\theta = 0.0$ and $\epsilon = 1.0$, and written as $H^N(\omega_1,\omega_2)$.

3. FINDING DIRECTION OF THE DECODED IMAGE

To apply the lowpass filter for each block, we have to detect the direction of the block prior to deblocking.

Consider the subset $\{\mathbf{d}_l\}_{l=1}^{L-1} (L \le N)$ of the 2-D DCT basis [1] for an $N \times N$ signal such that

$$d_l(p+qN) = \frac{\sqrt{2}}{N}C_l\cos\left[\frac{(2p+1)l\pi}{2N}\right], \quad (8)$$

$$p,q = 0,\ldots,N-1,$$
$$C_l = \begin{cases}1/\sqrt{2} & l=0,\\ 1 & \text{otherwise},\end{cases}$$

where we use one-dimensional notation such that $d_l(p+qI) = d_l(p,q)$. We extend d_l from the discrete function into the continuous one, and rotate the coordinate (p,q) by the angle ϕ. Then, we obtain the rotated version $\{\mathbf{d}_l^{\phi}\}_{l=0}^{L-1}$ such that

$$d_l^{\phi}(p+qN) = d_l(p'(\phi), q'(\phi)), \quad (9)$$

where

$$\begin{bmatrix}p'(\phi)\\ q'(\phi)\end{bmatrix} = \begin{bmatrix}\cos\phi & \sin\phi\\ -\sin\phi & \cos\phi\end{bmatrix}\begin{bmatrix}p-\frac{N}{2}\\ q-\frac{N}{2}\end{bmatrix} + \begin{bmatrix}\frac{N}{2}\\ \frac{N}{2}\end{bmatrix}, \quad (10)$$
$$p,q = 0,\ldots,N-1.$$

Obviously, the dc vector $\mathbf{d}_0$ is immutable, that is, $\mathbf{d}_0^{\phi} = \mathbf{d}_0$. Since the set of vectors $\{\mathbf{d}_l^{\phi}\}_{l=0}^{L-1}$ may not be an orthonormal system, they have to be orthonormalized in order to construct an orthogonal transform. For the purpose, finally, the Gram-Schmidt process [7] is performed. Figure 3 shows a process for constructing the orthonormal system $\{\mathbf{w}_i^{\phi}\}_{i=0}^{L-1}$ when $\phi = \pi/15$, as an example. The left and right figures indicate $\{\mathbf{d}_l\}_{l=0}^{3}$ and $\{\mathbf{w}_i^{\phi}\}_{i=0}^{3}$, respectively.

We find the direction ϕ of a decoded block using the orthonormal system $\{\mathbf{w}_l^{\phi}\}_{l=0}^{L-1}$. Let $\hat{\mathbf{f}}$ be a decoded block signal. Suppose that the direction ϕ is uniform quantized into M levels, that is, ϕ is an element of a set defined as

$$\Phi_M = \left\{\phi\,\Big|\,\phi_m = -\frac{\pi}{2} + \frac{\pi}{M}m,\ m = 0,\ldots,M-1\right\}. \quad (11)$$

If the variance of $\hat{\mathbf{f}}$ is less than a given threshold τ, this block is classified into the plane block, and then the non-directional filter is used. If the variance of $\hat{\mathbf{f}}$ is not less than

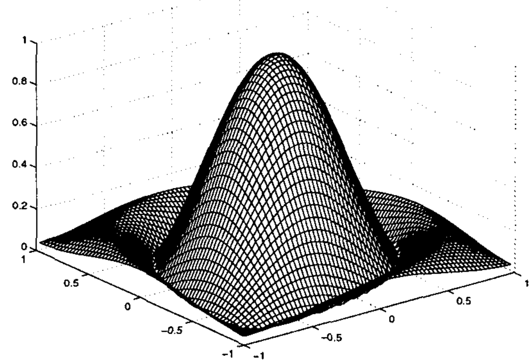

Figure 2: Frequency response of the DALPF for the angle $\theta = \pi/4$.

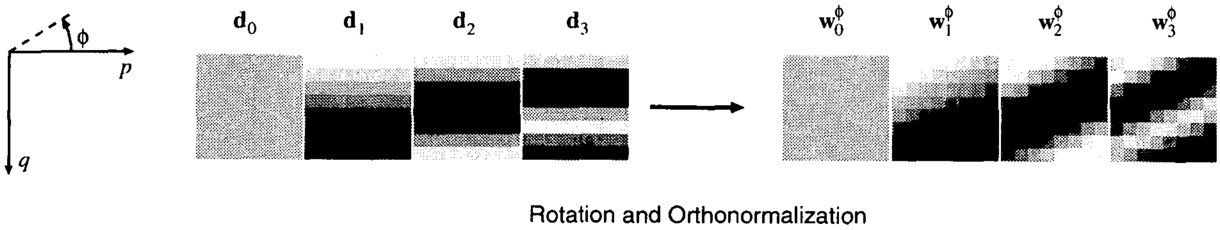

Figure 3: The process to obtain an orthogonal basis for a characteristic subspace W when $\phi = \pi/15$.

τ, this block is classified into the directional block, and then the directional filter is used. For every m, we find ϕ^* such that the corresponding orthonormal system $\{\mathbf{w}_l^{\phi}\}_{l=0}^{L-1}$ maximizes

$$E(\phi_m) = \sum_{l=0}^{L-1} |\langle \mathbf{w}_l^{\phi_m}, \hat{\mathbf{f}} \rangle|^2, \tag{12}$$

where $\langle \cdot, \cdot \rangle$ denotes the inner product. Finally, the most nearest angle $\phi \in \Phi_K$, where $K < M$, to the detected direction ϕ^* is chosen as the direction of the block.

4. ITERATIVE DEBLOCKING ALGORITHM

We now summarize our proposed iterative procedure as follows. As seen in the previous section, each block of the decoded image is categorized into $(K+1)$ classes, that is, a plain block and K DB's $\mathcal{B}^{\phi_k}$. Next, we perform the iterative step. In the first part of each iteration, adaptive filtering is performed. For the plane block, the NDLPF is applied. For the directional block of the angle ϕ_k, the corresponding DALPF $H^{\theta_k}(\omega_1, \omega_2)$ is applied. We use symmetric extension for the image boundary. In the second part of each iteration, the quantization constraint is applied. We transform the block with the DCT, and then we obtain the transform coefficients $c_{i,j}^{(i)}$, where i is the number of iterations. When $i = 0$, $c_{p,q}^{(i)}$ denotes the DCT coefficient of the decoded image. Let $\Delta_{p,q}$ be the step size of the scalar quantizer with respect to the coordinate (p, q). The DCT coefficient of the original image is in the range $[c_{p,q} - \Delta_{p,q}, c_{p,q} + \Delta_{p,q}]$. Therefore, we make the following modification:

$$\hat{c}_{p,q}^{(i)} = \begin{cases} c_{p,q} - \Delta_{p,q} & c_{p,q}^{(i)} < c_{p,q} - \Delta_{p,q} \\ c_{p,q} + \Delta_{p,q} & c_{p,q}^{(i)} > c_{p,q} + \Delta_{p,q} \\ c_{p,q}^{(i)} & \text{otherwise} \end{cases} \tag{13}$$

The modified coefficients $\hat{c}_{p,q}^{(i)}$ are transformed with the IDCT.

This modification for the DCT coefficients is very simple approach but effective to reduce blurring [3]. Some improvements [5] have been proposed by Narita *et al.*

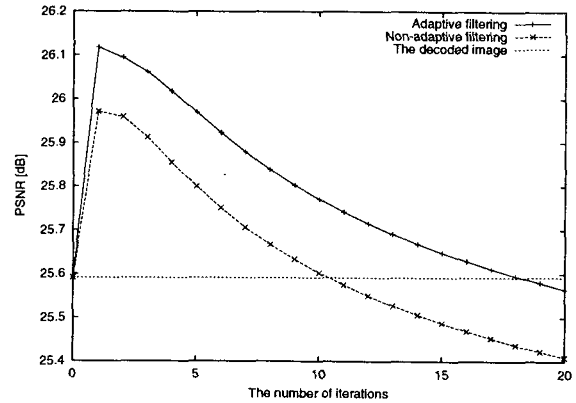

Figure 4: Comparison of PSNR's with respect to the number of iterations for 'Barbara'.

5. EXPERIMENTAL RESULTS

Four DALPF's for $\theta = -\pi/4, 0, \pi/4$ and $\pi/2$ are designed, that is, $K = 4$. The size of the filters is 3×3. The parameters that specify the passband and the stopband are $\Omega_p = 0.2\pi, \Omega_s = 0.6\pi$ and $\epsilon = 1.5$. $L = 8$ and $M = 16$ are chosen for the algorithm to detect the direction.

The input image is compressed by the JPEG-like coder, where all entries of the quantization table are the same. We compare our proposed method with Zakhor's method with the non-directional filter. Comparison of PSNR's with respect to the number of iterations is shown in Fig. 4. Table 1 shows rate-distortion characteristics of deblocked images for three iterations. It is observed that the proposed method consistently outperforms the non-adaptive filtering method in the PSNR sense.

Figure 5 shows the original 512×512 'Barbara', its DCT-compressed version at 0.30 bpp, and the deblocked version with the proposed method. In the right image, the blocking effects are strongly observed. It can be observed that the blocking artifacts are significantly reduced.

Figure 5: The original 512 × 512 'Barbara' (left), its compressed version at 0.30 bpp (center), and the deblocked image with the proposed iterative algorithm for three iterations (right).

Rate [bpp]	0.20	0.30	0.40
Decoded	23.15	25.59	27.43
Proposed	24.10	26.06	27.50
Conventional	24.05	25.91	27.30

Table 1: Results of applying the iterative algorithm to decoded 512 × 512 'Barbara' images for three iterations.

6. CONCLUSIONS

We have proposed the block-by-block adaptive filtering by the directional adaptive lowpass filter for iterative deblocking procedure. This method does not require any change of the encoder and any side information since the directionality of each block is detected from in the decoded image. Experimental results have shown that our proposed method provides higher PSNR than the non-adaptive filtering one at the same number of iterations.

In this paper, heuristic filters have been used for the adaptive image processing. This approach has improved performance of the deblocking procedure; however, we have not studied the effects when the optimal restoration filter such as the Wiener filter is used. Moreover, when the number of iterations increases, the MSE increases. These problems will be left for further research.

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