Optimal Pre- and Post-Processing for JPEG2000 Tiling Artifact Removal

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Abstract — This paper presents a pre-/post-filtering approach for JPEG 2000 tiling artifact removal, in which a pre-filter is applied at tile boundaries before wavelet compression, and a post-filter is invoked at the same locations after wavelet reconstruction. We first derive the optimal bit allocation and the corresponding boundary distortion for a given pre-/post-filter pair. The optimal pre-/post-filters are then obtained by minimizing the reconstruction error of the boundary filter bank. A low-complexity pre-/post-filter structure is proposed to approximate the optimal solutions, and its performance in JPEG2000 tiling artifact removal is demonstrated.

I. INTRODUCTION

It is well known that DCT-based image and video coding systems exhibit annoying blocking artifacts at low bit rates. The lapped transform (LT) [1] mitigates this problem by post-processing the DCT coefficients, generating basis functions that cover two data blocks. Recently, a new family of lapped transform via time-domain pre- and post-processing (TDLT) is developed [2], which offers further flexibilities.

The wavelet transform provides another solution of reducing the blocking artifact. It is obtained by successively iterating a 2-channel filter bank on its lowpass output. As a result, it generates an octave-band filter bank with longer low frequency basis functions and shorter high frequency basis functions. Therefore, when the wavelet transform is applied to the whole image, blocking artifact can be eliminated satisfactorily. This, together with other attractive properties of the wavelet transform, has made the wavelet transform the foundation of JPEG2000, the next generation image compression standard [3].

However, when the size of the image is very large, the memory requirement of the wavelet transform might be unacceptable for some computing platforms. Such large images can be encountered in digital cameras, document scanning and aerial photography, among others. In these cases, a simple trade-off for bounding memory requirement in both hardware and software implementations is to break a large image into smaller pieces and encode each part independently, similar to DCT-based schemes. This option is provided in JPEG2000, where each piece is called a tile. Although the tile size in JPEG2000 is much larger than the block size in JPEG (at least 128 \times 128 in JPEG2000), blocking artifacts known as tiling artifacts at tile boundaries are still noticeable at low bit rates [4, 5].

Some methods have been proposed to reduce the tiling artifacts in wavelet-based compression. These can be classified into two categories. Methods in the first categories apply post-processing at the decoder side. An example is the method of projection onto convex set [6]. A common problem with post-processing solutions is that they unavoidably introduce blurring, ringing, or other degradations.

In the second category, the problem is addressed by both the encoder and the decoder. These methods generally yield better performance than pure post-processing algorithms. In [7], a point-symmetric extension method is proposed to replace the conventional symmetric extension. In [8, 9], the tile size is chosen to be odd such that the first and the last subbands of each tile are always low-pass. The method is based on the observation that high-pass coefficients at the tile boundary have larger reconstruction errors than low-pass coefficients. Since the JPEG 2000 standard requires that low-pass coefficients must be located on even canvas coordinates and high-pass coefficients on odd coordinates, a method is further proposed in [10] to choose the tiles such that neighboring tiles are overlapped by one sample.

In this paper, we generalize the pre- and post-processing philosophy in [2] to the wavelet-based image compression framework. That is, a pre-processing operator is applied at tile boundaries before the wavelet compression of each tile. Accordingly, a post-processing is performed at the tile boundaries after inverse wavelet transform. A nice property of this approach is that the pre- and post-processing can be performed totally outside of existing JPEG2000 framework. Later we will show that at low bit rates, our proposed post-processing itself would be able to reduce the tiling artifact significantly.

To design the optimal pre- and post-filters, the first question that we need to address is to define a performance criterion for evaluating a given pair of pre- and post-filters. In this paper, we first derive the optimal bit allocation and the corresponding boundary distortion for a given pre-/post-system. The optimal pre-/post-filters are then obtained by minimizing the reconstruction error of the boundary filter bank. We then apply the fast pre-/post-processing structure in [2] to approximate the optimal solution. A further simplification is also proposed. These structures also enable lossless compression. Experimental results show that the proposed low-complexity scheme leads to significantly PSNR improvement at tile boundaries, and the visual quality is also enhanced satisfactorily.

II. PROBLEM FORMULATION

Fig. 1 illustrates the wavelet transform-based image compression model with the \( 2K \times 2K \) pre-filter \( P \) and post-filter \( P^{-1} \) at tile boundaries, where \( s_0, n \)'s and \( s_1, n \)'s (n =
0, . . . , N − 1) are input samples of two neighboring tiles of size N × N. The wavelet transform is implemented through a number of lifting and scaling steps [3], and symmetric extension is employed at tile boundary. For simplicity purpose, this paper only considers one-level of wavelet transform in designing the optimal pre- and post-filters, but the resulting filters can be applied to implementations with any level of wavelet transform with satisfactory performance.

Our objective is to find the optimal pre-/post-processing operators in the rate-distortion sense. To this end, we first need to identify the number of reconstructed pixels that are affected by the given pre- and post-filters. For instance, the example in Fig. 1 uses 5/3 wavelet transform and 4 × 4 pre-/post-filters. It is easy to see that in block s1, the pre-filtered boundary samples affect three wavelet coefficients after the forward wavelet transform: r1, 0, r1, 1, and r1, 2. In the decoder side, after the inverse wavelet transform, the effect of the pre-filter propagates to four output pixels in block s0. Similarly, one can verify that five reconstructed pixels in block s0 are influenced by the pre-filter, as labeled in Fig. 1.

Starting from these reconstructed pixels and tracing back, we can find all wavelet coefficients and all input samples that contribute to these reconstructed samples. In this example, Seven and six WT coefficients in block s0 and block s1 are involved, respectively. They are functions of eight and seven input samples, respectively, as shown in Fig. 1.

In general, we can obtain the system model as given in Fig. 2. Our objective is to find the pre-/post-filter pair such that the mean-square error (MSE) of the reconstructed boundary vectors ŷ0 and ŷ1 is minimized. The solution can be obtained as follows.

First, the boundary wavelet transform coefficients can be written as

\[ u \triangleq \begin{bmatrix} u_0 \\ u_1 \end{bmatrix} = \begin{bmatrix} F_0 & 0 \\ 0 & F_1 \end{bmatrix} \begin{bmatrix} I_{M_0-K} & 0 & 0 \\ 0 & P & 0 \\ 0 & 0 & I_{M_1-K} \end{bmatrix} \begin{bmatrix} x_0 \\ x_1 \end{bmatrix} \]

\[ \triangleq F x, \tag{1} \]

where the sizes of \( F_i \) and \( x_i \) are \( M_i \times N_i \) and \( N_i \times 1 \), respectively, and \( I_n \) is the \( n \times n \) identity matrix. \( F_i \) represents the boundary wavelet transform at each tile.

Let \( q_i \) be the quantization noise applied to \( u_i \), the reconstruction error would be

\[ e = \begin{bmatrix} ŷ_0 - y_0 \\ ŷ_1 - y_1 \end{bmatrix} = \begin{bmatrix} I_{M_0-K} & 0 & 0 \\ 0 & P^{-1} & 0 \\ 0 & 0 & I_{M_1-K} \end{bmatrix} \begin{bmatrix} G_0 & 0 & 0 \\ 0 & G_1 & 0 \\ 0 & 0 & I_{L_2-K} \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \end{bmatrix} \triangleq G q, \tag{2} \]

where \( G_i \) represents the boundary inverse wavelet transform, and the sizes of \( G_i \) and \( q_i \) are \( L_i \times M_i \) and \( M_i \times 1 \), respectively.

The MSE of tile boundaries can thus be expressed as

\[ \mathcal{E} = \text{trace}\{E\{e e^T\}\} = \text{trace}\{G R_q G^T\} = \text{trace}\{R_q G^T G\}. \tag{3} \]

Assume subband noises are uncorrelated, i.e., \( R_q \) is diagonal. We can write \( \mathcal{E} \) as

\[ \mathcal{E} = \sum_{k=0}^{M_0-1} \sigma_{q_{0,k}}^2 \| G_k \|^2 + \sum_{k=0}^{M_1-1} \sigma_{q_{1,k}}^2 \| G_{M_0+k} \|^2. \tag{4} \]
where $\sigma_{u,k}^2$ is the variance of the $k$-th entry in $u$, and $\left\| G_k \right\|_2^2$ is the norm of the $k$-th column of $G$.

To get $\sigma_q^2$, assume that the input has an autocorrelation matrix of $R_{xx}$, thus

$$R_{uu} = FR_{xx}F^T,$$  \hspace{1cm} (5)

and the variance of the $k$-th element in $u$ can be found from the $k$-th diagonal entry of $R_{uu}$, i.e.,

$$\sigma_{u_0,k}^2 = R_{uu}(k,k), \quad \sigma_{u_1,k}^2 = R_{uu}(M_0 + k, M_0 + k).$$  \hspace{1cm} (6)

The variance of the quantization noise $q$ applied to $u$ can be modeled by [11]

$$\sigma_q^2 = C 2^{-2b_i.k} \sigma_{u_i,k}^2,$$  \hspace{1cm} (7)

where $C$ is a constant that depends on the statistics of $u_i,k$, and $b_i,k$ is the number of bits allocated to the $k$-th channel in $u_i$.

Since the two blocks are quantized separately in tiling approach, the optimal bit allocation problem can be formulated as

$$E_{\text{min}} = \min_{b_0,b_1} \left\{ \sum_{k=0}^{M_0-1} C 2^{-2b_0,k} \sigma_{u_0,k}^2 \left\| G_k \right\|_2^2 \right. \left. + \sum_{k=0}^{M_1-1} C 2^{-2b_1,k} \sigma_{u_1,k}^2 \left\| G_{M_0+k} \right\|_2^2 \right\},$$  \hspace{1cm} (8)

subject to

$$\frac{1}{M_0} \sum_{k=0}^{M_0-1} b_{0,k} = \bar{b}_0,$$

$$\frac{1}{M_1} \sum_{k=0}^{M_1-1} b_{1,k} = \bar{b}_1,$$

where $\bar{b}_0$ and $\bar{b}_1$ are the targeted average bit rates of the two tiles.

This is a standard Lagrangian problem, which can be solved by writing the objective function as

$$L = E + \lambda_0 \left( \frac{1}{M_0} \sum_{k=0}^{M_0-1} b_{0,k} - \bar{b}_0 \right) + \lambda_1 \left( \frac{1}{M_1} \sum_{k=0}^{M_1-1} b_{1,k} - \bar{b}_1 \right).$$  \hspace{1cm} (9)

By setting $\partial L/\partial b_{i,k} = 0$, we arrive at

$$2^{-2b_0,k} \sigma_{u_0,k}^2 \left\| G_k \right\|_2^2 = C_0,$$

$$2^{-2b_1,k} \sigma_{u_1,k}^2 \left\| G_{M_0+k} \right\|_2^2 = C_1,$$  \hspace{1cm} (10)

for constant $C_0$ and $C_1$. Substituting into the constraints on average bit rates, $C_0$ and $C_1$ can be found to be

$$C_0 = 2^{-2b_0} \left( \prod_{k=0}^{M_0-1} \sigma_{u_0,k}^2 \left\| G_k \right\|_2^2 \right)^{1/M_0} \Delta 2^{-2b_0} \beta_0^2,$$

$$C_1 = 2^{-2b_1} \left( \prod_{k=0}^{M_1-1} \sigma_{u_1,k}^2 \left\| G_{M_0+k} \right\|_2^2 \right)^{1/M_1} \Delta 2^{-2b_1} \beta_1^2.$$  \hspace{1cm} (11)

The minimal MSE can be obtained by plugging (10) and (11) into (8).

Similar to standard subband coding problems, we can define the coding gain of the boundary filter bank with respect to the PCM scheme, where each sample is compressed directly to the bit rate of $\bar{b}_i$ in the two blocks. The mean squared error of PCM is thus

$$E_{\text{PCM}} = C \left( L_0 2^{-2b_0} + L_1 2^{-2b_1} \right) \sigma_q^2,$$  \hspace{1cm} (12)

where $L_i$ is the length of $y_i$. Therefore the coding gain can be written as

$$\gamma = \frac{E_{\text{PCM}}}{E_{\min}} = \left( \frac{L_0 2^{-2b_0} + L_1 2^{-2b_1}}{M_0 2^{-2b_0} \beta_0^2 + M_1 2^{-2b_1} \beta_1^2} \right) \sigma_q^2,$$  \hspace{1cm} (13)

where $\beta_0^2, \beta_1^2$ are defined in (11).

When the two blocks are encoded at the same bit rate, i.e., $\bar{b}_0 = \bar{b}_1$, the formula can be simplified into

$$\gamma = \gamma \left( \frac{L_0 + L_1}{M_0 \beta_0^2 + M_1 \beta_1^2} \right) \sigma_q^2.$$  \hspace{1cm} (14)

The optimal pre- and post-processing operator can be found by setting up an optimization program to maximize the coding gain.

Notice that when the bit allocations of $u_0$ and $u_1$ are treated together, the formula above reduces to

$$\gamma = \frac{\sigma_q^2}{\left( \prod_{k=0}^{M-1} \sigma_{u,k}^2 \left\| G_k \right\|_2^2 \right)^{1/M}},$$  \hspace{1cm} (15)

where $M = M_0 + M_1$. This is the coding gain of a standard biorthogonal filter bank.

III. EFFICIENT STRUCTURE FOR PRE/POST-FILTERS

In addition to the coding gain, some other properties are desired for a filter bank to be used in image and video compression successfully. In the pre/post-processing of the wavelet transform, these impose further constraints on the structure of the pre/post-filters. In this paper, we propose the following structure:

$$P = \left[ \begin{array}{c} I \ J \ -I \ J \\ 1 \ 0 \ V \ J \ -I \ J \\ -I \ J \ -I \\ 0 \ V \ -I \ 1 \end{array} \right],$$  \hspace{1cm} (16)

$$P^{-1} = \left[ \begin{array}{c} I \ J \ -I \ J \\ 1 \ 0 \ V \ J \ -I \ J \\ -I \ J \ -I \\ 0 \ V \ -I \ 1 \end{array} \right],$$  \hspace{1cm} (17)

where $J$ is the reversal identity matrix. This structure is identical to that of the pre-/post-filters in the time-domain lapped transform [2]. All freedoms in this structure lie in the $K \times K$ matrix $V$, which can be optimized for coding gain.

In the TDLT, the structure above is required to obtain linear-phase filter bank. In the wavelet framework, although linear phase is not a crucial requirement for boundary filters, the proposed structure does provide other attractive properties. In addition to fast implementation, the pre-filter does not make any change for a constant input vector $c$, i.e.,

$$Pc = c.$$  \hspace{1cm} (18)

Therefore the energy compaction capability of wavelet transform for a constant input is preserved. Moreover, the prefilter satisfies

$$P = JPJ,$$  \hspace{1cm} (19)

i.e., the prefilter itself provides identical boundary processing to both tiles.
Table 1: Coding gain (dB) of various pre/post-filtered WT for an AR(1) model with $\rho = 0.95$.

<table>
<thead>
<tr>
<th>Size of $P$</th>
<th>9/7 WT</th>
<th>5/3 WT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full $V$</td>
<td>Fast $V-I$</td>
</tr>
<tr>
<td>0</td>
<td>9.28</td>
<td>9.28</td>
</tr>
<tr>
<td>2 x 2</td>
<td>9.37</td>
<td>9.37</td>
</tr>
<tr>
<td>4 x 4</td>
<td>9.41</td>
<td>9.41</td>
</tr>
<tr>
<td>6 x 6</td>
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<tr>
<td>8 x 8</td>
<td>9.44</td>
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<tr>
<td>10 x 10</td>
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<td>12 x 12</td>
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<td>14 x 14</td>
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<td>9.45</td>
</tr>
<tr>
<td>16 x 16</td>
<td>9.52</td>
<td>9.46</td>
</tr>
</tbody>
</table>

Table 2: Optimal Parameters and Rational Approximations of Fast Pre/Post-filters in Fig. 3 (b) for 9/7 Wavelet.

<table>
<thead>
<tr>
<th>Size of $P$</th>
<th>$S_0$</th>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
<th>$U_0$</th>
<th>$U_1$</th>
<th>$U_2$</th>
<th>Gain (dB)</th>
</tr>
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<tbody>
<tr>
<td>2 x 2</td>
<td>1.76</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9.37</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9.36</td>
</tr>
<tr>
<td>4 x 4</td>
<td>1.63</td>
<td>1.30</td>
<td>-</td>
<td>-</td>
<td>0.55</td>
<td>-</td>
<td>-</td>
<td>9.41</td>
</tr>
<tr>
<td></td>
<td>3/2</td>
<td>5/4</td>
<td>-</td>
<td>-</td>
<td>1/2</td>
<td>-</td>
<td>-</td>
<td>9.40</td>
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<tr>
<td></td>
<td>2</td>
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<td>-</td>
<td>-</td>
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<td>-</td>
<td>-</td>
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<td>1.65</td>
<td>1.33</td>
<td>1.17</td>
<td>-</td>
<td>0.17</td>
<td>0.63</td>
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</tr>
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<td>0.21</td>
<td>0.63</td>
<td>9.43</td>
</tr>
<tr>
<td></td>
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<td>5/8</td>
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</tr>
<tr>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1/8</td>
<td>1/4</td>
<td>1/2</td>
<td>9.38</td>
</tr>
</tbody>
</table>

wavelet transform or 5/3 wavelet transform is used, respectively. Since pre/post-filters of different sizes involve different number of subbands in the coding gain expression (14), a more convenient way to study the performance of different pre/post-filters is to fix the size of $F_1$ and $G_i$ according to a larger pre/post-filter size, and then vary the actual size of pre/post-filter. In Table 1, the maximal pre/post-filter size is chosen to be $16 \times 16$. For 9/7 WT with four lifting steps, this corresponds to $M_0 = 19$, $M_1 = 18$, $L_0 = 15$, and $L_1 = 14$, whereas for 5/3 WT with two lifting steps, we have $M_0 = 13$, $M_1 = 12$, $L_0 = 11$, and $L_1 = 10$.

It can be seen from Table 1 that the coding gain increases steadily as the increase of the pre/post-filter size, although $2 \times 2$ and $4 \times 4$ pre/post-filters provide the most significant improvement.

Experimental results show that when $K < 5$, the $K \times K$ optimal matrix $V$ can also be approximated very well by one of the fast structures in [2], as shown in Fig. 3 (a), which involves $K$ scaling factors and $2K - 2$ lifting parameters. In fact, one upward lifting step between neighboring channels is sufficient in these cases. The corresponding prefilter is depicted in Fig. 3 (b). The optimized coding gains of these fast structures are also given in Table 1, labeled as Fast $V-I$ and Fast $V-II$, respectively. Clearly the one-lifting structure is as good as the two-lifting structure, and both are very close to the full model when the size of pre/post-filter is less than $10$.

Some optimal parameters for the fast pre-/post-filters in Fig. 3 (b) are listed in Table 2. Various rational approximations that allow fast implementation are also presented. Notice that those with integer scaling parameters can be used in lossless compression.

IV. IMAGE COMPRESSION EXPERIMENTS

To demonstrate the simplicity and efficiency of the proposed pre/post-filtering approach, we implement the pre-filtering and the post-filtering as independent operators. The input 8-bit raw image is first processed by the pre-filter with a specified tile size and the result is saved as a 16-bit raw image. Sixteen-bit resolution is required since after the pre-processing, some pixels could be out of the range of $[0, \ldots, 255]$. The pre-processed image can thus be compressed and reconstructed by any JPEG 2000-compliant encoder and decoder that support 16-bit data. Finally, the decoded image is processed by the post-filter to obtain the image with reduced tiling artifact. The JPEG 2000 software that we choose is the Kakadu version 3.4 [12].

The following examples use the 512 x 512 gray-scale image Barbara with a tile size of $128 \times 128$. The second configuration of $8 \times 8$ pre-filter in Table 2 is selected. Fig. 4 plot the average horizontal and vertical PSNR across all tile boundaries when the image is encoded at 0.2 bits/pixel. The first 10 samples belong to the left/upper tile, whereas the next 10 samples belong to the right/lower tile. In Fig. 4 (a) and (b), both pre- and post-processing are employed. The performance of the JPEG2000 has a sharp drop of $3 \sim 5$ dB at tile boundaries. Moreover, the left/upper tile has worse PSNR near the boundary than the right/lower tile, since its last subband is a high-pass subband, which has larger reconstruction error. This is the main reason for tiling artifact. This behavior has
been observed in [8, 9, 10]. With the help of pre- and post-
processing, the PSNR for the last pixel of the left/upper tile
is improved by more than 1.5 dB in this example. Other pix-
els near the boundary are also improved. Besides, the PSNR
gap at two sides of the boundary is also reduced, leading to
mitigated tiling artifacts.

When the bit rate is low, post-processing alone is effective
enough to reduce the tiling artifact, as demonstrated in Fig.
4 (c) and (d). In this case, the PSNR improvement of the
left/upper tile is very similar to Fig. 4 (a) and (b). The PSNR
of the right/lower tile is lower than that of the JPEG2000
result. However, the PSNR transition is actually smoother
across the boundary, which is helpful for visual quality.

The decoded images with different methods are shown in
Fig. 5. The tiling artifact can be clearly observed in the
JPEG 2000 result, but has been reduced considerably in the
pre-/post-processing and post-processing approaches.

V. Conclusion

In this paper, we present a pre-/post-processing approach
for the tiling artifact removal in wavelet-based image compres-
sion framework. We derive the coding gain expression for
the boundary filter bank, and propose a low-complexity structure
for the pre-/post-filter, based on the result in time-domain
lapped transform.

The pre-/post-processing solution can be directly employed
in 3-D wavelet-based scalable video coding [13], where the jit-
tering artifact at boundaries of groups of pictures (GOP) is
still a common problem for memory-constrained implementa-
tions. Similarly, the TDLT in [2] can be applied to 3-D
DCT-based video coding. Further results on image and video
coding will be reported elsewhere.

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Figure 4: PSNR of image Barbara across tile boundaries. The first 10 samples belong to the left (upper) tile and the next 10 samples belong to the right (lower) tile (0.2 bits/pixel, 5-level 9/7 wavelet, 128 × 128 tiles, and 8-point pre/post-filters): (a) Average PSNR across all horizontal tile boundaries. (b) Average PSNR across all vertical tile boundaries. (c) Post-processing only: Average PSNR across all horizontal tile boundaries. (d) Post-processing only: Average PSNR across all vertical tile boundaries.

Figure 5: A part of decoded image Barbara (0.2 bits/pixel, 5-level 9/7 wavelet, 128 × 128 tiles, and 8-point pre/post-filters): (a) JPEG 2000: 8-point tile boundary PSNR: 25.41 dB; (b) JPEG 2000 with both pre- and post-processing: 8-point tile boundary PSNR: 26.31 dB; (c) JPEG 2000 with post-processing only: 8-point tile boundary PSNR: 25.82 dB.