Design of a De-ringing Filter for Wavelet-based Compressed Image

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Abstract: JPEG2000 Standard is a new generation image compression technique, enabling encoding images at low bit-rates with acceptable quality. Since JPEG2000 is based on wavelet transforms, the reconstructed image will contain perceivable ringing artifacts in medium and low bit-rate regimes of lossy compression. This work utilizes a quad-tree partitioning scheme for post-processing the reconstructed image in a spatially varying manner and presents a voting strategy to determine a set of morphological filters to be used for reducing the ringing artifacts. Simulation results demonstrate that the proposed technique enhances reconstructed image quality compared to unprocessed JPEG2000 output at an equivalent bit-rate accounting for the side-information overhead, in terms of both Peak Signal-to-Noise Ratio (PSNR) and Visible Ringing Measure (VRM).

1. Introduction

JPEG2000's enhanced performance enabling image compression at very low bit-rates with acceptable quality, stems from a number of new and innovative features incorporated in its definition, its use of wavelet transforms being one such prominent feature [1]. Lossy wavelet-based image compression generally induces ringing artifacts around edges in the compressed image. These artifacts arise due to the fact that high frequency components of the image are either annihilated or coarsely represented by the quantization process in wavelet-based coders.

The filter against ringing artifact that proposed by Shen and Kuo [2] is considered to be a suitable post-processor for JPEG2000. The filter against ringing artifact replaces each pixel value with a function of the values of neighboring pixels that are within a specified window. For smoothing a sharp edge, the filter against ringing artifact uses a number of adaptive noise reduction algorithms. Essentially, the filter against ringing artifact attempts to detect edges in the image in a different way to preserve them. Shen and Kuo also introduced the idea of image ringing artifact reduction through nonlinear filtering by using different kinds of potential functions. Clearly, modeling the compression noise in the spatial domain is a difficult problem, particularly for ringing artifacts.

This work adopts the quad-tree partitioning scheme for post-processing the compressed image and presents a set of morphological filters for reducing the ringing artifacts of natural images. The proposed voting strategy is used to select the morphological filter for each quad-tree partition block to optimize the filtered image quality. Applying the appropriate morphological filter to each block can enhance image quality.

2. Proposed algorithm

2.1 Quad-tree decomposition

This work adopts the efficient quad-tree partitioning scheme [3], to post-process the compressed image. The main purpose of applying quad-tree partitioning is to enable the post-processing method to adapt to the local features of the compressed image to promote global image quality. Initially, a threshold is required to classify block smoothness as well as a predefined minimum block size to stop the process of iteratively sub-partitioning non-smooth blocks. To determine block smoothness, this study simply calculates the absolute difference between the maximum and the minimum gray level values in a block. If this absolute difference exceeds the predefined threshold, the block is further divided into four equal-sized sub-blocks. The partitioning process is iterated in each block until either the smoothness meets the predefined criterion or the block size equals the predefined minimum size. Figure 1 shows an example of quad-tree partitioning in the compressed image 'Lena'.

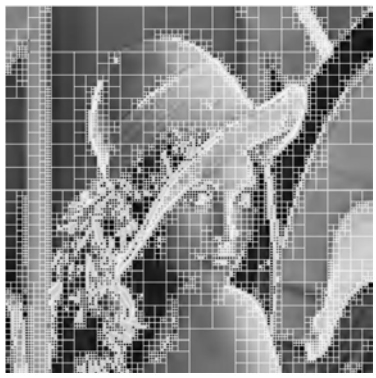

Figure 1. Quad-tree partitioning in the compressed image 'Lena'.

2.2 Mathematical morphology

After dividing the image into blocks, the main operation of the post-processing algorithm can be performed efficiently. In each block, morphological filtering [4] [5] is performed to enhance image quality. The best performing structuring element (SE) and morphological operation pair is determined for each partition block using the sum of absolute differences (SAD) measure between the filtered and the original image blocks. The algorithm selects the best filter as the one which minimizes the sum of absolute differences between the two blocks with "no filtering at all" being a viable option. Gray scale morphology defines gray scale dilation as an operation that selects the maximum pixel value within the mask window (same as the region of

support of the SE), provided that all elements in the SE are equal to zero. Similarly, gray scale erosion is defined as an operation that selects the minimum pixel value within the mask window (same as the region of support of the SE), provided that all elements in the SE are equal to zero. Gray scale dilation and erosion are represented as follows:
Gray scale dilation of f by b: denoted $f \oplus b$, is defined as

$$(f \oplus b)(s, t)=\max\{f(s - x, t - y) + b(x, y) \mid ((s - x), (t - y)) \in D_f;\ (x, y) \in D_b\} \quad (1)$$

Gray scale erosion of f by b: denoted $f \ominus b$, is defined as

$$(f \ominus b)(s, t)= \min\{f(s + x, t+ y) - b(x, y) \mid ((s+x), (t+ y)) \in D_f;\ (x, y) \in D_b\} \quad (2)$$

where D_f and D_b are the domains of f and b, respectively.
Mathematical morphology provides an interesting collection of nonlinear filters with smoothing properties and low implementation complexity, making it more coherent with the presented algorithm. Geometrical structures i.e. shape and size of image objects are frequently crucial features, and so they should be processed by systems that can accurately detect and properly modify them. Mathematical morphological filtering can capture certain characteristics of ringing artifacts and hence be applied with success to filter out these artifacts from the edge structures.
To reduce the complexity and computation time, this study only considers 3x3 SEs and dilation and erosion as morphological filters. This study assessed 16 predefined SEs, shown in Figure 2, covering all possible orientations and used in conjunction with the four fundamental morphological operations, namely dilation, erosion, opening, and closing. For all possible SE and operator combinations, Peak Signal-to-Noise Ratio (PSNR) improvements were measured. Table 1 lists the simulation of mean PSNR improvement achieved by each structural element in Figure 2. Data analysis yields the following guidelines for filter design. Most notably, the experimental results show that SE1 to SE8 are more successful in enhancing the compressed image contaminated with ringing artifacts and that each SE can improve specific features of the compressed image. In its final form as employed in this work, for a quad-tree partition block, the filter can select one of the four SEs (SE7, SE8, SE4, SE1) and use it in conjunction with one of the two morphological operations (dilation, erosion) according to the criterion of achieving the greatest improvement in SAD.

Table 1. Simulation based analysis of mean PSNR improvement achieved by each structural element in Figure 2. (D/E: the better of dilation and erosion, O/C: the better of opening and closing)

	SE1		**SE2**		**SE3**		**SE4**	
Image	**D/E**	**O/C**	**D/E**	**O/C**	**D/E**	**O/C**	**D/E**	**O/C**
F-16	0.10	-0.13	0.09	-0.18	0.13	-0.22	0.12	-0.18
Lena	0.09	-0.11	0.11	-0.16	0.10	-0.13	0.09	-0.14
Tiffany	0.08	-0.14	0.08	-0.17	0.07	-0.15	0.08	-0.16
	SE5		**SE6**		**SE7**		**SE8**	
Image	**D/E**	**O/C**	**D/E**	**O/C**	**D/E**	**O/C**	**D/E**	**O/C**
F-16	0.13	-0.12	0.10	-0.15	0.12	-0.21	0.11	-0.19
Lena	0.09	-0.13	0.08	-0.13	0.14	-0.19	0.12	-0.18
Tiffany	0.07	-0.13	0.06	-0.14	0.09	-0.17	0.07	-0.19
	SE9		**SE10**		**SE11**		**SE12**	
Image	**D/E**	**O/C**	**D/E**	**O/C**	**D/E**	**O/C**	**D/E**	**O/C**
F-16	0.04	-0.26	0.00	-0.38	0.04	-0.25	0.005	-0.37
Lena	0.02	-0.23	0.00	-0.38	0.03	-0.24	0.004	-0.36
Tiffany	0.02	-0.24	0.00	-0.39	0.02	-0.22	0.003	-0.43
	SE13		**SE14**		**SE15**		**SE16**	
Image	**D/E**	**O/C**	**D/E**	**O/C**	**D/E**	**O/C**	**D/E**	**O/C**
F-16	0.02	-0.29	0.02	-0.28	0.03	-0.23	0.02	-0.27
Lena	0.02	-0.28	0.03	-0.25	0.02	-0.26	0.01	-0.31
Tiffany	0.01	-0.24	0.01	-0.23	0.01	-0.28	0.01	-0.32

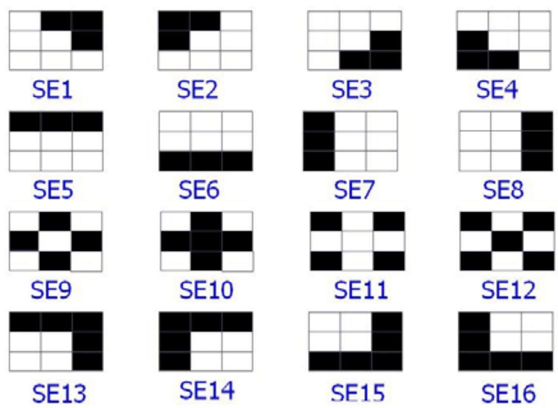

Figure 2. 16 predefined structuring elements.

2.3 encoder and decoder

On the encoding end, this study uses the voting strategy to choose the most suitable filters. That is to say, the encoder post-processor applies all eight morphological filters to each quad-tree partition block in the compressed image and measures the SAD improvement brought about by each filter. The filter leading to the minimum SAD value is selected. To reduce the bandwidth required by the side-information, the sequence of filter choices must be further encoded in a lossless manner. On the decoding end, once the decoder post-processor recovers the exact filter information, it applies the selected morphological filters to each block.

The post-processing algorithm can be summarized as follows:

At the encoder:

Input: Original image P, compressed image P', quad-tree partition threshold, minimum block dimension, edge map E and morphological operations (four SEs with both dilation and erosion) OP(1) ~ OP(8).

Output: Side information for filter against ringing artifact.

Step 1: Partition P' into unequal-sized blocks using quad-tree partition, and check whether the edge information in quad-tree partition (QT) is the same as E. If so, partition P using QT and go to step 2. Otherwise, change threshold and repeat step 1. (The edge map E is a bit map generated using the Canny edge detector. The edge information is also a bit map derived/extracted from QT that all 2x2 and 4x4 blocks represent as 1 and the other blocks represent as 0. If all 1 in E is higher than 90 % subset of 1 in edge information of QT, it can conclude that QT is the same as E.)

Step 2: Calculate the sum of absolute differences for every block of QT, $Diff(i) = \sum_{i} abs(P(x,y) - P'(x,y))$, where (x, y) are the coordinates of a pixel in the ith block. The summation is taken over all pixels in the ith block.

Step 3: Select an unprocessed block P' (i) and apply all eight morphological filters. Save the outputs from all eight filters, say MP'(1) ~ MP'(8).

Step 4: Sort MP'(k) by $\sum_{i} abs(MP'(x,y) - P(x,y))$, where (x, y) are the coordinates of a pixel in the ith block, select the filter number k for MP'(k) yielding the smallest SAD, and check whether the block SAD is smaller than Diff(i). If so, record the filter number. Otherwise, leave the block unchanged.

Step 5: Repeat starting from step 3 until all blocks are processed.

Step 6: Compress the filter information by entropy coding.

At the decoder:

Input: Compressed image P', threshold of quad-tree partition, minimum block dimension, and the sequence of morphological filters determined by encoder side post-processing

Output: Filtered image Q

Step 1: Copy P' to Q.

Step 2: Partition P' into unequal-sized blocks using quad-tree partitioning in a manner identical to the encoder side post-processing.

Step 3: Select an unprocessed block P'(i) and apply the signaled morphological filter to it. Assume that the filtered block is MP'(k).

Step 4: Replace the corresponding block in Q with MP'(k). However, if the side information of this block indicates that no suitable predefined filter exists, leave the block unchanged.

Step 5: Repeat starting from step 3 until all blocks are processed.

The algorithm uses (2, 4, 8…. 256, 512) as dimension threshold and uses (20, 40, 60, 80, 100) as partition threshold. If algorithm begins from (512, 100), the "change threshold " step will decide next threshold in one of (256, 80), (256, 100), (512, 80). The criterion is depending on result of total 1 bit in QT and E. If all 1 in E is higher than 90 % subset of 1 in edge information of QT, it can conclude that QT is the same as E. The number of bits needed to represent the side information associated with the filter against ringing artifact can be expressed as:

$$Bring = (Nn + \ldots\ldots + N4 + N2)*Bse \quad (3)$$

Where Nn represents the number of nxn blocks. The value of Bse depends on the number of SEs, and can be represented as:

$$Bse = ceil(\log2((2*\text{number of SEs}) + 1)) \quad (4)$$

where ceil(.) is the ceiling function, rounding all positive real numbers to the nearest integer equal to or greater than its argument. The multiplicative factor 2 is required due to the allowed use of both dilation and erosion operations with each SE, and the additive term 1 is required due to the option of not using any kind of filtering at all for a particular block. Equations 3 and 4 provide an upper bound on what can be achieved by an entropy coder acting on the side information. It can use the correlation structure of filter choices in neighboring blocks and look into exploiting such correlation to advantage for reducing the amount of side information through actual entropy coding based on predictive coding.

3. Simulation results

This section demonstrates some simulation results on the proposed post-processing algorithm. As described above, this work uses quad-tree partitioning as a preliminary step of the proposed post-processing algorithm. Two parameters strongly influence the quad-tree partition in the system described here. The first parameter is the partition threshold; the smaller the threshold is, the more blocks the image is divided into. The second parameter is the minimum block size. Generally, smaller blocks can preserve finer image features than larger blocks.

Two different objective measures were employed in our simulations for quantitative performance evaluation. The one is PSNR that is the classical measure, and the other is VRM which aims to quantify the amount of ringing in a given image consistent with human visual perception.

In this study some experiments were conducted on 512 x 512 grayscale images with 8 bits per pixel. A total of eight morphological filters were used. The minimum block size was set to 2 and partition threshold was set to 100. Lena image filtered by the proposed method is illustrated in Figure. 3. In these figures, the original image, the compressed image (compressed by JPEG2000), the filtered image, and another compressed image (again by JPEG2000) at a higher bit-rate to account for the side information overhead are shown. Note that, the visual quality of the filtered images is also enhanced. This study also lists the related objective measures, PSNR and VRM, in Tables 2.

(a) (b)

(c) (d)

Figure 3. (a) Lena, (b) compressed image (0.096 bpp, 28.63 dB), (c) filtered image (0.153 bpp, 30.39 dB), and (d) JPEG2000 compressed image at a bitrate accounting for the side information overhead (0.153 bpp, 30.08 bpp).

Table 2. Simulation results on the image "Lena".
Column(A):PSNR of image compressed by JPEG2000
Column(B):PSNR of image compressed by JPEG2000 with deringing
Column(C):PSNR of image deringed by our method
Column(D):VRM of image deringed by our method
Column(E):VRM of image compressed by JPEG2000 with deringing

Bit-rate (bpp)	A(dB)	B(dB)	C(dB)	D(dB)	E(dB)
0.046	25.94	28.63	29.14	10.32	10.56
0.080	27.94	29.93	30.36	10.37	10.55
0.096	28.66	31.08	30.39	10.29	10.38
0.149	30.34	31.53	31.72	10.49	10.55

4. Conclusions

As the compression ratio exceeds 12:1, the compressed images by JPEG2000 develop ringing artifacts. The proposed filter against ringing artifact is simpler and only needs 1.9% of additions, 0% of multiplications, and 8.2% of comparisons for each image in comparison with JPEG2000 VM 7.0 deringing filter [2]. The proposed method can efficiently eliminate ringing artifact for images coded at different bit rates without requiring a large computation overhead. Owing to its low complexity, the proposed filter is very suitable for hardware implementation.

The main attribute of the proposed algorithm is that it can, to a large extent, preserve the image information while smoothing out ringing artifacts. For regions with strong texture and edge detail, we perform the above introduced quad-tree partitioning and utilize information from an edge detector so as to avoid loss of edge information. For removing ringing artifacts from images, the proposed voting strategy can select the best morphological filter that can significantly improve the quality of the reconstructed images, in terms of both VRM and PSNR. Also, the fidelity restoration (PSNR increase) typically enabled by the filter proposed against ringing artifacts makes it a promising approach for stretching the applicability of wavelet based image compression to lower bit-rates.

References

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