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A Simple Approach to Improve the Performance of JPEG
(一個簡單有效改善 JPEG 壓縮性能的方法)

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Abstract
In this paper, a simple approach to improve the performance of JPEG is proposed. Note that in the JPEG ac quantized coefficients in high-frequency region generally have zero or little energies and thus they contribute nothing or little to PSNR (peak signal-to-noise ratio). It implies that the bit rate can be reduced by discarding some high-frequency ac coefficients with no or little loss in PSNR. Based on the idea, we incorporate the concept of zonal coding into the JPEG. This proposed approach is termed as zonal JPEG. In the proposed zonal JPEG, the coding scheme is identical to the JPEG except only a fixed number of coefficients are coded for each image block. Consequently, the proposed coding approach is totally compatible with the JPEG. Besides, the proposed zonal JPEG has two advantages over the traditional JPEG: (i) better bit rate utilization and (ii) achievable user-defined PSNR. These two advantages have been verified and confirmed by the simulation results.

Keywords: JPEG, PSNR estimation, bit rate reduction

1. Introduction
Up to present, the image coding standard JPEG [1] has been extensively applied in many applications such as digital camera, multimedia systems, and so forth. Though a new coding standard JPEG 2000 [2-3] has been proposed, the JPEG is still popular currently. The coding scheme in the JPEG is also a fundamental in video coding standards like MPEG1, MPEG2, H.261, and H.263 [4]. Consequently, a more effective JPEG coder could benefit storage or bandwidth utilization for a period of time before the new standard JPEG2000 prevails over the image coding community.

Recently, several approaches to improve the performance of JPEG have been reported. Here, we simply concentrate on those approaches whose outputs are totally compatible with the JPEG. In [5], the quantization matrix used in the JPEG is designed based on rate-distortion optimization. In general, this approach increases much computational complexity. Moreover, the optimized quantization matrix needs to be recalculated for different images. In [6], the quantization matrix used in the JPEG is determined by a human visual system model. Based on a modulation transfer function, the elements in a quantization matrix are modified. Then the modified quantization matrix is used in the coding process. As in [5], the approach has the problem to recalculate the quantization matrix when the input image is changed. In [7], for each ac coefficient a global threshold is found where the probability density function is assumed Laplacian. Then the global threshold is applied in quantizing the corresponding coefficient. If the coefficient is no less than the threshold, quantize it. Otherwise, set it to zero. The quantization matrix used in [7] is obtained by the optimization method presented in [8]. Therefore, the approach given in [7] is inherent with similar problems as in [5].

In this paper, we propose a simple approach to improve the performance of JPEG in two ways: (i) to utilize the bit rate more effectively and (ii) to make user-defined PSNR possible.
Note that ac coefficients in the high-frequency region are generally zero or of little energies and therefore contribute nothing or little to PSNR. It implies that the loss in PSNR would be zero or little if some high-frequency coefficients are discarded in the coding process. Consequently, the bit rate utilization can be improved with little PSNR loss. Based on the idea, only \( M \) coefficients for each transformed image block are coded in the proposed JPEG coder, which is termed as zonal JPEG. By this simple modification, the bit rate utilization is improved and a user-defined PSNR is achieved.

This paper is organized as follows. Section 2 a brief review of the JPEG is given and the motivations for the proposed approach is stated. Then, the proposed zonal JPEG is described in Section 3 where the way to estimate a user-defined PSNR is presented as well. In Section 4, examples are provided to justify the proposed zonal JPEG where simulation results are discussed as well. Finally, conclusions are made in Section 5.

2. Review of the JPEG and Motivations

In this section, the JPEG is briefly reviewed first and then the motivations for the proposed zonal JPEG are described.

2.1 The JPEG

The coding process of the JPEG is described in the following. For detail, one may consult [1, 4]. Given an \( L \times L \) 256 gray-level image \( O \), the implementation steps of the JPEG are given as follows.

Step 1. Divide image \( O \) as \( \tau \times \tau \) image blocks \( \{ b_i \} \) where \( L \) is a multiple of \( \tau \) and \( N_b = (L/\tau) \times (L/\tau) \) is the total number of image blocks. Then \( b_i \) is 128-level shifted, i.e., \( b_i = b_i - 128 \).

Step 2. Obtain \( B_i = DCT \{ b_i \} \) where \( DCT \{ \} \) denotes discrete cosine transform [4].

Step 3. Quantize \( B_i \) as \( \bar{B}_i = B_i ./ Q \) where the operation ./ is an element-to-element division and \( Q \) is a quantization matrix with appropriate dimension.

Step 4. Code elements of \( \bar{B}_i, \bar{B}(k,l) \), in the order of zigzag scan as follows: (i) the dc component is coded with DPCM (differential pulse code modulation) scheme and Huffman coding, and (ii) the ac coefficients are coded by RLE (run length encoding) and Huffman coding. When the rest of ac quantized coefficients are zeros, symbol EOB (end of block) is appended to terminate the coding process for the given image block.

Step 5. Continue Steps 2 to 4 until \( N_b \) image blocks are all processed.

Step 6. Calculate the bit rate (bit/pixel), \( BR \), as

\[
BR = \frac{B_u \times 8}{L \times L}
\]  

where \( B_u \) denotes the total number of bytes used in the bit stream obtained in Step 4.

Step 7. Calculate the PSNR of the reconstructed image \( \hat{O} \) as

\[
PSNR = 10 \log_{10} \frac{255^2}{MSE}
\]

where the mean squared error

\[
MSE = \frac{1}{L^2} \sum_{i=1}^{L} \sum_{j=1}^{L} (O(i,j) - \hat{O}(i,j))^2
\]
and \( O(i, j) \), \( \hat{O}(i, j) \) are elements of \( O \), \( \hat{O} \), respectively.

Basically, the coding process of JPEG consists of three stages: (i) to perform 2-D DCT transform, (ii) to quantize transform coefficients, and (iii) to code quantized transform coefficients. A reason to employ DCT transform in Stage (i) is the energy compaction property which means the transform coefficients of lower frequencies generally have larger energies than those in higher frequencies. Based on the energy compaction property, the zigzag scan is developed whose order is descending from low frequency to high frequency. As for Stage (ii), note that from a perception viewpoint, transform coefficients have different significance or visual sensitivities. The low-frequency coefficients usually are far more sensitive than the high-frequency coefficients. This property of HVS (human visual system) can be utilized in the coding process through weighting transform coefficients. An HVS weighting matrix for \( 8 \times 8 \) DCT coefficients can be found in [9]. In the JPEG, the HVS property is reflected in quantization matrix \( Q \) as given below in (4) where the low-frequency coefficients are finely quantized and the high-frequency coefficients coarsely quantized. After Stages (i) and (ii), many quantized ac coefficients reduce to zero, especially for high-frequency coefficients. Consequently, there is a high possibility to have a sequence of zeros in the region of higher frequencies. Therefore, in Stage (iii) the RLE, with the zigzag scan order, is used to effectively code zeros and the symbol EOB to deal with the zeros at the end of blocks. Note that all quantized transform coefficients are coded in the JPEG.

\[
Q = \begin{bmatrix}
16 & 11 & 10 & 16 & 24 & 40 & 51 & 61 \\
12 & 12 & 14 & 19 & 26 & 58 & 66 & 74 \\
14 & 13 & 16 & 24 & 40 & 57 & 69 & 76 \\
14 & 22 & 29 & 51 & 87 & 80 & 62 & 77 \\
18 & 22 & 29 & 51 & 87 & 109 & 103 & 77 \\
24 & 35 & 55 & 64 & 81 & 104 & 113 & 92 \\
49 & 64 & 78 & 87 & 103 & 121 & 120 & 101 \\
72 & 92 & 95 & 98 & 112 & 100 & 103 & 99 \\
\end{bmatrix}
\]

(4)

### 2.2 Motivations

The motivations for the proposed approach are described in the following. Note that the difficulty to apply the Parseval’s theorem [4] in the estimation of user-defined PSNR is mainly because no coefficient selection scheme is used in the JPEG. That is, different image blocks generally have different number of transform coefficients coded in the JPEG. Consequently, it is hard to trim transform coefficients such that a user-defined PSNR is met. By contrast, it would be easy if a selection scheme is applied such that only \( M \) transform coefficients are selected for each image block. In general, any selection approach will do as long as \( M \) transform coefficients are selected in each image block. However, a selection scheme that chooses significant transform coefficients is preferred when the PSNR is under consideration. In other words, the selection scheme should choose transform coefficients of higher energies first and then those of lower energies in the descending order. As described in Section 2.1, the order of zigzag scan in the JPEG is also the significance order of transform coefficients in general. Thus the coefficient selection scheme used in the proposed approach is based on the zigzag scan order. That is, the \( M \) transform coefficients for each image block are selected in the zigzag scan order. Since the concept of coefficient selection is similar to the zonal coding [10-11], the proposed modified JPEG is thus termed as the zonal JPEG which is able to meet a user-defined PSNR by adjusting parameter \( M \).

The selection scheme used in the zonal JPEG also provides a way to better bit rate utilization. As described in Section 2.1, many quantized ac coefficients in the high-frequency region reduce to zero. If some non-zero ac coefficients are sparsely located among zero ac
coefficients, the zeros between non-zero coefficients need to be coded in the JPEG. The purpose of coding zeros is to track the locations of transform coefficients appropriately for the correct decoding. Though the RLE is effective on coding zero ac coefficients, it, however, contributes nothing to PSNR improvement. Moreover, note that the energies in quantized coefficients are generally in the descending order from lower frequencies to higher frequencies because of the energy compaction property of DCT and HVS consideration in the quantization matrix $Q$. Therefore, non-zero ac coefficients in the high-frequency region are generally of little energies and thus have little improvement on PSNR. It suggests that by the proposed selection scheme the bit rate utilization can be improved with little PSNS loss, if an appropriate $M$ is given.

3. The Proposed Zonal JPEG

This section is divided into two subsections. In Section 3.1, the zonal JPEG modified from the JPEG is described. Next, the way to estimate a user-defined PSNR through parameter $M$ is given in Section 3.2.

3.1 The zonal JPEG

The zonal JPEG, which is modified from the JPEG, is introduced here. The coding process of the zonal JPEG is identical to the JPEG except that for each image block only $M$ transform coefficients are selected, quantized, and coded. That is, the only difference in the coding process between the JPEG and the zonal JPEG is Step 4 given in Section 2.1. In the zonal JPEG, Step 4 is modified as follows:

Step 4’. By the zigzag scan order, the first $M$ coefficients are selected and coded. The ways to code dc and ac coefficients are identical to that given in Step 4 in Section 2.1.

Though the modification is simple, at least three advantages can be achieved by the zonal JPEG. First, the zonal JPEG is able to meet a user-defined PSNR which is generally difficult for the JPEG. Second, the zonal JPEG has better bit rate utilization than the JPEG. Third, the zonal JPEG is totally compatible with the JPEG since the format of bit stream in the zonal JPEG is identical to that obtained in the JPEG. In the case of $M = 64$, the zonal JPEG becomes the traditional JPEG. The advantages described here will be justified later in Section 4 through examples.

3.2 Estimation of user-defined PSNR

Given a quantization matrix $Q$, in the JPEG it is not easy to obtain a reconstructed image of user-defined PSNR. However, in the proposed zonal JPEG a user-defined PSNR for a reconstructed image can be easily achieved by the estimation of $M$. The estimation of PSNR through parameter $M$ is described as follows. In the discussion, the image size is assumed $L \times L$ and image block size $\tau \times \tau$.

Note that DCT is an orthogonal transform and therefore is of energy-invariant property which gives

$$
\sum_{i=1}^{N_b} \sum_{m=1}^{\tau} \sum_{n=1}^{\tau} b_i^2 (m,n) = \sum_{k=1}^{N_b} \sum_{l=1}^{\tau} \sum_{l=1}^{\tau} B_i^2 (k,l)
$$

where $N_b = (L/\tau) \times (L/\tau)$ is the total number of image blocks and $b_i(m,n), B_i(k,l)$ are elements of $b_i, B_i$, respectively. For clear presentation, the 2-D index is converted into 1-D index with the zigzag scan order, as shown in Figure 1 where $\tau = 8$. With the 1-D index given in Figure 1, (5) can be rewritten as

$$
\sum_{i=1}^{N_b} \sum_{k=1}^{\tau} b_i^2 (k) = \sum_{k=1}^{N_b} \sum_{l=1}^{\tau} B_i^2 (k)
$$

(6)
Since the energy loss in the JPEG results from the quantization in matrix $Q$, for a given $M$ the energy loss in the transform domain can be shown as

$$E_M = \sum_{i=1}^{N_x} \sum_{k=1}^{N_y} B_i^2(k) - \sum_{i=1}^{N_x} \sum_{k=1}^{N_y} \overline{B}_i^2(k)$$

(7)

where $\overline{B}(k)$ are elements of $\overline{B}$ obtained from Step 3 in Section 2.1. In the light of Parseval’s theorem, $E_M$ is also the squared error in the spatial domain. Therefore, the MSE for the given $M$ can be estimated as

$$MSE_M = \frac{E_M}{L \times L}$$

(8)

Then the PSNR for the given $M$ is found as

$$PSNR_M = 10 \log \frac{255^2}{MSE_M}$$

(9)

For a given $PSNR_M$, $MSE_M$ can be easily obtained from (9) as

$$MSE_M = 255^2 \sqrt{10^{-0.1 \times PSNR_d}}$$

(10)

With (7), (8) and (9), it is easy to find the least number of $M$ to meet the user-defined PSNR, $PSNR_d$. Note that (9) also restricts the admissible range of $PSNR_d$. The minimum $PSNR_d$ is $PSNR_1$ and the maximum $PSNR_{64}$ for the case of $\tau = 8$. Given a user-defined PSNR, the way to find parameter $M$ is summarized as follows:

Step 1. Calculate $PSNR_1$ and $PSNR_{64}$.

Step 2. Check if $PSNR_d$ is within the range between $PSNR_1$ and $PSNR_{64}$. If yes, go to Step 3. Otherwise, display an error message and stop.

Step 3. Calculate the $MSE_d$ corresponding to the $PSNR_d$ by replacing $PSNR_M$ in (10) with the $PSNR_d$.

Step 4. By (7), (8), and (10), find the least number of $M$ such that $MSE_M$ is less than $MSE_d$.

Step 5. Save the $M$ and stop.

In case $PSNR_d$ is out of the range between $PSNR_1$ and $PSNR_{64}$, a possible solution is to scale quantization matrix $Q$.

4. Simulation Results and Discussions

In this section, simulation results are provided to verify the proposed zonal JPEG. In the simulation, four test images are used: Lena, Baboon, Peppers, and Goldhill. They are shown in Figures 2 to 5, respectively. All test images are of size $512 \times 512$ and image blocks of size $8 \times 8$, that is, $L = 512$ and $\tau = 8$. The default settings for the JPEG are used in the simulation. For details, one may consult [1, 4]. With these simulation conditions, the estimation approach of user-defined PSNR is justified in Section 4.1. Then the investigations on bit rate reduction and on the tradeoff between PSNR and BR in the zonal JPEG are given in Section 4.2.

4.1 Tests on user-defined PSNR estimation

The estimation of user-defined PSNR described in Section 3.2 is justified in this subsection. By the steps given in Section 3.2, The simulation results for images Lena, Baboon, Peppers, and Goldhill are, respectively, recorded in Tables 1 to 4 where $PSNR_d$ denotes as the user-defined PSNR, $PSNR_e$ as the estimated PSNR, $PSNR_a$ as the actual PSNR.
obtained from the zonal JPEG, $M_e$ as the estimated value of $M$, and $\Delta \text{PSNR}$ as $\text{PSNR}_e - \text{PSNR}_d$. From the simulation results shown in Tables 1 to 4, $\text{PSNR}_e$ and $\text{PSNR}_d$ are identical to each other as expected. Thus the estimation approach described in Section 3.2 is verified. As for $\Delta \text{PSNR}$, the difference between $\text{PSNR}_e$ and $\text{PSNR}_d$ is generally getting smaller as $M_e$ increases. The result implies that the transform coefficients in the higher frequency region generally have less effect on PSNR than that in lower frequency region. Consequently, there is a better match between $\text{PSNR}_e$ and $\text{PSNR}_d$ for cases with larger $M$. Though $\Delta \text{PSNR}$ is large in some cases with small $M$, the proposed approach to estimate $\text{PSNR}_d$ is still feasible, since for an acceptable reconstructed image the value of $M$ can not be small in general. Finally, consider $M_e$. Note that the bit rate is proportional to $M_e$, i.e., a larger $M_e$ results in higher bit rate. It implies that the bit rate can be reduced if $\text{PSNR}_d$ less than $\text{PSNR}_{64}$ is specified. The discussions on the tradeoff between PSNR and BR are given in the following section.

### 4.2 Tradeoff between PSNR and BR

This subsection is to demonstrate that the proposed zonal JPEG has better bit rate utilization than the JPEG where the tradeoff between PSNR and BR in the zonal JPEG is investigated. The simulation is performed as follows. First, the JPEG coding process is applied to images Lena, Baboon, Peppers, and Goldhill whose PSNR are obtained as 36.4003 dB, 28.1197 dB, 34.7112 dB, and 33.5758 dB, respectively. The reconstructed images are given in Figures 6 to 9, respectively. Next, the BR for images Lena, Baboon, Peppers, and Goldhill are found as 1.0641, 1.6479, 1.0996, and 1.2365, respectively. Then, all four images are coded by the proposed zonal JPEG with various values of $M$ at 8, 16, 24, 32, 40, 48, 56, and 64 where the bit rate for a given $M$ is denoted as $\text{BR}_M$. All $\text{PSNR}_e$ and $\text{BR}_M$ for images Lena, Baboon, Peppers, and Goldhill are, respectively, depicted in Figures 10 to 17 where the corresponding PSNR and BR obtained from the JPEG, are also indicated for comparison. From Figures 10 to 17, the simulation results indicate that the coefficients in higher frequency region have very little contribution to PSNR. Take an example. For image Lena, with 1-D index in Figure 1 the 41st to 64th coefficients almost have no improvement on PSNR since $\text{PSNR}_{64} = 36.3971$ dB is almost identical to $\text{PSNR}_{64}$ as shown in Figure 10. On the other hand, from $\text{BR}_{40}$ depicted in Figure 11 the difference between $\text{BR}_{40}$ and $\text{BR}_{64}$ is 0.2313. Note that $\text{PSNR}_{64}$ and $\text{BR}_{64}$ are for the JPEG. Thus, it comes to the conclusion that the JPEG pays 0.2313 of BR to improve 0.0032 dB on PSNR in this case. Or it can be said that the proposed zonal JPEG is able to trade 0.0032 dB of PSNR with 0.2313 bit rate reduction when compared with the JPEG. If more loss in PSNR is acceptable, the bit rate can be reduced more. For images Peppers and Goldhill, similar results are found. Even for image Baboon which is of high activity, the proposed zonal JPEG is able to trade 0.1491 dB of PSNR with 0.1729 in BR reduction when compared with the JPEG. The simulation results indicate that the JPEG wastes too much bit rate on the coding of high-frequency coefficients while the proposed zonal JPEG avoids it. As a rule of thumb, the reconstructed image with $M = 40$ is almost as good as that obtained from the JPEG for most of cases. For the case of $M = 40$, the reconstructed Lena, Baboon, Peppers, and Goldhill for the zonal JPEG are shown in Figures in 18 to 21, respectively. As described, the results are quite close to those in Figures 6 to 9.

5. Conclusions
In this paper, we propose a simple approach to improve the performance of JPEG. The coding process of the proposed approach is identical to the JPEG except that only \( M \) coefficients are coded in each image block. Since the scheme is similar to the zonal coding, the proposed approach is called zonal JPEG. The zonal JPEG is totally compatible with the JPEG since the format of bit stream is same as that in the JPEG. Though the modification is simple, the zonal JPEG, however, has at least two advantages over the JPEG. First, the bit rate utilization is more effective. In the zonal JPEG, it is possible to trade very little PSNR with significant bit rate reduction when compared with the JPEG. Second, a user-defined PSNR, if required, can be met by the zonal JPEG. That is, the zonal JPEG is able to provide a reconstructed image with some given PSNR as the user demands. If the PSNR is not specified, in our experiments a satisfactory reconstructed image can be achieved with \( M = 40 \) generally. Those two advantages have been justified by the simulation. The simulation results have confirmed the ideas in the proposed zonal JPEG.

References
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Table 2. $PSNR_d$, $PSNR_e$, $PSNR_a$, and $M_e$ for image Baboon

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Table 4. $PSNR_d$, $PSNR_e$, $PSNR_a$, and $M_e$ for image Goldhill

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Figure 1. 2D-to-1D index conversion with the zigzag scan order.

Figure 2. Original Lena

Figure 3. Original Baboon

Figure 4. Original Peppers

Figure 5. Original Goldhill
Figure 6. Reconstructed Lena (JPEG)

Figure 7. Reconstructed Baboon (JPEG)

Figure 8. Reconstructed Peppers (JPEG)

Figure 9. Reconstructed Goldhill (JPEG)

Figure 10. $PSNR_M$ for Lena

Figure 11. $BR_M$ for Lena
Figure 12. $PSNR_M$ for Baboon

Figure 13. $BR_M$ for Baboon

Figure 14. $PSNR_M$ for Peppers

Figure 15. $BR_M$ for Peppers

Figure 16. $PSNR_M$ for Goldhill

Figure 17. $BR_M$ for Goldhill
Figure 18.  Reconstructed Lena
(Zonal JPEG,  $M = 40$)

Figure 19.  Reconstructed Baboon
(Zonal JPEG,  $M = 40$)

Figure 20.  Reconstructed Peppers
(Zonal JPEG,  $M = 40$)

Figure 21.  Reconstructed Goldhill
(Zonal JPEG,  $M = 40$)