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Minimum entropy and histogram-pair based JPEG image reversible data hiding

Guorong Xuan [a,*], Xiaolong Li [b], Yun-Qing Shi [c]

[a] Dept. of Computer Science, Tongji University, 1239 Siping Rd., Shanghai 200092, China
[b] Institute of Information Science, Beijing Jiaotong University, Beijing 100044, China
[c] Department of Electrical and Computer Engineering, New Jersey Institute of Technology, 323 M. L. King Blvd. Newark, NJ 07102, USA

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ABSTRACT

In this paper, based on the block entropy in the spatial domain obtained by summing the squares of all AC coefficients of each 8×8 block, a reversible data hiding (RDH) scheme for JPEG images is presented which selects the DCT blocks with minimum entropy for RDH. This scheme applies Parseval theorem and entropy principle to achieve the minimum entropy in the spatial domain. It embeds data into the DCT coefficients based on a histogram–pair RDH scheme using histogram shifting. Moreover, four thresholds including the embedding amplitude threshold, the fluctuation threshold, the lower frequency threshold and the higher frequency threshold, are utilized and adjusted to achieve optimized embedding performance. In particular, the proposed scheme does not embed data into zero-valued DCT coefficients, and can obtain optimal PSNR with relatively small file-size increase. Experimental results have demonstrated that, compared with the prior arts, the quality of proposed marked image is higher, and the file-size increase after RDH is less as well.

1. Introduction

Reversible data hiding (RDH) is a special type of information hiding. With RDH, besides the embedded secret data, the cover medium can be recovered from the marked data as well. So far, there is a rapid increase of applications utilizing RDH, and several examples have been reported in the literature including image authentication, medical image processing, video error-concealment coding, stereo image coding, and data coloring in the cloud [1]. Many effective RDH methods have been proposed nowadays [1–10]. However, most of them are developed for uncompressed images in BMP format, only a few works are devoted to JPEG image RDH. As known, JPEG is the most popular image format and JPEG images are widely used in the reality. In this light, JPEG images are ideal covers for RDH, and the JPEG image RDH is highly desired. In this work, we consider JPEG images as covers and propose an efficient JPEG image RDH scheme.

Most current JPEG image RDH methods are implemented by modifying the DCT coefficients since the histogram of DCT coefficients has a Laplace-like distribution which is an ideal carrier for RDH. In [11], the authors proposed to modify the quantization table to achieve reversibility. In [12], the embedding capacity of [11] is increased by using a new quantization table in which certain quantization table entries are divided by an integer. In [13], the secret data is embedded into the cover image via modifying the quantization table and adjusting the length of consecutive zero coefficients. In [14], a histogram-pair based method is proposed in which an optimization strategy is applied to optimize the embedding performance by selecting the expansion bins and the embedding amplitude. In [15], the method [14] is improved by exploiting the smooth blocks using the variance of DC coefficients. In [16], a new method is proposed aiming at minimizing the file-size increase by using rate-distortion optimization. In [17], the data embedding is realized by modifying AC coefficients, in which only non-zero AC coefficients are modified. In addition, the smooth blocks are exploited in [17] to further improve the embedding performance. Here, for a block, its smoothness is measured by counting the number of zero-valued AC coefficients in the block.

Besides the visual quality, the marked image's file-size increase is another important criterion for JPEG images RDH. That is, the size of the marked image is larger than that of the cover image, and the file-size increase should be as small as possible. Moreover, it should be mentioned that, the overflow/underflow for uncompressed images, is no longer a problem for JPEG images RDH since the data embedding is directly implemented in the DCT domain.

* Corresponding author.
E-mail addresses: grxuan@tongji.edu.cn, xuanguorongtj@126.com (G. Xuan), lixl@bjtu.edu.cn (X. Li), shi@njit.edu (Y.-Q. Shi).

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Table 1
Data embedding into Lena JPEG image with QF = 80 and S = −1.

Payload (bpp)	# of scans	Sequence payload (bit)	Stop location (bit)	T	S	Time (s)
0.01	1	1369		1		0.10
	2	1252			−1	0.17
	Total	2621	6398			0.27
0.02	1	2582		1		0.32
	2	2660			−1	0.39
	Total	5242	14,521			0.71
0.03	1	3908		1		0.34
	2	3956			−1	0.41
	Total	7864	23,200			0.75
0.04	1	5303		1		0.38
	2	5182			−1	0.44
	Total	10,485	32,545			0.82
0.05	1	6590		1		0.39
	2	6517			−1	0.46
	Total	13,107	42,792			0.85
0.1	1	3192		−2		0.42
	2	11,647				0.52
	3	11,375			−1	0.61
	Total	26,214	125,007			1.55

Table 2
Results of the proposed method with QF = 80. Here, PL, FS and rate mean the embedded payload, the increased file size to the original JPEG image (in bits) and the rate of increased file size to the payload, respectively.

Lena (original JPEG size 37,937 bytes) QF 80, $S=-1$									
PL (bpp)	T	T_F	T_L	T_H	S	PSNR (dB)	PL (bits)	Inc. FS (bits)	Rate (%)
0.01	1	22	4	10	−1	54.32	2621	2776	6
0.02	1	70	4	11	−1	50.44	5243	5824	11
0.03	1	150	4	13	−1	48.13	7864	9560	22
0.04	1	220	2	14	−1	46.26	10,486	13,512	29
0.05	1	1200	2	14	−1	44.49	13,107	17,536	34
0.1	−2	3500	2	34	−1	37.9	26,214	39,168	49
Barbara (original JPEG size 48,335 bytes) QF 80, $S=-1$									
PL (bpp)	T	T_F	T_L	T_H	S	PSNR (dB)	PL (bits)	Inc. FS (bits)	Rate (%)
0.01	1	22	2	14	−1	53.03	2621	3360	28
0.02	1	50	2	25	−1	48.94	5243	7624	45
0.03	1	170	4	23	−1	46.37	7864	10,920	39
0.04	1	210	2	39	−1	42.75	10,486	16,040	53
0.05	−2	250	2	33	−1	40.4	13,107	19,456	48
0.1	−2	2700	2	29	−1	35.34	26,214	42,712	63
Baboon (original JPEG size 78,677 bytes) QF 80, $S=-1$									
PL (bpp)	T	T_F	T_L	T_H	S	PSNR (dB)	PL (bits)	Inc. FS (bits)	Rate (%)
0.01	1	190	6	14	−1	50.25	2621	3400	30
0.02	1	200	4	21	−1	46.66	5243	6872	31
0.03	1	430	4	20	−1	44.02	7864	11,304	44
0.04	−2	440	3	21	−1	41.35	10,486	15,192	45
0.05	−3	360	4	26	−1	39.16	13,107	17,552	34
0.1	1	1200	2	46	−1	33.60	26,214	37,080	41
Airplane (original JPEG size 38,344 bytes) QF 80, $S=-1$									
PL (bpp)	T	T_F	T_L	T_H	S	PSNR (dB)	PL (bits)	Inc. FS (bits)	Rate (%)
0.01	1	14	5	12	−1	54.01	2621	3080	18
0.02	1	40	5	13	−1	50.7	5243	6304	20
0.03	1	120	4	15	−1	47.92	7864	9512	21
0.04	1	270	2	15	−1	45.92	10,486	13,384	28
0.05	1	470	2	20	−1	44.18	13,107	17,904	37
0.1	−3	2300	2	39	−1	36.15	26,214	37,744	44

As mentioned above, RDH for JPEG images is an important topic while only a few works have been published. In this paper, a novel JPEG image RDH scheme is presented based on a minimum entropy strategy. By applying the histogram-pair based RDH technique, the proposed method modifies the DCT coefficients to embed data, and some new strategies are proposed in this work. Specifically, the variance of each 8×8 DCT block is computed and only the smooth blocks with smaller variance are utilized for data embedding so as to keep the marked image quality high. Moreover, only the DCT coefficients within some specified frequencies are selected for RDH while others are unchanged. Finally, four thresholds including the embedding amplitude threshold, the fluctuation threshold, the lower frequency threshold and the higher frequency threshold, are utilized and adjusted to achieve optimized

Table 3
Results of the proposed method with QF = 70.

PL (bpp)	T	T_F	T_L	T_H	S	PSNR (dB)	PL (bits)	Inc. FS (bits)	Rate (%)
Lena (original JPEG size 29,294 bytes) QF 70, $S = -1$									
0.01	1	20	5	10	−1	51.37	2621	3384	29
0.02	1	30	3	14	−1	47.59	5243	6712	28
0.03	1	80	3	15	−1	45.08	7864	10,096	28
0.04	1	300	2	14	−1	43.06	10,486	14,088	34
0.05	2	300	2	14	−1	39.69	13,107	17,880	36
0.1	−4	3000	3	40	−1	33.02	26,214	38,064	45
Barbara (original JPEG size 38,880 bytes) QF 70, $S = -1$									
PL (bpp)	T	T_F	T_L	T_H	S	PSNR (dB)	PL (bits)	Inc. FS (bits)	Rate (%)
0.01	1	40	5	10	−1	50.74	2621	3368	29
0.02	1	65	3	14	−1	46.7	5243	6656	27
0.03	1	265	4	23	−1	42.42	7864	10,520	34
0.04	1	220	4	21	−1	41.09	10,486	14,504	38
0.05	1	450	4	20	−1	39.55	13,107	18,560	42
0.1	−2	1300	2	39	−1	32.13	26,214	41,464	58
Baboon (original JPEG size 62,536 bytes) QF 70, $S = -1$									
PL (bpp)	T	T_F	T_L	T_H	S	PSNR (dB)	PL (bits)	Inc. FS (bits)	Rate (%)
0.01	1	70	5	14	−1	48.78	2621	3224	23
0.02	1	220	4	14	−1	44.46	5243	6880	31
0.03	1	200	4	21	−1	42.21	7864	10,472	33
0.04	1	300	3	20	−1	40.29	10,486	15,264	46
0.05	1	360	2	23	−1	38.52	13,107	19,208	47
0.1	1	1000	2	31	−1	33.19	26,214	41,120	57
Airplane (original JPEG size 30,636 bytes) QF 70, $S = -1$									
PL (bpp)	T	T_F	T_L	T_H	S	PSNR (dB)	PL (bits)	Inc. FS (bits)	Rate (%)
0.01	1	22	5	9	−1	51.41	2621	3400	30
0.02	1	40	4	15	−1	47.2	5243	6944	32
0.03	1	50	2	30	−1	44.34	7864	10,584	35
0.04	1	150	2	26	−1	42.11	10,486	14,240	36
0.05	−2	320	2	22	−1	39.48	13,107	18,096	38
0.1	3	2500	2	34	−1	32.67	26,214	37,344	42

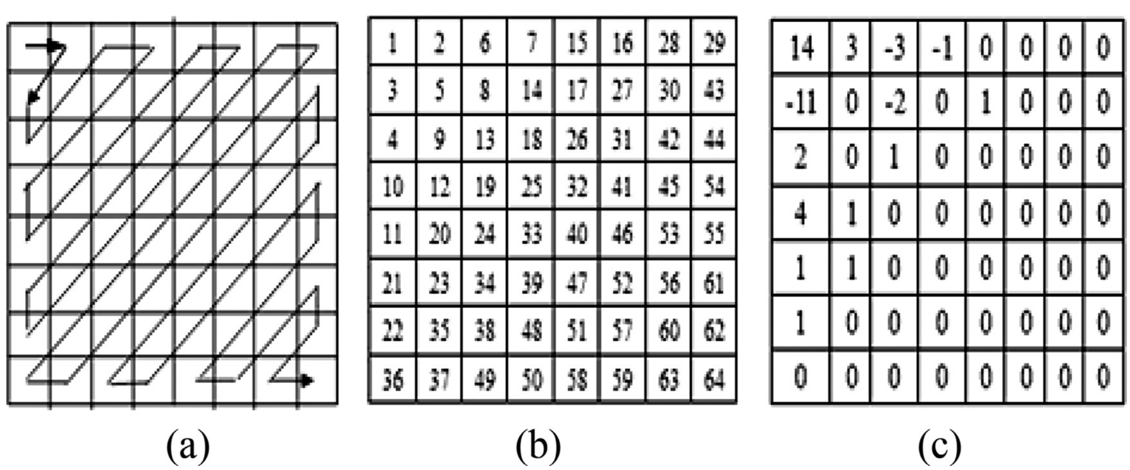

Fig. 1. Example of a DCT block. (a) Scanning order, (b) zigzag sequencing, and (c) quantized DCT coefficients.

embedding performance. Another important characteristic of the proposed method is that, the zero-valued AC coefficients are not utilized in data embedding. This is very helpful for reducing the file-size increase. The superiority of the proposed method has been verified by comparing it with some state-of-the-arts works [13–17].

In the rest of this paper, the proposed method is first presented in Section II. Then, the experimental results and some discussions are reported in Section III. Finally, we conclude our work in the last section.

2. Proposed method

2.1. Minimum entropy based DCT blocks' selection

A successful experience from RDH for uncompressed images is that, it is more suitable to embed data into a smooth image or smooth image areas. This approach has been proved to be effective for JPEG images RDH as well. We also utilize this technique to select smooth DCT blocks in our method.

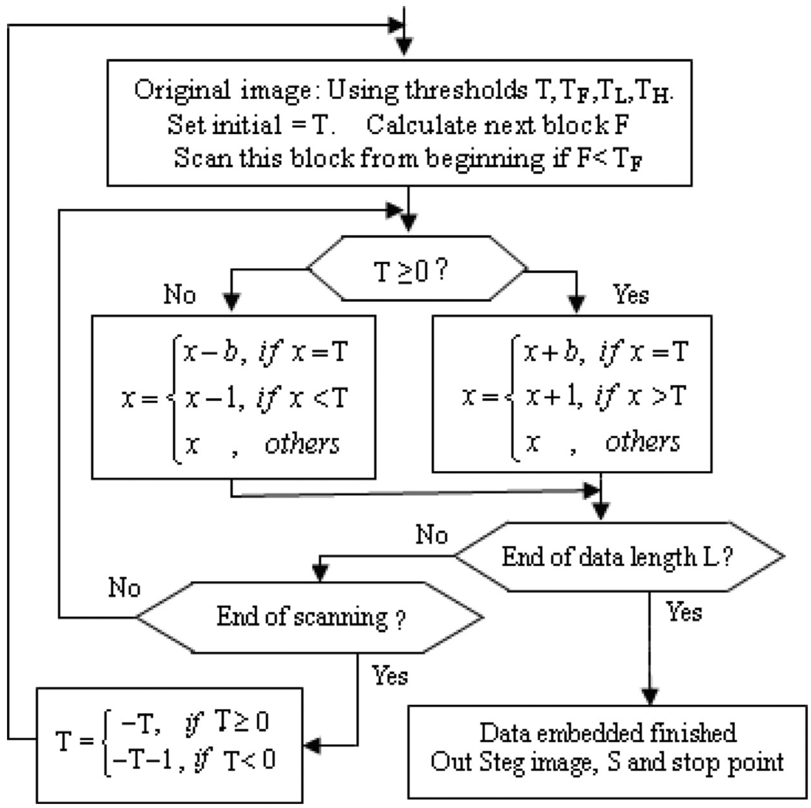

Fig. 2. Proposed data embedding procedure.

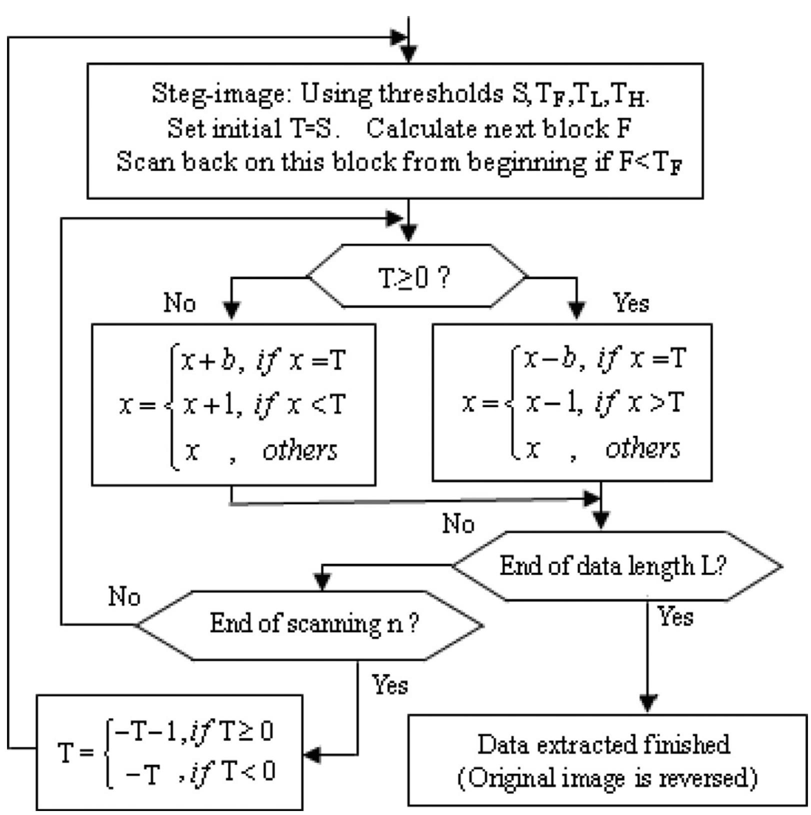

Fig. 3. Proposed data extraction procedure.

(a) Lena (b) Baboon (c) Barbara (d) Airplane

Fig. 4. Four JPEG images.

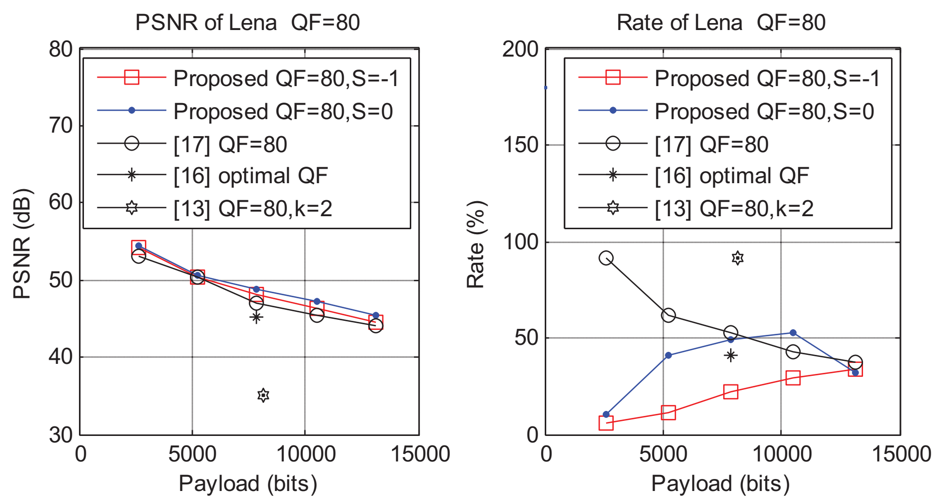

Fig. 5. Comparison of different RDH for Lena with QF = 80.

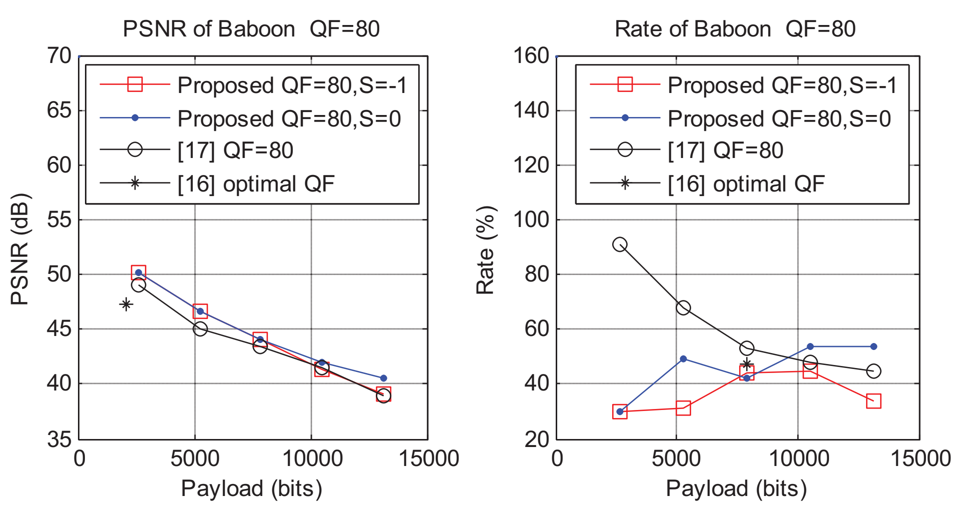

Fig. 6. Comparison of different RDH for Baboon with QF = 80.

Several methods have been proposed in JPEG image RDH to find smooth local areas for data embedding, such as the sorting technique by using the variance of DC coefficients [16] and the smoothness measuring method by using the number of zero-valued AC coefficients in a DCT block [17]. However, the block selection mechanism in this work is designed based on the DCT block entropy that is different from the previous works, and the proposed one is experimentally verified to perform better than the previous ones.

The entropy E under Gaussian distribution is defined as

$$E = \ln\left(\sqrt{2\pi e\sigma^2}\right) \tag{1}$$

where

$$\sigma^2 = \frac{1}{N}\sum_{n=1}^{N}(g_n - \bar{g})^2 \tag{2}$$

and g_n is n-th gray level in the spatial domain, $\bar{g}$ is the mean of g_n and σ^2 is the variance [18, p.244, Eq. 8.8], and N is the number of pixels in the DCT block (i.e., $N = 64$ when taking usual JPEG compression). Then, we use a fluctuation value, denoted by F, to

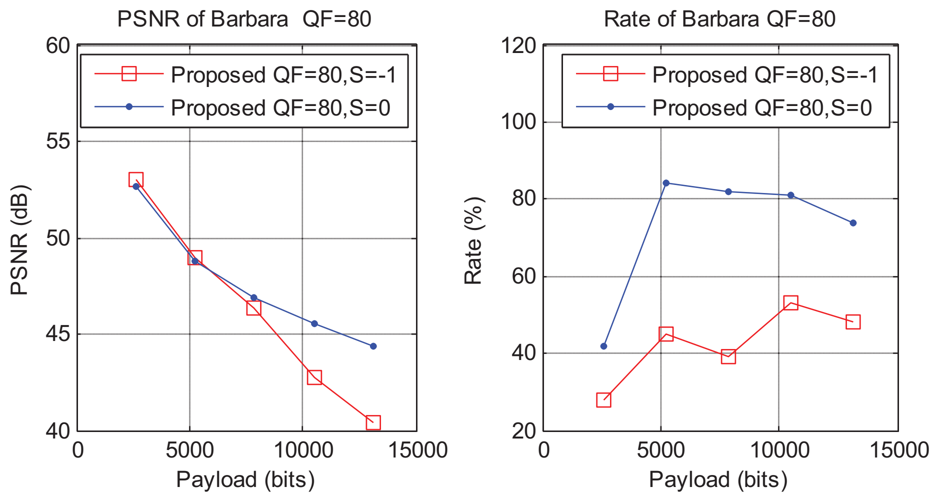

Fig. 7. Comparison of different RDH for Barbara with QF = 80.

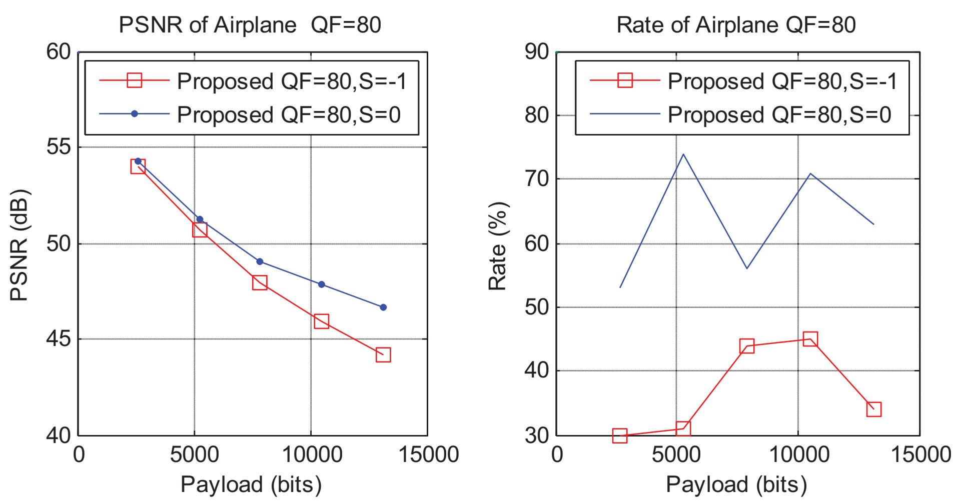

Fig. 8. Comparison of different RDH for Airplane with QF = 80.

measure the smoothness of each block:

$$F = \frac{1}{N}\sum_{k=2}^{N}(x_k)^2 \tag{3}$$

where x_k is the k-th AC coefficient in the DCT block. Notice that the index k in (3) is started from 2, since only AC coefficients are utilized in our scheme for fluctuation computation. One can prove $F = \sigma^2$ by using the Parseval's theorem as shown below. First of all, we see that

$$\sum_{k=1}^{N}(x_k)^2 = \sum_{n=1}^{N}(g_n)^2 \tag{4}$$

Moreover, since the DC coefficient $x_1 = \sqrt{N}\cdot\bar{g}$, then,

$$\left(\sum_{k=1}^{N}x_k^2\right) - (x_1)^2 = \left(\sum_{n=1}^{N}g_n^2\right) - N \times (\bar{g})^2 \tag{5}$$

This yields that

$$F = \frac{1}{N}\sum_{k=2}^{N}x_k^2 = \frac{1}{N}\sum_{n=1}^{N}(g_n - \bar{g})^2 = \sigma^2 \tag{6}$$

As a result, the fluctuation value, F, is just the variance of the block and it can be used for minimum entropy based RDH. Specifically, for a given threshold T_F, only the block with F smaller than T_F will be selected for data embedding, while other blocks are skipped and unmodified.

Moreover, since the data embedding is conducted block by block in a pre-defined order and the data extraction is just processed in a reverse order to guarantee the reversibility, instead of calculating the fluctuation of the block itself, the fluctuation value of each block is computed using the next block in a sequence scanning.

2.2. Histogram-pair based reversible data embedding

The proposed method is implemented via manipulating the histogram generated from the DCT coefficients, and the secret data is embedded based on the histogram-pair method proposed in our previous work [14]. Here, a histogram-pair is defined as two successive bins in the histogram such that one is zero-valued and another is not, i.e., either [h(x)≠0, h($x+1$) = 0] when $x \geq 0$ or [h(x-1) = 0, h(x) ≠0] when $x < 0$. Moreover, an embedding threshold T is used to select the embedding bin. That is to say, when $T \geq 0$, each DCT coefficient larger than T should be shifted towards the right by 1; when $T < 0$, each DCT coefficient smaller than T should be shifted towards the left by 1. Then the secret data can be embedded if the DCT coefficient x is equal to T, i.e., x is updated as $x + b$ if $T \geq 0$, or $x - b$ if $T < 0$, where b is a to-be-embedded binary bit.

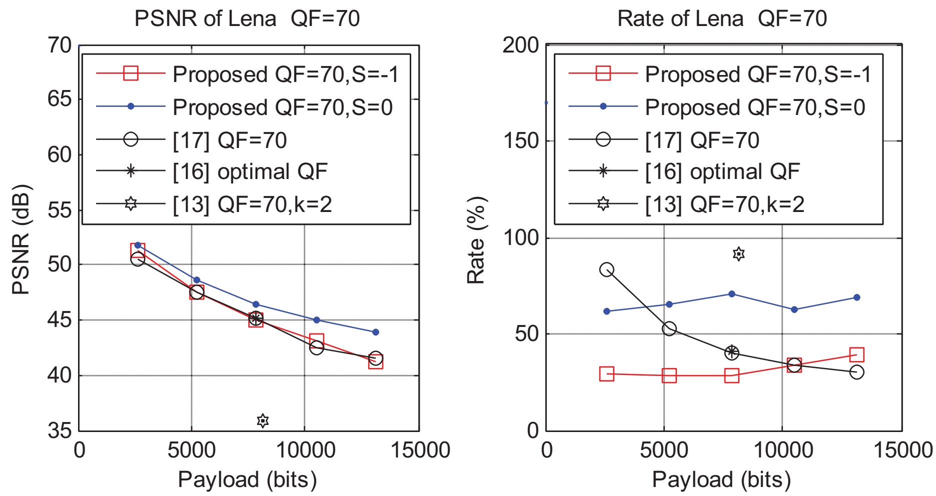

Fig. 9. Comparison of different RDH for Lena with QF = 70.

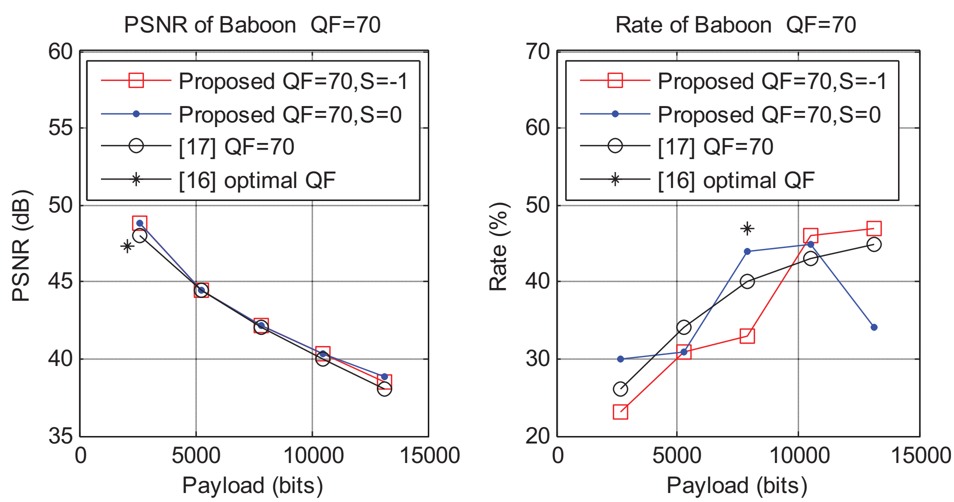

Fig. 10. Comparison of different RDH for Baboon with QF = 70.

If more data need to be embedded, an embedding threshold sequence will be utilized instead of taking only one embedding threshold T. Specifically, in addition to T, a stop threshold denoted S will be used. That is to say, for a given payload and an embedding threshold T, the embedding threshold sequence can be expressed as

$$[T, -T, T-1, -T+1, \ldots, 2, -2, 1, -1, 0] \text{ for } T > 0 \tag{7}$$

or

$$[T, -T-1, T+1, -T-2, T+2, \ldots, 2, -2, 1, -1, 0] \text{ for } T < 0 \tag{8}$$

In (7) and (8), it is clear that the data embedding sequences may end before 0 in the sequences. Then, the secret data is embedded into the cover image by iteratively using the threshold in the sequence until it is fully embedded. That is, a sequence starting at T and ending at S, $[T,\ldots,S]$, will be used as expanded bins such that the payload is just embedded into the cover image. Notice that, the stop threshold S is not necessarily equal to 0.

Moreover, four parameters including T, T_F, T_L and T_H will be used in our method. Then, to derive the best embedding result, the optimal thresholds are determined as follows

$$\{T, T_F, T_L, T_H\} = \underset{\text{Given Payload}}{\arg\max} \ (\text{PSNR}) \tag{9}$$

As mentioned before, there are many possible combinations of threshold values. However, in order to achieve the best possible PSNR, it is necessary to find and use appropriate threshold values based on the required payload. Such appropriate threshold values can be found by iteratively adjusting the threshold values in order to produce improved PSNR for our required payload.

The parameters T and T_F are already described in the context above. Here, T_L and T_H are two thresholds for selecting the frequencies, i.e., only DCT coefficients with frequencies in the range of $[T_L, T_H]$ will be selected for data embedding. For example, in Fig. 1(c), by zigzag scanning, the first 21 DCT coefficients are [14,3,−11,2,0,−3,−1,−2,0,4,1,1,1,0,0,0,1,0,0,1,1] and the remaining 43 DCT coefficients are all zeroes. If $T_L = 4$ and $T_H = 13$, then as shown in Fig. 1(c), the secret data are only embedded into the coefficients [2,0,−3,−1,−2,0,4,1,1,1].

After the histogram is generated by using the selected DCT coefficients, the data embedding will be implemented based on the histogram-pair method. The data embedding and extraction procedures are illustrated in Fig. 2 and Fig. 3, respectively.

We now describe the data embedding procedure with the given thresholds T, T_F, T_L and T_H.

Step 1: Scan the whole image from left to right and from top to bottom. For each selected DCT coefficient x, we use Eq. (6) to compute F. If $F > T_F$, skip the coefficient and move to the next one.

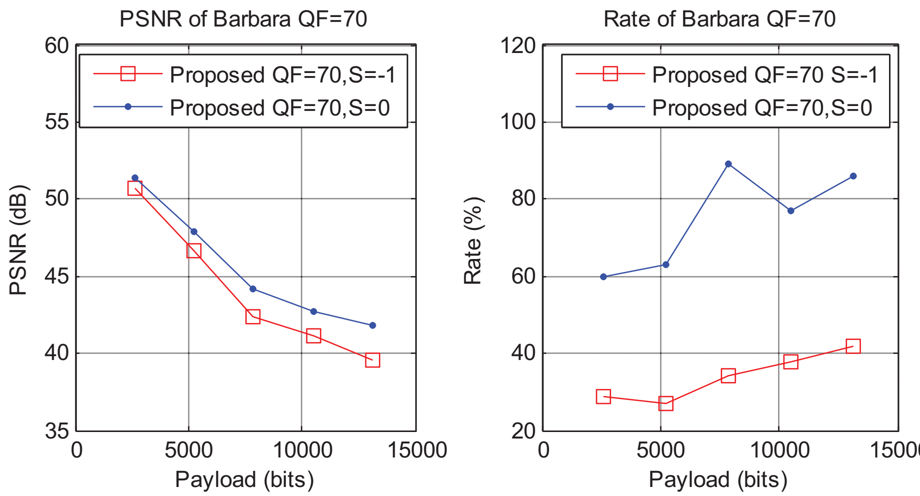

Fig. 11. Comparison of different RDH for Barbara with QF = 70.

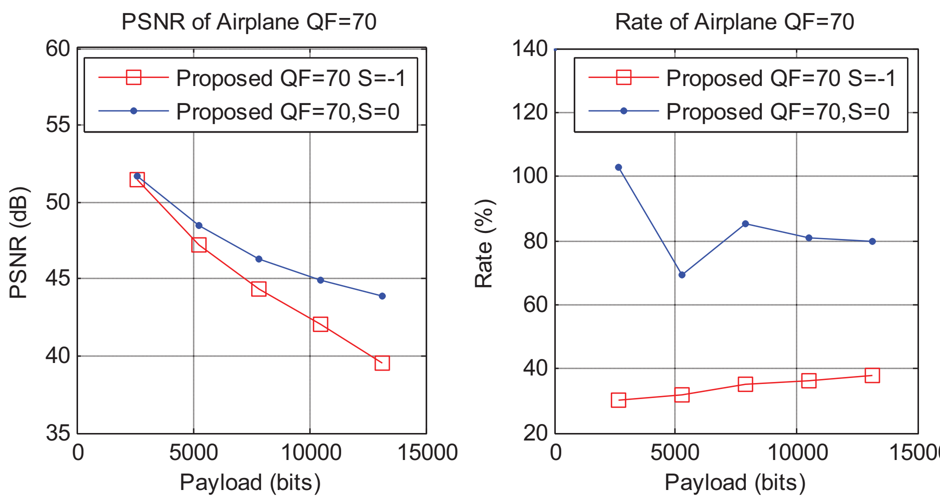

Fig. 12. Comparison of different RDH for Airplane with QF = 70.

Otherwise, x will be embedded as follows. If $T \geq 0$

$$x = \begin{cases} x+1 & \text{if } x > T \\ x+b & \text{if } x = T \\ x & \text{otherwise} \end{cases} \tag{10}$$

If $T < 0$

$$x = \begin{cases} x-1, & \text{if } x < T \\ x-b & \text{if } x = T \\ x & \text{otherwise} \end{cases} \tag{11}$$

Step 2: If secret data has not been fully embedded, take

$$T = \begin{cases} -T & \text{if } T \geq 0 \\ -T-1 & \text{if } T < 0 \end{cases}, \quad \text{go to Step 1} \tag{12}$$

Otherwise, take $S \leftarrow T$ until the data embedding is finished.

The proposed data extraction is just the reverse process of data embedding. Instead of providing a detailed description, only a flowchart is given in Fig. 3.

Finally, we discuss the selection of the stop threshold S. We hope to achieve higher PSNR and lower file-size increase at the same time. To this end, there are the following two ways to select the stop threshold S:

1) $S = -1$: In this way, S cannot be 0 and this is our main recommendation. That is, the same as [17], we will not embed data into zero-valued DCT coefficients.
2) $S = 0$ or no restriction: In this situation, S can be 0, and it can achieve higher PSNR, while the file-size increase is large at the same time. This situation can only be used when a very high embedding capacity is desired.

3. Experimetal results

First, the result of data embedding into Lena image with quality factor QF = 80, the thresholds $T = 1$ and $S = -1$ at different payloads using the proposed method is listed in Table 1.

The embedding threshold T is selected using Eqs. (2,3,5–7). The running time is also listed in this table, and one can see that the proposed method is computationally efficient.

For the proposed method and some state-of-the-art works, the experimental results of four JPEG images with different quality factors QF = 80 and QF = 70 at different embedding payloads are shown in Fig. 4–12. Moreover, the corresponding parameters of our method are introduced in detail in Tables 2 and 3. Here, the Rate of increased file size with payload is defined as

$$\text{Rate} = (\text{Increased File Size} - \text{payload})/(\text{payload}) \tag{13}$$

According to these figures, one can see that for both the embedding performance and the file-size increase, the proposed method is relatively better. For [13], it is based on modifying quantization table. However, neither optimal block finding nor optimal amplitude selecting is utilized in [13], and thus the file-size increase is quite large. For [16], it is aiming at minimizing the file-size increase by using rate-distortion optimization. But the PSNR is relatively low, and the PSNR achieved by our method is much better than that of [16]. In [17], an empirical method is proposed in which the zero-valued DC coefficients are not modified. However, the block selection method in [17] is not efficient and the proposed one improves [17].

4. Conclusion

In this paper, a new JEPG image RDH method is proposed. The proposed data embedding scheme is implemented by modifying the DCT coefficients with an advisable DCT block selection mechanism based on minimum entropy principle. Moreover, a threshold called stop threshold is utilized in this paper to adjust the relationship between PSNR and file-size increase. In general, by setting $S=-1$, then the increased file-size can be well-controlled with a relatively good PSNR. Moreover, the proposed four thresholds are simultaneously utilized so that the optimal embedding performance can be obtained

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