RATE-DISTORTION BASED REVERSIBLE WATERMARKING FOR JPEG IMAGES WITH QUALITY FACTORS SELECTION

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ABSTRACT

The improved reversible data hiding scheme which is a part of JPEG coding process is introduced. Generally, one of the common constraints imposed on digital watermarking in frequency domain is a small payload that can be embedded without causing high degradation of a JPEG stego image. Moreover, even at small hidden payload the stego image file size will increase to some extent. In no existing data hiding technique compliant with JPEG there is a possibility to define in advance the file size of the watermarked image. Therefore, in this paper we propose to use a rate-distortion theory that minimizes coding distortion subject to a coding rate constraint. An iterative algorithm based on a Lagrangian formulation is applied to obtain a vector of quality factors for each of the 8×8 blocks that scale the JPEG standard quantization table. The experimental results show the advantage of the proposed improved watermarking scheme in terms of data payload versus quality and file size compared with the state-of-the-art data hiding schemes, and, furthermore, clarify the improvements of its optimized counterpart.

***Index Terms*—** watermarking, reversible, JPEG, Rate-Distortion Optimization, Lagrangian relaxation

1. INTRODUCTION

The concept of reversibility, or in other words, the ability to reconstruct the original cover image after the secret message, or watermark, was restored is critical for images for legal or military consideration. A lot of efficient high payload reversible data hiding schemes based on difference expansion [1, 2] and histogram shifting [3, 4] show excellent performance for uncompressed images of different formats, though incompatible with JPEG. The number of reversible embedding methods compliant with JPEG are still quite limited. In [5] scheme that aims at keeping the size of the JPEG stego file remaining unchanged has been reported. The proposed technique operates on the sequence of intermediate symbols after Huffman decompression and modifies the amplitude of the certain DCT coefficients by at most one. The payload is rather limited and does not exceed 0.0176 bpp (bits per pixel), which is shown in [5]. In [6], a reversible technique for JPEG images based on histogram pairs is proposed. The JPEG stego file does not increase significantly, however, the distortion is very high when embedding is done into the noisy area of an image. The reversible technique in [7] improves the performance of the scheme in [6] by selecting only the embeddable "smooth" blocks. More precisely, the DC components of neighboring blocks are exploited to calculate the variance that is used for the blocks classification. In the experimental part it is shown that this technique shows an advantage in terms of decrease in file size and peak signal-to noise ratio (PSNR) compared with [6] but mostly only for smooth images. Reversible technique in [8] aims at embedding bits into the selected components of the compressed data such that it introduces a very little change to the original JPEG file. An extensive comparative analysis of the proposed method with the scheme defined in [8] will be held in experimental part. Another approach of reversible data hiding based on exploiting modification direction (EMD) is investigated in [9]. The scheme claims about significant improvement in terms of space storage compared to a number of techniques presented in [9], however, the PSNR results are quite low of about 28 dB for a payload of 12288 bits hidden in 512×512 Lena.

In this paper the reversible data hiding technique for raw format images developed in [4] is used as a base to obtain a stego JPEG image. The histogram shifting approach reported in [4] have shown excellent results in terms of the PSNR in spatial domain and is considered as the proper candidate to be used along with JPEG coding. As shown in the experimental part, the adjusted to the JPEG coding process data hiding scheme outperforms a number of efficient techniques [6]-[8]. Moreover, to overcome the main "obscurity" of JPEG embedding: the file size of the watermarked image that could not be predicted in advance by any scheme in the literature, we suggest to use a rate-distortion theory. The data embedding performance directly depends on the choice of the quality factor (QF) that scales the JPEG standard quantization table (SQT). Using higher QF corresponds to the substantial increase in the JPEG stego file size and PSNR, but decrease in payload. Therefore, our logical approach for improving the overall performance is to optimize the QF according to the statistics of the image to be compressed. We formalize the optimization problem into that of minimizing coding distortion subject to a constraint in the rate of the coding data, and solve it using the Lagrangian relaxation method. So at the output we obtain the QF parameter for each of the coding block of the image. The main advantage of the following approach is about 44 % increase in average in payload compared with the proposed unoptimized counterpart.

The rest of the paper is organized as follows. Section 2 comprises the detailed description of the data hiding proposed technique. In Section 3 the optimization of the proposed scheme is considered. The experimental analysis in Section 4 shows the main advantages of the described methods. Finally, the paper is summarized in conclusion.

2. PROPOSED SCHEME

The proposed data hiding JPEG codec includes the following steps: the digital image used as the cover signal is decomposed into a set of 8×8 blocks, then discrete cosine transform (DCT) is computed, after which the transformed coefficients are quantized using a JPEG SQT. The secret data in binary representation is then embedded into the quantized coefficients. The watermarked quantized coefficients are arranged in a zigzag order and pre-compressed using the differential pulse code modulation (DPCM) on DC coefficients and run-length encoding on AC coefficients. Finally the Huffman encoding takes place to obtain the stego compressed bit-stream. At the decoder, the inverse procedures are conducted: after Huffman decoding we extract the secret data from the DCT quantized coefficients and perform the inverse DCT. The final decompressed JPEG image is obtained after rounding the values. Taking into account that entropy encoding implies a lossless operation, the reversibility of the proposed data hiding is guaranteed.

2.1. Data embedding

Let $\mathbf{I}$ denote a cover $M \times N$ image, and $W = \{w_s\}$ be a secret data, $w_s = \overline{0,1}, s = \overline{1,S}$. The following procedure is repeated for each of the 8×8 blocks: after DCT computation and quantization based on the predefined QF, an integer that ranges from [0, 100], the block $B^k_{i,j}$ is ready for data embedding, here and further $k = \overline{1,K}$, where $K = \frac{M \times N}{8 \times 8}$, $i = j = \overline{1,8}$. We propose to use the data hiding scheme developed in [4] but improve and adjust it to perform efficiently in JPEG domain.

We introduce $m^k_{i,j}$, a local activity indicator (LAI), that allows to select only the to-be-embedded quantized coefficients in block $B^k_{i,j}$. Let $m^k_{i,j}$ be a measure of some statistical dispersion, for example, a maximum absolute deviation computed over some predefined region that is constant for all blocks $\Omega^k_{i,j} = \Omega_{i,j}$:

$$m^k_{i,j} = \max \mid \Omega_{i,j} - \text{mean}(\Omega_{i,j}) \mid . \quad (1)$$

LAI contributes by leaving out the noisy areas that can bring high distortion to the stego image from embedding operation. To select only the embeddable positions, LAI is bounded with the two user-specified thresholds T_{low} and T_{high}:

$$T_{low} \leq m^k_{i,j} \leq T_{high}. \quad (2)$$

The proper selection of the DCT quantized coefficients is one of the issues that is to be addressed when introducing an efficient scheme compliant with JPEG. Keeping in mind that varying DC components can easily cause blocking artifacts, we consider AC mid-frequency counterparts to be the candidate for data hiding, because the choice of high frequency AC components used for embedding will lead to visually significant changes. Note that AC components are specified by initializing the parameter AC as input to the data embedding algorithm.

In [4] the embedding scheme provides flexibility by bounding the prediction error by the interval $[-Q, Q)$, where Q specifies the bins utilized for embedding, being symmetric with respect to 0. Here we omit the prediction operation, because due to the high variance between neighboring ACs in our case the prediction error takes large values, and therefore, brings huge distortion to the stego image. So we perform data hiding directly on the specified quantized AC components. Moreover, we generalize the target interval to be symmetric with respect to h: $[-Q-h, -h) \cup [h, h+Q)$. Adding the new parameter h allows us to improve scheme's flexibility by leaving out embedding into zeros, which in terms of AC components easily bring visual changes and can significantly increase the file size. Note that operating in the frequency domain enables to omit employing under/overflow control. After verification of (2), we perform embedding for each block k with respect to the introduced parameter h and predefined Q, AC:

$$\tilde{B}^k_{i,j} = \begin{cases} B^k_{i,j} - Q, \text{if } B^k_{i,j} < -Q - h, \\ 2(B^k_{i,j} + 1) - w_s - 1 + h, \text{if} \\ -Q - h \leq B^k_{i,j} < -h, \\ 2B^k_{i,j} + w_s - h, \text{if} \\ h \leq B^k_{i,j} < h + Q, \\ B^k_{i,j} + Q, \text{if } B^k_{i,j} \geq Q + h. \end{cases} \quad (3)$$

In order to clarify the given equation, we visualize it in Fig. 1, where an embedding operation is shown for the case when $h = 0, Q = 3$. Note that data hiding operation is done only for the specified AC coefficients after verifying that condition (2) is fulfilled.

2.2. Data extraction

At the extraction phase after Huffman decoding, we calculate $m^k_{i,j}$ defined in (1) for the specified AC coefficients, and if (2) is correct, we get back the secret message and the quantized

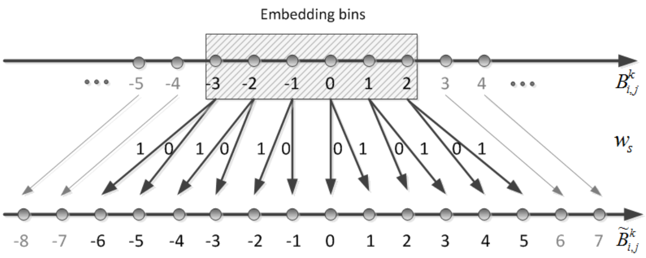

Fig. 1. Example of data hiding for the case $h = 0, Q = 3$.

DCT coefficients, respectively:

$$w_s = \begin{cases} ((h-1)\text{mod}2 - \tilde{B}^k_{i,j})\text{mod}2, & \text{if} \\ -h-2Q \le \tilde{B}^k_{i,j} < -h, & \\ (h\text{mod}2 + \tilde{B}^k_{i,j})\text{mod}2, & \text{if} \\ h \le \tilde{B}^k_{i,j} < h+2Q-1, & \end{cases} \tag{4}$$

$$B^k_{i,j} = \begin{cases} \tilde{B}^k_{i,j} + Q, & \text{if } \tilde{B}^k_{i,j} < -2Q-h, \\ \frac{\tilde{B}^k_{i,j}+w_s+1-h}{2} - 1, & \text{if } -h-2Q \le \tilde{B}^k_{i,j} < -h, \\ (\tilde{B}^k_{i,j} - w_s + h)/2, & \text{if } h \le \tilde{B}^k_{i,j} < h+2Q-1, \\ \tilde{B}^k_{i,j} - Q, & \text{if } \tilde{B}^k_{i,j} \ge 2Q+h. \end{cases} \tag{5}$$

2.3. File size preservation

Note that the described technique increases the file size of the embedded image. In order to prevent this negative property that potentially can negate the advantages of reversible data embedding techniques, we decided to perform an experiment, where we select only the embeddable AC components, for which the following property is fulfilled:

The size of JPEG bitstream after Huffman encoding plus the size of the secret message is larger than the size of JPEG watermarked bitsream.

Although the procedure is computationally expensive, a number of embeddable AC components that are capable of effective embedding without enlarging the image size are obtained. We perform the set of experiments presented in Table 1 on two 512×512 8-bit grayscale Lena and Mandrill images that are to be used extensively in the experimental part and are shown in Fig. 3. Note that the file sizes remain almost the same, which is indicated by the comparison with the compression ratios that without watermarking at quality factor 75 are 8.02 and 3.26 for Lena and Mandrill, respectively.

Taking into account that the procedure is computationally very expensive and do not contribute high payload as can be seen in Table 1, we proposed to use a rate-distortion optimization approach.

Table 1. Performance of Lena and Mandrill in terms of the file size preservation.

Image	Lena	Mandrill
h,Q	1,3	1,3
embeddable AC	[1, 2, 11, 16, 22, 29,48,53,61]	[15,16,22,26:29, 35,36,37,41]
Payload(bits)	2567	10846
PSNR vs JPEG	37.6	33.93
Ratio	8.0	3.25

3. RATE-DISTORTION OPTIMIZATION

Generally, rate-distortion theory formalizes the lossy compression goal into that of minimizing coding distortion subject to a constraint in the rate for the coding data. Here we combine the classical rate-distortion optimization problem with the reversible data hiding technique. Let us assume that the distortion and the bit size of the non-overlapped block B^k quantized at the QF ψ_k are $d_k^{\psi_k}$ and $r_k^{\psi_k}$, respectively. We measure the distortion $d_k^{\psi_k}$ as a mean squared error (MSE) between the original cover block B^k and decompressed watermarked block $\tilde{B}^k_{i,j}$ that was quantized using the quality factor ψ_k. Bit size $r_k^{\psi_k}$ is obtained as the number of bits after Huffman encoding that is applied to the watermarked block $\tilde{B}^k_{i,j}$, which was quantized using the quality factor ψ_k.

Here we define $\Psi = \{\psi_k\}$ as a set of decision vectors or quality factors, where ψ_k indicates that for the block B^k the solution vector ψ_k is applied. JPEG watermarked image distortion and bit rate for the set of decision vectors Ψ then can be obtained, respectively:

$$d(\Psi) = \sum_{k=1}^{K} d_k^{\psi_k}. \tag{6}$$

$$r(\Psi) = \sum_{k=1}^{K} r_k^{\psi_k}. \tag{7}$$

Therefore, the problem is formulated as follows: to find the vector decision set $\Psi^\star \in \{\Psi\}$, so that

$$\begin{cases} d(\Psi^\star) = \min d(\Psi), \\ r(\Psi^\star) \le R_{max}, \end{cases} \tag{8}$$

where R_{max} is the bit budget for the given watermarked JPEG file. A conventional way to solve this problem is an efficient iterative algorithm called the Lagrange relaxation method [10]. Before covering the method, the following proposition is to be made: for each $\lambda \ge 0$, the solution vector $\Psi^\star_\lambda \in \{\Psi\}$, which minimizes

$$d(\Psi) + \lambda r(\Psi), \tag{9}$$

is the optimal solution of the optimization task, if $r(\Psi^\star_\lambda) \le R_{max}$. Taking into account that all the blocks are coded independently, the following equation holds:

$$\min\{d(\Psi) + \lambda r(\Psi)\} = \min \sum_{k=1}^{K} (r_k^{\psi_k} + \lambda d_k^{\psi_k}) = \\ \sum_{k=1}^{K} \min(r_k^{\psi_k} + \lambda d_k^{\psi_k}). \tag{10}$$

Therefore, in order to search the solution vectors set $\Psi = \{\psi_k\}$ that minimizes (9) it is enough to minimize $r_k^{\psi_k} + \lambda d_k^{\psi_k}$ for each block separately. Thus,

$$\psi_k = \underset{z}{\operatorname{argmin}}\{r_k^z + \lambda d_k^z\}, \tag{11}$$

where z takes various values of QFs that are used for quantization of the block B^k.

Note that a positive constant λ controls the rate-distortion trade off, and can be found by using the bisection method shown in Fig. 2. The main advantage of the Lagrange relaxation method is that the full search of the decision set $\{\Psi\}$ is not required compared to the dynamic programming. The computational complexity overhead comprises $\frac{M*N}{64} * \mid QF \mid *n_{max}$ comparison operations and $\frac{M*N}{64} * n_{max}$ additions, where n_{max} indicates the maximum number of steps, and $\mid QF \mid$ corresponds to the number of the QFs used for optimization. In other words, the solution of the described optimization problem will give us an optimal vector $\Psi^\star$ that comprises individual quality factors for each of the blocks B^k that in total will minimize the distortion for the JPEG stego image keeping the watermarked file size at the given rate.

Step 1	Find values λ_1 and λ_2, so that $r(\Psi^*_{\lambda_1}) \le R_{max} \le r(\Psi^*_{\lambda_2})$ holds $\Psi^* := \Psi^*_{\lambda_1}$, n = 0.
Step 2	$\lambda := \frac{\lambda_1+\lambda_2}{2}$. Calculate $r(\Psi^*_\lambda)$. **if** $r(\Psi^*_\lambda) \le R_{max}$ and $r(\Psi^*_\lambda) > r(\Psi^*)$, then $\Psi^* = \Psi^*_\lambda$. $n := n + 1$.

Step 3	**if** $\lvert\lambda_1 - \lambda_2\rvert > \varepsilon$ and $n \le n_{max}$, then
	if $r(\Psi^*_\lambda) \le R_{max}$, then
	$\lambda_1 := \lambda$,
	else
	$\lambda_2 := \lambda$,
	go to **Step 2**.
	else, the set of solution vectors Ψ^* is found

Fig. 2. Lagrange relaxation method.

4. EXPERIMENTAL RESULTS

We implement the proposed reversible data hiding technique in compliant with JPEG and its optimized counterpart using Matlab software. In order to provide a comparative analysis

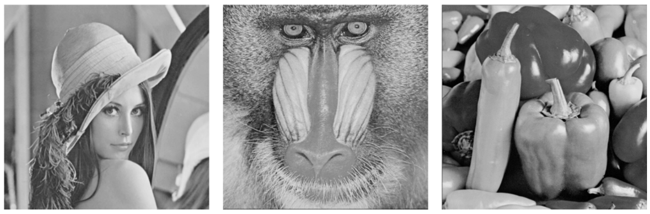

Fig. 3. Original 512×512 grayscale images used for data embedding. From left to right: Lena, Mandrill and Peppers, respectively.

with the state-of-the-art schemes [6]-[8] we used a common to all set of grayscale 8-bit pictures presented in Fig. 3. The secret data is taken as a uniform random sequence of 0 and 1. The PSNR is exploited to measure the stego image quality in dB.

4.1. Performance of the proposed scheme

We first examine the performance of the proposed data hiding scheme on Lena image in terms of the capacity, distortion and its effect on the file size. The results of the comparative analysis of various schemes [6]-[8] with the proposed one are summarized in Table 2. Note that all of schemes at the given rate provide quite small payload. The proposed technique achieves the highest payload keeping the smallest file size without degrading substantially the quality of the stego image.

Further, we would like to compare the proposed technique with [8] and perform a set of experiments on Lena at various quality factors ranging from 75 to 92. Note that in [8] the embedding is done only to 19-th AC coefficient per block that explains the small quantity of the overall embedded payload. We perform the comparison of the proposed method by showing the achieved payload versus quality results at the same or smaller to [8] file size. In order to properly investigate the visual degradation of the watermarked image we calculate PSNR between the stego image and both JPEG compressed Lena at the given QF, and original uncompressed Lena. It is worth noticing, that the proposed technique achieves in average 2.91 dB increase in terms of quality of the watermarked

Table 2. Comparative analysis of the proposed technique with [6]-[8] on Lena.

Method	[6]	[7]	[8], c[2,5]	[8], c[4,4]	Proposed
Payload, bits	1538	1538	5201	4480	13345
File size, bytes	32841	32819	39150.3	36588.9	32373
PSNR, dB	38.77	48.60	34.52	39.79	42.01

Table 3. Comparative analysis of the proposed technique with [8] on Lena.

Method	File size, bytes	Payload, bits	PSNR vs. jpeg,dB	PSNR vs. orig.,dB
[8]	39150.3	5201	34.52	-
Proposed	38864.1	22870	37.72	34.8
[8]	52560.4	4393	36.31	-
Proposed	50646.2	20720	40.1	36.73
[8]	63655.5	3747	38.54	-
Proposed	62718.8	18686	42.31	38.55
[8]	70968.2	3733	41.77	-
Proposed	67528.8	18170	42.66	39.33

image along with the gain of around 15kbits in terms of payload at similar file sizes compared with [8].

4.2. Performance of the optimized scheme

Now let us examine the performance of the optimized scheme that enables to define in advance the JPEG file size. So at the output of optimization procedure we get individual QFs for each of the blocks that in total minimize the distortion for the JPEG stego image keeping the watermarked file size at the given rate. If we consider 512×512 Lena that comprises 4096 8 × 8 blocks, then having 4096 QFs that vary from [0, 100] means adding 4096*7 bits = 28672 bits to the redundant data, which negates all the valuable payload. In order to overcome this problem we decide to limit the number of QFs up to 2 or 4, depending on the possible achieved capacity. Note that in case we consider only 2 QF the auxiliary data constitutes to 4096 bits, while in case of 4 QFs in order to get a payload we have to subtract 8192 bits from the embedding capacity.

Obviously we need to find the proper groups of QFs that at the end show the best performance. The full search might be an option, but it is very expensive in terms of computational costs. Therefore, we suggest performing initially an optimization procedure based on all possible QFs, and then sort them by the descending frequency of occurrences in all the blocks of the image. We observe how in average various grouping of the QFs starting from the most frequently used and shifting along the sorted sequence to the less used influence the quality of the stego image in Fig. 4, which allows to derive several important conclusions. Firstly, the first groups in sorted sequences of QFs indeed show the best results in terms of quality gain and are to be used for further experiments. Secondly, the average PSNR gain that is achieved by the optimization is about 1.2 dB compared to the unoptimized counterpart. At last, the grouping of 4 QFs shows half of the maximum PSNR improvement, and therefore, is a proper candidate to be used for experiments. We then perform the optimization experiments on a training set, and for various file sizes calculate the main characteristics. Fig. 5 presents the advantage of the optimization in terms of the embedding payload. Note that in average optimization brings of about 41 % increase in payload

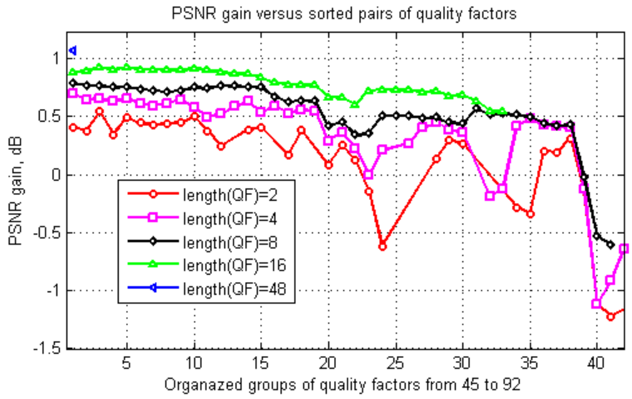

Fig. 4. PSNR gain versus sorted pairs of quality factors.

to Lena, around 47% to Mandrill, and about 45% to Peppers keeping the quality at the same level. Some detailed results of the optimization are presented in Table 4.

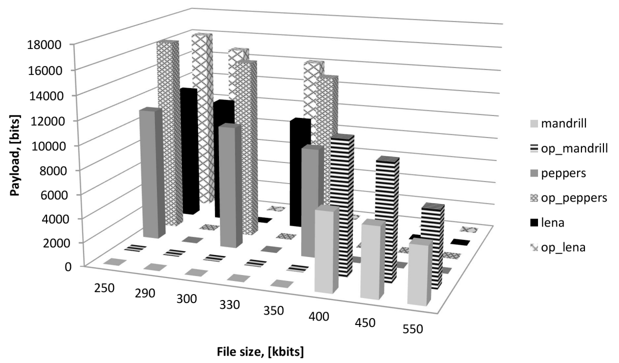

Fig. 5. Payloads of the proposed versus optimized schemes.

Moreover, taking into account another metric for calculating distortion, called PSNR-HVS-M (that considers the contrast sensitivity function, is based on the human visual system and demonstrates high correlation with the results of the subjective experiments [11]), we compared the optimized stegos of Lena based on PSNR and PSNR-HVS-M metrics. The PSNR value of the optimized stego Lena based on PSNR-HVS-M is 1 dB lower than its counterpart and comprises 44.31 dB at a payload of 6568 and file size of 32575 bytes. However, Fig. 6 demonstrates the distortion comparison of the optimized Lena based on PSNR metric and the optimized Lena based on PSNR-HVS-M, where the latter shows much smoother behavior.

5. CONCLUSION

In this paper the reversible data hiding scheme compliant with JPEG was introduced. In order to define in advance the file

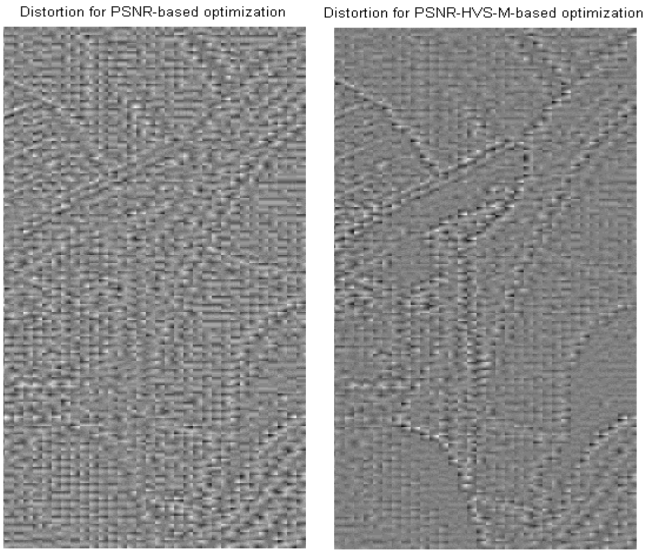

Fig. 6. Comparison of optimized stego images of scaled Lena based on PSNR and PSNR-HVS-M metrics, from left to right, respectively.

size of the watermarked image, we proposed to use a rate-distortion theory that enabled to obtain a vector of quality factors for each of the 8×8 blocks that scale the JPEG SQT. The experimental results have shown the advantage of the proposed watermarking scheme in terms of capacity versus quality and file size compared with the state-of-the-art data hiding schemes, and, furthermore, clarified the improvements of its optimized counterpart. Our future work will focus on the robustness issue that can be addressed by considering the redundancy when embedding the stronger watermark signal.

Table 4. Some details of the experiments of the proposed methods with and without optimization.

Lena

Optimization	without	with
File size, kbits	330	330
Payload, bits	9539	14048
PSNR vs. orig.	36.24	36.2
Parameters	QF=82	QF=[69,76,90,91] $\lambda = 2.4692$

Peppers

Optimization	without	with
File size, kbits	300	300
Payload, bits	10354	15079
PSNR vs. orig.	34.11	34.6
Parameters	QF=77	QF=[68,72,76,86] $\lambda = 2.0861$

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