Noname manuscript No.
(will be inserted by the editor)

Improved reversible data hiding based on PVO and adaptive pairwise embedding [*]

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Received: October 2018

Abstract Pixel-value-ordering (PVO) is an efficient technique of reversible data hiding (RDH). By PVO, the cover image is first divided into non-overlapping blocks with equal size. Then, the pixel values in each block are sorted in ascending order. Next, take the second largest/samllest pixel value as a prediction of the largest/samllest pixel value to derive two prediction-errors. Finally, the data embedding is constructed by modifying the generated prediction-errors of each block. After data embedding, the PVO of each block is unchanged, which guarantees the reversibility. Our key observation is that, in each block, the modification for the two prediction-errors is independent without exploiting the correlation between them, although they are closely correlated to each other. In light of this, an improved PVO-based RDH method is proposed in this work. The two prediction-errors of each block is considered as a pair, and the pairs are modified for data embedding based on adaptive two-dimensional histogram modification. The proposed method is experimentally verified better than the original PVO-based method and some of its improvements.

Keywords Reversible data hiding · Pixel-value-ordering · Two-dimensional histogram · Pairwise embedding · Adaptive embedding

[*]This work was supported by the National Key Research and Development of China (No. 2016YFB0800404), the National Science Foundation of China (Nos. 61572052, U1736213, 61532005, 61332012), and the Fundamental Research Funds for the Central Universities (Nos. 2018JBZ001, 2017RC008).

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1 Introduction

Reversible data hiding (RDH) is a special type of information hiding. By RDH, the decoder can perfectly recover the cover image after extracting the embedded secret data. The key question of RDH is how to minimize the embedding distortion for a given embedded capacity.

So far, RDH has been widely studied and many effective reversible embedding methods have been proposed in [1–26]. Among the present RDH methods, the ones based on prediction-error expansion (PEE) have shown an outstanding performance by exploiting the correlations between adjacent pixels. The PEE technique is first proposed by Thodi and Rodriguez in [3]. In this method, a prediction-error histogram is first generated, and then this histogram is modified to embed data based on expansion and shifting the histogram bins. Later on, the PEE technique has been widely adopted and developed in RDH studies. These developments are mainly based on, for example, sharper histogram generation with an accurate predictor design [5, 15, 19], adaptive histogram modification [6, 14, 22], two-dimensional histogram modification [10, 11, 20], and multiple histogram modification [17].

The pixel-value-ordering (PVO) based RDH is first proposed by Li *et al.* in [27]. In this method, a new predictor is designed based on PVO for PEE. Specifically, the cover image is first divided into non-overlapping blocks with equal size, and, for each block, its pixel values are sorted in ascending order. Next, the second largest/samllest pixel value is taken as a prediction of the largest/samllest pixel value to derive two prediction-errors. Finally, the data embedding is conducted by modifying the generated prediction-errors of each block. After data embedding, the PVO of each block remains unchanged, which ensures the reversibility. The PVO-based prediction can derive an accurate predictor, and its performance is proved better than some other

PEE-based methods, especially for low embedding capacities. Later on, the PVO-based method [27] has been improved in some works [28–34] in many aspects.

In this paper, we try to improve the embedding performance of PVO-based RDH. Our key observation is that, for the PVO-based methods such as [27] and [28], in each divided image block, the modification for the two prediction-errors is independent without exploiting the correlation between them, although they are closely correlated to each other. In this work, the two prediction-errors of each block is considered as a pair, and the pairs are modified for data embedding based on two-dimensional (2D) histogram modification. The 2D histogram modification manner is adaptively determined in our work such that the embedding performance is optimized. Moreover, inspired by [27, 28], a block selection strategy is employed as well. Only the smooth image blocks are selected for data embedding while the rough ones are unmodified. The experimental results show that the performance of the proposed method is better than the original PVO-based RDH method [27] and some of its improvements [28, 29].

The rest of the paper is arranged as follows. Section 2 provides a brief review for two typical PVO-based methods [27] and [28]. Section 3 introduces the proposed PVO-based RDH. Experimental results are reported in Section 4. Finally, Section 5 concludes this paper.

2 Related work

In this section, as a preparation, the original PVO-based RDH method [27] and its improvement [28] are reviewed.

2.1 PVO-based RDH [27]

The PVO-based RDH technique is first proposed by Li *et al.* in [27]. For this method, first, the cover image is divided into non-overlapping blocks sized $n_1 \times n_2$. Then, for a given block, sort its pixels $(p_1, \ldots, p_n)$ in ascending order according to the pixel values to obtain $(p_{\sigma(1)}, \ldots, p_{\sigma(n)})$, where $\sigma : \{1, \ldots, n\} \to \{1, \ldots, n\}$ is the unique one-to-one mapping satisfying $\sigma(i) < \sigma(j)$ if $p_{\sigma(i)} = p_{\sigma(j)}$ and $i < j$, and $n = n_1 \times n_2$. Next, take the second largest pixel value $p_{\sigma(n-1)}$ as the prediction of the largest pixel value $p_{\sigma(n)}$, and define the prediction-error as

$$d_{\max} = p_{\sigma(n)} - p_{\sigma(n-1)}. \tag{1}$$

Take the standard gray-scale Lena image with 2×2 sized blocks as an example, the histogram of prediction-error $d_{\max}$ is shown in Figure 1. It can be observed that the histogram is defined in the interval $[0, +\infty)$ since $d_{\max} \geq 0$, and it has a peak value at bin 1. Then, based on this peak property of the generated histogram, $d_{\max}$ is modified according to the following rule to derive the marked prediction-error $\widetilde{d}_{\max}$ as

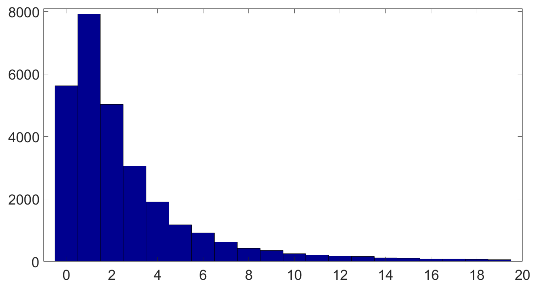


Fig. 1 Histogram of $d_{\max}$ defined in (1), for the standard 512×512 sized gray-scale image Lena with block size of 2×2.

$$\widetilde{d}_{\max} = \begin{cases} d_{\max}, & \text{if } d_{\max} = 0 \\ d_{\max} + b, & \text{if } d_{\max} = 1 \\ d_{\max} + 1, & \text{if } d_{\max} > 1 \end{cases} \tag{2}$$

where $b \in \{0, 1\}$ is a to-be-embedded secret data bit. Finally, the largest pixel value $p_{\sigma(n)}$ is modified as

$$\widetilde{p}_{\sigma(n)} = p_{\sigma(n-1)} + \widetilde{d}_{\max} \tag{3}$$

to derive the marked pixel value.

In the above procedure, for each block, only the largest pixel value with prediction-error larger than 0 maybe modified, in which this largest value is either unchanged or increased by 1 while other pixels remain unchanged. As a result, the PVO of each block is unchanged as well, and this property guarantees the reversibility. Specifically, for the decoder, the same as the data embedding process, the marked image is also divided into non-overlapping blocks of size $n_1 \times n_2$. Then, for a given block, sort its pixel values in ascending order to obtain $(\widetilde{p}_{\sigma(1)}, \ldots, \widetilde{p}_{\sigma(n)})$. Notice that $\widetilde{p}_{\sigma(i)} = p_{\sigma(i)}$ holds for each $1 \leq i \leq n-1$. Next, compute the marked prediction-error

$$\widetilde{d}_{\max} = \widetilde{p}_{\sigma(n)} - \widetilde{p}_{\sigma(n-1)}. \tag{4}$$

Finally, recover the original pixel value $p_{\sigma(n)}$ as

$$p_{\sigma(n)} = \begin{cases} \widetilde{p}_{\sigma(n)}, & \text{if } \widetilde{d}_{\max} \in \{0, 1\} \\ \widetilde{p}_{\sigma(n)} - 1, & \text{if } \widetilde{d}_{\max} > 1 \end{cases} \tag{5}$$

and extract the embedded data as $b = \widetilde{d}_{\max} - 1$ in the case of $\widetilde{d}_{\max} \in \{1, 2\}$. Moreover, since only the largest pixel value of each block maybe modified in the data embedding procedure, for each $1 \leq i \leq n-1$, $p_{\sigma(i)}$ can be recovered as $\widetilde{p}_{\sigma(i)}$ itself.

Furthermore, the smallest pixel value $p_{\sigma(1)}$ in each block can also be modified (either decreased by 1 or unchanged) to embed data. The similar data embedding and extraction procedures are omitted here.

2.2 Improved PVO-based RDH [28]

In the original PVO-based RDH method, the blocks with $d_{\max} = 0$ are not utilized to carry data. However, these blocks are usually smooth and suitable for reversible embedding. Based on this consideration, in order to take the advantage of the blocks with $d_{\max} = 0$, an improved PVO-based method is proposed by Peng *et al.* in [28].

For the data embedding of this method, first, for a given block with sorted values $(p_{\sigma(1)}, \ldots, p_{\sigma(n)})$, instead of computing the prediction-error $d_{\max}$ in (1) as the original PVO-based method does, it is redefined as follows considering the order of $\sigma(n-1)$ and $\sigma(n)$

$$d_{\max} = \begin{cases} p_{\sigma(n)} - p_{\sigma(n-1)}, \text{ if } \sigma(n) > \sigma(n-1) \\ p_{\sigma(n-1)} - p_{\sigma(n)}, \text{ if } \sigma(n) < \sigma(n-1) \end{cases}. \tag{6}$$

Clearly, one can verify that the redefined prediction-error satisfies $d_{\max} \geq 0$ if $\sigma(n) > \sigma(n-1)$, and $d_{\max} < 0$ if $\sigma(n) < \sigma(n-1)$. That is to say, the prediction-error defined in this way is ranged from $-\infty$ to $+\infty$. For example, for the Lena image, the histogram of the redefined prediction-error $d_{\max}$ is shown in Figure 2. This histogram is a Laplacian-like distribution centered at 0 with two sides decay. Then, the bins 0 and -1 are expanded for data embedding. More specifically, $d_{\max}$ is modified to derive the marked prediction-error $\widetilde{d}_{\max}$ in the following way

$$\widetilde{d}_{\max} = \begin{cases} d_{\max} + b, \text{ if } d_{\max} = 0 \\ d_{\max} - b, \text{ if } d_{\max} = -1 \\ d_{\max} + 1, \text{ if } d_{\max} \geq 1 \\ d_{\max} - 1, \text{ if } d_{\max} \leq -2 \end{cases} \tag{7}$$

where $b \in \{0, 1\}$ is a to-be-embedded data bit. Accordingly, the largest pixel value $p_{\sigma(n)}$ is modified as

$$\widetilde{p}_{\sigma(n)} = p_{\sigma(n-1)} + |\widetilde{d}_{\max}| \tag{8}$$

to derive the marked pixel value.

For this improved method, a key issue is that, unlike other expansion-shifting based RDH methods, the expansion bins can not be arbitrarily selected. To guarantee the reversibility, the sign of each prediction-error (i.e., "≥ 0" or "< 0") shouldn't be changed after data embedding.

Similar with [27], in each block, only the largest pixel value $p_{\sigma(n)}$ is either increased by 1 or unchanged, while other pixel values remain unchanged. The PVO of each block is unchanged as well, and thus the recovery and extraction process can be conducted accordingly. Specifically, for the decoder, the marked prediction-error $\widetilde{d}_{\max}$ is first computed for a marked block with sorted values $(\widetilde{p}_{\sigma(1)}, \ldots, \widetilde{p}_{\sigma(n)})$ as follows,

$$\widetilde{d}_{\max} = \begin{cases} \widetilde{p}_{\sigma(n)} - \widetilde{p}_{\sigma(n-1)}, \text{ if } \sigma(n) > \sigma(n-1) \\ \widetilde{p}_{\sigma(n-1)} - \widetilde{p}_{\sigma(n)}, \text{ if } \sigma(n) < \sigma(n-1) \end{cases}. \tag{9}$$

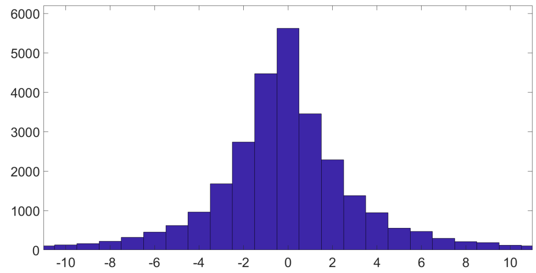


Fig. 2 Histogram of $d_{\max}$ defined in (6), for the standard 512×512 sized gray-scale image Lena with block size of 2×2.

Then, recover the original pixel value $p_{\sigma(n)}$ as

$$p_{\sigma(n)} = \begin{cases} \widetilde{p}_{\sigma(n)}, & \text{if } \widetilde{d}_{\max} \in \{0, -1\} \\ \widetilde{p}_{\sigma(n)} - 1, & \text{otherwise} \end{cases}. \tag{10}$$

In addition, for each $1 \leq i \leq n-1$, $p_{\sigma(i)}$ is recovered as $\widetilde{p}_{\sigma(i)}$ itself. And, the embedded data bit is 0 if $\widetilde{d}_{\max} \in \{0, -1\}$ or 1 if $\widetilde{d}_{\max} \in \{1, -2\}$.

Besides, in this method, the smallest pixel value $p_{\sigma(1)}$ of each block is also modified for data embedding, by considering the prediction-error defined as

$$d_{\min} = \begin{cases} p_{\sigma(2)} - p_{\sigma(1)}, \text{ if } \sigma(2) > \sigma(1) \\ p_{\sigma(1)} - p_{\sigma(2)}, \text{ if } \sigma(2) < \sigma(1) \end{cases}. \tag{11}$$

One can verify that $d_{\min} \geq 0$ if $\sigma(2) > \sigma(1)$, and $d_{\min} < 0$ if $\sigma(2) < \sigma(1)$. The histogram of $d_{\min}$ is also a Laplacian-like distribution centered at 0 with two sides decay. For brevity, the similar data embedding and extraction procedures by modfying the smallest pixel value are omitted here, and the details can be found in [28].

3 Proposed method

In this section, an improved RDH method based on PVO and adaptive pairwise embedding is proposed. Our idea is straightforward. Notice that in the original PVO-based method [27] and its improvement [28], the largest and smallest pixel values of each divided image block are independently modified to embed data. For example, for [28], this is conducted by modifying the prediction-errors $d_{\max}$ and $d_{\min}$ defined in (6) and (11), independently. However, inspired by the recently proposed RDH technique named pairwise PEE [10], we argue that this independent modification manner is unreasonable since $d_{\max}$ and $d_{\min}$ are related to each other. Then, for efficient reversible embedding, we propose to consider $d_{\max}$ and $d_{\min}$ as a pair, and then modify the prediction-error pairs based on 2D histogram modification strategies.

The notations utilized in this section are the same as Section 2.2, and we consider the prediction-errors $d_{\max}$ and $d_{\min}$ defined in (6) and (11) which take values in $(-\infty, \infty)$. Let us first see Figure 3, it shows the joint distribution of $d_{\max}$

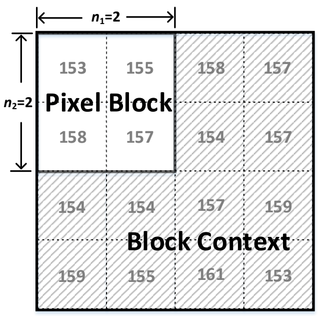


Fig. 4 Context (shadow pixels) of a given block for complexity computation.

and $d_{\min}$, for three standard 512×512 sized gray-scale images Lena, Baboon and Airplane. For each figure in Figure 3, we first divide the cover image into non-overlapping 2×2 sized blocks, and then compute the pair $(d_{\max}, d_{\min})$ for each divided block, and finally, derive the distribution of $(d_{\max}, d_{\min})$ based on all the divided blocks. According to these figures, one can see that the distribution has a peak at origin $(0,0)$ and it rapidly decreases toward the direction away from the origin, and the decrease trend is significant for the smooth image Airplane. This observation confirms that $d_{\max}$ and $d_{\min}$ are correlated to each other. And, the smoother the image is, the stronger the correlation is. Then, to achieve better performance of PVO-based RDH, we propose to modify the prediction-error pair $(d_{\max}, d_{\min})$ for data embedding based on 2D histogram modification strategies. We describe the embedding details as below.

First, inspired by previous works [27–29], we adopt the block selection strategy to select smooth blocks for histogram generation. More specifically, in order to evaluate the complexity of a block, the same as [29], a block context is first defined as shown in Figure 4, and then the complexity of a block is computed as the sum of the vertical and the horizontal absolute difference of every two adjacent pixels in the context. For a given threshold T, only the blocks with complexities less than T are selected. The blocks with large complexities are considered as rough ones and will not be used in our data embedding. These blocks remain unchanged during the data embedding procedure. Then, the prediction-error pair $(d_{\max}, d_{\min})$ is computed for each selected blocks, and the 2D histogram counting the distribution of $(d_{\max}, d_{\min})$ is generated. After that, the data embedding will be conducted by modifying the generated 2D histogram.

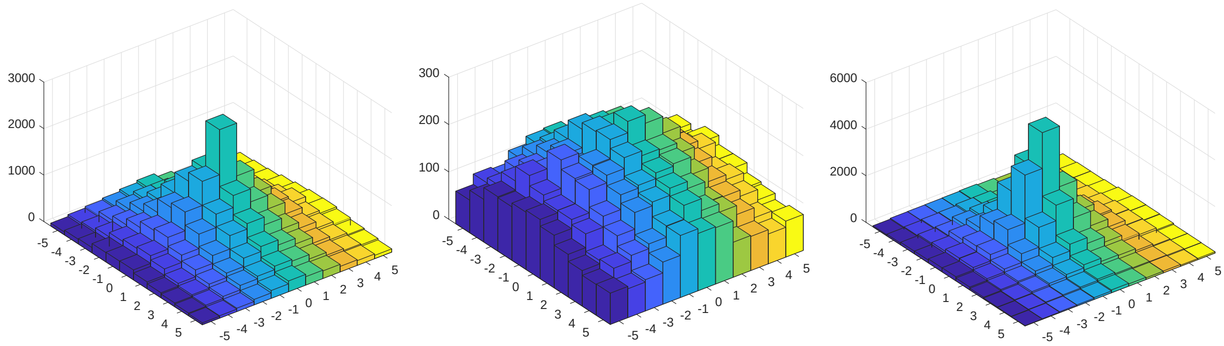
Clearly, one can directly apply the pairwise embedding mechanism of Ou *et al.* [10] to modify the generated histogram. For illustration, the pairwise embedding mechanism based on a 2D mapping is shown in Figure 5(a). The 2D mapping here is defined as a function

$$f : \mathbb{Z}^2 \mapsto \mathscr{P}(\mathbb{Z}^2) \quad (12)$$

where $\mathscr{P}(\mathbb{Z}^2)$ is the power set of $\mathbb{Z}^2$. For example, $f(0,0) = \{(0,0),(0,1),(1,0)\}$ means that in the data embedding process, the pair $(0,0)$ will be modified as one element of the set $\{(0,0),(0,1),(1,0)\}$ to embed $\log_2 3$ bits. Regard that, for a given embedding capacity, with pairwise embedding, the threshold T is determined as the smallest one such that the embedding capacity can be satisfied with the generated histogram. For example, for the Baboon image with 2×2 sized blocks and an embedding capacity of 10,000 bits, the threshold T is 235, and one can get a PSNR of 54.63 dB by applying the pairwise embedding to the corresponding histogram (this histogram is shown in Figure 5(c)). On the other hand, with the same block sizes and complexity computation method, the PSNR of Peng *et al.*'s method [28] is just 54.34 dB. That is to say, compared with [28], 0.29 dB of improvement is obtained by using pairwise embedding. Obviously, the improvement is due to the utilization of the correlation between $d_{\max}$ and $d_{\min}$.

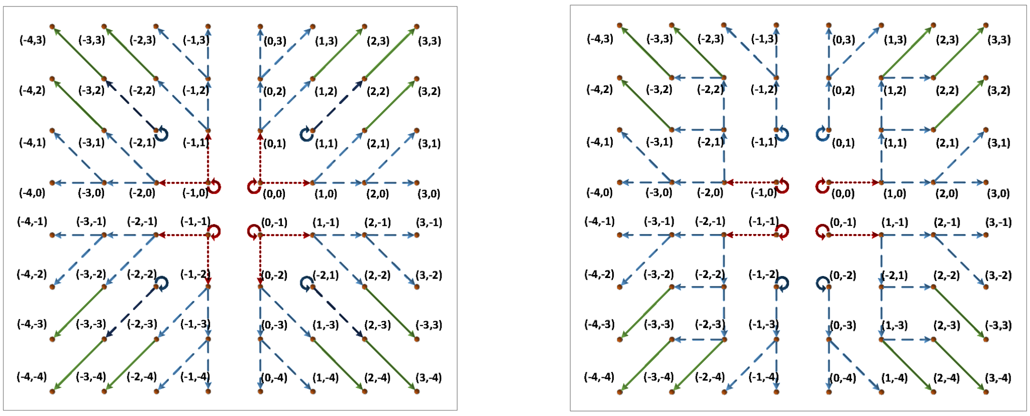
Based on pairwise embedding, the advantage of 2D histogram is verified. However, one can get better result since that, with the pairwise embedding mechanism of Ou *et al.* [10], only a fixed modification manner is simply utilized for the 2D histogram. Actually, there are many ways for 2D histogram modification, and one can take the best one to optimize the embedding performance. Obviously, any 2D mapping defined in $\mathbb{Z}^2$ can derive a reversible embedding if it satisfies the following condition: for any $x \in \mathbb{Z}^2$, there exists unique $y \in \mathbb{Z}^2$ such that $x \in f(y)$. For clarity, the 2D mappings considered in the following context are the ones satisfying this condition. We then propose to use adaptive 2D mapping to enhance the performance.

We will exhaustively search all the 2D mappings and find the optimal one such that it can provide the required embedding capacity while the embedding distortion is minimized. Considering that the generated 2D histogram is usually symmetric for the four quadrants, we then suppose that the 2D mapping is symmetric as well. More specifically, we only consider the 2D mapping $f : \mathbb{Z}^2 \mapsto \mathscr{P}(\mathbb{Z}^2)$ which satisfies the following condition: for each $x \geq 0$ and $y \geq 0$, $f(x,y) = f(-x-1,y) = f(x,-y-1) = f(-x-1,-y-1)$. Moreover, as the generated 2D histogram is concentred on $(0,0)$, we only modify the pairwise embedding in a small local region $[0,K] \times [0,K]$ to derive the 2D mappings. That is to say, besides the region $[0,K] \times [0,K]$, each tested 2D mapping coincides with the mapping of pairwise embedding in the first quadrant. Here, to balance the embedding performance and the running time cost, the parameter K is simply taken as 2. In this situation, we only need to test 1996 different 2D mappings in total. Then, for each 2D mapping, the same as the case of pairwise embedding, the complexity threshold T is determined as the smallest one such that the embedding capacity can be satisfied with the generated 2D histogram. After managing all the 2D mappings, one can



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

Fig. 3 Distribution of $(d_{\max}, d_{\min})$, for three standard 512×512 sized gray-scale images Lena, Baboon and Airplane, with block size of 2×2.



(a) (b)

$d_{\max}$ \ $d_{\min}$	-4	-3	-2	-1	0	1	2	3
3	64	92	128	122	142	139	94	99
2	97	125	150	151	156	166	147	119
1	111	153	172	181	179	173	151	123
0	111	144	173	216	227	212	178	138
-1	119	176	147	209	202	180	159	134
-2	139	131	151	187	176	183	139	114
-3	108	119	136	147	147	138	117	95
-4	84	99	109	125	124	130	73	89

(c)

$d_{\max}$ \ $d_{\min}$	-4	-3	-2	-1	0	1	2	3
3	62	91	127	118	140	139	93	98
2	97	121	144	151	154	163	147	118
1	109	151	168	179	179	170	150	116
0	109	142	171	213	224	208	177	138
-1	114	176	146	207	199	179	159	128
-2	138	130	150	184	175	183	138	112
-3	107	118	136	145	145	135	117	91
-4	80	96	107	123	120	128	73	88

(d)

Fig. 5 (a) 2D mapping of the pairwise embedding [10], (b) Optimal 2D mapping obtained by the proposed method, (c) 2D histogram for the Baboon image with block size 2×2 and complexity threshold $T = 235$, (d) 2D histogram for the Baboon image with block size 2×2 and complexity threshold $T = 225$.

finally get the optimal mapping with minimized distortion. For example, for the Baboon image with 2×2 sized blocks and an embedding capacity of 10,000 bits, the optimal 2D mapping is shown in Figure 5(b), the corresponding complexity threshold $T = 225$, and the derived 2D histogram is shown in Figure 5(d). In this case, one can get a PSNR of 54.90 dB, and 0.27 dB of improvement is obtained compared with pairwise embedding. We see then, with optimal 2D mapping, the method [28] is further improved.

Finally, similar with the previous methods [27, 28], the above embedding procedure is implemented several times for different block size $n_1, n_2 \in \{2, 3, 4, 5\}$, and the best embedding result is taken as our final embedding result.

Table 1 Optimal parameters of the proposed method for the embedding capacity of 10,000 bits.

Images	PSNR(dB)	n_1	n_2	T
Lena	61.09	4	2	67
Baboon	54.90	2	2	225
Airplane	63.87	3	2	24
Barbara	61.04	2	3	54
Lake	59.74	2	2	61
Boat	58.66	2	4	140
Peppers	59.63	3	3	107
Elaine	58.07	2	2	81

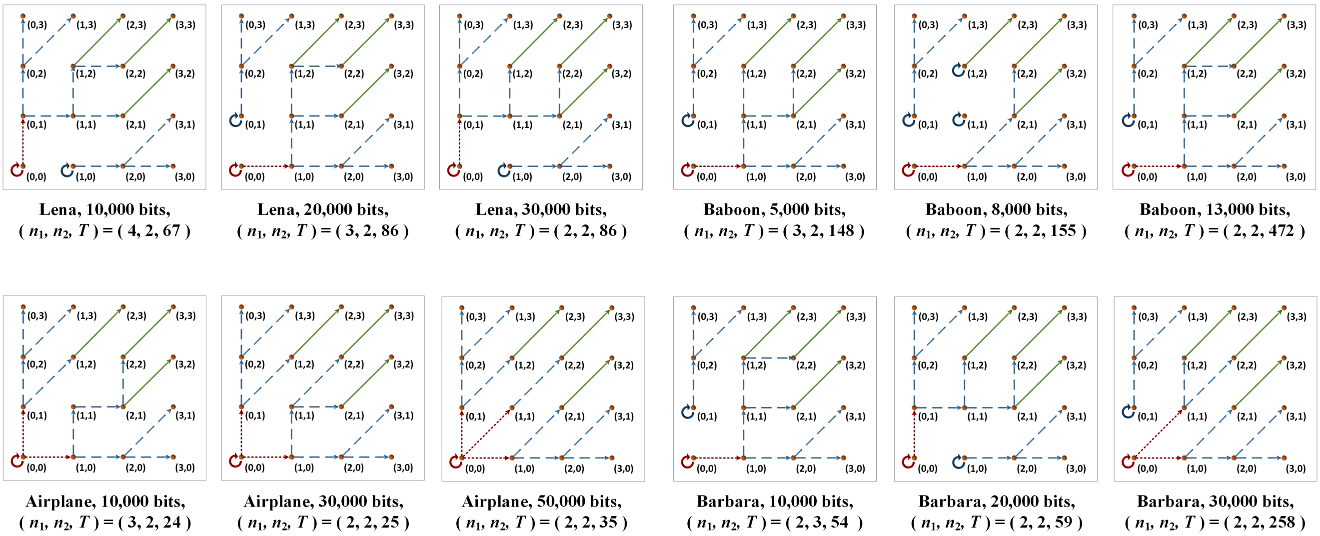


Fig. 6 Optimal 2D mappings for some test images with different embedding capacities.

5 Conclusion

Based on PVO and adaptive pairwise modification, an improved RDH method is proposed in this paper. After dividing the cover image into non-overlapping equal-sized blocks, unlike previous PVO-based works [27–29], the prediction-errors for the largest and smallest pixel values of each block are jointed as a pair. Then, the secret data is embedded into the cover image by adaptively modifying the 2D histogram which is generated based on the prediction-error pairs of smooth image blocks. The proposed method is experimentally verified better than the previous works [27–29]. To enhance the embedding capacity and further improve the embedding performance, one possible direction of PVO-based RDH approach is to take more pixels in each block for data embedding.

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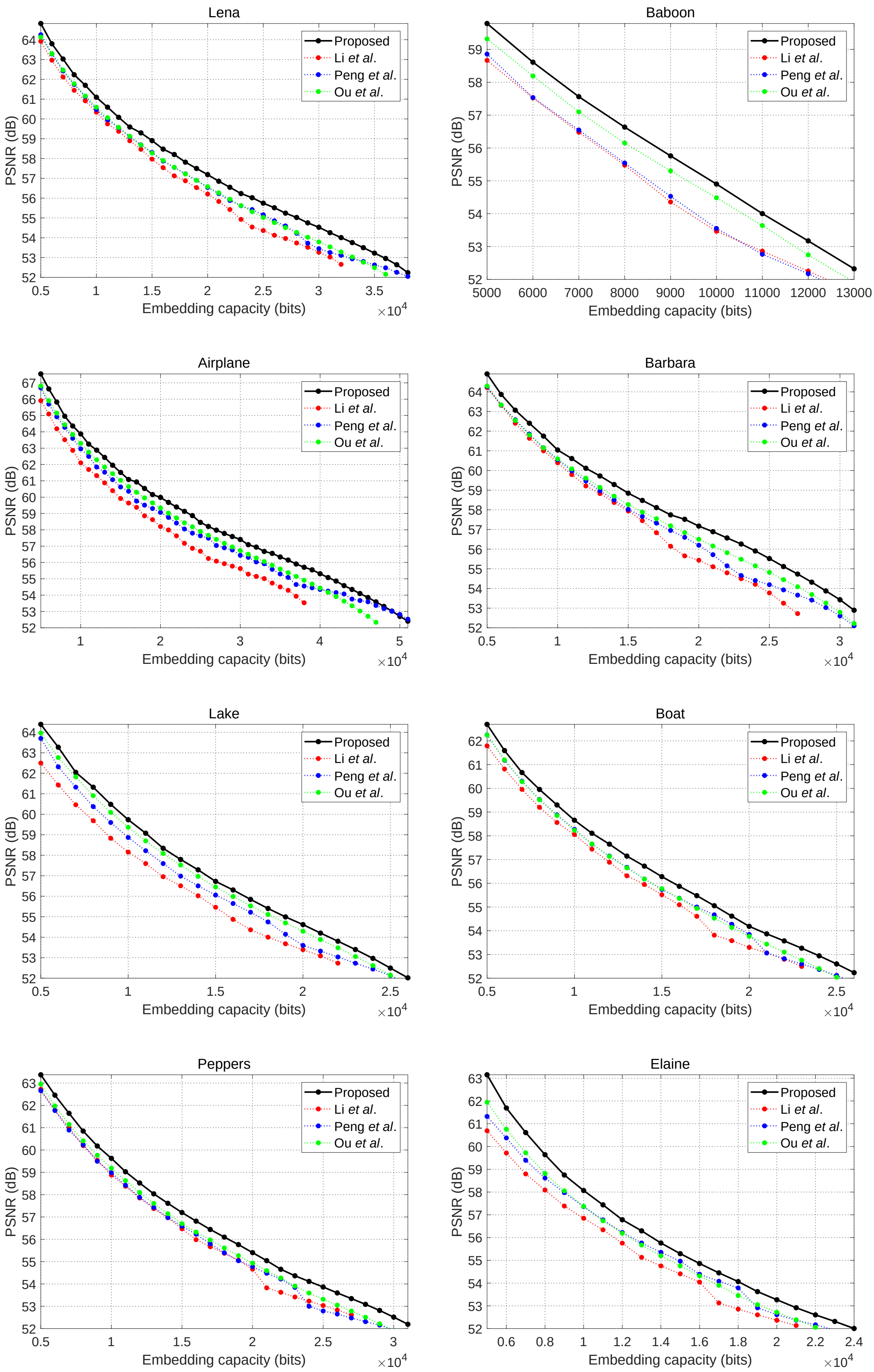

Fig. 7 Performance comparison between the proposed method and Li *et al.*'s method [27], Peng *et al.*'s method [28], and Ou *et al.*'s method [29].

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