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Dual-Histograms Reversible Data Hiding Capable of Avoiding Underflow/Overflow Problems

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Abstract. *In this paper, we propose a reversible data hiding method based on dual-histograms. In the proposed method, the cover image is partitioned into several non-overlapping blocks, which can be classified into the embeddable block or nonembeddable block. Nonembeddable blocks remain unchanged and embeddable blocks are used to generate two histograms. The first histogram, which comprises the prediction error between the embeddable pixel and its prediction value, adopts the addition operation to embed secret data and avoid the underflow problem effectively, in which the prediction value is smaller than half of maximum grayscale pixel. The second histogram hides the secret data by using the subtraction operation to evade the overflow problem, in which the prediction value is higher than half of maximum grayscale pixel. Since the proposed method does not incur underflow/overflow problems, it does not need to record any extra data during the embedding phase. Experimental results demonstrate that the proposed method has better hiding ability and image quality than recently proposed methods. Meanwhile, the proposed method can keep all interesting features in the cover image.*

Keywords: Dual-histograms, Addition operation, Subtraction operation, Underflow/overflow problems, Hiding ability, Image quality

1. **Introduction.** Reversible data hiding scheme has been proposed several years. Most of reversible schemes have some common disadvantages. For example, some schemes suffer from underflow/overflow problems, or some of them need to record huge extra information. For example, in 2003, Tian [8] proposed a difference expansion (DE) hiding method that can embed one secret message into a pair of two adjacent cover pixels. In this method, the difference of each pixel pair is expanded and embedded by one secret message. However, if the difference is large, serious image distortion or underflow/overflow problems will occur. In order to avoid these problems, the pixel pair with the large difference cannot be allowed to hide any secret message. Moreover, these nonembeddable pixel pairs need to be recorded using a location map, which is hidden into the cover image, thereby diminishing the hiding capacity.

In order to overcome the shortcoming of Tian's method, Sachnev et al. [3] proposed a sorting scheme. In the method, the variance of the four neighboring pixels of the cover pixel was used to determine the embedding order. The small variance has higher embedding priority than the large variance, because the small variance implies that the cover pixel was located on the smooth region of the image. After determining the embedding order, the average value of the four neighboring pixels of the cover pixel was used as the prediction value. Like the embedding procedure of the DE method, the prediction error between the cover pixel and the prediction value was expanded and increased by one secret bit. The pixel with the large prediction error are not used to embed secret data, if the number of secret data is small. Consequently, the image distortion and underflow/overflow problems will not occur. Since Sachnev et al.'s method does not require the location map or any extra message in the case of small hiding capacity, their method outperforms Tian's method.

In 2007, Thodi and Rodrguez [9] proposed a hiding scheme that perfectly combines the DE hiding method [8] and the edge-detection mechanism, which can determine the relationship of three neighboring pixels of the present pixel to obtain an accurate prediction value. Since the difference between the cover pixel and its prediction value is small, it does not cause serious pixel distortion after the expansion difference procedure. However, the method may incur underflow/overflow problems after the embedding phase. Hence, extra data such as location map or flag bits are needed to record whether each difference has underflow or overflow problem. These extra data are compressed and embedded into the cover image. This causes more computation costs and decreases both the hiding ability and the quality of stego image.

In 2009, Hong et al. [2] simplified Thodi and Rodrguezs scheme without using any compression technique. Similar to Thodi and Rodrguezs scheme, Hong et al. computed the difference between the cover pixel and its prediction value. However, Hong et al.'s method only uses histogram shifting for hiding secret data. Only the pixel with the difference which is equal to 0 or -1 can be allowed to hide one secret message. Their scheme does not expand the difference, so the probability of underflow/overflow problems is low. However, some extreme pixels which are all equal to 0 or 255 will still incur underflow or overflow problem. In order to losslessly recover the image, they need extra information to record the position information of each extreme pixel.

In 2009, Tai et al. [10] proposed a lossless information hiding scheme. They rearrange a two-dimensional cover image to a one-dimensional array according to the inverse S-order. In the one-dimensional array, the absolute difference between each pixel and its right pixel is calculated and compiled to obtain a histogram. The absolute difference can be used to embed one secret message if it is smaller than a predefined threshold. Otherwise, the absolute difference that is larger than the threshold cannot be used to embed any secret message and is modified by the histogram shifting operation. Building on this, three prediction-based hiding methods [4, 5, 7] have been proposed, which calculate the difference between the cover pixel and the average value of several adjacent pixels to obtain a large amount of small differences. These small differences can be used to embed more secret data and maintain a satisfactory stego image.

In 2013, Li et al. [11] proposed a two-dimensional difference-histogram modification method that can embed secret data and maintain good visual quality of the stego image. The cover image sized $L \times W$ was divided into non-overlapping pixel-pairs, where L and W denote the length and the width of the cover image, respectively. In each pixel-pair, the sum of the differences between the ten neighboring pixels was calculated to determine whether the pixel-pair can be used to embed one secret bit or not. If the sum of the differences was higher than the pre-established threshold, the nonembeddable pixel-pair remains unchanged to maintain good image quality. Otherwise, the embeddable pixel-pairs will be used to embed secret data by the following procedure.

The difference d_1 between the two pixels (X, Y) in the embeddable pixel-pairs was calculated, i.e., $d_1 = X - Y$. In addition, the prediction value $\hat{P}$ of the second pixel Y was generated by the GAP method [1], thereby deriving the prediction error $d_2 = Y - \hat{P}$. According to the embedding rules and (d_1, d_2), only one cover pixel in the pixel-pair was modified to embed one secret bit. After data embedding, the visual quality of the stego image was satisfactory. However, the maximum embedding capacity of the method was $(L \times W)/2$ bits, which were less than that of the other embedding methods. In addition, the method used the location map to solve the underflow/overflow problems, where the location map was embedded into the cover image. The procedure of embedding the location map increases the computational cost and decreases the hiding capacity.

On the other hand, Fallahpour et al. proposed a multi-histogram hiding method [1]. In their method, a cover image is divided into several blocks. In order to protect the characteristic of the image, the block which contains some interesting features will be categorized into the nonembeddable block. The other blocks are categorized into the embeddable block. According to the appearance frequency of the cover pixel, they generate a histogram for each embeddable block. In each histogram, the t pairs of the peak point and zero point are used to embed the secret data. Fallahpour et al.'s method can achieve high hiding capacity, only if t is set to large and the block size is set to small. However, the information of t peak points and t zero points of each histogram must be transmitted to the receiver for extracting secret data and recovering pixels. Hence, Fallahpour et al.'s scheme suffers from extra information problem.

In this paper, we propose a reversible data hiding method based on dual-histograms, which can effectively overcome Fallahpour et al.'s drawback [1] and Hong et al.'s shortcoming [2]. In other words, the proposed method does not generate massive extra information and can embed secret data into all extreme pixels. Additionally, the proposed method holds the advantages of the above two methods. The proposed method is briefly described as follows.

Similar to Fallahpour et al.'s method, the cover image is partitioned into several non-overlapping blocks. The block with the interesting feature is nonembeddable. Unlike Fallahpour et al.'s method, embeddable blocks without any feature are combined to form one sub-image. In the sub-image, the prediction value of each pixel is calculated, and then its prediction error is obtained. The prediction error is attributed to the first histogram if the prediction value is smaller than half of the maximum grayscale pixel. Otherwise, the prediction error is attributed to the second histogram if the prediction value is larger than half of the maximum grayscale pixel.

Since the first histogram consists of the prediction error of the small prediction value, the underflow problem will easily occur if the secret message is embedded using the subtraction operation. Hence, the proposed method uses the addition operation to hide the secret data into the first histogram, which can avoid the underflow problem effectively. On the other hand, the second histogram includes the prediction error of the large prediction value. The probability of overflow problem will substantially increase if the secret message is concealed using the addition operation. Consequently, the proposed method uses the subtraction operation to embed the secret data and evade the overflow problem. The proposed method can achieve four properties, i.e.,

(a) All interesting features hold constant after embedding secret data.
(b) Only the peak point and the zero point of the two histograms must be transmitted to the receiver. Thus, the transmission information of the proposed method is lower than that of Fallahpour et al.'s method.
(c) The proposed method modifies the prediction error of the small prediction value using the addition operation and alters the prediction error of the large value using the subtraction operation that can avoid underflow/overflow problems.
(d) The proposed method can effectively embed the secret data into the extreme pixel, so it can embed more secret data than Hong et al.'s method.

2. **Related Work.** In 2011, Fallahpour et al. [1] proposed a reversible data hiding method based on multi-histogram to achieve high hiding capacity. In this method, the cover image is partitioned into SI/BS non-overlapping blocks, where SI denotes the size of the image and BS represents the block size. These blocks can be categorized into the embeddable block or nonembeddable block. If the block contains some interesting features, it will be categorized into the nonembeddable block. The nonembeddable block remains unchanged and cannot embed any secret message. The embeddable block can embed the secret data using the following procedure.

The histogram of each embeddable block can be generated by compiling the occurrence number of cover pixels, thereby setting t pairs of peak point P_i ($i = 1, 2, ..., t$) and zero point Z_i. Parameter t is a threshold capable of controlling the hiding capacity and image quality. With the increase of parameter t, the number of embeddable pixels increases. The secret data embedding algorithm is described below.

Input: Cover image, secret data and threshold t

Output: Stego image, the information of t peak points and t zero points of SI/BS histograms, and the ID number of the nonembeddable blocks

Step 1: Partition the cover image into SI/BS non-overlapping blocks.

Step 2: Output the ID number of the block if it includes some interesting features. Additionally, the pixels in the block remain unchanged. Otherwise, go to Step 3.

Step 3: Calculate the occurrence number of cover pixels to generate a pixel histogram for each embeddable block.

Step 4: Set t pairs of peak point P_i and zero point Z_i for each histogram.

Step 5: Create two hiding spaces, i.e., P_i and $P_i + 1$, by using the following shifting rules.

(a) Modify the pixels between $Z_i + 1$ and P_i by subtracting one if $P_i > Z_i$.

(b) Modify the pixels between $P_i + 1$ and $Z_i - 1$ by adding one if $P_i < Z_i$.

Step 6: Hide secret data into the cover pixel by using the embedding rules.

(a) The pixel is added by one secret message s if the cover pixel is equal to $P_i - 1$ and the peak point P_i is higher than the zero point Z_i.

(b) The pixel is increased by one secret message s if the cover pixel is equal to P_i and the peak point P_i is lower than the zero point Z_i.

3. **Proposed Method.** Fallahpour et al. proposed the multi-histogram method to achieve high hiding performance [1]. However, in order to extract secret data and recover the image, the information of peak points and zero points in each histogram are needed, thereby increasing the size of extra information. Moreover, the position information of the pixel with the minimum occurrence frequency must be recorded and embedded into the cover image if the zero point does not exist in the histogram. This procedure generates a large amount of extra data.

In order to solve these drawbacks, we propose a reversible data hiding method based on dual-histograms. Similar to Fallahpour et al.'s method, the cover image is partitioned into several non-overlapping blocks, which can be categorized into the embeddable block or nonembeddable block. Unlike Fallahpour et al.'s method, the proposed method combines the embeddable blocks to form a sub-image. The sub-image is used to embed secret data by the following embedding procedure.

In the sub-image, the prediction value $\hat{P}$ of the cover pixel $P_{(i,j)}$ is first calculated by using the median edge detection predictor [2, 9], where $1 < i \leq h$ and $1 < j \leq w$. The symbols h and w denote the height and width of the sub-image, respectively. Then, its prediction error is obtained by the formula $e_{(i,j)} = P_{(i,j)}$ - $\hat{P}$. The prediction error $e_{(i,j)}$ belongs to the first histogram if $\hat{P} < MG/2$, where MG denotes the maximum grayscale pixel. Otherwise, the prediction error $e_{(i,j)}$ belongs to the second histogram if $\hat{P} \geq MG/2$. Since the first histogram consists of the prediction errors of the small prediction value, these prediction errors embed secret data using the addition operation, which can avoid the underflow problem effectively. The second histogram, which consists of the prediction errors of the large prediction value, adopts the subtraction operation for hiding data and avoiding the overflow problem. The detailed algorithm is as follows.

3.1. **Embedding Algorithm.**

Input: Cover image I and secret data S

Output: Stego image I' and the ID number of each nonembeddable block

Step 1: Partition the cover image into SI/BS non-overlapping blocks, where SI denotes the size of the cover image and BS represents the block size.

Step 2: Output the ID number of the block if it includes some interesting features. Additionally, the pixels in the block remain unchanged. Otherwise, go to Step 3.

Step 3: Combine those blocks without any feature to form a sub-image P, where the height and width of the sub-image are denoted by h and w, respectively.

Step 4: Calculate the prediction value $\hat{P}$ of the cover pixel $P_{(i,j)}$ in the sub-image by the median edge detection predictor

$$\hat{P} = \begin{cases} min(P_{(i-1,j)}, P_{(i,j-1)}), & \text{if } P_{(i-1,j-1)} \geq max(P_{(i-1,j)}, P_{(i,j-1)}), \\ max(P_{(i-1,j)}, P_{(i,j-1)}), & \text{if } P_{(i-1,j-1)} \leq min(P_{(i-1,j)}, P_{(i,j-1)}), \\ P_{(i-1,j)} + P_{(i,j-1)} - P_{(i,j-1)}, & \text{otherwise.} \end{cases}$$

Step 5: Calculate the prediction error $e_{(i,j)}$ between the cover pixel $P_{(i,j)}$ and its prediction value by $e_{(i,j)} = P_{(i,j)}$ - $\hat{P}$.

Step 6: Categorize all prediction errors into two groups by the following classification rules.

(a) The prediction error $e_{(i,j)}$ belongs to Group 1 if $\hat{P} < MG/2$,

(b) The prediction error $e_{(i,j)}$ belongs to Group 2 if $\hat{P} \geq MG/2$.

Step 7: Generate the histogram for each group according to the appearance frequency of the prediction error.

Step 8: Find the peak point of each histogram. Let the peak points in the first histogram and the second histogram to be GP_1 and GP_2, respectively.

Step 9: Select the appropriate zero point of each histogram by using the following rules.
(a) In the first histogram, the appropriate zero point Z_1 must larger than the peak point GP_1, while the distance between the peak point GP_1 and the appropriate zero point Z_1 must shorter than other distances between the peak point GP_1 and the other zero points.
(b) In the second histogram, the appropriate zero point Z_2 must smaller than the peak point GP_2. Furthermore, their distance is shortest in all distances between the peak point GP_2 and the zero points.

Step 10: Use the addition or subtraction operation to shift the prediction errors between the peak point and zero point and hide the secret bit s into the prediction error $e_{(i,j)}$ that is equal to the peak point.
(a) The first histogram adopts the addition operation to embed secret data and avoid the underflow problem effectively. The hiding equation is

$$e'_{(i,j)} = \begin{cases} e_{(i,j)} + 1, & \text{if } GP_1 < e_{(i,j)} < Z_1 \text{and } \hat{P} < MG/2, \\ e_{(i,j)} + s, & \text{if } e_{(i,j)} = GP_1 \text{and } \hat{P} < MG/2, \\ e_{(i,j)}, & \text{otherwise.} \end{cases}$$

(b) The second histogram adopts the subtraction operation to hide secret data and evade the overflow problem effectively. The hiding equation is

$$e'_{(i,j)} = \begin{cases} e_{(i,j)} - 1, & \text{if } GP_2 > e_{(i,j)} > Z_2 \text{and } \hat{P} \geq MG/2, \\ e_{(i,j)} - s, & \text{if } e_{(i,j)} = GP_2 \text{and } \hat{P} \geq MG/2, \\ e_{(i,j)}, & \text{otherwise.} \end{cases}$$

Step 11: Obtain the stego pixel $P'_{(i,j)}$ by adding the altered prediction error $e'_{(i,j)}$ into the prediction value $\hat{P}$, i.e., $P'_{(i,j)} = e'_{(i,j)} + \hat{P}$.

Step 12: Combine the stego pixels and the pixels in the nonembeddable blocks to form the stego image.

The proposed embedding algorithm can effectively avoid underflow/overflow problems, as discussed in Section 4. However, underflow/overflow problems can still occur in the following two cases:
(a) The overflow problem in the first histogram is invoked if $P_{(i,j)} = 255$ and the prediction error $e_{(i,j)}$ belongs to the range $[GP_1, Z_1]$.
(b) The underflow problem in the second histogram is incurred if $P_{(i,j)} = 0$ and the prediction error $e_{(i,j)}$ belongs to the range $[GP_2, Z_2]$.
If the above problems occur, the pixel is not modified and its position information is recorded, as in Hong et al.'s method [2]. However, the probability of underflow/overflow problems of the proposed method approaches 0% for natural images and medical images.

3.2. **Extraction and Recovery Algorithm.** The proposed extraction and recovery algorithm first partitions the stego image into SI/BS non-overlapping blocks and then discriminates between embeddable and nonembeddable blocks according to the received ID number of the nonembeddable block. Embeddable blocks can be combined to form a sub-image. Next, the prediction error $e'_{(i,j)}$ between the stego pixel $P'_{(i,j)}$ and its prediction value $\hat{P}$ generated by Eq. (1) is calculated. According to the prediction value and the information of the peak point and zero point, the secret data can be extracted, and the pixel can be recovered. These recovered pixels are combined with the pixels of all nonembeddable blocks, thereby obtaining the original image. The extraction and recovery algorithm is as follows.

Input: Stego image I', two peak points (GP_1 and GP_2), two zero points (Z_1 and Z_2) and the ID number of the nonembeddable blocks
Output: Secret data S and cover image I
Step 1: Partition the stego image into SI/BS non-overlapping blocks.
Step 2: Distinguish between embeddable and nonembeddable blocks according to the received ID number of the nonembeddable blocks.
Step 3: Combine all embeddable blocks to form a sub-image of size $h \times w$.
Step 4: Calculate the prediction error $e'_{(i,j)}$ between the stego pixel $P'_{(i,j)}$ and its prediction value $\hat{P}$ obtained by Eq. (1).
Step 5: Obtain the secret bit s by the following extraction equation

$$s = \begin{cases} 0, & \text{if } \hat{P} < MG/2 \text{and } e'_{(i,j)} = GP_1, \\ 1, & \text{if } \hat{P} < MG/2 \text{and } e'_{(i,j)} = GP_1 + 1, \\ 0, & \text{if } \hat{P} \geq MG/2 \text{and } e'_{(i,j)} = GP_2, \\ 1, & \text{if } \hat{P} \geq MG/2 \text{and } e'_{(i,j)} = GP_2 - 1, \end{cases}$$

Step 6: Derive the original prediction error $e_{(i,j)}$ by using the inverse shifting equation

$$e_{(i,j)} = \begin{cases} e'_{(i,j)} - 1, & \text{if } \hat{P} < MG/2 \text{and } GP_1 < e'_{(i,j)} \leq Z_1, \\ e'_{(i,j)} + 1, & \text{if } \hat{P} \geq MG/2 \text{and } GP_2 > e'_{(i,j)} \geq Z_2, \end{cases}$$

Step 7: Recover the cover pixel $P_{(i,j)}$ by adding the original prediction error $e_{(i,j)}$ to the prediction value $\hat{P_{i,j}}$, where $P_{(i,j)} = e_{(i,j)} + \hat{P}$.
Step 8: Combine all recovered pixels with the pixels of all nonembeddable blocks, thereby obtaining the cover image.

4. **Experimental Results.** We implemented the proposed method and four related reversible data hiding methods [1, 2, 4, 5]. Fig. 1 shows sixteen grayscale images, including ten natural images and six medical images. Table 1 shows that all hiding capacities of the proposed method are higher than that of Fallahpour et al.'s method [1]. Moreover, PSNR values of the proposed method are also higher except for that of medical image MI-6. This is because the peak point and the zero point, which are obtained by Fallahpour et al.'s method, are neighbors for each histogram. This characteristic implies that their method does not modify any nonembeddable pixel, thereby achieving good image quality. Although the image quality of the medical image MI-6 of the proposed method is worse than that of Fallahpour et al.'s method, the proposed method can hide more secret data into the medical image MI-6.

Table 1. Performance comparisons of Fallahpour et al.'s method and the proposed method with respect to the hiding capacity (HC) and PSNR

Medical image	HC [1]	PSNR [1]	Our HC	Our PSNR
MI-1	129,558	48.96	130,558	51.17
MI-2	52,635	50.09	86,805	51.24
MI-3	149,149	49.61	152,165	51.23
MI-4	136,142	48.45	137,915	51.29
MI-5	111,928	47.25	130,538	51.24
MI-6	223,169	51.60	231,445	51.16

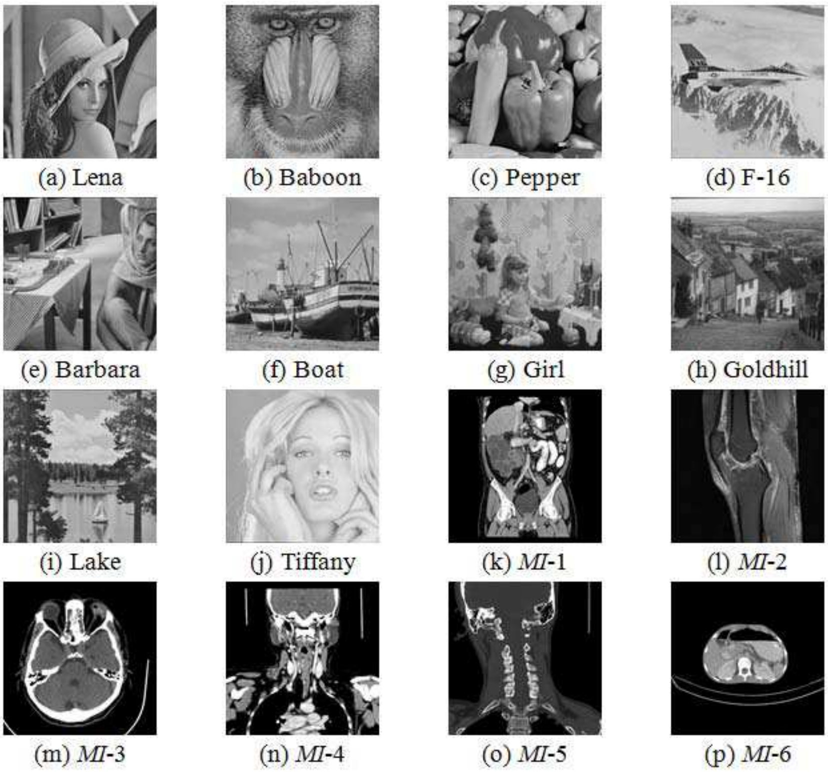

Figure 1. Sixteen test images

Table 2 shows that all image qualities and hiding capacities of the proposed method are better than those of Fallahpour et al.'s method. This is because the occurrence frequency of the cover pixel in the natural image approaches normal distribution. This implies that Fallahpour et al.'s method needs to modify massive nonembeddable pixels. Unlike Fallahpour et al.'s method, the proposed method creates a large amount of small prediction errors by using the median edge detection predictor. These prediction errors can embed secret data and generate slight pixel distortion, so the proposed method outperforms Fallahpour et al.'s method in terms of hiding capacity and image quality.

Table 2. Performance comparisons between Fallahpour et al.'s method and the proposed method

Natural image	HC [1]	PSNR [1]	Our HC	Our PSNR
Lena	10,003	47.30	42,585	51.13
Baboon	5,965	47.69	15,075	50.94
Pepper	8,535	48.89	36,885	51.20
F-16	27,396	47.81	51,376	51.28
Barbara	6,747	47.59	21,514	50.94
Boat	13,851	49.09	29,387	51.19
Girl	9,895	49.04	36,930	51.24
Goldhill	7,568	48.60	29,607	51.15
Lake	10,395	48.49	17,581	51.22
Tiffany	17,280	49.17	37,787	51.23

Table 3 reveals that the hiding capacity, PSNR and extra data of Hong et al.'s method [2] and the proposed method. These experimental results indicate that Hong et al.'s method is unsuitable for medical images. This is because medical images include a large amount of extreme pixels that equal 0 or 255, which cannot embed secret data by using Hong et al.'s method. Because the position information of each extreme pixel is recorded by 18 bits, Hong et al.'s method has a large amount of extra data. In the proposed embedding method, the prediction error of the small prediction value embeds the secret data using the addition operation, and the prediction error of the large prediction value hides secret data using the subtraction operation, thereby avoiding underflow/overflow problems and enhancing the number of embeddable pixels.

Table 3. Performance comparisons of Hong et al.'s method and the proposed method in terms of HC, PSNR and extra data (ED)

Image	HC [2]	ED [2]	PSNR [2]	Our HC	Our ED	Our PSNR
MI-1	14,499	2,336,868	51.37	130,558	36	51.17
MI-2	102,852	0	49.09	86,805	36	51.24
MI-3	27,803	2,682,234	52.39	152,165	36	51.23
MI-4	22,405	2,500,308	51.86	137,915	36	51.29
MI-5	48,452	1,845,306	51.03	130,538	36	51.24
MI-6	18,875	3,880,278	56.74	231,445	36	51.16

With the same hiding capacity, the proposed method has higher PSNR than recently developed methods [1, 2, 4, 5], as shown in Fig. 2. The PSNR of the proposed method exceeds that of two prediction-based reversible data hiding methods [4, 5], which do not calculate the relationship between the neighboring pixels in the prediction phase. Lee and Chen [4] use the stego pixel rather than the original pixel to predict the current pixel, thereby decreasing the prediction accuracy. This low prediction accuracy causes a large amount of nonembeddable prediction errors, which are altered by the shifting operation, thereby decreasing the image quality. The proposed method uses original pixels and analyzes the relationship between the neighboring pixels in the prediction phase, thus obtaining accurate prediction results. The proposed method has a large amount of embeddable pixels and few nonembeddable pixels that cause slight image distortion. Thus, the proposed method has good image quality.

Fig. 3 demonstrates that the pure hiding capacity and PSNR of the proposed method for repetitive embedding. Not only the pure embedding capacity can achieve several hundred thousands, but also each PSNR can exceed 40 dB. These advantages imply that the proposed method is a useful reversible data hiding method.

Table 4 presents the performances of the proposed method, Sachnev et al.'s method [3] and Li et al.'s method [11]. Under the same embedding conditions, the performance of the proposed method for the natural image is similar to those of Sachnev et al.'s method and Li et al.'s method. However, the proposed method can embed more secret bits into the medical images than the two related methods. This is because there are lots of the extreme pixels 0 and 255 in the medical images, which are effectively used to embed secret data by Eqs. (2)-(3) in the proposed method.

Although Sachnev et al.'s method can embed secret data into the extreme pixels, the method needs a location map to record the extreme pixels. Embedding the location map into the cover image causes reduction of the pure hiding capacity. Different from Sachnev et al.'s method, Li et al. used the location map to recognize whether each pixel-pair has an underflow/overflow problem or not. In other words, the size of the location map is equal to the number of the non-overlapping pixel-pairs, i.e., $(L \times W)/2$ bits. The location map was compressed by the arithmetic coding method to reduce the size of the location

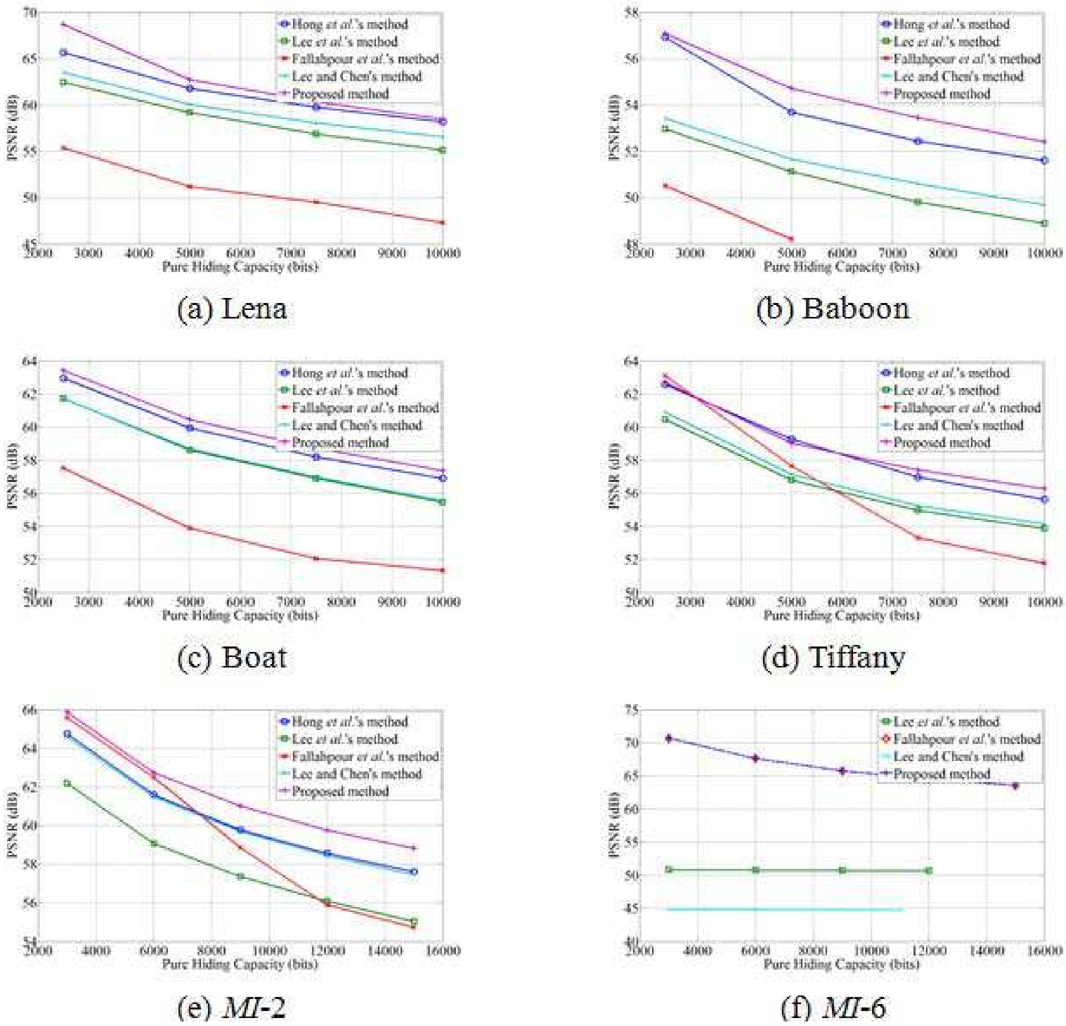

FIGURE 2. PSNR comparisons of recently proposed methods [1, 2, 4, 5] and our proposed method in the case of same hiding capacity

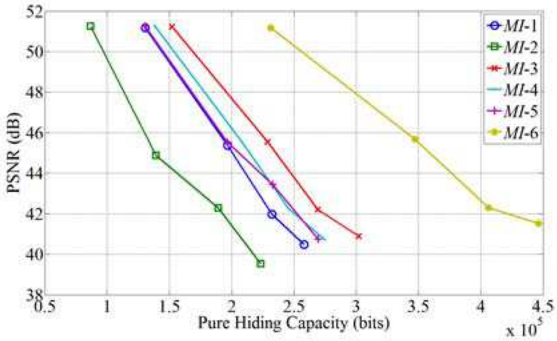

FIGURE 3. Pure hiding capacity and PSNR of the repetitive embedding for the proposed method

map. However, in the location map, the probability of recording the underflow/overflow problem is about 50%. Similarly, the probability of recording the pixel-pair without any underflow/overflow problem is about 50%. The underflow/overflow problem causes low compression efficiency.

TABLE 4. Performance comparison among the proposed method, Sachnev et al.'s method [3] and Li et al.'s method [11] in terms of hiding capacity (HC), peak signal-to-noise ratio (PSNR) and extra data (ED)

Images	Performances	Methods		
		Sachnev et al.	Li et al.	Our
Lena	HC (bits)	26,293	26550	42,585
	ED (bits)	0	0	36
	Pure capacity (bits)	26,293	26,550	42,549
	PSNR (dB)	53.63	54.20	51.13
MI-1	HC (bits)	73,242	63,685	130,558
	ED (bits)	4,337	130,936	36
	Pure capacity (bits)	68,905	N/A	130,522
	PSNR (dB)	49.76	N/A	51.17
MI-4	HC (bits)	67,327	67,184	137,915
	ED (bits)	3,956	131,072	36
	Pure capacity (bits)	63,371	N/A	137,879
	PSNR (dB)	54.22	N/A	51.29
MI-6	HC (bits)	114,345	115,375	231,445
	ED (bits)	0	87,334	36
	Pure capacity (bits)	114,345	28,041	231,409
	PSNR (dB)	53.97	54.30	51.16

5. **Conclusions.** In this paper, we propose a reversible data hiding method based on dual-histograms to avoid underflow/overflow problems. The first histogram comprises the prediction errors of the small prediction values. The prediction errors between the peak point and the zero point are altered using the addition operation, thereby avoiding the underflow problem effectively. The second histogram consists of the prediction errors of the large prediction value. The prediction errors between the peak point and the zero points are modified using the subtraction operation, which evade the overflow problem. According to the above embedding rules, the proposed method can embed secret data into the extreme pixels and does not generate any extra data. Thus, it successfully solves the drawback of Hong et al.'s method [2].

In addition, the proposed method only records the information of the peak point and the zero point of two histograms, so the transmission cost is lower than Fallahpour et al.'s transmission cost [1], which consists of t peak points and t zero points of each histogram. Moreover, the proposed method maintains the merit of Fallahpour et al.'s method such as protecting all interesting features in the original image. Experimental results demonstrate that the proposed method has higher hiding capacity, better image quality, and lower transmission cost and extra data than recently developed reversible data hiding methods. In the future, we will try to combine the proposed method with Lin et al.'s optimal weight-based prediction scheme [6], thereby enhancing the performances.

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