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Reversible Data Hiding for High Quality Using Secret Data Transformation Strategy

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Abstract. *The reversible data hiding technique, which can recover the cover image without any distortion after the embedded data are extracted, has been used extensively in various fields of medical, military and art. Lee and Chen in 2012 proposed an adjustable prediction-based reversible data hiding scheme that can embed a great deal of secret data. However, if most secret data are 1, most pixels must be modified, thereby descending the stego image quality. As a result, we proposed an almost optimal secret data transformation algorithm that can reduce the image distortion and keep the high embedding rate of the existing method by changing the original datum from 1 to 0. Experimental results show that the proposed method achieves higher embedding capacity and better visual quality, which confirms that the performance of the proposed method is better than that of the existing methods.*
Keywords: Prediction-based reversible data hiding, Almost optimal secret data transformation, Image distortion, Embedding capacity, Visual quality

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1. **Introduction.** The reversible data hiding technique, which can recover the cover image without any distortion after the embedded data are extracted, has been used extensively in various fields of medical, military and art [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. In 2003, Tian proposed a reversible data hiding scheme based on difference expansion (DE) [1]. Since the difference between two adjacent pixels can be used to embed one secret bit, the ideal embedding rate of Tian's scheme is 0.5 bpp (bit per pixel). However, in

Tian's scheme, the pixel after embedding secret datum may have the overflow or underflow problem. In order to overcome the problem, the scheme used a location map (i.e., extra message) to recognize whether the pixel has the overflow or underflow problem or not. The extra messages were embedded into the cover image, thereby reducing both the image quality and the hiding capacity.

In order to improve the performances of Tian's scheme, Ni et al. in 2006 proposed a reversible data hiding scheme based on pixel histogram [2]. The stego image has good visual quality because only a few pixels were modified. However, only the pixel that was equal to the peak point in the histogram can be used to embed secret message, thereby limiting the hiding capacity.

In 2007, Thodi and Rodriguez proposed a reversible data hiding scheme based on prediction error expansion, in which the prediction error was obtained by calculating the difference between the current embedding pixel and one of its surrounding pixels [3]. Then, the prediction error was expanded by doubling it and was used to embed secret data. Thodi and Rodriguezs scheme has a high embedding rate that was around 1 bpp. However, the overflow and underflow problems may occur after the prediction error was expanded. In order to solve this problem, the position of the pixel having the overflow or underflow problem was recorded and compressed by JBIG2 code, which increased more computation costs.

On the other hand, Hong et al. [4] proposed a histogram-shifting method to solve the underflow and overflow problems. Similar to Thodi and Rodriguezs method [3], the prediction error between the current embedding pixel and its prediction value was calculated. Different from Thodi and Rodriguez's method, only the prediction error that was equal to 0 or -1 was used to embed one secret bit. Therefore, the hiding capacity of Hong et al.'s method was less than that of Thodi and Rodriguez's method. However, in the method, each cover pixel was only modified by one level to avoid the underflow and overflow problems.

In order to hide more secret data and maintain good image quality, Tai et al. [5] combined the difference expansion method [1] and the histogram-shifting method [2]. According to the inverse S-order, the pixels with 2-dimensional coordinates were rearranged into the form of 1-dimensional coordinates. The difference d between the current pixel and its previous pixel was calculated to determine whether the current pixel can hide secret data or not. If the difference d was equal to or smaller than the pre-determined threshold T, the current pixel was used to embed one secret bit by the difference expansion method [1]. Conversely, if $d > T$, the non-embeddable pixel was modified by the histogram-shifting method [2] to avoid serious image distortion.

In 2009, Tseng and Hsieh proposed a prediction-based reversible data hiding scheme without any compression operation [6]. In the scheme, the difference between the current embedding pixel and the average of its upper and left pixels was calculated. Then, only the differences ranged in $[T/2, T]$ were used to embed secret data, where T is a predetermined threshold. As a result, the hiding capacity of Tseng and Hsieh's scheme was low.

In order to increase the number of embeddable prediction error, Lee et al. [7] proposed a reversible data hiding scheme that expanded the range of the embeddable prediction error from $[T/2, T]$ to $[0, T]$. Consequently, their hiding capacity was satisfactory. However, in the method, the average of two neighboring pixels was used as the prediction value, which was not close to the current embedding pixel. Since the prediction error between the current pixel and its prediction value was large, a serious distortion problem occurred after the prediction error was expanded.

In order to overcome the problem, Lu et al. [8] used the bi-linear interpolation method to yield the exact prediction value. The pixels in the cover image were classified into the embeddable pixels and the reference pixels. After that, the prediction value of the embeddable pixel was yielded by the bi-linear interpolation method and the reference pixels. The error between the embeddable pixel and the prediction value, which was smaller than the pre-determined threshold, was used to embed one secret bit by the difference expansion method [1]. Otherwise, the non-embeddable error that was higher than the pre-determined threshold was modified by the histogram-shifting method [2].

In order to enhance the prediction accuracy, Lee and Chen in 2012 proposed an adjustable prediction-based reversible data hiding scheme that used the average of four neighboring pixels as a prediction value [9]. Although the scheme can embed a great deal of secret data into the cover image, most pixels must be modified if most secret data are "1". In order to reduce the modification frequency, we proposed an almost optimal secret data transformation (AOSDT) method that changes the secret datum from "1" to "0", thereby reducing the image distortion.

2. **Proposed Method.** Lee and Chen proposed an adjustable reversible data hiding scheme that can embed massive secret data. However, in their method, if the secret bit was equal to 1, the pixel was increased/decreased by one gray level, while the pixel was unchanged if the secret bit was equal to 0. Consequently, the distortion of the stego image will significantly rise if more secret bits are 1. In this paper, we propose a method to overcome this shortcoming. The method is described as follows.

2.1. **AOSDT Method.** In our method, every set of K secret bits in S is transformed into a decimal integer d_i, where S is the secret data and d_i belongs to $[0, 2^K - 1]$. The notation K is an adjustable parameter, which determines the transformation results. The larger the parameter K is, the better the transformation results become. Then, the occurrence frequency of the decimal value is counted and the counted result is denoted as C_{d_i}. Next, the occurrence frequencies are sorted in decreasing order, and the sorted results are denoted as $\{sd_0, sd_1, ..., sd_{2^K-1}\}$. Meanwhile, in order to recover the original secret data in the decoding phase, the decimal values $\{d_0, d_1, ..., d_i, ..., d_{2^K-1}\}$ are re-arranged as extra data $\{ed_0, ed_1, ..., ed_i, ..., ed_{2^K-1}\}$ according to the sorted results $\{sd_0, sd_1, ..., sd_{2^K-1}\}$. On the other hand, the decimal values ranged in $[0, 2^K - 1]$ are re-arranged in decreasing order of the number of "0" of their binary form, where the re-arranged results are denoted as $\{d'_0, d'_1, ..., d'_i, ..., d'_{2^K-1}\}$. Then, the decimal value d_i with the highest occurrence frequency is replaced by the first re-arranged decimal value d'_0 that make sure the maximum number of secret bits "0" can be created, where $0 \leq i \leq 2^K - 1$. Finally, the decimal value d'_i is transformed into K secret bits to achieve the secret data transformation. The detailed algorithm is described as follows, where K is set to be 3.

Step 1: Transform each set of three secret bits $\{s_1, s_2, s_3\}$ into a decimal value d_i, where $0 \leq d_i \leq 7$.

Step 2: Count the occurrence frequency of the decimal value d_i, in which the counting results are denoted as $\{C_0, C_1, ..., C_7\}$.

Step 3: Sort the occurrence frequencies in decreasing order, where the sorted results are denoted as $\{sd_0, sd_1, ..., sd_7\}$.

Step 4: The decimal values ranged in [0, 7] are re-arranged in decreasing order of the number of "0" of their binary form, where the re-arranged results are {0, 1, 2, 4, 3, 5, 6, 7}.

Step 5: Modify the decimal value d_i by the following four rules:

a) The decimal value d_i with the highest occurrence frequency (i.e., $C_{d_i} = sd_0$) is replaced by 0, i.e., $d'_i = 0$.
b) The decimal values d_i with the second highest occurrence frequency to the fourth highest occurrence frequency are modified as {1, 2, 4}, i.e.,

$$d'_i = \begin{cases} 1, & \text{if } C_{d_i} = sd_1, \\ 2, & \text{if } C_{d_i} = sd_2, \\ 4, & \text{if } C_{d_i} = sd_3. \end{cases}$$

c) The decimal values d_i with the fifth highest occurrence frequency to the seventh highest occurrence frequency are modified as {3, 5, 6}, i.e.,

$$d'_i = \begin{cases} 3, & \text{if } C_{d_i} = sd_4, \\ 5, & \text{if } C_{d_i} = sd_5, \\ 6, & \text{if } C_{d_i} = sd_6. \end{cases}$$

d) The decimal value d_i with the lowest occurrence frequency (i.e., $C_{d_i} = sd_7$) is replaced by 7, i.e., $d'_i = 7$.

Step 6: Transform the decimal value d'_i into three almost optimal secret bits $\{s'_1, s'_2, s'_3\}$.

2.2. **Embedding Algorithm.** After obtaining almost optimal secret bits, these bits are embedded into the image by Lee and Chen's embedding algorithm [9], which is described below.

Step 1: To avoid the underflow and overflow problems, the cover pixel ranged between 0 and $T + 1$ is modified as $T + 1$, and $log_2(T + 2)$ least significant bits (LSBs) of the original cover pixel are recorded for recovering the original pixel. Meanwhile, the cover pixel ranged between $255 - T - 1$ and 255 is modified as $255 - T - 1$, and $log_2(T + 2)$ LSBs of the cover pixel are also recorded. The recorded LSBs are added into the front of the almost optimal secret data, and they will be embedded into the image by Step 2 through Step 5. The notation T is an adjustable threshold, which can control the visual quality of the stego image and the hiding capacity. The larger the threshold T, the higher the hiding capacity becomes, meanwhile, the worse the image quality becomes. Contrarily, the lower the threshold T, the lower the hiding capacity becomes, meanwhile, the better the image quality becomes.

Step 2: Compute the prediction value $\hat{P}$ of the current embedding pixel $P_{(i,j)}$ by

$$\hat{P} = \begin{cases} (\hat{P}_{UL} + \hat{P}_{UR} + \hat{P}_{DL} + \hat{P}_{DR})/4, & \text{if } 2 \leq i \leq H-1 \text{and} 2 \leq j \leq W-1, \\ (\hat{P}_{UL} + \hat{P}_{UR})/2, & \text{if } i = H \text{and} 2 \leq j \leq W-1, \\ (\hat{P}_{UL} + \hat{P}_{DL})/2, & \text{if } 2 \leq i \leq H-1 \text{and} j = W, \\ \hat{P}_{UL}, & \text{if } i = H \text{and} j = W, \end{cases}$$

where both the initial values of i and j are 2; H and W denote the height and width of the cover image, respectively. The formulas of four types of average value are listed, i.e., $\hat{P}_{UL} = (P_{(i-1,j)} + P_{(i,j-1)})/2$, $\hat{P}_{UR} = (P_{(i-1,j)} + P_{(i,j+1)})/2$, $\hat{P}_{DL} = (P_{(i+1,j)} + P_{(i,j-1)})/2$ and $\hat{P}_{DR} = (P_{(i+1,j)} + P_{(i,j+1)})/2$, as shown in Fig. 1.

Step 3: Calculate the absolute value of the prediction error between the prediction value $\hat{P}$ and the current embedding pixel $P_{(i,j)}$, i.e., $e_{(i,j)} = |\hat{P} - P_{(i,j)}|$.

Step 4: If $e_{(i,j)} \leq T$, then one almost optimal secret bit s' is embedded by using the formula:

$$P'_{(i,j)} = \begin{cases} \hat{P} + 2e_{(i,j)} + s', & \text{if } P_{(i,j)} \geq \hat{P}, \\ \hat{P} - 2e_{(i,j)} - s', & \text{otherwise.} \end{cases}$$

where $P'_{(i,j)}$ is the stego pixel. Otherwise, if $e_{(i,j)} > T$, no bit is concealed and the pixel $P_{(i,j)}$ is modified by

$$P'_{(i,j)} = \begin{cases} P_{(i,j)} + T + 1, & \text{if } P_{(i,j)} \geq \hat{P}, \\ P_{(i,j)} - T - 1, & \text{otherwise.} \end{cases}$$

Step 5: Update the image coordinate, i.e., i and j.

Step 6: Repeat Step 2 to Step 6 until $i = H$ and $j = W$.

2.3. **Extraction and Recovery Algorithm.** When the legal user receives the stego image, secret data and the cover image can be obtained by the extraction and recovery algorithm, which is described as follows.

Step 1: Compute the prediction value $\hat{P}$ of the stego pixel $P'_{(i,j)}$ by using Formula (3), where the initial values of i and j are H and W, respectively.

Step 2: Calculate the absolute value of the prediction error between the prediction value $\hat{P}$ and the stego pixel $P'_{(i,j)}$, i.e., $e'_{(i,j)} = |\hat{P} - P'_{(i,j)}|$.

Step 3: If $e'_{(i,j)} \leq 2T + 1$, the almost optimal secret bit s' is extracted using the formula: $s' = e'_{(i,j)} \bmod 2$. Furthermore, the cover pixel $P_{(i,j)}$ is recovered by the formula:

$$P_{(i,j)} = \begin{cases} \hat{P} + e'_{(i,j)}/2, & \text{if } P'_{(i,j)} \geq \hat{P}, \\ \hat{P} - e'_{(i,j)}/2, & \text{otherwise.} \end{cases}$$

Otherwise, if $e'_{(i,j)} > 2T + 1$, the cover pixel $P_(i,j)$ is restored by using the formula:

$$P_{(i,j)} = \begin{cases} \hat{P} - T - 1, & \text{if } P'_{(i,j)} \geq \hat{P}, \\ \hat{P} + T + 1, & \text{otherwise.} \end{cases}$$

Step 4: Update the image coordinate, i.e., i and j.

Step 5: Repeat Step 1 through Step 6 until $i = 2$ and $j = 2$.

Step 6: If the recovered pixel equals $T + 1$ or $255 - T - 1$, the $log_2(T + 2)$ LSBs of the recovered pixel are replaced by the $log_2(T + 2)$ recorded LSBs to obtain the original cover pixel.

2.4. **Decoding Almost Optimal Secret Data.** After the almost optimal secret bits are extracted, the original secret bits can be revealed by inversing almost optimal secret data algorithm. First, each set of K almost optimal secret bits is transformed into a decimal value d'_i. Second, the decimal values ranged in $[0, 2^K - 1]$ are re-arranged in decreasing order of the number of "0" of their binary form, where the re-arranged results are denoted as $\{sd_0, sd_1, ..., sd_{2^K-1}\}$. Third, the decimal values d'_i are replaced by extra data $\{ed_0, ed_1, ..., ed_{2^K-1}\}$ according to the re-arranged results $\{sd_0, sd_1, ..., sd_{2^K-1}\}$, thereby recovering the original decimal value. Finally, the decimal value d_i is transformed into K original secret bits. The detailed algorithm is described as follows, where K is set to be 3.

Step 1: Transform each set of three almost optimal secret bits $\{s'_1, s'_2, s'_3\}$ into a decimal value d'_i, where $0 \leq d'_i \leq 7$.

Step 2: The decimal values ranged in [0, 7] are re-arranged in decreasing order of the number of "0" of their binary form, where the re-arranged results are {0, 1, 2, 4, 3, 5, 6, 7}.

Step 3: Recover the original decimal integer d_i by the following four rules:

a) If the decimal value d'_i is equal to 0, the decimal value d'_i is modified as ed_0, i.e., $d_i = ed_0$.

b) If the decimal value d'_i belongs to $\{1, 2, 4\}$, the decimal value d'_i is modified as one element of $\{ed_1, ed_2, ed_3\}$. Its formula is listed as follows.

$$d_i = \begin{cases} ed_1, & \text{if } d'_i = 1, \\ ed_2, & \text{if } d'_i = 2, \\ ed_3, & \text{if } d'_i = 4. \end{cases}$$

c) If the decimal value d'_i belongs to $\{3, 5, 6\}$, the decimal value d'_i is modified as one element of $\{ed_4, ed_5, ed6\}$. Its formula is listed as follows.

$$d_i = \begin{cases} ed_4, & \text{if } d'_i = 3, \\ ed_5, & \text{if } d'_i = 5, \\ ed_6, & \text{if } d'_i = 6. \end{cases}$$

d) If the decimal value d'_i is equal to 7, the decimal value d'_i is replaced by ed_7.

Step 4: Transform the original decimal value d_i into three original secret bits $\{s_1, s_2, s_3\}$.

$P_{(i-1,j-1)}$	$P_{(i-1,j)}$	$P_{(i-1,j+1)}$
$P_{(i,j-1)}$	$P_{(i,j)}$	$P_{(i,j+1)}$
$P_{(i+1,j-1)}$	$P_{(i+1,j)}$	$P_{(i+1,j+1)}$

FIGURE 1. The structure of pixels used to calculate the prediction value of $P_{(i,j)}$

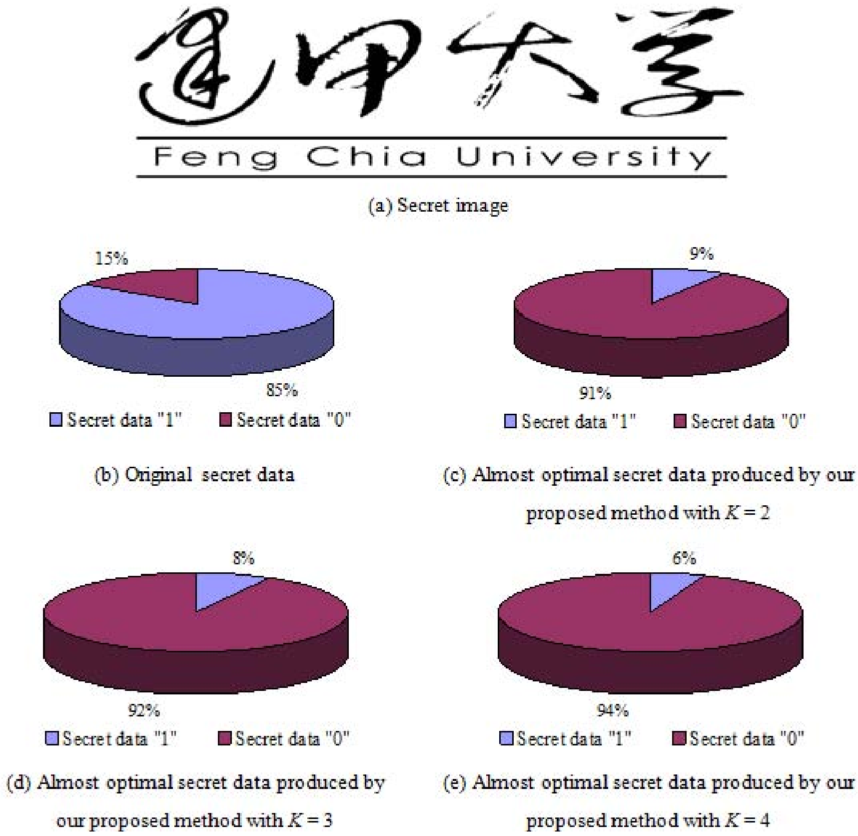

FIGURE 2. Secret information

FIGURE 3. Cover image and stego image with size of 512×512

3. **Experimental Results and Discussion.** We implemented our proposed scheme, Tseng and Hsieh's scheme [6], Lee et al.'s scheme [7] and Lee and Chen's scheme [9] to compare their performances. Figs. 2 (a)-(b) show the binary secret image and its bit distribution, where the height and the width of the secret image are 786 and 314, respectively. Figs. 2 (c)-(e) show that most secret bits "1" were changed as "0" by the data transformation scheme, confirming that the proposed scheme is effective. Table 1 through Table 3 show the embedding rate and PSNR value of our proposed scheme with different parameters K and different thresholds T. Although the PSNR value of $K = 4$ is a little higher than that of $K \leq 3$, the extra data of $K = 4$ is 40 bits more than that of $K \leq 3$. Therefore, the appropriate parameter K is 3. Fig. 3 displays that the stego image produced by our proposed scheme is very similar to that of the cover image. Moreover, each image can be used to embed 185,195 secret bits. It indicates that the proposed scheme achieves high hiding capacity and PSNR value.

Fig. 4 shows that our embedding rate and PSNR value exceed those of the recently developed methods [6, 7, 9]. In Tseng and Hsieh's method [6] and Lee et al.'s method [7], only the mean of the two adjacent pixels of each pixel is used as the prediction value, thus, the prediction accurate is not high. This result causes more non-embeddable pixels and more image distortions. Different from the two methods [6, 7], Lee and Chen [9] calculated the mean of the four adjacent pixels to obtain the exact prediction result.

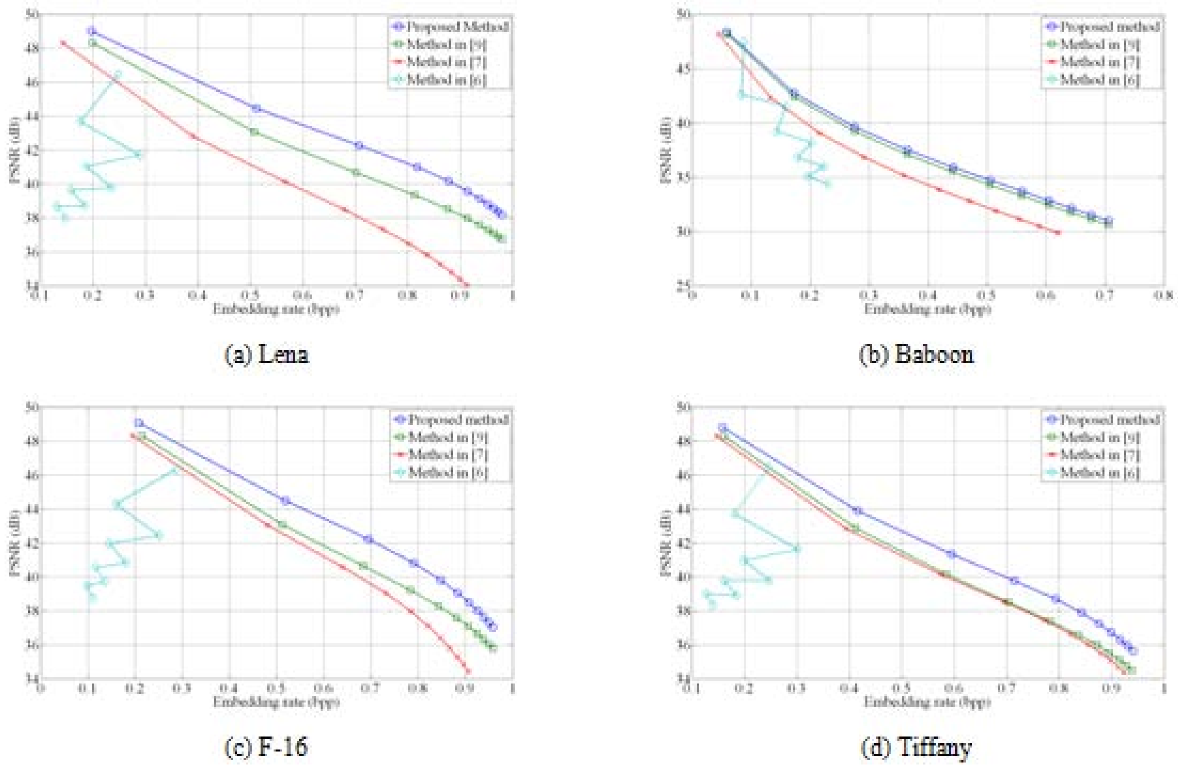

FIGURE 4. Performance comparison of our proposed method and recently developed methods in [6, 7, 9]

However, Lee and Chen's method must modify massive pixels to embed a large amount of secret bits "1". In our method, many secret bits "1" are transformed into the secret bits "0". Thus, most cover pixels in the proposed method are not altered after embedding the transformed secret bits.

TABLE 1. Embedding rate (ER) and PSNR of our proposed method with differents parameters K and different thresholds T for Lena

Threshold	$K = 2$		$K = 3$		$K = 4$	
	ER (bpp)	PSNR (dB)	ER (bpp)	PSNR (dB)	ER (bpp)	PSNR (dB)
1	0.512	44.4	0.512	44.437	0.512	44.471
2	0.707	42.231	0.707	42.269	0.708	42.304
3	0.817	40.967	0.817	41.005	0.817	41.04
4	0.878	40.124	0.878	40.165	0.878	40.199
5	0.913	39.535	0.913	39.573	0.913	39.606
6	0.937	39.102	0.937	39.138	0.937	39.171
7	0.952	38.774	0.952	38.807	0.952	38.837
8	0.964	38.513	0.964	38.548	0.964	38.579
9	0.972	38.318	0.972	38.353	0.972	38.381
10	0.978	38.163	0.978	38.197	0.978	38.226

Fig. 5 shows that, under the same embedding rate, the PSNR value of the proposed method is obviously higher than that of Tai et al.'s method [5] and Lu et al.'s method [8]. This is because the accuracy of our prediction method is higher than that of the two methods. After expanding the prediction errors and embedding the secret data, the

TABLE 2. Experimental results of the image Baboon

Threshold	$K = 2$		$K = 3$		$K = 4$	
	ER (bpp)	PSNR (dB)	ER (bpp)	PSNR (dB)	ER (bpp)	PSNR (dB)
1	0.172	42.745	0.172	42.757	0.172	42.766
2	0.275	39.617	0.275	39.627	0.275	39.637
3	0.364	37.496	0.364	37.506	0.364	37.515
4	0.441	35.92	0.441	35.931	0.441	35.94
5	0.505	34.692	0.506	34.702	0.506	34.711
6	0.559	33.691	0.559	33.7	0.559	33.71
7	0.604	32.853	0.604	32.862	0.604	32.871
8	0.642	32.137	0.642	32.147	0.642	32.154
9	0.677	31.52	0.677	31.528	0.677	31.536
10	0.706	30.978	0.706	30.986	0.706	30.995

TABLE 3. Experimental results of the image F-16

Threshold	$K = 2$		$K = 3$		$K = 4$	
	ER (bpp)	PSNR (dB)	ER (bpp)	PSNR (dB)	ER (bpp)	PSNR (dB)
1	0.519	44.457	0.519	44.491	0.519	44.525
2	0.694	42.189	0.694	42.222	0.694	42.258
3	0.79	40.779	0.79	40.814	0.791	40.847
4	0.847	39.786	0.847	39.818	0.847	39.849
5	0.883	39.039	0.883	39.072	0.883	39.101
6	0.908	38.458	0.908	38.489	0.908	38.517
7	0.925	37.992	0.925	38.021	0.925	38.049
8	0.939	37.607	0.939	37.636	0.939	37.663
9	0.949	37.281	0.949	37.309	0.949	37.334
10	0.958	37.013	0.958	37.039	0.958	37.062

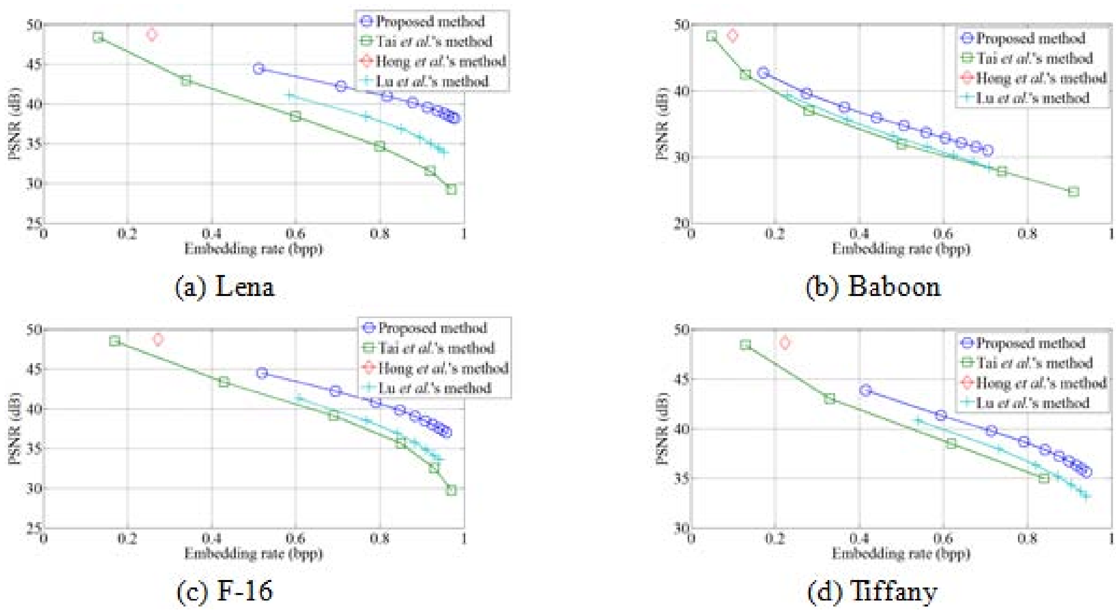

FIGURE 5. Comparison between the proposed method and the three related methods proposed by Hong et al. [4], Tai et al. [5] and Lu et al. [8]

stego image of the proposed method does not have acute distortion. Experimental results show that the maximum embedding rate of Hong et al.'s method is 0.27 bpp. This is because only the prediction error that is equal to 0 or -1 can be used to embed one secret bit. Different from Hong et al.'s method, the threshold of the proposed method can be adjusted, thereby achieving high embedding rate.

4. **Conclusions.** In this paper, a secret data transformation algorithm is proposed to transform the secret bit "1" into the bit "0". Consequently, most cover pixels remain unchanged after embedding the transformed secret bits. On the other hand, we skillfully combine the proposed transformation method and the Lee and Chen's method to achieve high hiding capacity and image quality. Therefore, our PSNR value and embedding rate are higher than those of recently developed methods.

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