

# Very Effective Multi-Layer Reversible Embedding Method Using Low Distortion Modification

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**ABSTRACT.** *In recent years, prediction-based reversible information hiding approaches have been widely developed. For example, Lee and Chen proposed an adjustable prediction-based reversible information hiding approach, hiding capacity of which is higher than that of previous approaches. However, the altered pixels used for embedding secret data are used to predict the next pixel. The prediction results decrease significantly because the previous pixels may suffer from the large modification. In order to solve this problem, in this paper, we propose a new approach with low distortion modification, which modifies each pixel by increasing or decreasing at most one gray level. Thus, the distortions to cover pixels are slight. Moreover, in the proposed approach, some pixels are not altered to enhance the prediction efficiency in the next embedding round. Consequently, the proposed approach is very suitable for multi-layer embedding. Experimental results show that the proposed approach has better image quality than recent prediction-based reversible information hiding approaches under the same hiding rate.*

**Keywords:** Prediction-based reversible information hiding; Low distortion modification; Image quality; Hiding rate.

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1. **Introduction.** Most reversible information hiding approaches can be categorized into difference expansion (DE) [9, 11], compression and replacement [3], mapping and substitution [8], histogram shifting [6], reversible contrast mapping (RCM) [1], multiple steganography images [2], and prediction-based approaches [4, 5, 7, 10]. Each of them has their own advantages and disadvantages.

The DE-based reversible information hiding approach, which was first proposed by Tian [9] in 2003, doubled the difference between two cover pixels and then embedded one secret bit into the difference, thereby gaining two stego pixels. This approach can hide secret data into the cover image effectively. However, serious image distortions emerged after expanding pixel pairs with a large difference. In order to avoid the large difference

expansion problem, Tian used a location map to record whether the difference between the pixel pair can hide one secret bit or not. If the cover pixel is embeddable, then the bit in the location map is set to 0. Otherwise, the bit is set to 1. Afterwards, the location map was compressed and embedded into the cover image. However, the location map cannot be compressed effectively. Embedding the large-sized location map decreases the hiding capacity and the visual quality of stego image.

In order to reduce the size of the location map, Weng et al. [15] proposed an improvement method in 2008. Different from the Tian's method, the non-embeddable pixels were modified. However, if the modified pixel does not have any underflow or overflow problem, the bit in the location map is set to 0. Since most bits in the location map are 0, the location map can be compressed effectively. Weng et al. successfully solve the problem of Tian's method.

On the other hand, Weng et al. [12] proposed a novel reversible data hiding that can embed at least  $(n - 1)$  secret bit into the set of  $n$  cover pixels, where  $n > 1$ . In this method, the difference between the  $n^{th}$  pixels and the mean of the  $(n - 1)$  pixels was calculated. If the difference is smaller than the pre-determined threshold, the set of  $n$  cover pixels located at the smooth region can be used to embed  $2(n - 1)$  secret bits. Therefore, the hiding capacity of Weng et al.'s method is significantly greater than that of Tian's method.

A compression-based reversible information hiding approach was proposed by Celik et al. [3] in 2005. In this approach, unimportant features in cover image were compressed using an arithmetic encoding algorithm [14]. Moreover, these features were replaced by the compressed result as well as secret data. This replacement rule implied that the approach can accomplish high hiding performance if the size of the compressed result was small.

In 2006, Ni et al. [6] proposed a reversible information hiding approach using the histogram shifting, which overcame the shortcoming of Tian's approach. In this approach, a histogram was generated according to the appearance frequency of the pixels in the whole cover image. The most frequently occurring pixel was denoted as the peak point  $F$ , and the most infrequently occurring pixel was represented as the zero point  $I$  in the histogram. The pixels between the peak point and its nearest zero point were shifted by one unit toward the direction of the zero point, thereby gaining a concealing space. Secret data were embedded into the most frequently occurring pixels. In the embedding phase, the pixels were only modified by increasing or decreasing at most one gray level; thus, the quality of the stego image was satisfactory. However, this approach only allowed the most frequently occurring pixels to hide secret data.

The RCM-based reversible information hiding approach, which was first proposed by Coltuc and Chassery [1] in 2007, can hide secret data into the converted pixel pairs gained by the RCM operation. This approach can hide secret data into each pixel pair, so the hiding rate was very high. However, the conversion for the pixel pairs caused serious image distortion.

Chang et al. [2] proposed a dual-image reversible information hiding approach that reproduced the cover image to gain two of the same images, which were used to hide secret data. In the hiding phase, according to the lookup table of pixel pairs and secret data, each pixel pair in the two images was modified to embed one secret bit. If the corresponding value of the pixel pair was not equal to the embedded data, the pixel pair was replaced by one of its surrounding pixel pairs in the lookup table, where its corresponding value was equal to the embedded data. Thus, in the extraction phase, the secret data hidden in each pixel pair can be retrieved easily by matching the lookup table. Each pixel pair can be used to embed secret data by using this approach, so the hiding

capacity was high. However, this approach needed two stego images to correctly extract secret data and recover the original image.

In 2007, Thodi and Rodriguez [10] proposed a prediction-based reversible information hiding approach. This approach doubled the prediction error between the cover pixel and its prediction value, where the prediction value was generated through the inherent edge-detection predictor. The expanded prediction error was increased by one secret bit, and then it was increased by the prediction value, thereby gaining a stego pixel. The approach can generate the exact prediction value for each cover pixel; thus, the image can retain good visual quality after expanding the prediction errors and embedding the secret bits. However, the pixel in the complex region of the cover image may have a larger prediction error; adding the error and one secret bit into the cover pixel may cause serious image distortion as well as the underflow or overflow problem. In order to avoid these problems, extra data were required to distinguish between embeddable and non-embeddable pixels.

Different from Thodi and Rodriguez's method, Weng and Pan [13] proposed multiple prediction modes that use the closest neighboring pixels of the cover pixel to calculate the prediction value and the local variance. Under the smaller local variance, the cover pixel can be used to embed two secret bits. Therefore, the hiding capacity of Weng and Pan's method is significantly greater than that of Thodi and Rodriguez's method.

In 2010, Lee et al. [5] proposed an image pre-processing mechanism to reduce the volume of extra data and solve the underflow and overflow problems. In this mechanism, original pixels that were smaller than  $T + 1$  or greater than  $255 - (T + 1)$  became  $T + 1$  and  $255 - (T + 1)$ , respectively. The notation  $T$  denoted the pre-determined threshold. Thus, these altered pixels can be reused to embed secret data; that was why the hiding rate of Lee et al.'s approach was higher than that of Thodi and Rodriguez's approach. In addition, the mechanism only recorded these altered pixels for recovering the original pixel, so there were less extra data than in Thodi and Rodriguez's approach. However, in the prediction approach, the average value of the top pixel and the left pixel was only used as the prediction value of the current embedding pixel. As a result, some prediction values were dissimilar to the original pixels, thereby increasing more non-embeddable pixels and more image distortions.

In order to enhance the prediction efficiency, Qin et al. [7] and Lee and Chen [4] used the average of more adjacent pixels as one prediction value, the accuracy of which was better than that of Thodi and Rodriguez's approach. However, in Lee and Chen's approach, in order to correctly recover image, the original pixel together with the previous altered pixels (also called stego pixel) were used to generate the prediction value of the next pixel. Since some stego pixels suffered from the large modification previously, the accuracy decreased after using them for prediction.

In order to overcome this problem, in this paper, we propose a low distortion modification strategy that modifies each pixel by increasing or decreasing at most one gray level in each embedding round. Thus, in the next embedding round, although our approach also uses the stego pixels that are modified slightly, the prediction precision doesn't decrease significantly. The advantage implies that our approach is better than Lee and Chen's approach. The rest of this paper is organized as follows. Sections 2 through 3 describe Lee and Chen's approach and our proposed approach. Section 4 compares the performances between the proposed approach and the recently reported approaches. The conclusions are given in Section 5.

**2. Related Approach.** In 2012, Lee and Chen [4] proposed an adjustable prediction reversible information approach that calculated the average value of the most adjacent

pixels of the current embedding pixel to obtain an accurate prediction value. The prediction formula is listed as follows.

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

where  $(x, y)$  represents the coordinate of the cover image;  $H$  and  $W$  denote the height and the width of the image, respectively;  $\hat{P}_{TL}$  represents the average of the top pixel  $P_{(x-1,y)}$  and the left pixel  $P_{(x,y-1)}$ ;  $\hat{P}_{TR}$  denotes the average of the top pixel  $P_{(x-1,y)}$  and the right pixel  $P_{(x,y+1)}$ ;  $\hat{P}_{BL}$  represents the average of the bottom pixel  $P_{(x+1,y)}$  and the left pixel  $P_{(x,y-1)}$ ;  $\hat{P}_{BR}$  denotes the average of the bottom pixel  $P_{(x+1,y)}$  and the right pixel  $P_{(x,y+1)}$ .

After the prediction value  $\hat{P}_{(x,y)}$  was generated, the absolute value of the prediction error between the cover pixel  $P_{(x,y)}$  and the prediction value  $\hat{P}_{(x,y)}$  is calculated, i.e.,  $e_{(x,y)} = |P_{(x,y)} - \hat{P}_{(x,y)}|$ . If the absolute value of prediction error  $e_{(x,y)}$  is equal to or smaller than the threshold  $T$ , the cover pixel  $P_{(x,y)}$  can be used to embed one secret bit  $s$  through the following embedding formula, i.e.,

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

Otherwise, if the absolute value of the prediction error  $e_{(x,y)}$  is higher than the threshold  $T$ , the pixel was modified by the following formula.

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

The above prediction and embedding procedures were performed for each cover pixel, until all secret bits were embedded in the image or all pixels have been used to embed the secret data.

**3. Proposed Approach.** Lee and Chen’s approach can achieve high embedding rate. However, the stego pixels in this approach were used to generate the prediction value of the next embedding pixel. The prediction result is inaccurate because the difference between the original pixel and stego pixel is large. In order to overcome this problem, we propose a low distortion modification strategy for multi-layer embedding. Fig. 1 shows the flowcharts of the embedding procedure and the extraction and recovery procedures.

**3.1. Hiding Phase.** In the proposed approach, the threshold  $T$  is decided by the user. Then, the  $n$  least significant bit ( $n - LSB$ ) of the pixel  $P_{(x,y)}$  in the two ranges  $[0, T]$  and  $[255 - T, 255]$  is recorded and then modified as  $T$  and  $255 - T$  to avoid the underflow and overflow problems. Note that no extra data are generated if the pixel does not belong to the two ranges. After performing the above procedure, each pixel  $\tilde{P}_{(x,y)}$  can be used to embed secret data.

During the data embedding, the prediction value  $\hat{P}_{(x,y)}$  is generated by Lee and Chen’s prediction approach [4]. The pixel  $\tilde{P}_{(x,y)}$  remains unchanged if the prediction error  $e_{(x,y)}$  between the pixel  $\tilde{P}_{(x,y)}$  and its prediction value  $\hat{P}_{(x,y)}$  is smaller than  $T$  or higher than  $-T + 1$ . Otherwise, the pixel  $\tilde{P}_{(x,y)}$  is increased or decreased by at most one. Consequently, the proposed approach only modifies some pixels, and the distortions to the pixels are

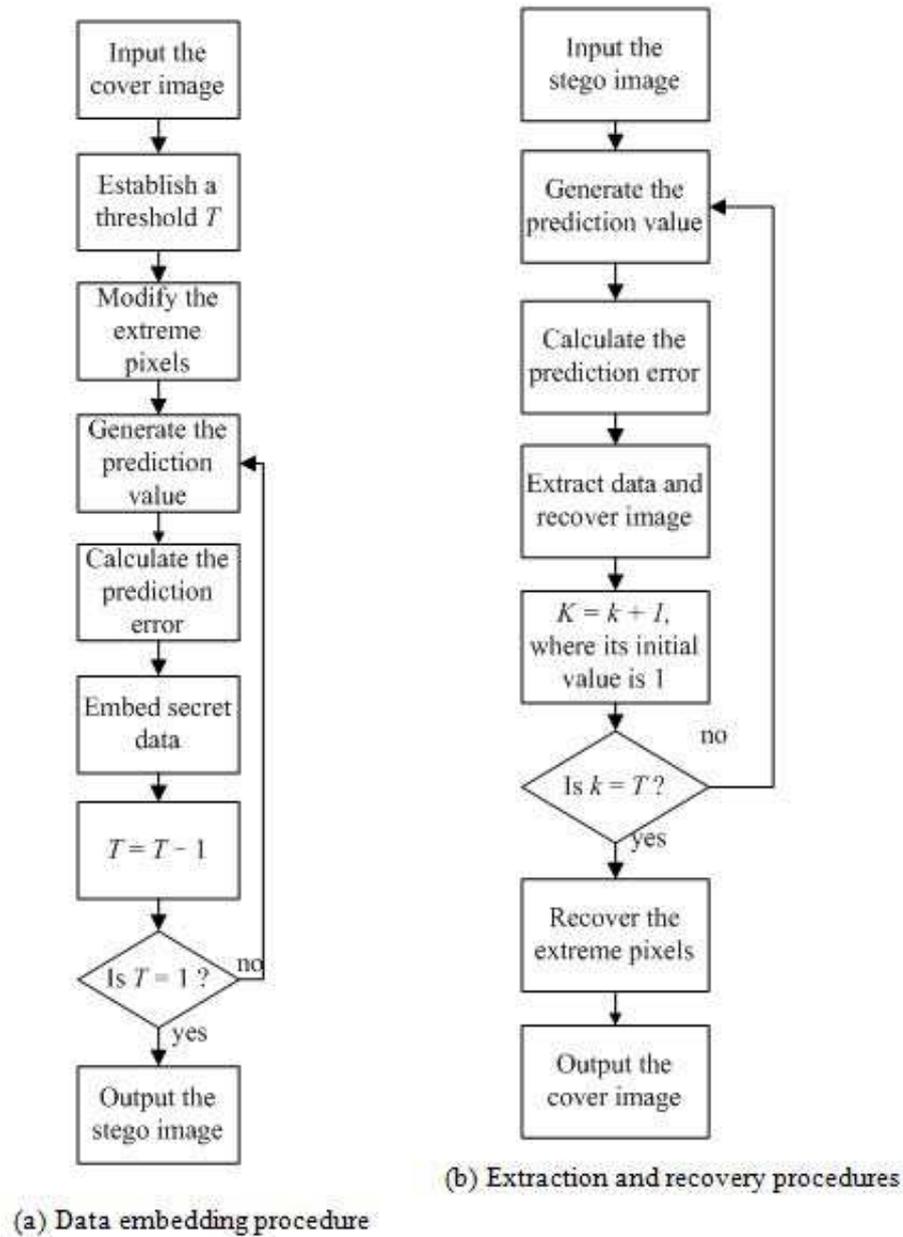


FIGURE 1. Flowchart of the proposed approach

slight. That is why the image quality of our approach is better than that of Lee and Chen's approach. Finally, the pixels whose prediction errors are equal to  $T$  or  $-T + 1$  are used to embed secret data by the proposed embedding approach. After the above procedure, the threshold  $T$  is decreased by one, and then the embedding procedure is repeated until  $T = 1$ . Thus, the larger the threshold  $T$  is, the higher the hiding rate becomes. The algorithm of data embedding is described as follows.

Input: Cover image and a threshold

Output: Stego image

Step 1: Record the  $n$ -LSB of the extreme pixels, which are smaller than  $T$  or higher than  $255 - T$ . These recorded LSBs are hidden in the cover image together with the secret data.

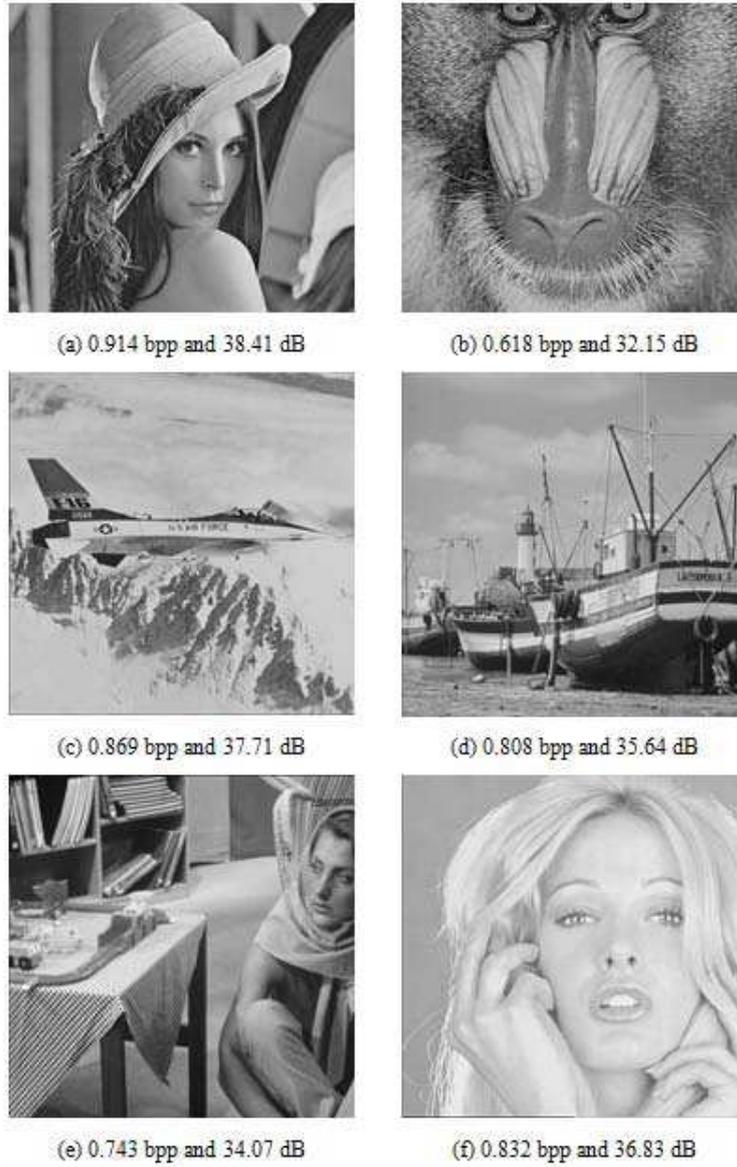


FIGURE 2. Stego images

Step 2: Modify the extreme pixels through the following equation to avoid the underflow or overflow problem.

$$\tilde{P}_{(x,y)} = \begin{cases} T, & \text{if } P_{(x,y)} \leq T + 1, \\ 255 - T, & \text{if } P_{(x,y)} \geq 255 - T, \\ P_{(x,y)}, & \text{otherwise.} \end{cases}$$

Step 3: Generate the prediction value  $\hat{P}_{(x,y)}$  of the pixel  $\tilde{P}_{(x,y)}$  through the prediction approach of Lee and Chen.

Step 4: Calculate the prediction error  $e_{(x,y)}$  between the pixel  $\tilde{P}_{(x,y)}$  and its prediction value  $\hat{P}_{(x,y)}$ , i.e.,  $e_{(x,y)} = \tilde{P}_{(x,y)} - \hat{P}_{(x,y)}$ .

Step 5: Obtain the stego pixel  $P'_{(x,y)}$  through the following embedding equation:

$$P'_{(x,y)} = \begin{cases} \tilde{P}_{(x,y)} + s, & \text{if } e_{(x,y)} = T, \\ \tilde{P}_{(x,y)} - s, & \text{if } e_{(x,y)} = -T + 1, \\ \tilde{P}_{(x,y)} + 1, & \text{if } e_{(x,y)} > T, \\ \tilde{P}_{(x,y)} - 1, & \text{if } e_{(x,y)} < -T + 1, \\ \tilde{P}_{(x,y)}, & \text{otherwise,} \end{cases}$$

Step 6:  $T = T - 1$ .

Step 7: Repeat Steps 3 through 7 until  $T = 1$ .



FIGURE 3. Six test images

**3.2. Extraction and Recovery Phase.** In the extract and recovery phase, the prediction error  $e'_{(x,y)}$  between the stego pixel  $P'_{(x,y)}$  and its prediction value  $\hat{P}_{(x,y)}$  is calculated, where the prediction value  $\hat{P}_{(x,y)}$  is generated through Lee and Chen's prediction approach. One secret bit  $s$  can be extracted if the prediction error  $e'_{(x,y)}$  belongs to the two ranges  $[-k, -k + 1]$  and  $[k, k + 1]$ , where the initial value of  $k$  is 1. Note that there is no secret

bit  $s$  in the stego pixel  $P'_{(x,y)}$  if the prediction error  $e'_{(x,y)}$  does not belong to these two ranges. After the secret bits are extracted, the pixels are recovered through the following recovery procedure.

The pixels whose prediction errors  $e'_{(x,y)}$  belong to the range  $[k + 2, k - 1]$  do not require any recovery operations because they are not modified in the embedding phase. Otherwise, the pixels are increased or decreased by one gray level for recovery. After the pixels are recovered, the parameter  $k$  is increased by one, and then, the above extraction and recovery procedures are repeated until  $k = T$ . When all of the embedded data are extracted and the pixels are recovered, the  $n$ -LSB of the extreme pixels that are equal to  $T$  or  $255 - T$  is replaced by the recorded LSB of the embedded data, thereby obtaining the original image.

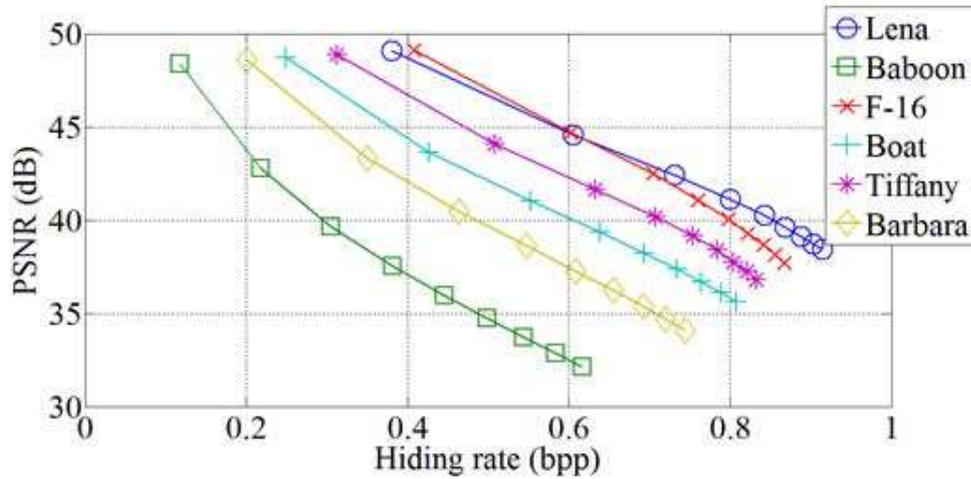


FIGURE 4. Hiding rates and PSNR values obtained by the proposed approach using different thresholds  $T$

Input: Stego image and the threshold

Output: Cover image

Step 1: Generate the prediction value  $\hat{P}_{(x,y)}$  of the stego pixel  $P'_{(x,y)}$  through Lee and Chen's prediction approach.

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

Step 3: Extract the secret bit  $s$  from the prediction error  $e'_{(x,y)}$  through the following equation:

$$s = \begin{cases} 0, & \text{if } e'_{(x,y)} = k \text{ or } e'_{(x,y)} = -k + 1, \\ 1, & \text{if } e'_{(x,y)} = k + 1 \text{ or } e'_{(x,y)} = -k. \end{cases}$$

Step 4: Recover the pixel  $\tilde{P}_{(x,y)}$  through the following equation:

$$\tilde{P}_{(x,y)} = \begin{cases} P'_{(x,y)} - 1, & \text{if } e'_{(x,y)} \geq k + 1, \\ P'_{(x,y)} + 1, & \text{if } e'_{(x,y)} \leq -k, \\ P'_{(x,y)}, & \text{otherwise.} \end{cases}$$

Step 5:  $k = k + 1$ .

Step 6: Repeat Steps 1 through 6 until  $k = T$ .

Step 7: Replace the  $n$ -LSB of the pixel  $\tilde{P}_{(x,y)}$  by the recorded LSBs of the embedded data to recover the original pixel  $P_{(x,y)}$ .

**4. Experimental Results.** The proposed approach and the recent reversible information hiding approaches were implemented to compare the hiding capacity and the stego image quality. The hiding rate (HR) was measured by the formula  $HR = (\text{number of embeddable pixels} - \text{number of recorded bits}) / \text{number of cover pixels}$ . Additionally, the quality of stego image was measured by the peak signal-to-noise ratio (PSNR), i.e.,  $PSNR = 10 \log_{10}(255^2/mse)$ .

Fig. 3 shows the six test images sized  $512 \times 512$ . Fig. 2 shows the stego images and their corresponding hiding rates. The proposed approach can achieve 0.797 bpp for hiding capacity and 35.80 dB for PSNR value averagely. The high PSNR value implies that the difference between the stego image and the cover image cannot be distinguished easily by the human eye. Fig. 4 shows the hiding rates and PSNR values gained by the proposed approach with the different thresholds  $T$  ranging from 1 to 9. Under the same threshold  $T$ , the hiding rate and the PSNR value of the smooth image Lena are significantly higher than those of the complex image Baboon. It is because that, in the complex image Baboon, the difference between the pixel and its adjacent pixel is large, thereby decreasing the prediction accuracy. Consequently, the proposed method is more suitable for the smoother images.

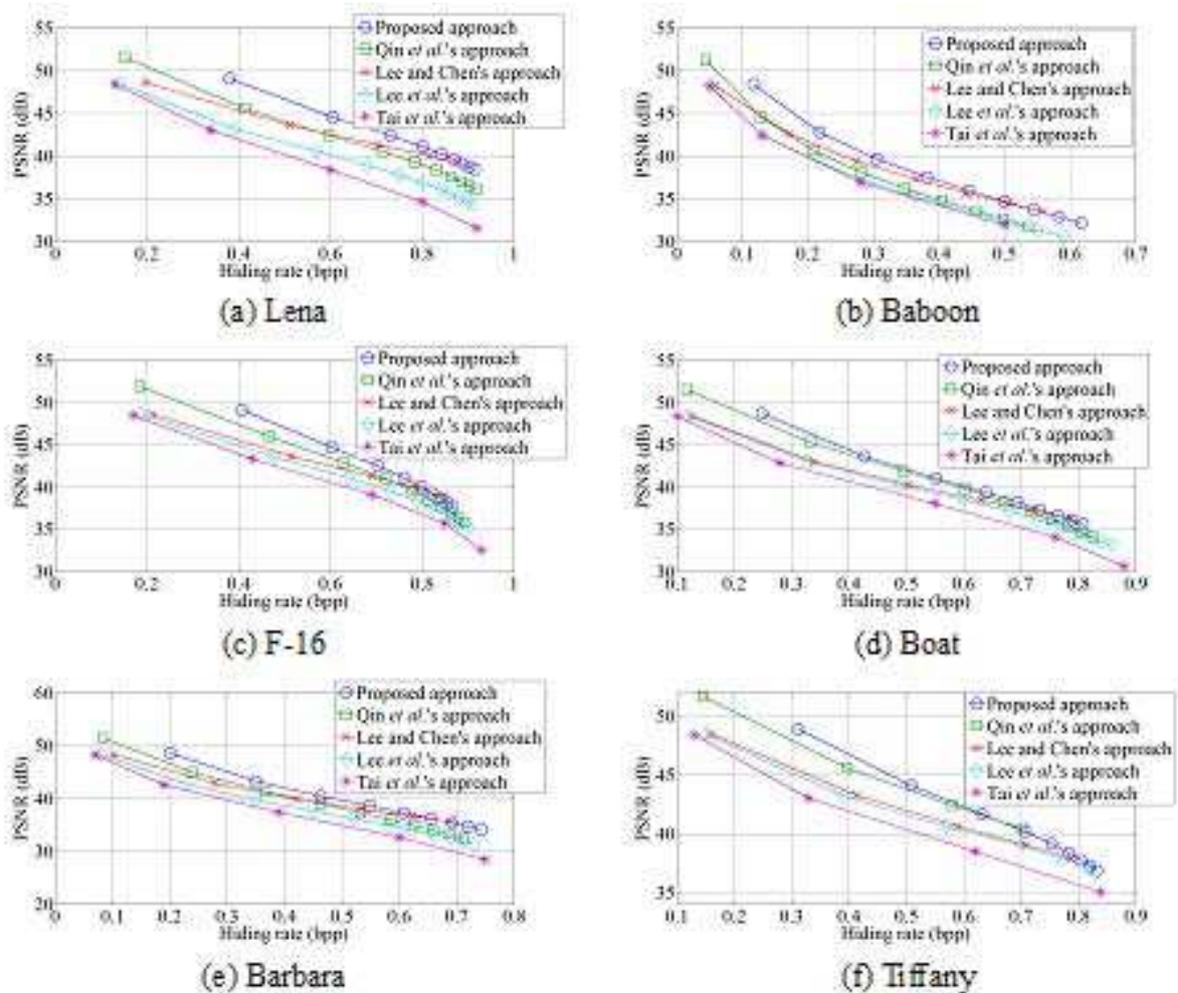


FIGURE 5. Comparison between the proposed approach and recent reversible information hiding approaches in terms of hiding rate and PSNR

In addition, it can be observed from Fig. 4 that the PSNR value can be significantly enhanced by decreasing the threshold  $T$ . For example, although the hiding rate with  $T = 1$  is 0.17 bpp that is lower than the value with  $T = 2$ , the PSNR value with  $T = 1$  is 4.957 dB that is higher than the value with  $T = 2$ . It is because that the small threshold  $T$  does not allow the large prediction error to hide secret data. Thus, the threshold  $T$  can effectively control stego image quality.

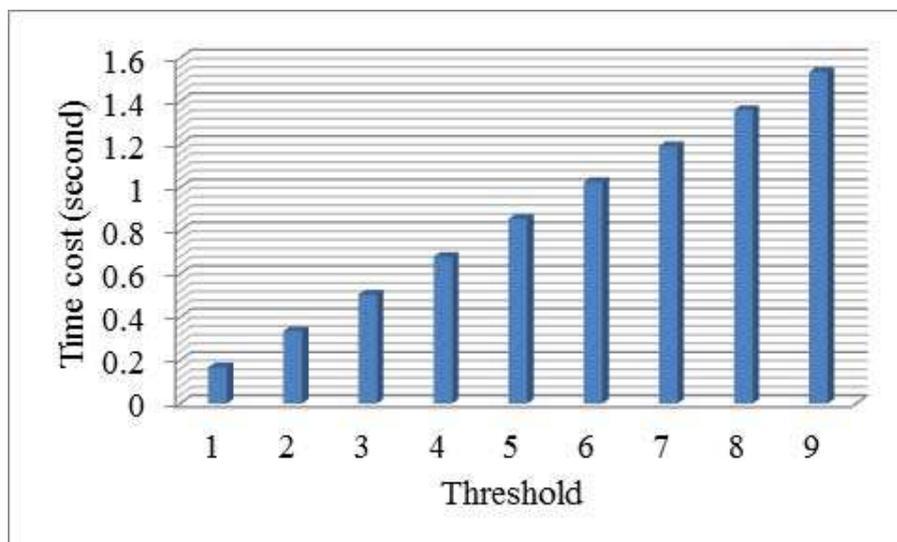


FIGURE 6. Time cost of our approach using different thresholds

Fig. 5 shows the comparison results of the proposed approach and the recently reported approaches [4, 5, 7, 11]. Since our approach and Lee and Chen's approach [4] used more adjacent pixels to obtain the accurate prediction value, both the hiding rates and the PSNR values of the proposed approach were higher than those of other approaches [5, 7, 11]. In addition, the hiding rate and PSNR value of our approach were higher than those of Lee and Chen's approach because the pixels in our approach was increased or decreased by at most one gray level. In Lee and Chen's approach, the embeddable pixels were increased or decreased according to their prediction errors and the secret bit, and all of the non-embeddable pixels were increased or decreased by  $T + 1$ , which caused severe image distortions.

In our approach, the image was reused for  $T$  times to accomplish the data hiding, thus, the time complexity of the proposed approach was higher than that of other approaches. Fig. 6 shows that our time cost  $c$  is linear growth, i.e.,  $c = 10T$ , where the constant "10" may be changed for different computers. The maximum cost time was two minutes, which can be accepted for practical use.

**5. Conclusions.** This paper proposes an information hiding approach that can embed secret data reversibly in the cover image. In each embedding round, only the pixels that their prediction errors are higher than  $T$  or  $-T + 1$  are altered by increasing or decreasing one gray level. Thus, the number of the modified pixels is less and the distortions to the image are slight. Consequently, in the next embedding round, the prediction result is still accurate even if the stego pixels are used for prediction. The high prediction efficiency enhances the hiding capacity and the visual quality of stego image. Experimental results demonstrate that the proposed approach can overcome the shortcoming of Lee and Chen's approach and hide more secret data in cover image and retain satisfactory image quality.

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## REFERENCES

- [1] D. Coltuc and J. M. Chassery, Very fast watermarking by reversible contrast mapping, *IEEE Signal Processing Letters*, vol. 14, no. 4, pp. 255-258, 2007.
- [2] C. C. Chang, D. Kieu, and Y. C. Chou, Reversible data hiding scheme using two steganographic images, *Proceedings of the IEEE TENCON 2007*, Taipei, Taiwan, pp. 1-4, 2007.
- [3] M. U. Celik, G. Sharma, A. M. Tekalp, and E. Saber, Lossless generalized-LSB data embedding, *IEEE Trans. Image Processing*, vol. 14, no. 2, pp. 253-266, 2005.
- [4] C. F. Lee and H. L. Chen, Adjustable prediction-based reversible data hiding, *Digital Signal Processing*, vol. 22, no. 6, pp. 941-953, 2012.
- [5] C. F. Lee, H. L. Chen and H. K. Tso, Embedding capacity raising in reversible data hiding based on prediction of difference expansion, *Journal of Systems and Software*, vol. 83, no. 10, pp. 1864-1872, 2010.
- [6] Z. Ni, Y. Q. Shi, N. Ansari and W. Su, Reversible data hiding, *IEEE Trans. Circuits and Systems for Video Technology*, vol. 16, no. 3, pp. 354-362, 2006.
- [7] C. Qin, C. C. Chang, and L. T. Liao, An adaptive prediction-error expansion oriented reversible information hiding scheme, *Pattern Recognition Letters*, vol. 33, no. 16, pp. 2166-2172, 2012.
- [8] C. Qin, C. C. Chang, and S. T. Wang, A novel lossless steganographic scheme for data hiding in traditional Chinese text files, *Journal of Information Hiding and Multimedia Signal Processing*, vol. 5, no. 3, pp. 534-545, 2014.
- [9] J. Tian, Reversible data embedding using a difference expansion, *IEEE Trans. Circuits and Systems for Video Technology*, vol. 13, no. 8, pp. 890-896, 2003.
- [10] D. M. Thodi and J. J. Rodriguez, Expansion embedding techniques for reversible watermarking, *IEEE Trans. Image Processing*, vol. 16, no. 3, pp. 721-730, 2007.
- [11] W. L. Tai, C. M. Yeh, and C. C. Chang, Reversible data hiding based on histogram modification of pixel differences, *IEEE Trans. Circuits and Systems for Video Technology*, vol. 19, no. 6, pp. 906-910, 2009.
- [12] S. Weng, S. C. Chu, N. Cai and R. Zhan, Invariability of mean value based reversible watermarking, *Journal of Information Hiding and Multimedia Signal Processing*, vol. 4, no. 2, pp. 90-98, 2013.
- [13] S. Weng and J. S. Pan, Reversible watermarking based on multiple prediction modes and adaptive watermark embedding, *Multimedia Tools and Applications*, vol. 72, no. 3, pp. 3063-3083, 2014.
- [14] I. H. Witten, M. Radford, and J. G. Cleary, Arithmetic coding for data compression, *Communications of the ACM*, vol. 30, no. 6, pp. 520-540, 1987.
- [15] S. Weng, Y. Zhao, J. S. Pan, and R. Ni, Reversible watermarking based on invariability and adjustment on pixel pairs, *IEEE Signal Processing Letters*, vol. 15, pp. 721-724, 2008.