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A HIGH-CAPACITY REVERSIBLE DATA HIDING SCHEME BASED ON PAIRWISE PEE AND EMD

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Abstract – *This paper proposes a high embedding capacity reversible data hiding algorithm using pairwise prediction error expansion and exploiting modification direction. In this algorithm, the original image is first decomposed into 4 × 4 blocks, and each block is divided into inner and outer sub-blocks. Next, the standard deviation (δ) of the pixels in the outer sub-block is used to evaluate the statistical properties of the inner sub-block. If the value δ of the outer sub-block is less than a given threshold, the inner sub-block is considered embeddable, otherwise, it is labeled non-embeddable. A pairwise prediction error expansion mapping is adopted for embeddable inner sub-blocks. Additionally, to improve the embedding capacity of the proposed scheme, an exploiting modification direction table is developed to modify the prediction error histogram. Through careful selection of error pairs for mapping using the exploiting modification direction table, the quality of the stego image can be preserved while the embedding capacity of the proposed method can be significantly improved. Experimental results illustrate that our method achieves better performance than previous works, especially in terms of image quality.*

Keywords: exploiting modification direction, pairwise prediction error expansion, reversible data hiding, rhombus predictor.

I. INTRODUCTION

With the rapid growth of technology and mobile usage, keeping our data safe has become a big concern for both governments and businesses. One way to do this is by hiding sensitive information in a cover medium, such as text, audio, images, or video, ensuring that only authorized users can access it. Data hiding schemes typically fall into two categories, i.e., irreversible and reversible data hiding. Irreversible data hiding schemes only enable the extraction of hidden data, making it impossible to recover the original cover media [1]. Conversely, reversible data hiding (RDH) techniques allow for the retrieval of both the hidden data and cover data during extraction [2]. RDH schemes have attracted considerable attention from researchers, especially those utilizing various cover media types for data embedding. Among these, digital images are frequently chosen due to their high redundancy. Image RDH schemes can be primarily divided into two groups: difference expansion (DE) [3–7] and histogram shifting (HS) [8–16].

In the DE-based RDH group, the scheme, initially introduced by Tian [3], involves partitioning the cover image into pixel pairs (p and q), where the difference between p and q is expanded to conceal one secret bit. However, Tian's approach has a limited embedding capacity (EC) of 0.5 bits per pixel (bpp). To overcome this constraint, Al-Qershi et al. [4] proposed a novel DE-based RDH scheme for medical images. Leveraging the characteristics of large smooth regions commonly found in medical images, Al-Qershi et al. [4] categorized the cover image into smooth and complex regions. In the smooth region, image pixels are grouped into blocks with size of 2 × 2 pixels. This segmentation enables the modification of up to three differences to embed three secret bits, thereby enhancing the EC in the smooth region. In original DE-based RDH schemes, the disparity between two pixels in complexity blocks typically exceeds that in smooth blocks. This

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discrepancy can impact image quality. To mitigate this issue, researchers have devised various RDH schemes aimed at minimizing the original difference. These include reduced difference expansion (RDE), improved reduced difference expansion (IRDE), and enhanced difference expansion (ERDE) [5, 7].

In the HS-based RDH group, a significant method was first presented by Ni et al. [8]. This method efficiently restores the original image without distortion by constructing the histogram of the cover image and shifting the bins within peak and zero-point ranges to make room for embedding data. The EC of HS-based RDH relies on the peak point of the histogram, indicating that a sharper histogram leads to a higher EC. To achieve sharper histograms for embedding more secret bits, Fu et al. [9] introduced an RDH method using prediction-error histogram (PEH) mapping. This method exploits the similarity of adjacent pixels in the original image to compute the predicted pixel and generate the PEH. To enhance EC further, several novel RDH schemes based on multiple histogram modifications were proposed in the studies of Li et al. [10] and Rad et al. [11]. Unlike conventional HS schemes, these multiple HS approaches achieve higher EC by using multiple bins to accommodate embedded data.

Several prediction error expansion (PEE) based RDH methods were proposed to enhance the performance of the RDH method. For example, Sachnev et al. [12] introduced an RDH method based on PEE using a rhombus predictor. The method introduced a rhombus predictor, which considers four nearby pixels for the prediction of the value of the center pixel. To enhance the EC and the image quality, the cover image is scanned into a chessboard pattern, and the secret message is embedded in two passes using PEH modification. Then, Li et al. [13] presented an RDH method utilizing the pixel value ordering (PVO) technique, resulting in high-quality stego images with good EC. This scheme decomposes the original image into uniformly sized blocks and sorts the pixels of each block in ascending order. Then, the prediction errors are generated by computing the intensity difference between the first and the second pixels at the block's extreme ends. As a result, the PEH derived from the differences of the sorted pixels is typically sharper than that generated by traditional HS schemes. While the scheme ensures high-quality stego images, its EC is often constrained, typically utilizing only one of the peak points to embed data. Kumar et al.'s approach [14] has drawn considerable interest due to its significant increase in EC with minimal impact on the stego image quality. Their scheme employs both pairwise PEE and pairwise PVO mechanisms to embed data in each block. Nevertheless, the method has shown inefficiencies in creating smooth blocks by leveraging spatial location effectively. Moreover, it may introduce ± 2 changes of the pixel value in some cases, negatively affecting stego image quality. To overcome the limitation of the scheme [14], Kumar et al. [15] proposed an adaptive RDH method that optimally chooses the embedding mechanism according to the image block classification. Specifically, for smooth blocks, a pairwise PEE mapping is applied, while for moderately complex blocks, a pairwise PVO strategy is adopted. Otherwise, blocks that do not meet these criteria are skipped unchanged. By effectively leveraging both PEE and PVO strategies, the RDH scheme achieved higher EC and better image quality. However, the two-dimensional histogram shifting mechanism proposed by Kumar et al. [15] did not thoroughly select pairs of prediction errors to be shifted, resulting in the unnecessary shifting of several values. Additionally, each pair could only be maximum shifted up to three directions, limiting the maximum EC to log2(3) bits and constraining the overall EC.

To address the drawbacks of previous schemes, this paper proposes a high EC RDH based on pairwise PEE and exploiting modification direction (EMD) mapping. This scheme partitions the cover image into 4×4 blocks using a sliding window to ensure uniform block size. Each block is then further decomposed into inner and outer sub-blocks. The outer sub-block serves as a reference for the inner sub-block to assess its statistical properties through standard deviation. If the outer sub-block's standard deviation is below a given threshold, the inner sub-block is an embeddable block for embedding the secret data by using pairwise PEE and EMD mapping. Otherwise, this inner sub-block is a non-embeddable block. By carefully selecting a pair of bins to apply the EMD table, the proposed scheme can embed up to three bits in error pairs (0, 0), leading to higher EC and better image quality.

II. RELATED WORKS

A. PEE based RDH scheme

Sachnev et al. [12] introduced a reversible watermarking method based on PEE using sorting of predictors. The method introduced a rhombus predictor, which considers all nearby pixels for reference pixel prediction. To embed the secret message, the original image is scanned into a chessboard pattern as shown in Figure 1. Then, the secret message is embedded in two phases. In the initial phase, pixels marked with an 'x' sign are processed. In the second phase, the pixels marked with an 'o' sign are addressed. Subsequently, the pixels are sorted according to their local variance to prioritize the least complex pixels for embedding the secret data.

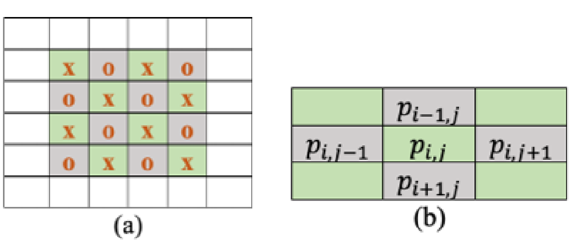


Fig. 1: Cover image and rhombus pattern (a) checkboard pattern of the cover image and (b) rhombus context of pixel $p_{i,j}$

First, the prediction value of the pixel $p_{i,j}$ is calculated by a rhombus context, which includes neighboring pixels $p_{i,j-1}$, $p_{i-1,j}$, $p_{i,j+1}$ and $p_{i+1,j}$, as depicted in Figure 1(b). The prediction value is determined by Equation (1).

$$p'_{i,j} = \left(\frac{p_{i,j-1} + p_{i-1,j} + p_{i,j+1} + p_{i+1,j}}{4}\right) \quad (1)$$

where the predicted value of the pixel $p_{i,j}$ is denotes $p'_{i,j}$. The prediction error $E_{i,j}$ is then conducted by using Equation (2).

$$E_{i,j} = p_{i,j} - p'_{i,j} \quad (2)$$

Then, the prediction error sequence is used to construct the PEH by counting the frequency of prediction-errors. The data is embedded by using Equation (3).

$$E'_{i,j} = \begin{cases} 2E_{i,j} + s, & if\ E_{i,j} \in (-T, T) \\ E_{i,j} + T, & if\ E_{i,j} \in [T, \infty) \\ E_{i,j} - T, & if\ E_{i,j} \in (-\infty, -T] \end{cases} \quad (3)$$

where T represents a given threshold that helps balance the tradeoff between the EC and the quality of image, and s represents a secret bit. Then, the pixel $p_{i,j}$ is modified by using Equation (4).

$$p_{i,j} = p'_{i,j} + E'_{i,j} \quad (4)$$

This alteration is applied to each pixel marked with an 'x' sign for completion the first phase of embedding. In the second phase, a similar process is repeated for the pixels marked with an 'o' sign, using the updated image.

B. Pairwise PEE based RDH scheme

Ou et al. [17] presented an RDH method based on pairwise PEE mapping. This scheme leverages the correlation of adjacent prediction errors for embedding data efficiently through two-dimensional (2D) PEH expansion. The pairwise PEE scheme scans the original image into the chessboard form, as illustrated in Figure 1(a), and conducts the embedding process in two phases. For pairwise embedding, the value of each pixel is predicted by calculating the rhombus mean. Two adjacent predicted values $p'_{i,j}$ and $p'_{i+1,j+1}$ of the pixels $p_{i,j}$ and $p_{i+1,j+1}$ are determined based on rhombus prediction by using Equation (1).

These prediction-errors $E'_{i,j}$ and $E'_{i+1,j+1}$ for the pixel pairs are computed by using Equation (2). Then, the prediction-error sequence is utilized to create the PEH by tallying the frequency of prediction-errors, as shown in Figure 2.

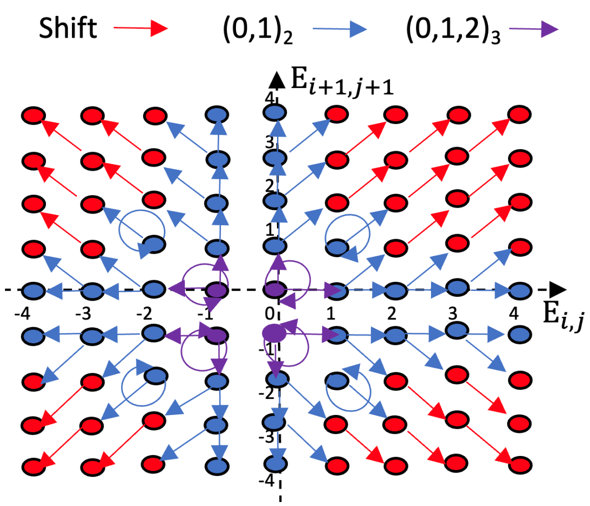


Fig. 2: 2D PEH mapping of PEE

Subsequently, the pixels, $p_{i,j}$ and $p_{i+1,j+1}$, are modified together to embed the data based on the 2D shifting of prediction errors as depicted in Figure 2. Like the traditional 1D shifting, the values of $p_{i,j}$ and $p_{i+1,j+1}$ are adjusted by a maximum of ±1 in the 2D PEH shifting. However, the pairwise embedding process expands prediction-error pairs like (0, 0) to only three possible pairs: (0, 0), (0, 1), and (1, 0), enabling the embedding of $\log_2(3)$ bits. Conversely, expansion from (0, 0) to (1, 1) is avoided to keep the changes to only 1, thus minimizing distortion while reducing EC slightly.

To offset the decrease in EC resulting from the reduced expansion, the scheme additionally leverages prediction-error (1, 1) to embed one bit by modifying it to either (1, 1) or (2, 2) depending on the secret bit either 0 or 1, thereby augmenting the EC.

III. THE PROPOSED SCHEME

In this section, the proposed RDH method based on pairwise PEE and EMD mapping is introduced. The diagram of the method is shown in Figure 3. A detailed explanation of this scheme is given in the following subsections.

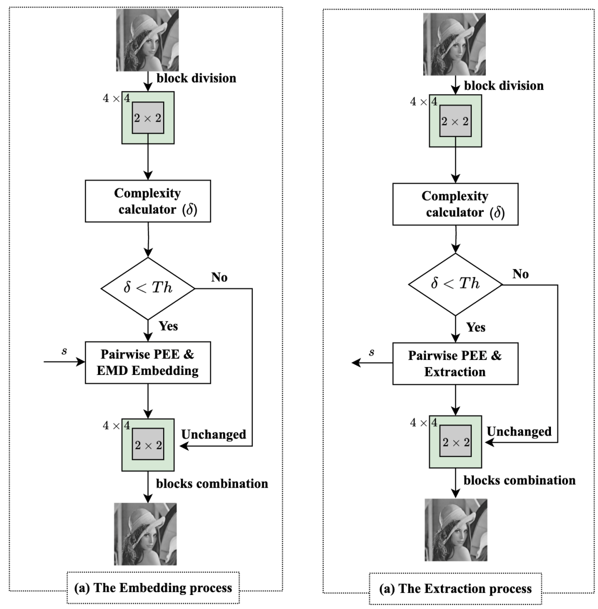


Fig. 3: The diagram of the proposed method, (a) the Embedding process, (b) the Extraction process

A. *Block decomposition and complexity calculation*

The proposed scheme involves dividing the host image into blocks with a size of 4×4. Each block is then decomposed into outer sub-block and inner sub-block as depicted in Figure 4. The outer sub-block encompasses all surrounding pixels, providing the most accurate representation of the local context for the pixels in the inner sub-block. Therefore, the pixel distribution of the outer sub-block effectively characterizes the pixel distribution of the inner sub-block.

To evaluate the complexity of a block, the standard deviation δ of outer sub-block is calculated. Based on δ, the inner sub-block is categorized into two groups: embeddable and non-embeddable sub-blocks. If the δ of the outer sub-block is less than a given threshold Th, the inner sub-block belongs to the embeddable group,

ou_1	ou_2	ou_3	ou_4
ou_{12}	in_1	in_2	ou_5
ou_{11}	in_4	in_3	ou_6
ou_{10}	ou_9	ou_8	ou_7

Fig. 4: The illustration of the inner and outer sub-block

otherwise, it is considered in a non-embeddable group. The δ of outer sub-block is determined by using Equation (5).

$$\delta = \sqrt{\frac{\sum(ou_i - \mu_{ou})^2}{M}} \tag{5}$$

where μ_{ou} represents the mean value of all pixels of the outer sub-block, and M denotes the number of pixels of the outer sub-block.

B. Pairwise PEE and EMD based RDH

For the inner sub-block belonging to embeddable group, we conduct two pairs of pixels which the first pair has pixel p_6 and p_{11} and the second pair has pixels p_7 and p_{10} as depicted in Figures 5(b) and 5(c).

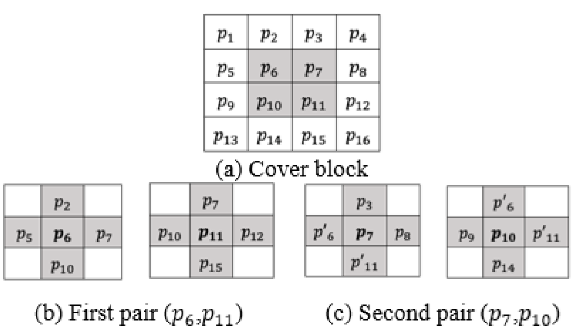


Fig. 5: The example a cover block and determination of rhombus context

For each first pair, the prediction error value for each pixel is calculated by using Equations (1) and (2), getting pairwise prediction errors E_1 and E_2. Then, the 2D PEH histogram is generated from E_1 and E_2 as illustrated in Figure 6(a). In the proposed scheme, error pairs such as (0, 0) are expanded by using EMD table for data embedding. To generate the EMD table with size of 3 × 3, each three secret bits are converted into decimal form, obtaining values from 0 to 7. These values are then filled into the EMD table, as shown in Figure 6(b). By employing the EMD for expansion during embedding, the proposed scheme can embed up to $\log_2(8)$ bits instead of $\log_2(3)$ bits as with conventional pairwise PEE. As a result, the quality of stego image can be preserved while significantly enhancing the EC of the proposed method.

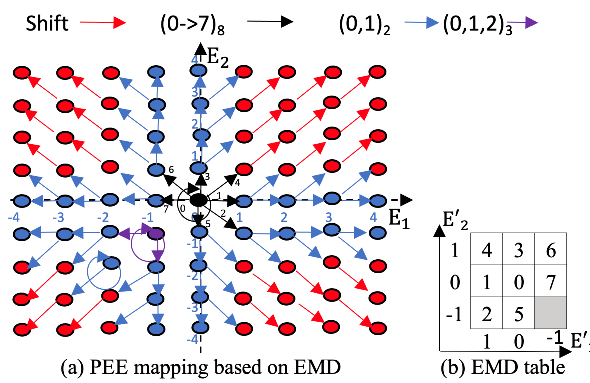


Fig. 6: The illustration of pairwise PEE and EMD mapping

C. The embedding procedure

The process of data embedding into the cover image is outlined step by step as follows:

Input: Cover block $B_i = p_1, \ldots, p_{16}$ as shown in Figure 5(a), embedding threshold Th, and secret bit s

Output: Stego block B_i'

1. Divide block: Split block B_i into inner sub-block $I_i = p_6, p_7, p_{10}, p_{11}$ and outer sub-block $O_i = p_1, p_2, p_3, p_4, p_5, p_8, p_9, p_{12}, p_{13}, p_{14}, p_{15}, p_{16}$

2. Location map: Conduct location map LM for the block B_i for overflow/underflow avoided.

3. Block classification: Use Equation (5) for block classification.

If $\delta \leq Th$, it indicates that the inner sub-block I_i is embeddable.

Embed data in this block using PEE and EMD mapping (defined in subsection B), as shown in Figure 6.

Output the stego sub-block B'_i with modified pixel pair of inner sub-block I'_i

Otherwise, if $Th < \delta$, the inner sub-block belongs to the embeddable group. In this case, skip the sub-block B_i without any modification.

4. Repeat: Repeat the above steps for the next sub-block until data is embedded completely.

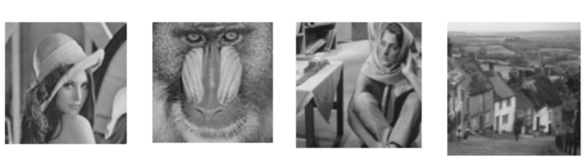
5. Combine block: Combine the sub-block to obtain stego image.

D. The extraction procedure

The extraction procedure follows the inverse of the data embedding. First, the support information such as embedding threshold Th, EMD table, and location map LM are extracted. Next, the hidden data is extracted, and the original pixels are restored. For simplicity, the details of the extraction process are omitted.

IV. EXPERIMENTAL RESULTS

To evaluate the performance of the proposed scheme, four common grayscale cover images size of 512 × 512 were tested, as depicted in Figure 7. All methods were implemented in MATLAB R2014a with randomly assigned secret bit embedding.



(a) Lena (b) Baboon (c) Barbara (d) Goldhill

Fig. 7: Image dataset [20]

To evaluate the impact of block classification on the EC (in bit) and the image quality (in dB), various embedding threshold Th were tested in the first experiment by using Lena image.

The result depicted in Figure 8 shows that, the EC of the proposed scheme increases with using

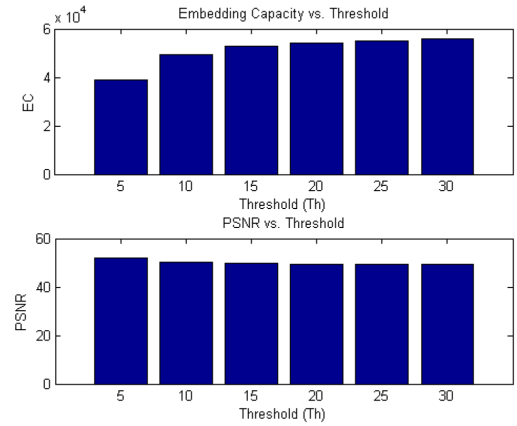


Fig. 8: Comparison of EC and PSNR of Lenna image under different thresholds Th

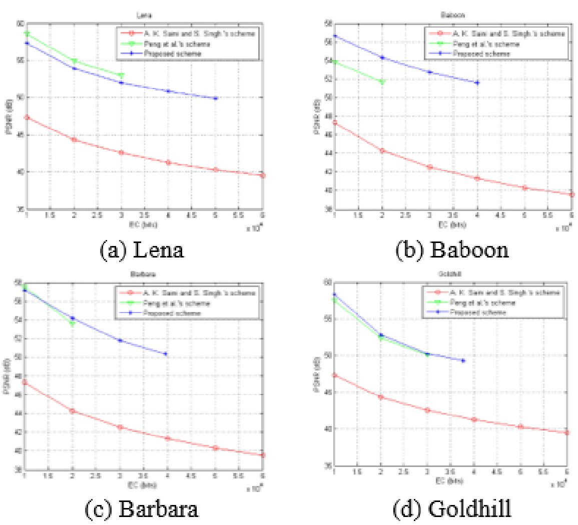
the higher Th value. This is attributed to the presence of more embeddable blocks with higher Th values. Specifically, the EC is approximately 40,000 bits and 56,000 bits for Th = 5 and 10, respectively. However, it is noted that higher Th values lead to slightly lower image quality.

Table 1: Comparison of EC and PSNR between the proposed methods and Peng et al.'s scheme [18] under Th = 20

	Proposed scheme		**Peng et al.'s scheme**	
Image	EC	PSNR	EC	PSNR
Lena	54.310	49.50	38.775	51.83
Baboon	47.195	50.86	20.905	51.50
Barbara	39.649	50.36	29.331	51.65
Goldhill	37.792	49.29	28.739	51.64
Average	**44.737**	**50,00**	**29.438**	**51.66**

To illustrate the embedding performance of the pairwise PEE and EMD mapping, the comparison of both EC and PSNR between the proposed scheme and Peng et al.'s method [18]. Table 1 shows that the average maximum EC of the proposed scheme is higher than that of Peng et al. [18], with an EC value of 44.373 bits and 29.438 bits, respectively. Since the proposed scheme utilizes the 2D PEH shifting using the EMD table, each error pair (0, 0) can embedded up to three bits. Consequently, the scheme performs better than the previous scheme [18].

To further measure the outperform of the method, the study evaluated the PSNR for stego image under the same EC compared to Peng et al.'s method [18] and Saini et al.'s method [16]. As depicted in Figure 9, it is evident that the quality of almost all tested images obtained using the method surpasses that of previous methods when the same amount of secret bits are used. This serves as a more illustrative demonstration of the embedding performance of the pairwise PEE and EMD based RDH.



(a) Lena (b) Baboon (c) Barbara (d) Goldhill

Fig. 9: Comparison of PSNR under the same EC between the proposed scheme and previous methods

V. CONCLUSION

This paper presents a high-capacity RDH method using pairwise PEE and EMD mapping. In our method, the original image is first divided into 4 $\times$ 4 blocks of the same size, which are then classified as either embeddable or non-embeddable blocks based on the given embedding threshold. For embeddable blocks, the prediction-error value of each pixel pair is computed, and the 2D PEH histogram is generated. Additionally, the EMD table is developed to modify the PEH histogram to improve the EC. By careful selection of error pairs for expansion during embedding, our algorithm achieves enhanced EC while maintaining the quality of the image. Experimental results demonstrate that the proposed method achieved high performance in terms of EC and quality of image compared to previous works.

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