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RESEARCH ARTICLE

An Image Hiding Method of Block Matching Way With Improved Texture Fusion Feature and High Embedding Capacity Product Code Over Z4

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ABSTRACT This paper presents a novel image hiding method with improved block matching way and high embedding capacity that allows the Important Image (IM) to be several times larger than the cover image. Multi-layered Least-Significant-Bit (LSB) planes of the Cover Image (CI) are obtained for constructing the Candidate Block-Matching Set (CBMS) by using the features fusion which consists of the texture features of wavelet transform and gray level difference; By combining features way to search the best-matching blocks from the CBMS, and the Huffman coding is used to compress the data including the indices of the best-matching blocks, the not-well-matched blocks part of IM and the parameters into a secret information flow which is embedded into the double-layered bit planes of CI by using a high embedding rate encoder. Because the high embedding payload we need, the SPAM features will be chosen to test the performance of resisting steganalysis attack which can obviously improve the security of the stego images.

INDEX TERMS Block matching way, high embedding capacity, the features fusion, wavelet transform, the double-layer LSB planes, SPAM features.

I. INTRODUCTION

Recently, the use of internet to hide the secret information into multimedia data for the covert communication is widely adopted and plays an important role in national defense security and trade secret field. The traditional way to directly transmit the encrypted message by using the convert channel would lead to the underlying security information disclosure problem. However, it can effectively restrict the like probability of the illegal access by an adversary through steganography techniques which can maximize the goals of protecting transmission content and concealing transmission behavior. Embed the secret information into the cover object called the stego-object which must be visually indistinguishable from the cover object. To avoid adversary to access the secret information easily, the stego-object usually can be placed in public network environment to be transmitted. Because of the high concealment with the stego-object, an unintended observer will not perceive or detect the existence of the attacked object. For the receiver, it is sure that the embedded information should maintain the continuity and re-extracted characteristic. The choice of transmission cover can often be the text, image, audio and video, etc. One of the most advantageous and widely used methods is image steganography.

However, the existence form of secret information is usually based on text characters which can't accurately express some concrete figures in steganography. Conclusions based on making sure high imperceptibility and powerful anti-statistical attack, it has high practicability and research value to find way how to embed all these recordable concrete figures into the cover image. At present, the main approach is the theoretical system of steganography based on Syndrome Trellis Codes (STCs) with distortion cost [1]–[9]. These methods need to research the texture features of the embedding location, get a globally optimal distortion cost solution for each time embedding. It chooses the adaptive

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coding method to modify the embedding location with minimum distortion cost, therefore, it can resist high dimension steganalysis techniques [10], [11] attacks and obtains high security. However, these methods are based on the way of single layer or double layer embedding, which embedding rate reaches $\alpha \log_2^q |q \in \{2, 3, 5\}, \alpha = 0.5bbp$. It denotes the upper bound of single layer embedding rate. Therefore, the security of this kind of algorithms is only based on prescribing a limit to small embedding capacity. Because the embeddable information is usually stored in a plain text file, it is difficult to effectively implement the task of transmitting secret image. Recent years, many scholars have focused in the problems. The initial relevant studies directly replace the multilayer Least Significant Bit (LSB)of bit plane from the cover with the secret image or named important image [12]–[14]. Although it can completely recover the secret image, because of the limitation of the number of disturbed embedding layers results in the size of secret image is only close to 25%-50% of the cover image. In order to obtain the way of embedding high-definition image, the researches on designing a mapping rule are to embed the secret image and adjust the embeddable pixels so as to minimize the distortion error between cover and stego through the optimizing strategy. Scholors Wang *et. al.* [14] proposed an image hiding method based on LSB substitution and genetic algorithm. Chang *et. al.* [15] proposed dynamic programming strategy to accelerate the optimal substitution search process, Thien and Lin [16] utilize modular arithmetic to achieve the bitwise embedding method. Although the algorithms worked well, the size of the embedded message is no more than 25% of the cover image. The research still focuses on how to further enlarge the size of the secret image when the image quality holds better. Searching the matched-block features between cover image and stego image to reconstruct secret image makes it possible to hide one or more images in one cover image. One of the most common approaches is to use Vector Quantization (VQ) compression technique to embed jumbo size image. Because of the reconstructed secret image allows certain degree of distortion, Hu [17] utilizes indices VQ compression technique with modular function to embed the secret image several times bigger than the cover image into the cover image, but the obviously blocking artifacts is happened. Wang *et. al.* [18], [19] proposed the VQ technique hiding method based on searching the high similarity blocks between secret image and cover image. Literature [18] makes use of mean square errors as matching rule to select blocks, and adopts K-means clustering method to generate representative blocks for reducing blocking artifacts of the reconstructed image. Literature [19] proposed a k-way matching block image hiding method that a "Base+ Difference" concept is used to construct candidate blocks odd-even set, which embeds the indices of best-matching blocks and no-well-matched blocks into multilayer LSB bit plane of the cover image. Chen *et al.* [20] proposed extended k-way matching block hiding method, Hsieh *et al.* [21] utilized the modulus substitution of the code book to encode the matched-blocks into indices set in its hiding method. Although all the above algorithms increased the hiding capacity by VQ technique, the kernel embedding algorithm is multilayer LSB substitution so that it couldn't resist the steganographic analysis technique with statistical characteristics. In 2016, Han *et al.* combined the VQ technique with efficient STCs to resist structured steganography analysis technique [22]–[24]. This approach can embed the secret image with one or four times bigger than cover image into the cover image within 3 to 4 LSB-planes. However, although it adopts the high efficiency STCs, it still may be difficult to resist the general high dimensional feature statistics attack because the embedding layers are more than two.

Based on the above analysis, the article proposed an image hiding method which has high capacity by using Improved Product Code over Z4 (Z4MPC) [26] encoder and improves block matching way by using features fusion, which is based on wavelet transform and gray difference. The embedding rate of Z4MPC encoder reaches to $1.78bpp$, the embedding efficiency reaches to 3. The embedding rate is higher than the upper bound of binary STCs and ternary STCs [2], and the distortion LSB layers is no more than 2 for hiding the secret image several times bigger than cover image. Literate [27] has proved that effective way of resisting high-dimensional steganography attacks is keeping the embedding distortion of the STCs within double LSB layers. Although the existing methods [18], [19], [25] only considered the difference mean square errors of the blocks for matching process, they also ignored the problem of texture feature difference among blocks. From this, the improved texture matching technique is fused into this proposed method. This method combines multi-directional texture features extracted by using wavelet transform with grey difference features of the blocks to construct feature matching set. The fusion features have the advantage of high matching precision, and the refined candidate block-matching set make the length of index shorter. Finally, we compress the information of the indices of the best-matching blocks, the no-well-matched blocks and other parameters by using Huffman code and embed them into the cover image by using Z4MPC.

II. PRODUCT CODE OVER Z4

Product code [28] is a technique of high efficiency long code combined with short component hamming code, which is referred to as a two-dimensional linear code in terms of the two linear code direct product. Suppose linear codes $C_1(n_1, k_1)$ and $C_2(n_2, k_2)$ are computed over Z4 residual class integer ring $(Z, +, .)$.The product code is the tensor product of two linear codes denoted as $\boldsymbol{u} \otimes \boldsymbol{v}, \boldsymbol{u} = \{u_1, \ldots, u_n\} \in C_1$ and $\boldsymbol{v} = \{v_1, \ldots, v_n\} \in C_2$. The specific embedding process is as follows: Embed secret message into each line code C_2 within the code matrix for n_1 times; Find the first k_2 columns and embed secret message into each column code C_1 for k_2 times; Modification operation is needed to restore the embeddable row message when the column embedding to be performed. The secret message extracting procedure needs to use formula $Hy^T = \boldsymbol{m}$ to implement. For each time coding, the additive Abelian group, multiplicative semi-abelian groups operation needs to satisfy Gray Mapping: $\phi(0,0) = 0$, $\phi(0,1) = 1$, $\phi(1,1) = 3$, $\phi(1,0) = 2$. Z4MPC method provides a double embedding channel consisted of the LSB and SLSB (Second Least Significant Bit) of the pixel, thus, it is based on Lee distance decoding method [29] and uses theorems of the literature [26, Lemma 4-6] for the interleaving coding.

III. THE PROPOSED METHOD

Given the size of the image IM $h_{IM} \times w_{IM}$, the size of the image CI $h_{CI} \times w_{CI}$, both of which are the $q = 8$ bit gray-level images. Due to one image IM is embedded into the image CI to form the Stego Image (SI), the image hiding algorithm needs to be satisfied the following features: 1) Stego images should has the invisibility of steganographic behavior, it is the premise of the validity of the algorithm. 2) It is a research difficulty to guarantee the statistical security of stego images by using high dimension statistical model to detect the changes of the steganographic features. 3) It is the algorithm's pursuing objective to obtain the high-fidelity and high-visual-quality extract images recovered from the stego images. Due to the reason, the paper utilizes the large embedding rate product code Z4MPC to embed the secret image information into the double LSB bit planes, this scheme can have better performances against high dimension statistical attacks than the existing methods [18]–[21], [25]. The way of original block substitution for the no-well-matched blocks can allow the extract image to obtain high visual quality. Furthermore, in order to obtain the high similarity between best-matching blocks and the no-well-matched blocks, this proposed method adopts the features fusion combining wavelet feature with gray level difference feature to achieve precise matching task.

A. CONSTRUC CANDIDATE BLOCK-MATCHING SET

Suppose p-LSB denotes the pth least significant bit. Reconstruct Bit-planes Image (BI) from the cover image, that is, the total $\{p - LSB\}|p \in \{8, 7, 6, 5, 4, 3, i, j\}, i, j \subseteq [3, 8]$ bit-planes overlay together to consist the reconstructed image BI. Suppose there is one certain pixel of the cover image denoted by pix_i which binary code is $x_8x_7x_6x_5x_4x_3x_2x_1$, the binary code of pixel pix_i' of the image BI is $x_8x_7x_6x_5x_4x_3x_ix_j$, $i, j \subseteq [3, 8]$. For each pixel of the image BI, we want to make use of its high-four bits cyclic displacement to construct the candidate block-matching set. Suppose the binary code of a certain pixel is 11010111, the process is summarized in the following steps: 1) Replace the 1-LSB and 2-LSB of this pixel by its 3-LSB and 4-LSB. 2) The high-four bits move one bit to the right for three times while the low-four-digits are immovability. The Fig. 1 shows the procedure.

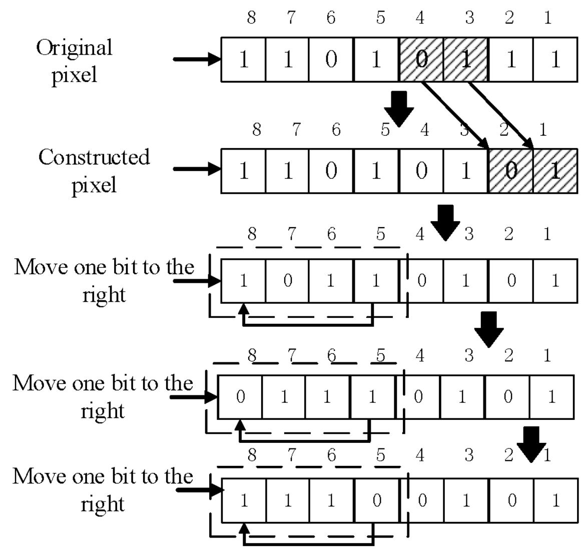
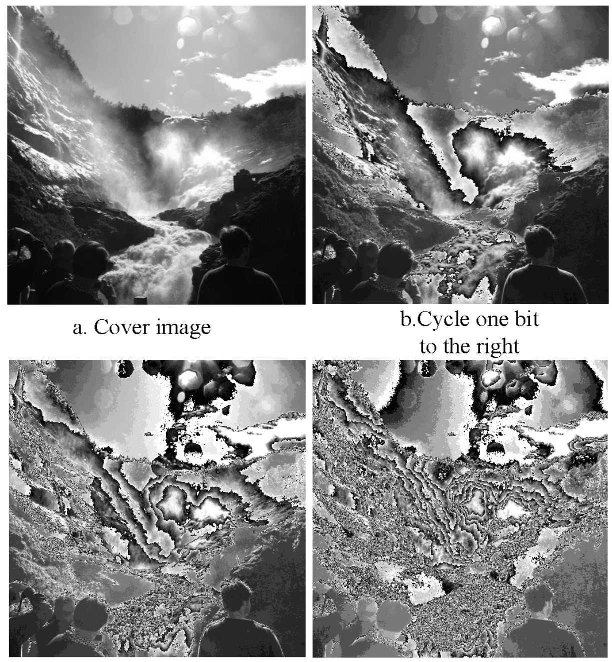


FIGURE 1. The high-four bits cyclic displacement process.

The image 25.pgm is chosen from Bossbase1.01, and the generated three cyclic displacement images are as follows:



a. Cover image

b.Cycle one bit to the right

c.Cycle two bit to the right

d.Cycle three bit to the right

FIGURE 2. Cyclic displacement images.

Fig.2(c) and Fig.2 (d) indicate that the spatial relationship of the pixels is severely damaged. A user knowing the blocks from the serious distortion of these pictures will lead to the significantly blocking artifacts, and thereby this paper only chooses Fig.1(a) and Fig.1(b) to generate the candidate block-matching set.

Suppose that there is an IM of size $h_{IM} \times w_{IM}$. If we split IM into nonoverlapping blocks of size $b = m \times n$, the number of blocks of IM is defined as:

$$b_{IM} = \frac{h_{IM} \times w_{IM}}{m \times n}, \tag{1}$$

thereby, the number of blocks of the candidate block-matching set is $b_{CI} = 2 \times b_{IM}$, the candidate block-matching set consists of some blocks denoted by $\{D_i\}\,|0 <= i <= b_{CI} - 1$.

Suppose $C_i^j(k,l)\,|1 \le k \le m, 1 \le l \le n$ denotes the j-LSB data of the chosen $(k,l)\,th$ pixel in the ith block, the value of the $(k,l)\,th$ pixel in block D_i is defined as:

$$D_i(k,l) = \sum_{j=p+1|p=2}^{q} 2^{j-1}C_i^j(k,l) + \sum_{j=1|p=2}^{p} 2^{j-1}C_i^{j+2}(k,l), \quad (2)$$

Suppose there is a maximum index value of all the candidate matching blocks in set $\{D_i\}$, the length of the binary value of the maximum index is,

$$\lceil lb\,(b_{CI})\rceil\,, \quad (3)$$

where $lb(b_{CI})$ is $log_{10}\,(b_{CI})/log_{10}\,(2)$.

B. EMBEDDING AND EXTRACTING PROCESS

In this paper, some important procedure parameters need to be given, such as the size of coding matrix, the maximum embeddable number of bits and the proportion of the best-matching blocks in IM.

Suppose the product code over Z_4 is the tensor product of two linear codes denoted as $C_1 \otimes C_2$, $C_1(n_1,k_1)|r_1 = n_1 - k_1, n_1 = 2^{r_1} - 1$ and $C_2(n_2,k_2)|r_2 = n_2 - k_2, n_2 = 2^{r_2} - 1$, where $n_1 = n_2 = 3, k_1 = k_2 = 1$. The size of coding matrix is 3×3. Based on the chosen embedding channel consists of $\{p - LSB\}|p \in \{1,2\}$ bit planes, the number of the coding matrixes is calculated using,

$$\frac{h_{CI} \times w_{CI} - 1}{n_1 \times n_2}. \quad (4)$$

The embedding rate α_{Z4} of Z4MPC [26, eq. (4)] is calculated using

$$\frac{(r_2 \times (2^{r_1} - 1) + r_1 \times (2^{r_2} - 1 - r_2)) \times \lceil \log_2 4 \rceil}{(2^{r_1} - 1) \times (2^{r_2} - 1)}, \quad (5)$$

and hence, the maximum embeddable number of bits of the image CI denoted as Max Bits for Cover (MBC) is calculated using

$$\alpha_{Z4} \times (h_{CI} \times w_{CI} - 1)\,. \quad (6)$$

The embeddable number of bits for each block is $\alpha_{Z4} \times (n_1 \times n_2)$, thereby $(h_{CI} \times w_{CI} - 1)/(n_1 \times n_2)$ blocks are used to embed MBC which is obtained by applying the formula $\alpha_{Z4} \times (h_{CI} \times w_{CI} - 1)$.

In this paper, it needs to satisfy the condition that the needed embedding space is no more than the offered embeddable space of the cover image CI. The condition is related with the proportion of the best-matching blocks. When the proportion is smaller, the occupied space is larger, conversely, the less.

Theorem1: Suppose the size of blocks of image CI is $m \times n$, the best-matching block proportion parameter of image IM is δ, the compression rate of Huffman coding is β, and hence the proportion parameter δ is satisfied as follows:

$$\delta \ge \frac{m \times n \times q - \frac{1}{\beta} \times \frac{m \times n}{h_{IM} \times w_{IM}} \times (\alpha_{Z_4} \times (h_{CI} \times w_{CI} - 1))}{m \times n \times q - \lceil lb\,(b_{CI})\rceil}. \quad (7)$$

Proof: Based on Eq. (3), $\lceil lb\,(b_{CI})\rceil$ is the bits number of each index, the total storage of these best-matching blocks in image IM occupies $(h_{IM} \times w_{IM})/(m \times n) \times \delta \times \lceil lb\,(b_{CI})\rceil$ bits. In order to precisely compose the texture of the blocks for obtaining a high visual quality, the remaining no-well-matched blocks are to be the substitution blocks embedded directly in the image CI. Because the no-well-matched block proportion is $(1 - \delta)$, the needed storage space for these blocks is $(h_{IM} \times w_{IM})/(m \times n) \times (1 - \delta) \times (m \times n \times q)$. The total storage space for embedding the secret information is Max Bits for Important Image (MBI) calculated using $\begin{pmatrix} (h_{IM} \times w_{IM})/(m \times n) \times \delta \times \lceil lb\,(b_{CI})\rceil + \\ (h_{IM} \times w_{IM})/(m \times n) \times (1 - \delta) \times (m \times n \times q) \end{pmatrix}$. Suppose the compression proportion of Huffman coding is β, based on Eq. (6) and the condition that the length of embedding message is no more than MBC, the theoretic deduction is,

$$\begin{aligned} &\begin{pmatrix} (h_{IM} \times w_{IM})/(m \times n) \times \delta \times \lceil lb\,(b_{CI})\rceil + \\ (h_{IM} \times w_{IM})/(m \times n) \times (1 - \delta) \times (m \times n \times q) \end{pmatrix} \times \beta, \\ &\le \alpha_{Z_4} \times (h_{CI} \times w_{CI} - 1) \\ &\Rightarrow \delta \ge \frac{m \times n \times q - \frac{1}{\beta} \times \frac{m \times n}{h_{IM} \times w_{IM}} \times (\alpha_{Z_4} \times (h_{CI} \times w_{CI} - 1))}{m \times n \times q - \lceil lb\,(b_{CI})\rceil} \end{aligned}$$

is proved, where the lower bound of δ is

$$\underline{\delta} = \frac{m \times n \times q - \frac{1}{\beta} \times \frac{m \times n}{h_{IM} \times w_{IM}} \times (\alpha_{Z_4} \times (h_{CI} \times w_{CI} - 1))}{m \times n \times q - \lceil lb\,(b_{CI})\rceil}.$$

The upper bound of parameter δ is 1, denoted as $\delta = 1$. That means the extract image's blocks are all replaced by the blocks in the candidate block-matching set. Thus, the needed embedding space is close to the minimum value, however, the worst visual quality of the extract image obtained.

The block similarity calculation method called Square Error Value (SEV) measures the distance between block A and block B has been almost used in the existing literatures [18], [19], [25]. Although SEV only considered the grayscale difference among blocks, the difference of the texture features has never worked in block matching process. Basing on the generalized analysis factors such as the content, structure, texture and grayscale features of the blocks, the presented method produces more reasonable and credible synthesis results for the improved matching algorithm. This paper makes a generalized analysis about combining the grayscale feature with the texture feature for the blocks matching. Firstly, given the Manhattan Distance (MD) between the block D_i and block D_j is calculated using

$$MD(D_i, D_j) = \frac{255}{m \times n}\left(\sum_{k=1}^{m}\sum_{l=1}^{n}\left(D_i(k,l) - D_j(k,l)\right)\right), \quad (8)$$

where $D_i(k,l)$ and $D_j(k,l)$ are the (k,l)th pixel within the two blocks. But the error between an IM block and its best-matching block may still be sufficiently large to cause serious degradation to the IM. Secondly, we continue to utilize harr wavelet transform to obtain high-frequency filtering values in all directions for further matching the similarity of these

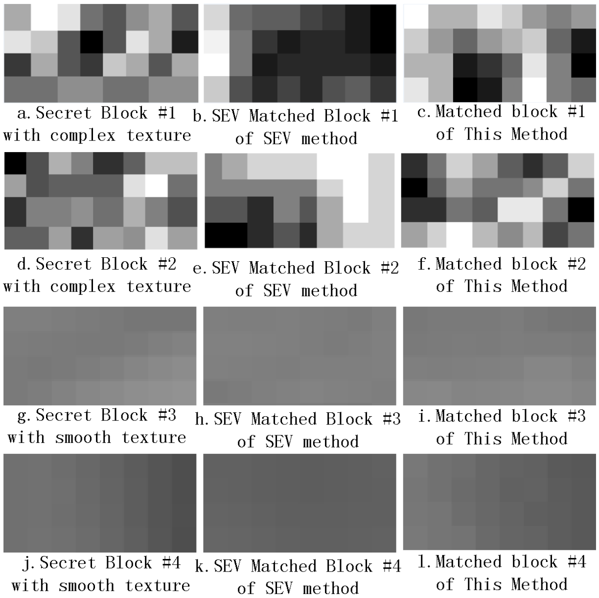


FIGURE 3. Block detail comparison results.

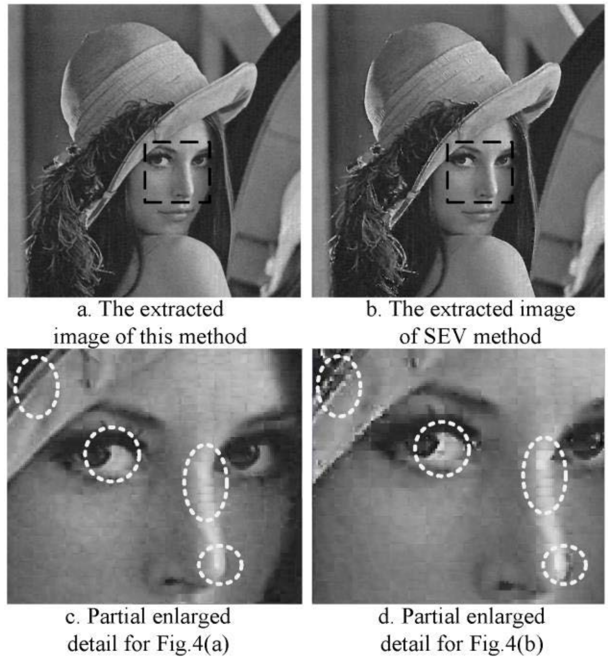


FIGURE 4. Overall effect comparison results between this method and SEV method.

blocks. The optional four 4 × 8 blocks in image IM are compared with the best-similar blocks obtained in candidate block-matching set by using the block-matching procedure. Fig.3 shows the comparison results between the traditional grayscale SEV matching method and this proposed method.

It is seen from Fig. 3(b), 3(e), 3(h), 3(k) that the texture distribution features of the best-matching block based on SEV matching method has big difference from the original secret block. The two best-matching blocks with complex texture are shown in Fig. (b) and Fig. (e), we can see that the variation regularity of gray scales within the block has a large different from the original secret block; the two best-matching blocks with smooth texture are shown in Fig. (h) and Fig. (k), the variation regularity of gray scales within the blocks is almost consistent that there aren't more texture details can be obtained in the searched best-matching blocks. The results of this proposed method in the Fig.3(c), 3(f), 3(i), 3(l) show that the way of combining the grayscale feature with the texture feature will reduce the degradation introduced into the important image. The texture similarity for the IM blocks is significantly improved. In this paper, we choose 25.pmg from BossBase1.01 as a cover image, lena.bmp as a secret important image. Given the size of the blocks 4 × 8, we compare the corresponding extract images between this proposed method and SEV matching method. Fig.4 shows an illustration of the degradation of extracted images in different methods. It can be analyzed that because the SEV matching method only considered gray difference which would cause of the phenomenon that although the gray difference is small the texture feature difference is big during matching process. From the results shown in Fig. 4(d), we can see that there are some obviously random noises and the block effects in texture and edge region.

This section uses orthogonally normalized wavelet transform to break down the blocks into horizontal, vertical, diagonal high-frequency texture signal. The matching blocks algorithm synthetically analyzes the grayscale and texture features of best-similar blocks, which is given as follows:

The Algorithm3 realizes the extracting process:

IV. EXPERIMENTAL RESULTS AND ANALYSIS

A. VISUAL INVISIBILITY EXPERIMENT

The used sample images come from BOSSBase1.01, which are 8 bit gray-level images with the size of 512 × 512. We utilize the Peak Signal to Noise Ratio (PSNR) value to test the visual quality of the images.

$$PSNR = 10 \times \lg\left(\frac{255 \times 255}{MSE}\right), \tag{9}$$

where Mean Square Error (MSE) is defined as follows:

$$MSE = \frac{1}{M \times N}\sum_{i=1}^{M}\sum_{j=1}^{N}\left(x_{i,j} - y_{i,j}\right)^2, \tag{10}$$

where $x_{i,j}$ and $y_{i,j}$ are the pixels respectively located in the same position (i, j) of the two images with the size of $M \times N$. In this paper, we suppose the PSNR between image SI and image CI denoted as $psnr_{ST}$. When the $psnr_{ST}$ value is high, the good visual imperceptibility of image SI is obtained. The PSNR between image IM and extract image EI denotes as $psnr_{EI}$. When the $psnr_{EI}$ value is high, the degradation introduced into the image EI is small.

For this proposed method, we need to set some restrictive condition and parameters which are provided below.

1) CHOOSE THE DOUBLE LSB BIT PLANES OF ONE IMAGE

We choose the double LSB bit planes of one cover image from Bossbase1.01 as an embedding channel. Suppose the sizes of

Algorithm 1 Construct candidate block-matching set Algorithm

Step1: Input one secret important image IM= $\{im_j\}$, where $0 \le j \le h_{IM} \times w_{IM}$, one $h_{CI} \times w_{CI}$ cover image CI = $\{ci_j\}$, where $0 \le j \le h_{CI} \times w_{CI}$, the entire secret important image is split into multiple nonoverlapping blocks of size $b = m \times n$. The IM image is represented in block form as $\{IM_i, 0 \le i \le (h_{IM} \times w_{IM})/b\}$, where $IM_i = \sum_{j=0,1,\ldots,b-1} im_{i\times b+j}$ denotes the ith block in IM. Use the method illustrated in section III (A) to construct candidate block-matching set $\Gamma = \{D_k\} | 0 <= k <= b_{CI} - 1$.
Step2: For all the blocks in set Γ, we use the harr wavelet transform to calculate the feature values of high frequency in three directions of each block which is going to be stored in the matrix vector $\boldsymbol{HARR}_{CI} = \left\{\text{dwt2}(D_k)^{\rightarrow}, \text{dwt2}(D_k)^{\searrow}, \text{dwt2}(D_k)^{\downarrow}\right\}$, where $dwt2(\cdot)$ is wavelet transform function from MATLAB tool.
Step3: Compare the ith block IM_i with each block $D_k | 0 \le k \le b_{CI} - 1$ in set Γ to calculate the minimum MD of the grayscale difference between them, which denotes $MD_{\min} = min\left(\{MD(IM_i, D_k)\}\right)$, and search all the best-similar blocks $\left\{D_k^{MD_{\min}} \in \Gamma\right\}$ with the equal $MD_{\min}$ value.
Step4: For the ith block IM_i, we calculate its texture feature by using wavelet transform which is stored in vector $harr_i = \left(\text{dwt2}(IM_i)^{\rightarrow}, \text{dwt2}(IM_i)^{\searrow}, \text{dwt2}(IM_i)^{\downarrow}\right)$. Because there are blocks $\left\{D_k^{MD_{\min}}\right\}$ obtained from **Step3**, the corresponding wavelet transform vectors denoted as $\left\{harr_k^{MD_{\min}}\right\}$ of the blocks can be obtained from matrix vector $\boldsymbol{HARR}_{CI}$ in **Step1**. Calculate the $MD\left(harr_i, harr_k^{MD_{\min}}\right)$ between block IM_i and block $D_k^{MD_{\min}}$ for all the best-similar blocks $\left\{D_k^{MD_{\min}} \in \Gamma\right\}$. Finally, we obtain the best-matching block $D_z^{MD_{\min}}$ with minimum Manhattan Distance of the texture feature, and the index value of the block is $z = \arg\min\left\{MD\left(harr_i, harr_k^{MD_{\min}}\right)\right\}$.We use a Z4MPC encoder [26] to accomplish the randomized embedding process illustrated in the Algorithm2.

block are $b = 4 \times 4$ and $b = 4 \times 8$, the number of binary bits of the maximum index value are $14bit$ and $13bits$ respectively based on Eq. (3).

2) THE PARAMETER HUFFMAN CODING COMPRESSION RATE β

The parameter Huffman coding compression rate β needs to be given based on Theorem1. After converting the varying length binary string generated by random function to character string, we use the Huffman coder to compress the character string. The comparison of varying length of character string compression rate is shown in Table 1. The parameter β of this method is set 0.87.

Algorithm 2 Embedding procefure Algorithm

Step1: Obtain the secret important image $IM = \{IM_i, 0 \le i \le (h_{IM} \times w_{IM})/b\}$, the cover image CI, the size of non-overlapping blocks $b = m \times n$ and the candidate block-matching set Γ from Step1 of the Algorithm1.
Step2: For each secret block IM_i, we try to search its best-matching block $D_z^{MD_{\min}}$ with the small $MD_{\min}$ based on Algorithm1. If the searched block with large $MD_{\min}$, the block IM_i is called the not-well-matched block. Suppose there is a grayscale difference parameter φ, if the constraint condition that let $\varphi \ge \min\{MD(IM_i, D_k), D_k \in \Gamma\}$ be satisfied, then the best-similar block $D_k^{MD_{\min}}$ is classified into one set to calculate the best-matching block $D_z^{MD_{\min}}$ for the block IM_i. After all the best-matching blocks are found, the proportion of the best-matching blocks parameter δ is obtained. Record the corresponding indices set $Z^{\delta} = \left\{z = \arg\min\left\{MD\left(harr_i, harr_k^{MD_{\min}}\right)\right\}\right\} | 0 \le z \le b_{CI} - 1$ for all the best-matching blocks $\left\{D_k^{MD_{\min}}\right\} | k \in Z^{\delta}$ with the proportion δ based on Algorithm1. The not-well-matched blocks $\{IM_i\}^{1-\delta}$ are denoted as the substitution blocks embedded into the CI.
Step3: Given the initial parameter $\varphi = \varphi_0$, where φ_0 is a small initial integer. For each block IM_i, we repeat the **Step2** to search best-matching blocks with the proportion δ, and adjust the parameter φ step by step with recursion $\varphi = \varphi_0 + \Delta\varphi$, $\Delta\varphi = 1$ to get the new proportion δ which needs to be satisfied the restrictive condition of **Theorem1** until the needed good visual equality of the extract image is obtained.
Step4: Random scramble the cover image CI and obtain the 1-LSB and 2-LSB bit planes of the CI as a cover channel $\boldsymbol{x}$. Compress the information of some parameters such as δ, β, check matrix $\boldsymbol{H}$, h_{IM}, w_{IM}, b, the indices set Z^{δ}, the substitution blocks $\{IM_i\}^{1-\delta}$ and into a Binary secret message flow $\boldsymbol{m}'$ on the cover channel $\boldsymbol{x}$ by using Huffman encoder with Huffman compression proportion β. Use Z4MPC encoder [26] to embed the message $\boldsymbol{m}'$ into the stego channel $\boldsymbol{y}$. After that, we reverse scramble the stego channel $\boldsymbol{y}$ and combine it with the rest bit planes of the cover image CI to construct the stego image SI.

3) THE MANHATTAN DISTANCE OF GRAYSCALE DIFFERENCE PARAMETERφ

The Manhattan distance of grayscale difference parameter is φ which decides the best-matching block proportion parameter δ, the parameter φ should be adjusted step by step based on **Algorithm2**.

4) THE PROPORTION PARAMETER MBI/MBC

Based on Theorem1, the proportion parameter MBI/MBC is calculated from the total storage space for embedding the secret information divided by the maximum number of bits that can be embedded within the double layers of a cover image.

Algorithm 3 Extracting procedure Algorithm

Step1: Input the image SI, scramble the stego channel $\boldsymbol{y}$ from the 1-LSB and 2-LSB bit planes of the stego image SI. Compute the formula $\boldsymbol{H}\boldsymbol{y}^T = \boldsymbol{m}$ to extract secret message $\boldsymbol{m}$ and utilize Huffman decoder to decompress the $\boldsymbol{m}$ into binary message flow $\boldsymbol{m}'$. The parameters such as δ, β, check matrix $\boldsymbol{H}$, h_{IM}, w_{IM}, b, indices set Z^{δ} and the substitution blocks $\{IM_i\}^{1-\delta}$ information are obtained from $\boldsymbol{m}'$.

Step2: Obtain the high 6-bit planes from the image SI to construct the candidate block-matching set $\{D_i\}$ based on section III (A). Search the best-matching block set $\left\{D_k^{MD_{\min}}\right\} | k \in Z^{\delta}$ based on indices set Z^{δ} and the proportion parameter δ obtained from binary message flow $\boldsymbol{m}'$. Furthermore, we combine the blocks $\left\{D_k^{MD_{\min}}\right\} | k \in Z^{\delta}$ with the substitution blocks $\{IM_i\}^{1-\delta}$ of image IM obtained from the rest message flow $\boldsymbol{m}'$ to generate the Extract Image (EI).

TABLE 1. Huffman coding compression rate.

Number of precompression characters	Number of compressed characters	Compression rate
100	76	0.76
200	161	0.8
400	339	0.84
600	516	0.86
800	690	0.8625
1000	865	0.865
2000	1742	0.865
10000	8736	0.8736
100000	87393	0.8702

All the experimental images involved in this paper are shown in Fig.5. We choose 30.pgm from BossBase1.01 as the cover image, Lena secret image is embedded into the 1-LSB and 2-LSB of the cover image. The Fig.6 shows the visual quality contrast effect with different φ values. The sizes of the divided non-overlapping blocks are set 4×4 and 4×8 respectively. The data of Table 2 shows the contrast parameters during the embedding process.

As shown in Fig.6 and Table 2, it can be concluded that when the parameter φ approaches the lower bound, the visual quality of the extract image is high, however, it needs more occupied storage space for the embeddable secret information which will influence the statistical imperceptibility of the stego images shown in Fig. 6(e)(i). It is because of the double layers embedding way applied in this method, the quality of the stego-image is also high that unintended observers will not be aware of the existence of the hidden secret important image. As seen from Fig. 6(d)(h), when the φ value increases, the visual quality of the extract image goes down and the occupied storage space is reduced, however, the statistical imperceptibility of stego images are improved gradually. Furthermore, it is seen from the Table 2 that when the cover image on the condition that the 4×4 well-matched blocks are chosen the image visual equality of the extract image is obviously better than the extract images with 4×8 well-matched blocks. Because the upper bound of MBI/MBC is close to 0.4360 on the condition of 4×4 well-matched blocks based on Table 2, the cover image couldn't embed the four secret important images with the same size of the cover image.

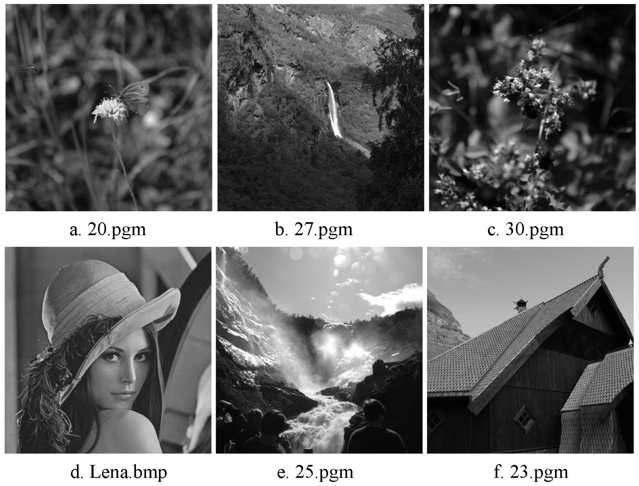


FIGURE 5. The test images used in this paper.

TABLE 2. The $psnr_{EI}/psnr_{ST}$ contrast results based on different parameters of this method.

	φ	δ	MBI/MBC	$psnr_{EI}$	$psnr_{ST}$	Payload (bpp)
4×8	28	0.9993	0.2012	32.5711	57.3221	0.3581
	24	0.9963	0.2123	32.6150	56.9806	0.3779
	20	0.9875	0.2450	32.7039	56.3440	0.4360
	18	0.9788	0.2772	32.8270	55.8774	0.4935
	14	0.9518	0.3775	33.2084	54.5263	0.6719
	11	0.9113	0.5278	33.5390	53.0453	0.9394
	10	0.8867	0.6191	33.6587	52.3599	1.1020
	9	0.8610	0.7145	33.7412	51.7379	1.2717
	8	0.8208	0.8637	33.8573	51.0749	1.5373
4×4	24	0.9976	0.4360	38.9848	53.9176	0.7761
	20	0.9941	0.4482	39.0294	53.7507	0.7978
	18	0.9907	0.4601	39.0709	53.6430	0.8189
	13	0.9720	0.5252	39.2979	53.0925	0.9348
	12	0.9636	0.5544	39.4004	52.8687	0.9869
	11	0.9537	0.5889	39.5276	52.5696	1.0483
	10	0.9636	0.6373	39.6935	52.2514	1.1344
	9	0.9219	0.6997	39.9090	51.8495	1.2454
	8	0.8978	0.7836	40.2054	51.3321	1.3948
	7	0.8622	0.9076	40.6367	50.7135	1.6154

In this paper, we set the rules that when one cover image wants to embed one secret important image the chosen size of the well-matched blocks should be 4×4, otherwise the size should be 4×8 for embedding multiple secret important images. We choose some images, such as 25.pgm, 20.pgm, 27.pgm, 30.pgm, 23.pgm and Lena.bmp, and analyze the texture details of the secret image whether effect the visual equality of the extract images on the condition of 4×4 well-matched blocks, the Table 3 shows the corresponding results.

It is concluded from the Table 3 that the imperceptibility of the stego image has no connection with texture details of the cover image, and the stego image can also obtain high

TABLE 3. The contrast results of $psnr_{ST}/psnr_{EI}$ for this method when embedding one image on the condition of 4 × 4 well-matched blocks and parameter $\varphi = 7$.

Cover image	Secret important image					
	20	27	30	25	23	Lena
20	--	(50.6224/ 40.4577)	(50.6142/ 40.2309)	(50.7483/ 40.6637)	(50.6526/ 40.2259)	(50.5736/ 40.7738)
27	(50.7753/ 40.4258)	--	(50.5487/ 40.3205)	(50.6643/ 40.7326)	(50.6427/ 40.5246)	(50.7632/ 40.7929)
30	(50.5743/ 40.7166)	(50.6573/ 40.5837)	--	(50.7544/ 40.7758)	(50.6574/ 40.6818)	(50.7135/ 40.8872)
25	(50.6529/ 40.0996)	(50.5469/ 39.9167)	(50.6286/ 39.7684)	--	(50.7535/ 40.3053)	(50.6658/ 40.1845)
23	(50.5765/ 40.0337)	(50.7462/ 39.8983)	(50.6146/ 39.9649)	(50.5463/ 40.0404)	--	(50.6753/ 40.0122)
Lena	(50.6854/ 40.3588)	(50.6753/ 40.2237)	(50.5645/ 40.0984)	(50.7943/ 40.5019)	(50.7744/ 39.4535)	--

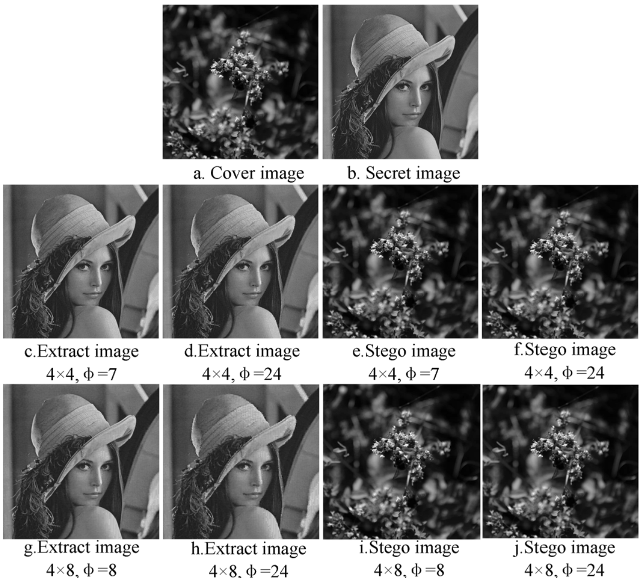


FIGURE 6. The visual equality compared results with different parameter φ and different block sizes for the extract images.

visual equality. For the cover image with complex texture, it can be used to reconstruct the extract images with good visual equality. For example, images 20.pgm, 27.pgm and 30.pgm are chosen to be the cover images will have more advantages than the others, and the $psnr_{EI}$ can be improved 1-2 percentage points.

Let $(MBI/MBC)^{i\in\{1,2,3,4\}}$ denotes the proportion parameter of the ith secret important image, and each value should be closer to 0.25. If one $M \times N$ cover image embeds $n \in \{1, 2, 3, 4\}$ secret images with the size $M \times N$, thus, the payload of the cover image is calculated using

$$\frac{\sum_{i=1}^{n}\left(\left(\frac{MBI}{MBC}\right)^{i} \times MBC\right)}{M \times N}. \tag{11}$$

We embed the secret important images chosen from 20.pmg, 27.pmg, 25.pmg and lena.bmp into the cover image 30.pgm. Table 4 shows the contrast payload results for embedding the secret important images mentioned above and the Fig. 7 shows the embedding and extracting effects.

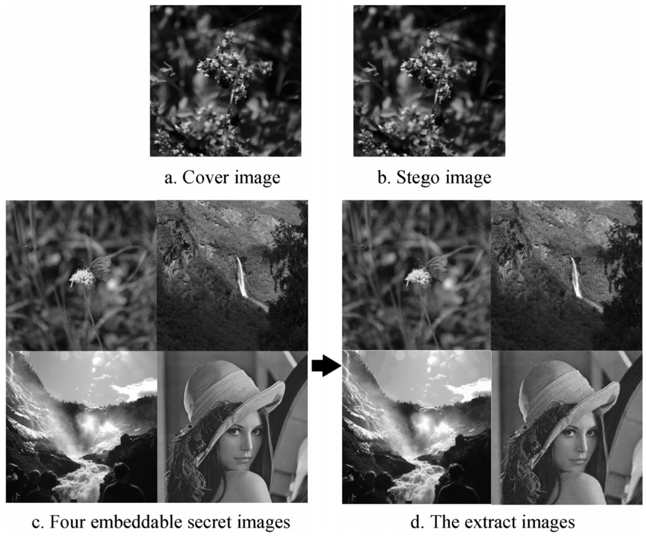


FIGURE 7. The effect pictures for embedding multiple secret images.

TABLE 4. The contrast payload results for embedding different size of secret important images.

Secret important Images	φ	$(MBI/MBC)^n$	Payload (bpp)
20.pgm	24	$0.2096\| n=1$	0.3726
27.pgm	24	$0.2360\| n=1$	0.4195
30.pgm	24	$0.2274\| n=1$	0.4043
Lena.bmp	24	$0.2123\ n=1$	0.3779
Embedding the above four images	24	$0.8853\| n=4$	1.5598

We can see from Fig.7 that the visual quality of stego images and extract images is also good when the cover image embeds four images. Specifically, the stego images still keep high visual imperceptibility. Table 5 shows the comparison results between this method and the methods of literatures [18]–[21], [25] when the cover image embeds the secret images with the equal size or four times sizes of cover image. This method can greatly improve the statistical imperceptibility of the stego images while the extract images also obtain a good visual equality whenever one cover image embeds one or four secret images. When one secret image is embedded, the $psnr_{ST}$ performance of this method

TABLE 5. The comparison of the $psnr_{ST}/psnr_{EI}$ for different embedding method.

Hiding method	Secret images	
	Lena.bmp	20.pgm, 27.pgm, 30.pgm, Lena.bmp
Literature [18]	(44.0531/34.7564)	(37.6785/29.4978)
Literature [19]	(44.2324/39.3643)	(37.8835/32.4312)
Literature [20]	(45.1463/39.5845)	(39.3451/32.1189)
Literature [21]	(47.0324/38.8343)	(36.7903/30.5602)
Literature [25]	(47.2432/40.1863)	(39.2305/32.5211)
This method (b=4×4 , φ =8)	(51.3321/40.2054)	--
This method (b=4×8 , φ =24)	--	(50.8504/32.4473)

can be improved nearly 8%; When four secret images are embedded, the $psnr_{ST}$ performance of this method can be improved nearly 23%. The reason is that this paper uses the streamline candidate matched-blocks set to reduce the bit space of the best-matching blocks' indices occupied so that the total storage space for embedding the secret information MBI is decreased. Furthermore, because the characteristics of the large payload of the Z4MPC make the secret information be limited within double LSB bit planes and due to the help of the high embedding efficiency of the code, the stego image could obtain less disturbance than other methods to maintain the security of the stego images.

B. RESIST STATISTICAL STEGANALYSIS EXPERIMENT

In this section, we will test the steganography security of this proposed method. When the cover image embeds one 8-bit gray level secret important image with the size of 512 × 512, the divided non-overlapping block size will be set to $b = 4 \times 4$ and the parameter φ will be given different values to test the performance of the pictures. The corresponding payloads of this condition mentioned above are about as follows:

1) The chosen payloads with the parameter $b = 4 \times 4$:

$$\alpha \in \{1.62|\phi = 7, 1.40|\phi = 8, 1.25|\phi = 9, 1.05|\phi = 11, 0.93|\phi = 13, 0.82|\phi = 18, 0.78|\phi = 24\}.$$

2) The chosen payloads with the parameter $b = 4 \times 8$:

$$\alpha \in \{1.54|\phi = 8, 1.10|\phi = 10, 0.67|\phi = 14, 0.44|\phi = 20, 0.38|\phi = 24, 0.36|\phi = 28\}$$

3) When we want to embed four secret important images with the same size of the cover image, the size of divided non-overlapping should be chosen $b = 4 \times 8$ and the parameter φ will be set to be 24 by analyzing the occupied payloads shown in Table 4 and the total embedding payload is about 1.56*bpp*.

In the experiments, we randomly choose 5000 images from Bossbase1.01, and randomly choose 2500 images to train out the training set classifier. The other 2500 images can be as a test set for testing, the dimension of random subspace is $d\_\sup = 300$. When we train the classifier, the used five-fold cross-validation method will decide the optimal parameter for

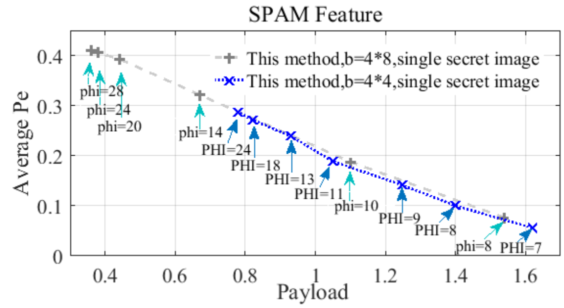


FIGURE 8. Contrast the average detection rates of this method among different payloads for embedding single secret image by using SPAM feature and $b = 4 \times 4$, $b = 4 \times 8$ parameters.

the trained classifier. It can repeat 10 times of steganogrphic tests and the average error rate is as the final result. We use SPAM steganalysis features [11] and ensemble2.0 classifier [30] to have a statistical attack for testing the security. The experiment needs to supply the detection rate of the statistical attack which is average value of missing rate and false alarm rate. The missing rate is referred to as the probability that the stego image of the testing set which is predicted for the normal cover image, while the false alarm rate is referred to as the probability that the normal cover image of the testing set which is predicted for the stego image:

$$\overline{p_e} = \min_{p_{FA}} \frac{1}{2} \left(p_{FA} + p_{MD}(p_{FA})\right), \tag{12}$$

where p_{FA} and p_{MD} respectively express the missing rate and false alarm rate. As seen from Fig.8, Fig.9, Fig.10, we can learn that when the parameter φ is closer to the lower bound the $\overline{p_e}$ value is going to be the lowest one. It is because when the parameter φ is smaller, the more information can be embedded for this method and the greater the likelihood that it will be less safe. As indicated in Fig. 8, when the large block size is set to be $b = 4 \times 8$, the higher security the stego images can obtain due to the *MBI* storage space decreasing. Although the security of the stego images is very important, the obtained good visual quality for the extract images has to be considered at the same time. Based on the data of Table 2, we know that $psnr_{EI}$ values of the extract images according to the parameter $b = 4 \times 8$ are lower around 2 percent than the $psnr_{EI}$ values with the parameter $b = 4 \times 4$.

Actually, the relationship between the visual equality and the security observes a rule that the good visual equality of the extract images leads to the low security of the stego images, however the high security requirements result in the not very good visual equality of the extract images. Thereby, we get the conclusion that when we want to get an extract image with good visual quality and a stego image with high security performance the parameter $b = 4 \times 4$ should be set and if the large size of secret image needed to be embedded, the parameter $b = 4 \times 8$ should be set.

The resisting high dimension stenanalysis attack performances are also tested between this proposed method and Literature [25] method. The other existed methods such as Literatures [18]–[21] are all based on the LSB substitution

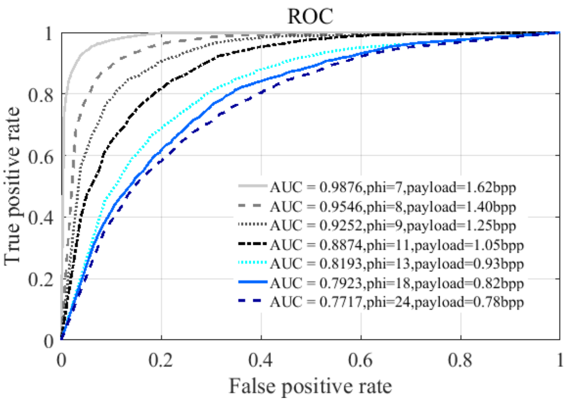


FIGURE 9. **The ROC curves of this method with different payloads for embedding single secret image based on SPAM feature and $b = 4 \times 4$ parameter.**

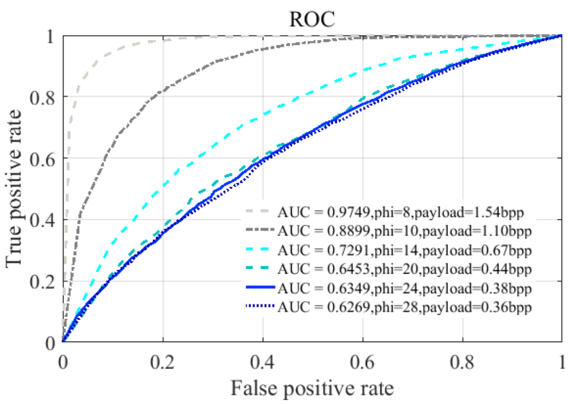


FIGURE 10. **The ROC curves of this method with different payloads for embedding single secret image based on SPAM feature and $b = 4 \times 8$ parameter.**

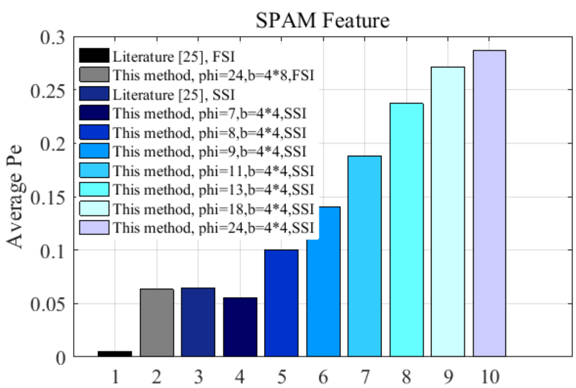


FIGURE 11. **The average detection rates of this method to be compared with Literature [25] for embedding single secret image (SSI) with $b = 4 \times 4$ or four secret images (FSI) with $b = 4 \times 8$ based on SPAM Feature.**

method which message are embedded within the 2-3 LSB bit planes of the cover image, however, that methods can't resist the high dimension stenanalysis attack. In this paper, we compare the experimental results of embedding single and four secret images of this proposed method with Literature [25] method. The parameters of this proposed method should be $\varphi \in \{7, 8, 9, 11, 13, 18, 24\}$, $b = 4 \times 4$ for embedding single secret image and parameters $\varphi = 24$, $b = 4 \times 8$ are

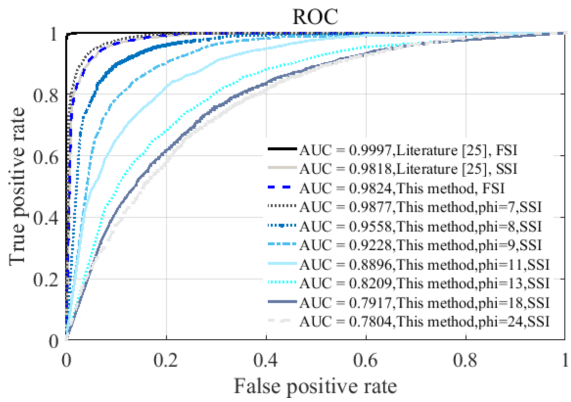


FIGURE 12. **The ROC curves of this method and Literature [25] method with different payloads for embedding single secret image (SSI) and four secret images (FSI) based on SPAM feature and $b = 4 \times 4$ parameter.**

set for embedding four secret images. The corresponding compared experimental results such as average $\overline{p_e}$ values and ROC curves between the two methods are shown in Fig. 11, Fig. 12. Fig. 11 indicates that when we embed one secret important image the $\overline{p_e}$ value of this method from $\varphi = 8$ to $\varphi = 24$ is almost several times higher than the Literature [25] method with the exception of the result with $\varphi = 7$. When we embed four secret images, the $\overline{p_e}$ value of this method is much higher than the other method, and the $psnr_{EI}$ value is around 32 which means that the visual quality of the extracted image is tolerable based on Table 5. The security of this method is gradually improved with the value of the φ increasing while the visual quality of the corresponding stego image is so good that the range of the $psnr_{ST}$ value is around from 50 to 54 based on Table 2. If the user wants to obtain higher security of the stego image, the proper larger φ should be given while a little degradation will be brought into the extracted images shown in Fig. 6, Fig. 7.

V. CONCLUSION

The existence form of secret information is usually based on text characters which can't accurately express some concrete figures in steganography. Conclusions based on making sure high imperceptibility and powerful anti-statistical attack, it has high practicability and research value to find way how to embed all these recordable concrete figures into the cover. Because the article needs a high embedding rate product code over Z4 to embed the large-scale image, the SPM feature is used to test the security performance. The experimental results of the paper are something referential value for using some high efficiency encoders with large payload such as Ternary STCs when the size of the embeddable IM is small, the required visual equality of the extracting image is low ($b = 4 \times 8$ and φ is less than 18), and then the high security based on this condition will be greatly improved.

REFERENCES

[1] T. Pevny, T. Filler, and P. Bas, "Using high-dimensional image models to perform highly undetectable steganography," in *Proc. Int. Workshop Inf. Hiding*, in Lecture Notes in Computer Science, 2010, pp. 161–177, doi: 10.1007/978-3-642-16435-4_13.

[2] T. Filler, J. Judas, and J. Fridrich, "Minimizing additive distortion in steganography using syndrome-trellis codes," *IEEE Trans. Inf. Forensics Security*, vol. 6, no. 3, pp. 920–935, Sep. 2011, doi: 10.1109/TIFS.2011.2134094.

[3] V. Holub and J. Fridrich, "Designing steganographic distortion using directional filters," in *Proc. IEEE Int. Workshop Inf. Forensics Secur. (WIFS)*, Costa Adeje, Spain, Dec. 2012, pp. 161–177, doi: 10.1109/WIFS.2012.6412655.

[4] V. Holub and J. Fridrich, "Digital image steganography using universal distortion," in *Proc. 1st ACM Workshop Inf. Hiding Multimedia Secur.*, Montpellier, France, 2013, pp. 59–68, doi: 10.1145/2482513.2482514.

[5] J. Fridrich and J. Kodovsky, "Multivariate Gaussian model for designing additive distortion for steganography," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process.*, Vancouver, BC, Canada, May 2013, pp. 2949–2953, doi: 10.1109/ICASSP.2013.6638198.

[6] B. Li, M. Wang, X. Li, S. Tan, and J. Huang, "A strategy of clustering modification directions in spatial image steganography," *IEEE Trans. Inf. Forensics Security*, vol. 10, no. 9, pp. 1905–1917, Sep. 2015, doi: 10.1109/TIFS.2015.2434600.

[7] T. Denemark and J. Fridrich, "Improving steganographic security by synchronizing the selection channel," in *Proc. 3rd ACM Workshop Inf. Hiding Multimedia Secur.*, 2015, pp. 5–14, doi: 10.1145/2756601.2756620.

[8] V. Sedighi, R. Cogranne, and J. Fridrich, "Content-adaptive steganography by minimizing statistical detectability," *IEEE Trans. Inf. Forensics Security*, vol. 11, no. 2, pp. 221–234, Feb. 2016, doi: 10.1109/TIFS.2015.2486744.

[9] J. Butora, "Minimum perturbation cost modulation for side-informed steganography," in *Proc. IS&T, Electron. Imag., Media Watermarking, Secur., Forensics*, San Francisco, CA, USA, 2020, pp. 26–30.

[10] J. Fridrich and J. Kodovský, "Rich models for steganalysis of digital images," *IEEE Trans. Inf. Forensics Security*, vol. 7, no. 3, pp. 868–882, Jun. 2012, doi: 10.1109/TIFS.2012.2190402.

[11] T. Pevn and P. Bas, "Steganalysis by subtractive pixel adjacency matrix," in *Proc. ACM Multimedia Secur. Workshop*, Princeton, NJ, USA, 2009, pp. 75–84, doi: 10.1109/TIFS.2010.2045842.

[12] C.-K. Chan and L. M. Cheng, "Hiding data in images by simple LSB substitution," *Pattern Recognit.*, vol. 37, no. 3, pp. 469–474, Mar. 2004, doi: 10.1016/J.PATCOG.2003.08.007.

[13] C. C. Chang, J. Y. Hsiao, and C. S. Chan, "Finding optimal least-significant-bits substitution in image hiding by dynamic programming strategy," *Pattern Recognit.*, vol. 36, no. 7, pp. 1583–1595, 2003, doi: 10.1016/S0031-3203(02)00289-3.

[14] R.-Z. Wang, C.-F. Lin, and J.-C. Lin, "Image hiding by optimal LSB substitution and genetic algorithm," *Pattern Recognit.*, vol. 34, no. 3, pp. 671–683, 2001, doi: 10.1016/S0031-3203(00)00015-7.

[15] C. C. Chang, C. S. Chan, and Y. H. Fan, "Image hiding scheme with modulus function and dynamic programming strategy on partitioned pixels," *Pattern Recognit.*, vol. 39, no. 6, pp. 1155–1167, 2006, doi: 10.1016/j.patcog.2005.12.011.

[16] C. C. Thien and J. C. Lin, "A simple and high-hiding capacity method for hiding digit-by-digit data in images based on modulus function," *Pattern Recognit.*, vol. 36, no. 12, pp. 2875–2881, 2003, doi: 10.1016/S0031-3203(03)00221-8.

[17] Y.-C. Hu, "High-capacity image hiding scheme based on vector quantization," *Pattern Recognit.*, vol. 39, no. 9, pp. 1715–1724, Sep. 2006, doi: 10.1016/j.patcog.2006.02.005.

[18] R.-Z. Wang and Y.-D. Tsai, "An image-hiding method with high hiding capacity based on best-block matching and k-means clustering," *Pattern Recognit.*, vol. 40, no. 2, pp. 398–409, Feb. 2007, doi: 10.1016/j.patcog.2006.07.015.

[19] R.-Z. Wang and Y.-S. Chen, "High-payload image steganography using two-way block matching," *IEEE Signal Process. Lett.*, vol. 13, no. 3, pp. 161–164, Mar. 2006, doi: 10.1109/LSP.2005.862603.

[20] S. K. Chen and R. Z. Wang, "High-payload image hiding scheme using k-way block matching," in *Proc. 6th Int. Conf. Intell. Inf. Hiding Multimedia Signal Process.*, Darmstadt, Germany, 2010, pp. 70–73, doi: 10.1109/IIHMSP.2010.25.

[21] Y. P. Hsieh, C. C. Chang, and L. J. Liu, "A two-codebook combination and three-phase block matching based image-hiding scheme with high embedding capacity," *Pattern Recognit.*, vol. 41, no. 10, pp. 3104–3113, 2008, doi: 10.1016/j.patcog.2008.03.021.

[22] S. Dumtrescu, X. L. Wu, and Z. Wang, "Detection of LSB steganography via sample pair analysis," *IEEE Trans. Signal Process.*, vol. 51, no. 7, pp. 1995–2007, Jul. 2003, doi: 10.1109/TSP.2003.812753.

[23] J. Fridrich, M. Goljan, D. Hogea, and D. Soukal, "Quantitative steganalysis of digital images: Estimating the secret message length," *Multimedia Syst.*, vol. 9, no. 3, pp. 288–302, Sep. 2003, doi: 10.1007/S00530-003-0100-9.

[24] A. D. Ker and R. Bohme, "Revisiting weighted stego-image steganalysis," *Proc. SPIE*, vol. 6819, pp. 501–517, Mar. 2008.

[25] T. Han, J. L. Fei, S. L. Liu, X. Chen, and Y. F. Zhu, "Large-payload image-hiding method based on block matching and syndrome-trellis codes," *J. Comput.-Aided Des. Comput.*, vol. 28, no. 2, pp. 271–279, 2016, doi: 10.3969/j.issn.1003-9775.2016.02.009.

[26] L. Zhang and D. Chen, "A modified product code over in steganography with large embedding rate," *KSII Trans. Internet Inf. Syst.*, vol. 10, no. 7, pp. 3353–3370, 2016, doi: 10.3837/TIIS.2016.07.027.

[27] Z. Zhao, Q. Guan, and X. Zhao, "Constructing near-optimal double-layered syndrome-trellis codes for spatial steganography," in *Proc. 4th ACM Workshop Inf. Hiding Multimedia Secur.*, Vigo, Spain, 2016, pp. 139–148, doi: 10.1145/2909827.2930802.

[28] H. Rifà-Pous and J. Rifà, "Product perfect codes and steganography," *Digit. Signal Process.*, vol. 19, no. 4, pp. 764–769, 2009, doi: 10.1016/j.dsp.2008.11.005.

[29] C. Lee, "Some properties of nonbinary error-correcting codes," *IEEE Trans. Inf. Theory*, vol. IT-4, no. 2, pp. 77–82, Jun. 1958, doi: 10.1109/TIT.1958.1057446.

[30] J. Kodovský, J. Fridrich, and V. Holub, "Ensemble classifiers for steganalysis of digital media," *IEEE Trans. Inf. Forensics Security*, vol. 7, no. 2, pp. 432–444, Apr. 2012, doi: 10.1109/TIFS.2011.2175919.

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