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SRIS-Net: a robust image steganography algorithm based on feature score maps*

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Abstract: Image steganography algorithms based on deep learning are often trained using either spatial- or frequency-domain features. It is difficult for features from a single domain to comprehensively express the content of an entire image, which usually leads to poor performance because steganography is commonly multi-task. To solve this problem, this paper proposes a robust image steganography algorithm based on feature score maps, called the secure and robust image steganography network (SRIS-Net). First, instead of spatial-domain steganography, our proposed algorithm utilizes a convolutional neural network to obtain shallow spatial-domain features. These features are decomposed by Laplacian pyramid frequency-domain decomposition (LPFDD) to hide secret information in the different frequency sub-bands with a progressive assisted hiding strategy that significantly reduces the influence of the secret information on the cover image, achieving significant invisibility and robust performance. In addition, we propose a global–local embedding module (GLEM) to achieve embedding by considering the overall structure of the image and the local details, and a dual multi-scale aggregation sub-network (DMSubNet) to perform multi-scale reconstruction to improve the quality of the carrier image. For security, we propose a dual-task discriminator structure, while giving a real/fake judgment of the image, which can generate a feature score map of the cover image's region of interest (ROI) to guide the embedding module to generate a carrier image with higher imperceptibility and undetectability. Experimental results on BOSSBase show that our SRIS-Net outperforms mainstream methods in terms of undetectability and robustness, with more than 9.2 and 3.4 dB improvement in visual quality, respectively, and the capacity can be increased up to approximately 72–96 bits per pixel.

Key words: Image steganography; Robustness; Undetectability; Dual-task discriminator
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1 Introduction

Image steganography (Cheddad et al., 2010; Wengrowski and Dana, 2019; Tancik et al., 2020) hides information by exploiting image redundancy. A secret image is embedded in a cover image to generate a carrier image, while maintaining better visual quality of the carrier image and higher accuracy of the secret image extraction. Based on security considerations, the carrier image is usually required to be visually indistinguishable from the cover image. Traditional methods often hide the secret information using the least significant bit (LSB) (Barni et al., 2001; Li XL et al., 2009). These methods can hide only a limited amount of information and are not robust enough against various attacks, such as steganalysis detection (Ren et al., 2025).

In recent years, deep learning (DL)-based image steganography has shown promising results (Hu et al., 2018; ur Rehman et al., 2018). Baluja (2017) proposed the first convolutional neural network

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(CNN) in this domain. Researchers further improved image steganography performance by improving the network structure (Baluja, 2020) and introducing new loss functions (Singh et al., 2022). Invertible neural networks (INNs) demonstrate superior performance in image steganography (Lu et al., 2021; Yang et al., 2024) due to their precise fulfillment of the inverse relationship between embedding and extraction processes. Some studies (Chen et al., 2020) focused on designing frameworks with good robustness, and other works improved robustness by introducing noise in training (Ying et al., 2022). Attention-based data hiding using a generative adversarial network (ADH-GAN) (Yu, 2020) guarantees both robustness and capacity. However, extensive training of an attention module is required to obtain attention weight maps for steganography assistance. Inspired by PatchGAN (Isola et al., 2017), a discriminator can evaluate the entire image generated by the generator and feed the attention back to each patch. As for the image steganography task, if the region of interest (ROI) of the steganalysis can be known before embedding, higher security can be achieved. The above methods directly concatenate or add the cover image and the secret image, or extract their features and then concatenate or add them, without considering the correlation and adaptability between features, and thus it is not optimal for the network to excel in only some aspects of performance but perform poorly in others. Moreover, image steganography based on DL is usually trained using features in a single domain, such as the spatial (Lu et al., 2021) or frequency (Jing et al., 2021) domain, which makes comprehensively expressing the content of the image difficult. Compared with the pixel domain, the embedding capacity of the feature domain is larger (Xu YM et al., 2022) and more robust. In addition, embedding the features of a secret image instead of the original itself can assist in encrypting the secret image (Chen et al., 2020).

Based on the above, we design a robust image steganography algorithm named the secure and robust image steganography network (SRIS-Net). SRIS-Net uses Laplacian pyramid frequency-domain decomposition (LPFDD) (Lai et al., 2019) to perform multi-scale decomposition of the spatial-domain features of the cover image, and uses these features to achieve progressive embedding and reconstruction in the sub-bands of different frequency domains. Based on a progressive assisted hiding strategy, SRIS-Net uses these frequency-domain features to enhance robustness. Additionally, SRIS-Net employs a dual-task discriminator that not only identifies the authenticity of the image but also provides the feature score map of the discriminator's ROI to guide the embedding process. Consequently, SRIS-Net achieves good performance on steganographic quality, security, robustness, and capacity. The main contributions of this paper include the following:

1. We propose a robust image steganography algorithm, SRIS-Net, based on feature score maps, which performs LPFDD on the image spatial domain and implements incremental embedding and reconstruction across various frequency sub-bands. This strategy minimizes the impact of hidden information on the cover image, and ensures significant invisibility and robust performance.

2. An embedding block (the global–local embedding module, or GLEM) and a dual multi-scale aggregation sub-network (DMSubNet) are introduced which enhance embedding by considering the correlation and adaptation between the cover and secret images. These components reconstruct image features to improve the quality of image steganography.

3. A dual-task discriminator structure is proposed for security. It can not only determine real (cover) or fake (carrier), but also generate a feature score map of the ROI for the cover image to guide the embedding module to generate a carrier image with higher imperceptibility and undetectability.

2 Related works

2.1 Steganography

Steganography is a technique for hiding a message, audio, image, or video in other media to avoid arousing suspicion. LSB (Tamimi et al., 2013) is the traditional spatial-domain-based method in steganography, but it suffers from texture replication artifacts, particularly in smooth regions, making it vulnerable to steganalysis (Xu GS et al., 2016; Ye et al., 2017). Frequency-domain methods, such as the discrete cosine transform (DCT) (Ruanaidh et al., 1996) and the discrete wavelet transform (DWT) (Barni et al., 2001), offer more robustness and are harder to detect, although they conceal only bit-level information.

The combination of DL and image steganography has significantly improved performance. Shi HC et al. (2018) used a GAN-based encoder–decoder architecture to enhance resistance to steganalysis. Many image steganography methods have been proposed based on different network architectures, including the method by Liu et al. (2022) based on ResNet, residual structures (Wu et al., 2018), U-Net structure (Duan et al., 2019), and the Xception block-based method (Duan et al., 2020a), which are designed mainly to optimize capacity and visual quality. Singh et al. (2022) proposed a GAN-based architecture for image steganography, StegGAN, which is combined with dual discriminators, significantly improving the quality of both the carrier and secret images but ensuring only noiseless extraction. GAN-based steganography algorithms have higher security than normal ones. However, previous GAN-based steganography primarily uses the discriminator for real/false judgments during training, discarding it afterward. There is potential for the discriminator to provide more valuable feedback and aid the generator in creating more realistic and secure carrier images.

2.2 LPFDD

The Laplacian pyramid (Lai et al., 2019) is a multi-scale image representation method widely used in the fields of image super-segmentation and image reconstruction. It is created by convolving the original image through successive Gaussian filters to generate blurred images at various scales and then subtracting each Gaussian pyramid layer from the up-sampled image of its predecessor, as defined in Eq. (1):

$$L_i = G_i - \text{Expand}(G_{i+1}), \tag{1}$$

where L_i denotes the i^{th} layer of the Laplacian pyramid image, G_i represents the i^{th} layer of the Gaussian pyramid image, and $\text{Expand}(G_{i+1})$ is the up-sampled previous layer of the Gaussian pyramid image. This construction allows for multi-scale analysis and processing of the image. By using LPFDD, features are embedded and reconstructed in different sub-bands, with lower-frequency features assisting the higher-frequency features in completing the image steganography task. This approach minimizes the impact of secret information on the cover image, effectively improving visual quality and capacity.

3 Method

SRIS-Net consists of three main components: an LPFDD embedding network, an LPFDD extraction network, and a dual-task discriminator. Fig. 1 shows the overall architecture of SRIS-Net. Table 1 shows the notation used in this paper.

Table 1 Explanation of symbols in this paper

Symbol	Description
$\boldsymbol{I}_{\text{co}}$	Cover image, i.e., the image to hide secret information
$\boldsymbol{I}_{\text{ca}}$	Carrier image, i.e., the image with secret information inside
$\boldsymbol{I}_{\text{se}}$	Secret image, i.e., the image to be hidden
$\boldsymbol{I}_{\text{re}}$	Recovered secret image from a carrier image

3.1 LPFDD embedding network

Information embedded in the high-frequency regions is hard to detect but susceptible to attacks (Jing et al., 2021), while embedding information in the low-frequency regions improves robustness but often arouses visual suspicion (Li ZZ et al., 2022). Both domains have suitable embedding regions, and using only one region impacts capacity, image quality, and security. Therefore, our method embeds information across multiple frequency domains, finding suitable locations through GLEM and reconstructing features with DMSub-Net to enhance embedding capacity and image quality.

As shown in Fig. 1, the LPFDD embedding network we propose divides image steganography into high-frequency ($\boldsymbol{h}_0$), medium-frequency ($\boldsymbol{h}_1$), and low-frequency ($\boldsymbol{h}_2$) stages for progressive embedding and reconstruction. Given a cover image $\boldsymbol{I}_{\text{co}} \in \mathbb{R}^{h\times w\times 1}$, we first extract the shallow features $\boldsymbol{I}_0 \in \mathbb{R}^{h\times w\times c}$, where h and w are the spatial dimensions and c is the channel number. LPFDD is then used to obtain the frequency features $\boldsymbol{H} = [\boldsymbol{h}_0,\ \boldsymbol{h}_1,\ \boldsymbol{h}_2]$, with resolutions of $\frac{h}{2^i}\times\frac{w}{2^i}\times c,\ i = 0,1,2$. For a secret image $\boldsymbol{I}_{\text{se}} \in \mathbb{R}^{h\times w\times 1}$, features $\boldsymbol{S} = [\boldsymbol{s}_0,\ \boldsymbol{s}_1,\ \boldsymbol{s}_2]$ are extracted progressively by the secret image feature extraction module with resolutions of $\frac{h}{2^i}\times\frac{w}{2^i}\times c,\ i = 0,1,2$ (Fig. 1). Then, guided by the dual-task discriminator feature maps, the information of $\boldsymbol{H}$ and $\boldsymbol{S}$ is fed into three network branches for hierarchical embedding and reconstruction, respectively.

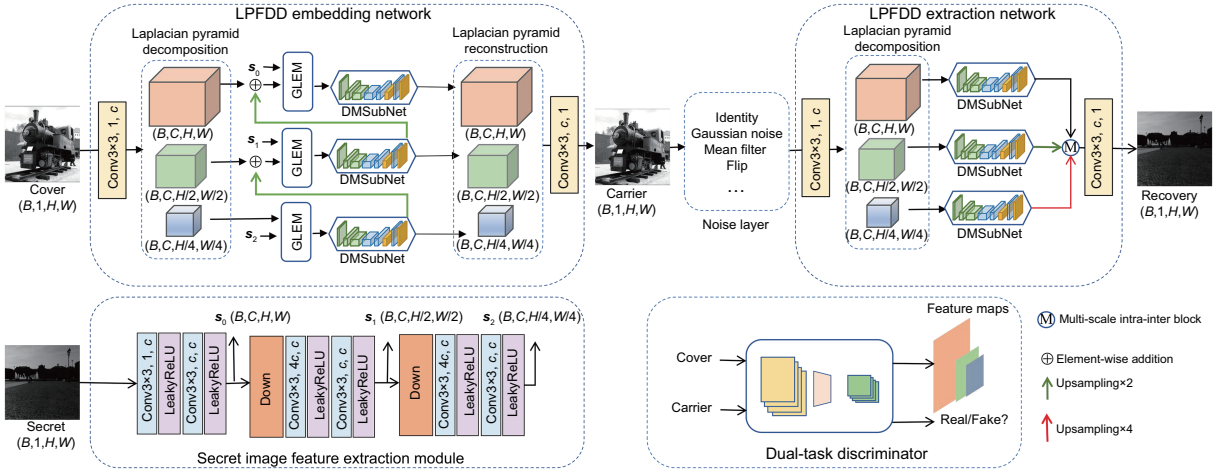


Fig. 1 SRIS-Net framework. First, through the secret image feature extraction module, the progressive resolution features $S = [s_0,\ s_1,\ s_2]$ of the secret image are extracted. Then, S and the cover image features are separately embedded through the GLEM guided by the dual-task discriminator feature maps, and reconstructed through DMSubNet of the three branches in the LPFDD embedding network. At the receiver end, the carrier image is processed by the LPFDD extraction network to extract the recovered secret image. The dual-task discriminator can not only distinguish real from fake, but also provide a feature score map for the ROI to guide the embedding of secret information. B: batch size; C: channel count; H: height; W: width (dimensions of the batch of images)

The low-frequency embedding and reconstruction process is shown in Eq. (2):

$$\hat{\boldsymbol{h}}_2 = \mathrm{DM}_2\left(\mathrm{EM}_2\left(\boldsymbol{h}_2,\ \boldsymbol{s}_2,\ \mathbf{map}_2\right)\right), \tag{2}$$

where $\boldsymbol{h}_2 \in \mathbb{R}^{\frac{h}{4}\times\frac{w}{4}\times c}$, $\boldsymbol{s}_2 \in \mathbb{R}^{\frac{h}{4}\times\frac{w}{4}\times c}$, and $\mathbf{map}_2 \in \mathbb{R}^{\frac{h}{4}\times\frac{w}{4}\times c}$ are the low-frequency features of the cover image, secret image, and feature score maps from the discriminator, respectively. EM is the module for GLEM, and DM is DMSubNet. $\hat{\boldsymbol{h}}_2 \in \mathbb{R}^{\frac{h}{4}\times\frac{w}{4}\times c}$ is the reconstructed feature of the low-frequency region.

Given the relatively small amount of information in $\boldsymbol{h}_0$ and $\boldsymbol{h}_1$, direct embedding may cause serious information loss, so we adopt a progressive embedding strategy. We up-sample $\hat{\boldsymbol{h}}_2$ to $\hat{\boldsymbol{h}}_2\uparrow$ with the size of $\boldsymbol{h}_1$ using bilinear interpolation. Then we add it to $\boldsymbol{h}_1$ to assist in embedding. This process is repeated for $\boldsymbol{h}_0$, with each step similar to that in the $\boldsymbol{h}_2$ embedding process described in Eq. (3). The progressive embedding strategy ensures better preservation of information and improved embedding quality, and can effectively break the limitation of single-domain hiding on capacity.

$$\hat{\boldsymbol{h}}_i = \mathrm{DM}_i\left(\mathrm{EM}_i\left(\boldsymbol{h}_i + \hat{\boldsymbol{h}}_{i+1}\uparrow, \boldsymbol{s}_i, \mathbf{map}_i\right)\right). \tag{3}$$

3.1.1 GLEM

GLEM embeds secret information adaptively by considering both the overall image structure and local details (Fig. 2). Guided by $\mathbf{map}_i \in \mathbb{R}^{\frac{h}{2^i}\times\frac{w}{2^i}\times c}$, we embed $\boldsymbol{s}_i \in \mathbb{R}^{\frac{h}{2^i}\times\frac{w}{2^i}\times c}$ into $\boldsymbol{h}_i \in \mathbb{R}^{\frac{h}{2^i}\times\frac{w}{2^i}\times c}$ through global and local branches, so the secret information embedding is more adaptive to the cover image, thus improving robustness and security. The global branch uses a self-attention mechanism (Zamir et al., 2022), and the local branch uses Conv1×1 for detail embedding. $\boldsymbol{Q}$, $\boldsymbol{K}$, and $\boldsymbol{V}$ are generated with Conv1×1 and DWConv3×3 (Fig. 2).

3.1.2 DMSubNet

To handle multi-frequency-domain embedding and extraction, DMSubNet uses multi-scale

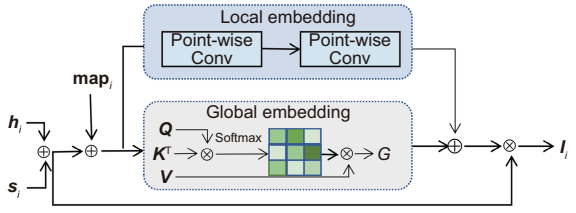


Fig. 2 GLEM embeds the secret image in the cover image under the guidance of the feature map, and includes a global embedding branch and a local embedding branch

intra-blocks (MSIBs) and a selective fusion module (SFM) (Fig. 3). DMSubNet down-samples and up-samples (Shi WZ et al., 2016) features hierarchically, leveraging multi-scale representations to accurately process image details. Meanwhile, for the image steganography reconstruction and extraction process, the manner in which shallow features are directly added with deep features is not applicable. Specifically, in the reconstruction of the secret image, shallow features often contain more carrier image information. Therefore, secret image features are extracted selectively, so the addition operation will directly lead to recovering the secret image unsuccessfully. Therefore, SFM enables the aggregation of low-level image features and high-level features selectively, preserving fine structural and textural details for better reconstruction and extraction.

3.1.3 SFM

SFM (Fig. 3) achieves fusion of the shallow features and the deeper features selectively. Specifically, we generate the attention map by global average pooling of the low-resolution deep feature map $\boldsymbol{L}_i$, and then split it along the channels. Then we apply element-by-element multiplication, followed by Conv1×1 to transform the channels. The high-resolution shallow feature $\boldsymbol{H}_i$ is then multiplied with this attention weight map to selectively extract features that are useful for low-resolution deep feature reconstruction. The low-resolution deep features are then up-sampled (Shi WZ et al., 2016) and added to the extracted high-resolution feature to obtain the final feature.

3.1.4 MSIB

MSIB (Fig. 3) enhances multi-level feature understanding with a multi-scale global perceptual (MSGP) branch and a local contextual perceptual (LCP) branch. It uses different DWConv kernels for global multi-scale information and Conv3×3 for local details. LayerNorm is applied for better performance. LCP uses a bottleneck design for efficient local spatial modeling (Zhou et al., 2020).

DMSubNet allows adaptive and robust information embedding across multiple frequency domains, improving both the capacity and quality of the steganographic images.

3.2 LPFDD extraction network

The LPFDD extraction network adopts a similar structure to the LPFDD embedding network. It begins by taking the carrier image as input and extracting shallow features using Conv3×3. The high-, medium-, and low-frequency features are then obtained via LPFDD. These features are processed by DMSubNet to extract the secret information. The low-frequency features are up-sampled (Shi WZ et al., 2016) by a factor of 4 and the medium-frequency features by a factor of 2, and then concatenated with the high-frequency features. The combined features pass through two MSIB modules to produce the recovered secret image $\boldsymbol{I}_{\mathrm{re}}$, as shown

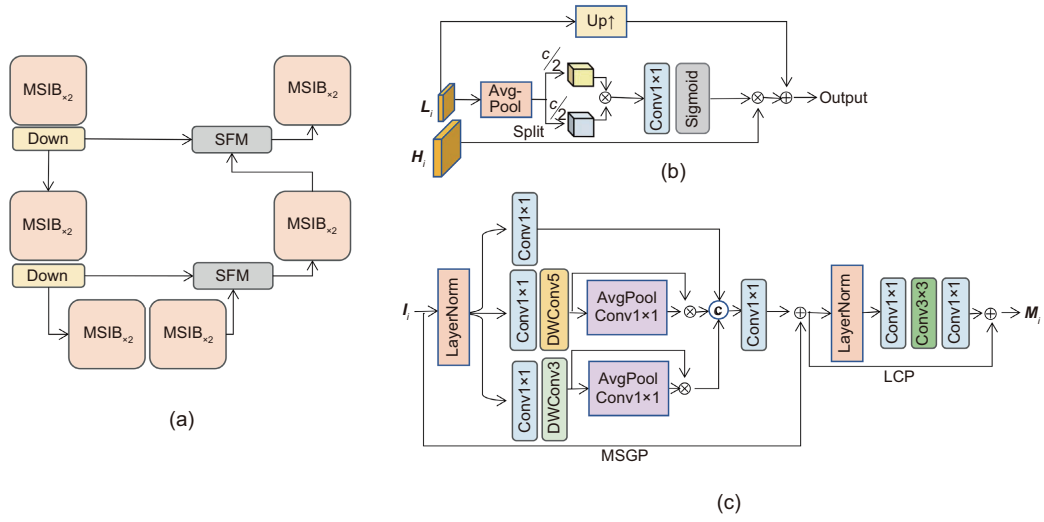


Fig. 3 DMSubNet architecture (a), SFM (b), and MSIB (c)

in Fig. 1. To enhance robustness, a noise layer is introduced before extraction, including a mean filter, Gaussian filter, sharpening, Gaussian noise, flipping, and identity processing.

3.3 Dual-task discriminator

Traditional discriminators focus on classifying images as real (cover) or fake (carrier) (Fu et al., 2020) and aid in generating a carrier image that closely resembles the cover. These discriminators are usually discarded after training. However, we argue that the role of the discriminator depends not only on classifying the inputs as fake or real, but also on having the ability to evaluate the whole image, generating a map of evaluation scores concerning the ROI. This evaluation score map can be regarded as a kind of prior knowledge of the embedding. This knowledge is fed back to the generator to guide it to pay more attention to the regions that are more suitable for embedding during embedding and reconstruction, and to generate a more realistic image of the carrier image. Meanwhile, the classification of the discriminator is based on the difference between the distinguishing regions in the original and generated images, and the feature map weight of each layer in the network is of great significance in the final results of the classifier.

Based on this, our study improves the classical steganalysis method Zhu-Net (Zhang R et al., 2020), as shown in Fig. 4, which includes a preprocessing layer, two separable convolution (sepconv) blocks, four basic blocks for feature extraction, a spatial pyramid pooling (SPP) module, a fully connected (FC) layer, and softmax. We up-sample the features from each basic block to match the original feature size by bilinear interpolation. This is followed by channel concatenation, average pooling, and normalization to obtain the feature score map. The score map is then decomposed into multi-scale feature sub-bands using LPFDD, which are fed back to the generator to guide the embedding process. This dual-task discriminator not only classifies real or fake but also provides detailed guidance, improving the security and visual quality of the generated images.

3.4 Loss function

The SRIS-Net loss function primarily comprises the generator's reconstruction loss, extraction loss, adversarial loss, and the discriminator's loss.

3.4.1 Generator's loss

1. Reconstruction loss

To ensure that the carrier image $\boldsymbol{I}_{\mathrm{ca}}$ generated by hiding $\boldsymbol{I}_{\mathrm{se}}$ in $\boldsymbol{I}_{\mathrm{co}}$ is indistinguishable from $\boldsymbol{I}_{\mathrm{co}}$, we also propose a specialized Laplace frequency-domain loss. This enhances the similarity between the carrier and cover images in both pixel and frequency domains, improving security and visual quality. The reconstruction loss L_{rec} is given as follows:

$$\begin{aligned} L_{\mathrm{rec}} =& L_{1\mathrm{loss}}\left(\boldsymbol{I}_{\mathrm{co}}, \boldsymbol{I}_{\mathrm{ca}}\right)+L_{\mathrm{lp}}\left(\boldsymbol{I}_{\mathrm{co}}, \boldsymbol{I}_{\mathrm{ca}}\right) \\ &+\alpha L_{\mathrm{per}}\left(\boldsymbol{I}_{\mathrm{co}}, \boldsymbol{I}_{\mathrm{ca}}\right). \end{aligned} \tag{4}$$

Here, $L_{1\mathrm{loss}}$ is the L1 loss of $\boldsymbol{I}_{\mathrm{co}}$ and $\boldsymbol{I}_{\mathrm{ca}}$ in the pixel domain:

$$L_{1\mathrm{loss}}\left(\boldsymbol{X}, \boldsymbol{X}'\right)=\frac{1}{HWC}\sum_{i=1}^{H}\sum_{j=1}^{W}\sum_{k=1}^{C}\left\|\boldsymbol{X}_{ijk}-\boldsymbol{X}'_{ijk}\right\|. \tag{5}$$

L_{lp} is the frequency-domain L1 loss of $\boldsymbol{I}_{\mathrm{co}}$ and $\boldsymbol{I}_{\mathrm{ca}}$

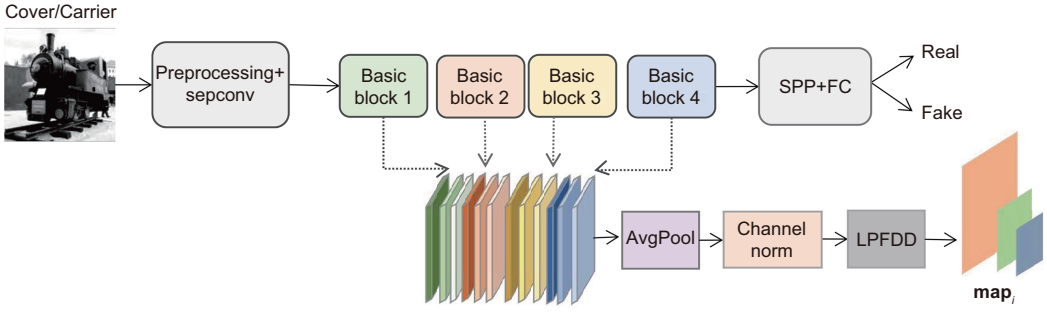


Fig. 4 Dual-task discriminator structure (we up-sample the features from each basic block to obtain the feature score map)

using LPFDD:

$$L_{\mathrm{lp}}(\boldsymbol{X},\boldsymbol{X}')=\sum_{i=0,1,2}L_{\mathrm{1loss}}\left(\mathrm{LP}(\boldsymbol{X})_i,\mathrm{LP}(\boldsymbol{X}')_i\right), \tag{6}$$

where LP represents applying the Laplacian pyramid frequency-domain transformation to the image. L_{per} is the perceptual loss (Johnson et al., 2016), which can help enhance image details and texture information, and α is the trade-off coefficient which adjusts the importance of different losses to the total loss function (we set α=0.1).

2. Extraction loss

The extraction network aims to recover the secret image $\boldsymbol{I}_{\mathrm{se}}$ from the carrier image $\boldsymbol{I}_{\mathrm{ca}}$. The extraction loss is defined as follows:

$$L_{\mathrm{ext}}=L_{\mathrm{1loss}}\left(\boldsymbol{I}_{\mathrm{se}},\boldsymbol{I}_{\mathrm{re}}\right)+L_{\mathrm{per}}\left(\boldsymbol{I}_{\mathrm{se}},\boldsymbol{I}_{\mathrm{re}}\right). \tag{7}$$

3. Adversarial loss

We use LSGAN (Mao et al., 2017) for the adversarial loss to ensure stable training, as follows:

$$L_{\mathrm{adv}}=E_{z\sim p(z)}\left[D(G(\boldsymbol{X}))-1\right], \tag{8}$$

where G stands for the generator and D stands for the discriminator. In addition, z follows the distribution $p(z)$ (a standard normal distribution).

The total loss of the SRIS-Net generator is then given by Eq. (9), where β is the trade-off factor, set to 0.0004:

$$L_{\mathrm{total}}=L_{\mathrm{rec}}+L_{\mathrm{ext}}+\beta L_{\mathrm{adv}}. \tag{9}$$

3.4.2 Discriminator's loss

The dual-task discriminator loss also uses LSGAN (Mao et al., 2017):

$$L_{\mathrm{D}}=\frac{E_{z\sim p(z)}\left[D(G(\boldsymbol{X}))-0\right]+E_{x\sim p(x)}\left[D(\boldsymbol{X})-1\right]}{2}. \tag{10}$$

This structured approach ensures that each component of SRIS-Net is optimized for its specific task, resulting in improved steganography and extraction performance.

4 Experiments

4.1 Setup

The proposed model is trained for 160 epochs on an NVIDIA A100 GPU. The number of channels is 48. The initial learning rate is 0.0004, adjusted using StepLR with a step size of 25 and a weight decay of 0.5. The batch size is 8. The generator is optimized by Adam with standard parameters, and the dual-task discriminator is optimized by stochastic gradient descent (SGD) with a momentum of 0.9 and a weight decay of 0.0005. The generator and discriminator are trained jointly with alternating updates.

We evaluate SRIS-Net on BOSSBase (Bas et al., 2011), which contains 10 000 grayscale images at resolutions of 512×512. We set the input size to 160×160 using center-cropping. The dataset is split into 9000 training images and 1000 test images. Both the cover and secret images are randomly paired from the training set.

There are five metrics adopted to measure the quality of cover/carrier image pairs and secret/recovery image pairs: mean squared error (MSE), peak signal-to-noise ratio (PSNR), structural similarity index measure (SSIM), multi-scale structural similarity index measure (MS-SSIM), and Spearman correlation coefficient (SCC) (Otazu et al., 2005).

4.2 Comparison

To verify the effectiveness of our method, we compare it with SimultaneousCNN (Van et al., 2019), ISGAN (Zhang R et al., 2019), StegNet (Wu et al., 2018), U-Net structure (Duan et al., 2019), Huang (Huang et al., 2019), HCRGAN (Chen et al., 2020), encoder–decoder (ur Rehman et al., 2018), Baluja (Baluja, 2017), SteganoCNN (Duan et al., 2020b), Liu (Liu et al., 2022), improved Xception (Duan et al., 2020a), StegGAN (Singh et al., 2022), DBPSNet (Li ZZ et al., 2022), DAH-Net (Zhang L et al., 2023), and PRIS (Yang et al., 2024). All of the methods are trained and tested using grayscale images (Bas et al., 2011).

4.2.1 Steganographic quality

1. Quantitative results

As shown in Table 2, SRIS-Net (ours) significantly outperforms all the other methods in terms of the five metrics for the cover/carrier, with MSE=0.000 06, PSNR=43.55 dB, SSIM=0.9990, MS-SSIM=0.9990, and SCC=0.9979. For secret/recovery, PRIS achieves the optimal performance due to the use of INNs, with MSE=0.000 11, PSNR=40.58 dB, SSIM=0.9981, MS-SSIM=0.9977, and SCC=0.9964. However, its strict reversibility

often exhibits vulnerability when subjected to noise and other attacks. From Tables 3 and 4, it is evident that PRIS is inferior to our method in terms of security and robustness.

2. Qualitative results

We randomly choose a pair of cover and secret

Table 2 Image hiding quality results

Method	Cover/Carrier				
	MSE↓	PSNR (dB)↑	SSIM↑	MS-SSIM↑	SCC↑
SimultaneousCNN	0.002 15	25.63	0.9420	0.9774	0.9790
ISGAN	0.011 20	18.95	0.8863	0.9036	0.9637
StegNet	0.004 12	22.38	0.9069	0.9554	0.9082
U-Net structure	0.001 21	27.76	0.9430	0.9805	0.9795
Huang	0.009 74	19.97	0.9023	0.9142	0.9528
HCRGAN	0.009 95	18.29	0.7754	0.8961	0.7470
Encoder–decoder	0.000 51	31.38	0.9099	0.9891	0.8565
Baluja	0.000 35	33.26	0.9338	0.9923	0.9024
SteganoCNN	0.000 32	33.47	0.9568	0.9922	0.9126
Liu	0.000 30	33.89	0.9721	0.9916	0.9534
Improved Xception	0.000 20	35.86	0.9651	0.9959	0.9482
StegGAN	0.000 41	33.19	0.9574	0.9834	0.9154
DBPSNet	0.000 25	34.26	0.9922	0.9921	0.9811
DAH-Net	0.000 62	32.35	0.9920	0.9900	0.9797
PRIS	0.000 10	40.88	0.9982	0.9978	0.9964
Ours	**0.000 06**	**43.55**	**0.9990**	**0.9990**	**0.9979**
Method	Secret/Recovery				
	MSE↓	PSNR (dB)↑	SSIM↑	MS-SSIM↑	SCC↑
SimultaneousCNN	0.002 00	25.33	0.9034	0.9492	0.9632
ISGAN	0.006 21	21.09	0.8887	0.9353	0.9316
StegNet	0.002 93	24.21	0.9134	0.9599	0.9756
U-Net structure	0.001 39	26.69	0.9276	0.9707	0.9699
Huang	0.005 26	21.86	0.9052	0.9391	0.9533
HCRGAN	0.010 33	16.14	0.6933	0.8448	0.7097
Encoder–decoder	0.000 92	28.70	0.8972	0.9747	0.9207
Baluja	0.000 37	31.38	0.9310	0.9798	0.9577
SteganoCNN	0.000 67	30.88	0.9651	0.9878	0.9804
Liu	0.000 32	32.64	0.9398	0.9847	0.9726
Improved Xception	0.001 58	26.42	0.9502	0.9788	0.9828
StegGAN	0.000 43	31.54	0.9293	0.9485	0.9667
DBPSNet	0.000 23	36.31	0.9902	0.9966	0.9957
DAH-Net	0.000 68	32.21	0.9892	0.9817	0.9805
PRIS	**0.000 11**	**40.58**	**0.9981**	**0.9977**	**0.9964**
Ours	0.000 13	39.78	0.9979	0.9956	0.9952

The best results are in bold; the second best results are underlined. ↑ means the larger the value, the better the result; ↓ means the smaller the value, the better the result

Table 3 Assessment of steganography security

Method	Error detection rate (%)			Method	Error detection rate (%)		
	SRM	CSR	XuNet		SRM	CSR	XuNet
SimultaneousCNN	10.52	14.42	23	SteganoCNN	15.22	16.24	14
ISGAN	2.08	3.97	11	Liu	17.36	18.73	20
StegNet	12.10	14.39	19	Improved Xception	16.40	17.85	16
U-Net structure	12.90	15.03	23	StegGAN	15.97	18.60	16
Huang	4.08	6.49	12	DBPSNet	22.56	27.51	34
HCRGAN	2.18	3.69	4	DAH-Net	15.80	18.98	16
Encoder–decoder	5.26	8.39	14	PRIS	18.80	20.00	17
Baluja	9.06	11.27	17	Ours	**24.38**	**40.60**	**36**

The best results are in bold; the second best results are underlined

Table 4 Image steganography robustness evaluation

Method	Mean filtering			Gaussian filtering			Sharpening		
	MSE↓	PSNR (dB)↑	SSIM↑	MSE↓	PSNR (dB)↑	SSIM↑	MSE↓	PSNR (dB)↑	SSIM↑
SimultaneousCNN	0.015 10	16.74	0.4503	0.045 66	13.71	0.3073	0.019 04	16.89	0.6210
ISGAN	0.028 76	13.65	0.2099	0.029 69	12.25	0.3391	0.008 57	19.26	0.8437
StegNet	0.021 09	17.20	0.2474	0.023 08	17.68	0.4810	0.017 00	18.35	0.6220
U-Net structure	0.014 94	16.56	0.4490	0.048 98	13.10	0.3267	0.016 02	17.80	0.6714
Huang	0.024 62	16.03	0.2432	0.039 28	14.76	0.3605	0.007 11	20.60	0.8529
HCRGAN	0.027 07	12.07	0.3507	0.021 95	13.01	0.4799	0.012 95	15.03	0.6092
Encoder–decoder	0.076 54	6.67	0.1190	0.065 29	5.11	0.2060	0.794 31	14.07	0.1600
Baluja	0.062 80	7.47	0.2420	0.057 99	11.25	0.3019	0.602 21	2.32	0.2266
SteganoCNN	0.016 67	18.22	0.4638	0.039 76	14.19	0.3861	0.002 14	26.29	0.8764
Liu	0.016 21	16.29	0.4466	0.038 97	14.69	0.3469	0.009 45	17.55	0.7869
Improved Xception	0.017 21	18.13	0.4153	0.019 63	18.75	0.5387	0.039 98	15.02	0.5305
StegGAN	0.143 70	18.38	0.4874	0.034 15	15.46	0.4956	0.007 92	19.27	0.8004
DBPSNet	0.000 68	31.30	0.9611	0.000 23	36.09	0.9916	0.000 26	35.86	0.9905
DAH-Net	0.001 22	29.72	0.9805	0.000 88	31.13	0.9864	0.000 45	34.05	0.9931
PRIS	0.000 61	32.44	0.9887	0.000 91	31.27	0.9855	0.000 16	39.07	0.9975
Ours	**0.000 13**	**36.62**	**0.9957**	**0.000 15**	**39.23**	**0.9976**	**0.000 15**	**39.29**	**0.9976**

Method	Gaussian noise			Flipping		
	MSE↓	PSNR (dB)↑	SSIM↑	MSE↓	PSNR (dB)↑	SSIM↑
SimultaneousCNN	0.007 72	20.44	0.5404	0.045 95	12.65	0.3541
ISGAN	0.053 60	11.81	0.1260	0.056 60	11.38	0.3282
StegNet	0.031 61	13.66	0.1994	0.050 03	12.75	0.2778
U-Net structure	0.034 53	14.29	0.1944	0.044 17	12.68	0.3418
Huang	0.046 25	12.94	0.1374	0.054 00	11.96	0.3096
HCRGAN	0.032 30	10.98	0.1866	0.047 89	9.84	0.3068
Encoder–decoder	0.017 56	17.15	0.3316	0.050 79	14.92	0.2109
Baluja	0.041 24	13.44	0.2256	0.047 58	12.48	0.2006
SteganoCNN	0.048 70	12.41	0.1522	0.044 67	12.72	0.3264
Liu	0.008 13	18.69	0.4536	0.046 83	12.65	0.3217
Improved Xception	0.035 32	14.45	0.1836	0.068 91	11.82	0.1982
StegGAN	0.007 78	19.27	0.4818	0.042 88	13.12	0.3787
DBPSNet	0.000 27	34.76	0.9870	0.003 91	13.80	0.5623
DAH-Net	0.001 14	29.80	0.9817	0.003 59	25.01	0.9420
PRIS	0.000 48	33.49	0.9921	0.049 56	13.29	0.1119
Ours	**0.000 23**	**36.77**	**0.9964**	**0.002 45**	**26.95**	**0.9635**

Under noise or attack scenarios, we calculate the MSE, PSNR, and SSIM of the secret/recovery pairs extracted by different methods. The best results are in bold; the second best results are underlined. ↑ means the larger the value, the better the result; ↓ means the smaller the value, the better the result

images and compare the carrier and recovery images generated by different methods. Given the space constraints, we show only the comparison of some of the methods. As shown in Fig. 5, HCRGAN, DAH-Net, and StegGAN generate blurred images, while our model and DBPSNet can generate clear carrier images. However, our method produces even clearer carrier images. We further show the residual frequency histogram of cover/carrier pairs and secret/recovery pairs. As shown in Fig. 5, our method achieves a frequency of 0-pixel value greater than 0.8, and the average pixel value of the residual is 0.2948, achieving the best visual results among the comparison methods. Although our method provides a sub-optimal average pixel value compared to DBPSNet, our method also achieves a frequency of 0-pixel value of 0.55 and an average pixel value of 0.5551, indicating that the quality of the secret image reconstructed by our method remains impressive.

Through both quantitative and qualitative experimental results, our method demonstrates significant hiding and restoration capabilities. It can generate a visually undetectable carrier and accurately extract the secret image from the carrier image.

4.2.2 Security

Security is crucial for image steganography algorithms. We evaluate the ability of SRIS-Net to resist

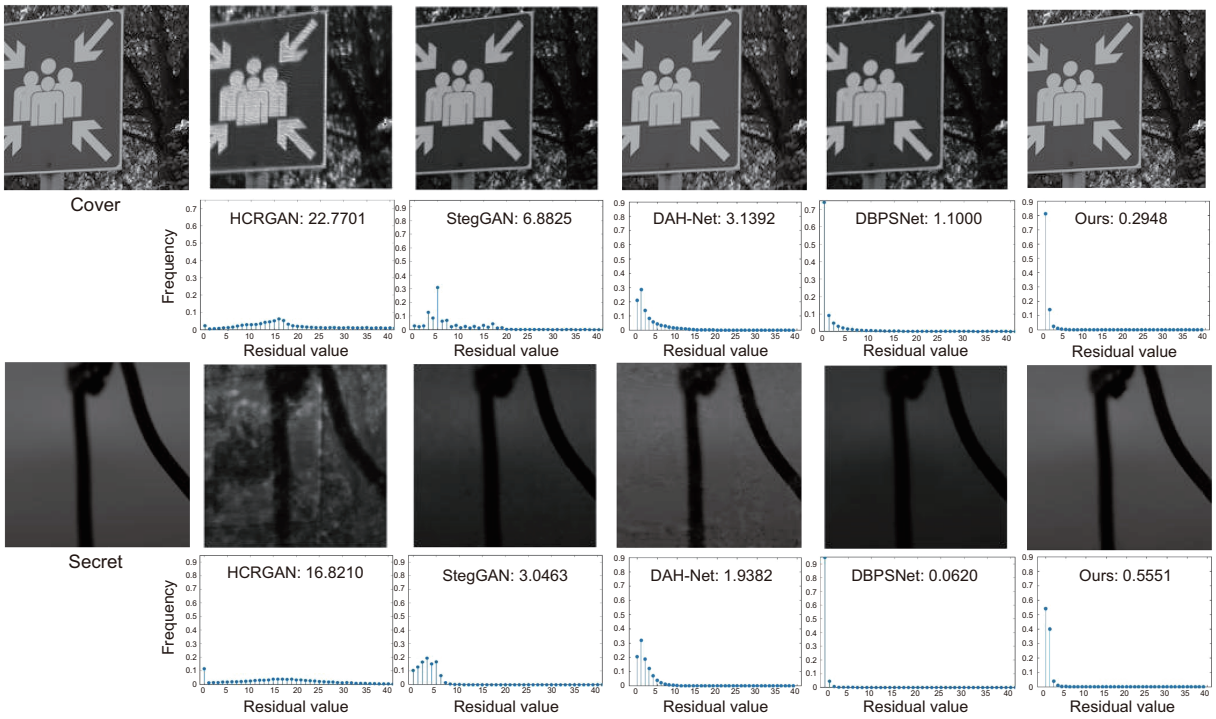


Fig. 5 Random visualization of the same cover/carrier and secret/recovery pairs generated through different methods (the value after the method represents the corresponding average residual value)

steganalysis detection. We choose the classical DL-based algorithm XuNet (Xu GS et al., 2016) to assess steganalysis performance. We pre-train XuNet with carrier images generated by the S-UNIWARD algorithm (Holub et al., 2014) from 10 000 pairs of images in BOSSBase at a payload of 0.4 bits per pixel. Then we randomly pair 1000 images in the test set with 500 cover/secret pairs and use various models to generate 500 carrier images. From these, 450 carrier images are used to fine-tune XuNet (Xu GS et al., 2016), which is then used to detect the remaining carriers and calculate the error detection rate. As shown in Table 3, SRIS-Net (ours) achieves the best error detection rate of 36%, two percentage points higher than that of DBPSNet, whereas all the other methods score below 30%.

Then, we use traditional SRM (Fridrich and Kodovsky, 2012) and CSR (Denemark et al., 2014) for steganalysis evaluation, employing "ensemble" (Kodovsky et al., 2012) as the classifier. We split the carrier and cover images for training and testing, averaging results over 10 cross-tests. SRIS-Net achieves the best results (24.38% for SRM and 40.60% for CSR).

These evaluations demonstrate that SRIS-Net (ours), combined with discriminator feature score maps, can generate highly secure carrier images. The discriminator guides the generator to distribute secret signals to more undetectable regions, enhancing the security of the steganography process.

4.2.3 Anti-distortion capability

To increase the model's robustness, we introduce a noise layer to train the model to reveal the secret image in noisy conditions, as shown in Fig. 1. We choose MSE, PSNR, and SSIM as robustness evaluation metrics. As shown in Table 4, SRIS-Net (ours) performs well under various noise conditions, including mean filtering, Gaussian filtering, sharpening, Gaussian noise, and flipping. Specifically, with mean and Gaussian filtering using 5×5 filters, Laplacian sharpening, and Gaussian noise with a variance of 0.01, our extraction network effectively reveals the secret image. SRIS-Net outperforms other methods in MSE, PSNR, and SSIM. Notably, when the carrier image is attacked by flipping, SRIS-Net still reconstructs the secret image with a PSNR of 26.95 dB.

To further demonstrate the model's performance under multiple distortions, we conduct experiments using various combinations of Gaussian

filtering, Gaussian noise, mean filtering, and sharpening, as well as constructing a noise pool, as shown in Table 5. The performance of SRIS-Net under combined noise conditions is indeed worse than that under single noise conditions, but it still achieves relatively good results. Specifically, under Gaussian filtering and sharpening, it attains MSE, PSNR, and SSIM values of 0.000 17, 38.46 dB, and 0.9972, respectively. The worst performance is with the combination of mean filtering and Gaussian noise, yet it still achieves an MSE of 0.000 63, PSNR of 32.51 dB, and SSIM of 0.9899. In addition, SRIS-Net still achieves an MSE of 0.000 30, PSNR of 36.08 dB, and SSIM of 0.9951 under random noise. These results demonstrate that SRIS-Net possesses robust steganographic capabilities.

4.2.4 Capacity

In some scenarios, capacity is extremely important. We compare SRIS-Net with StegGAN by conducting experiments to embed 2, 3, and 4 images in one cover image. Table 6 shows the average PSNR results for the cover/carrier and secret/recovery image pairs. When embedding two images, our method achieves an average PSNR of 41.96 dB for cover/carrier images and 34.65 dB for secret/recovery images. Even when embedding three images, the performance remains good. Remarkably, with four images, the average PSNR is 41.46 dB for cover/carrier images and 30.85 dB for secret/recovery images. However, the performance of StegGAN significantly deteriorates, showing an average PSNR of 33.21 dB for cover/carrier pairs and 21.41 dB for secret/recovery pairs when embedding two images. As the number of embedded images increases, the image quality of StegGAN declines sharply.

Fig. 6 shows examples of cover/carrier and secret/recovery pairs constructed by SRIS-Net and StegGAN when embedding two images. Despite some distortion, the secret images remain relatively clear with SRIS-Net. Fig. 7 visualizes pairs generated by our method with four embedded images, demonstrating that the images are still relatively clear. These results indicate that SRIS-Net can achieve a maximum payload of approximately 72–96 bits per pixel, demonstrating superior capacity both visually and quantitatively.

Table 5 Quantitative evaluation of combined noise and random noise

Combination	MSE↓	PSNR (dB)↑	SSIM↑
Gaussian filtering +Gaussian noise	0.000 47	33.88	0.9926
Gaussian filtering +Mean filtering	0.000 39	34.95	0.9941
Gaussian noise +Sharpening	0.000 19	37.86	0.9971
Sharpening +Mean filtering	0.000 26	36.90	0.9959
Mean filtering +Gaussian noise	0.000 63	32.51	0.9899
Gaussian filtering +Sharpening	0.000 17	38.46	0.9972
Random	0.000 30	36.08	0.9951

The random noise is applied by randomly using one of the noise types. ↑ means the larger the value, the better the result; ↓ means the smaller the value, the better the result

4.3 Ablation study

1. Effectiveness of DMSubNet

To verify the effectiveness of DMSubNet, we construct one variation, SSubNet, for which the

Table 6 Results for capacity of StegGAN and SRIS-Net

Number of images embedded	PSNR (dB)			
	Cover/Carrier		Secret/Recovery	
	StegGAN	Ours	StegGAN	Ours
2	33.21	41.96	21.41	34.65
3	31.35	41.56	18.56	32.33
4	29.87	41.46	16.18	30.85

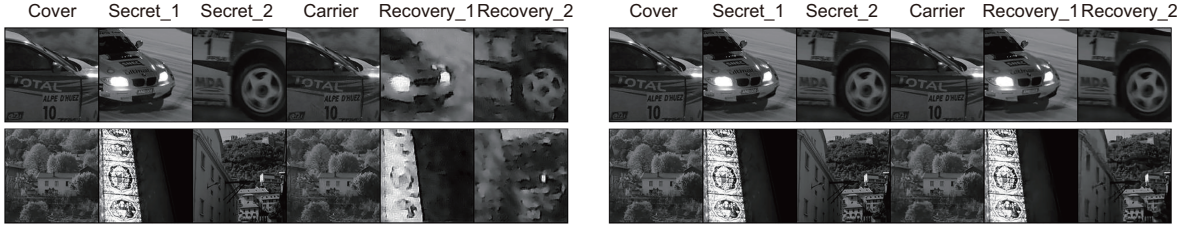


Fig. 6 StegGAN (left) vs. SRIS-Net (right) when two images are embedded in one cover image

single-scale reconstruction subnetwork maintains a fixed inter-block scale and includes only one branch of 3×3 as the basic block, removing the SFM inter-scale correlation fusion module. For shallow and deep feature fusion, residual addition is used. As shown in Table 7, compared to SSubNet, the PSNR value increases by 2.31 dB and 4.31 dB for cover/carrier and secret/recovery pairs respectively, and the error detection rate of CSR increases by 8.84 percentage points, indicating that DMSubNet with the dual multi-scale network design is more effective in hiding information.

2. Effectiveness of GLEM

DMSubNet fuses the cover image and secret image by directly adding their feature values. However, DMSubNet+GLEM uses the GLEM module for fusion. As shown in Table 7, compared to DMSubNet, the PSNR values of DMSubNet+GLEM increase by 0.34 dB and 0.15 dB for cover/carrier and secret/recovery pairs, respectively. The ability to resist CSR and SRM detection has been improved by 4.14 percentage points and 2.66 percentage points, respectively. This improvement is due to the global–local adaptive embedding, which helps the secret signals better adapt to the structure and details of the cover image. Thus, GLEM significantly enhances embedding and extraction performance, as well as security.



Fig. 7 Embedding four secret images on one cover image using SRIS-Net (obviously, the recovery images are all still clearly visible)

Table 7 Results of ablation experiments

Method	Cover/Carrier					Error detection rate (%)	
	MSE↓	PSNR (dB)↑	SSIM↑	MS-SSIM↑	SCC↑	SRM	CSR
SSubNet	0.000 09	41.18	0.9986	0.9983	0.9969	1.32	18.90
DMSubNet	0.000 06	43.49	0.9989	0.9989	0.9979	3.64	27.74
DMSubNet+GLEM	0.000 06	43.83	0.9990	0.9990	0.9980	6.30	31.88
DMSubNet+GLEM+GAN	0.000 06	43.31	0.9989	0.9989	0.9977	19.80	36.24
Ours	0.000 06	43.55	0.9990	0.9990	0.9979	24.38	40.60

Method	Secret/Recovery				
	MSE↓	PSNR (dB)↑	SSIM↑	MS-SSIM↑	SCC↑
SSubNet	0.000 25	36.78	0.9964	0.9932	0.9931
DMSubNet	0.000 10	41.09	0.9983	0.9973	0.9963
DMSubNet+GLEM	0.000 10	41.24	0.9984	0.9972	0.9963
DMSubNet+GLEM+GAN	0.000 14	39.24	0.9976	0.9949	0.9947
Ours	0.000 13	39.78	0.9979	0.9956	0.9952

↑ means the larger the value, the better the result; ↓ means the smaller the value, the better the result

3. Effectiveness of the dual-task discriminator

Although our network achieves high image quality without the discriminator, it is vulnerable to steganalysis detection. The misdetection rate by SRM is only 6.30% for DMSubNet+GLEM. To demonstrate the guidance provided by our dual-task discriminator, we compare DMSubNet+GLEM+GAN, which uses only a plain discriminator, with our approach. As shown in Table 7, there is a reduction in visual quality for DMSubNet+GLEM and DMSubNet+GLEM+GAN due to conflicting metrics between visual quality and resistance to steganalysis. However, resistance to SRM steganalysis detection increases by 13.5 percentage points. Our dual-task discriminator iteratively guides embedding using the discriminator feature map. Compared with DMSubNet+GLEM+GAN, the visual quality of ours increases by 0.24 dB and 0.54 dB for cover/carrier and secret/recovery pairs, respectively (Table 7). Additionally, in terms of undetectability, the error detection rates for CSR and SRM are 40.60% and 24.38%, improved by 4.36 percentage points and 4.58 percentage points respectively. These experiments illustrate that our dual-task discriminator effectively improves the security and quality of the carrier image by providing valuable embedding guidance to the generator. We randomly show the visual effect of four sets of image pairs constructed by our method in Fig. 8. It is difficult to distinguish them from the appearance of the images. For better observation, we magnify the residuals by 5, and still, hardly any difference is visible. The frequency histograms of these images are shown in Figs. 8e–8h. The horizontal axis ranges from 0 to 40, covering almost all pixel values in the residual image, and the vertical axis represents the frequency of each pixel value; the higher frequency of low pixel values indicates higher similarity between the carrier and cover images. The average pixel values of the residual maps are given, with the lowest being 0.0968 and the highest 1.0457. These quantitative and qualitative results demonstrate the effectiveness of our proposed algorithm.

5 Conclusions

This paper proposes a robust image steganography algorithm, SRIS-Net, based on feature score maps. SRIS-Net integrates spatial- and frequency-domain features, employing a progressive assisted hiding strategy. It utilizes GLEM and DMSubNet for progressive embedding and multi-scale feature reconstruction. These techniques minimize the impact of hidden information on the cover image, enhancing the robustness, visual quality, and security of the carrier image. The proposed dual-task discriminator structure assesses real/fake images and generates feature score maps of the cover image's ROI, guiding the embedding module to achieve higher imperceptibility and undetectability. Extensive experiments demonstrate SRIS-Net's superior performance in terms of capacity, visual quality, security, and robustness, validating the efficacy of the algorithm.

Contributors

Ai XIAO designed the research and drafted the paper. Zhi LI, Guomei WANG, Long ZHENG, and Haoyuan SUN helped organize the paper. Zhi LI revised and finalized the paper.

Conflict of interest

All the authors declare that they have no conflict of interest.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Baluja S, 2017. Hiding images in plain sight: deep steganography. Proc 31st Int Conf on Neural Information Processing Systems, p.2066-2076.

Baluja S, 2020. Hiding images within images. *IEEE Trans Patt Anal Mach Intell*, 42(7):1685-1697. https://doi.org/10.1109/TPAMI.2019.2901877

Barni M, Bartolini F, Piva A, 2001. Improved wavelet-based watermarking through pixel-wise masking. *IEEE Trans Image Process*, 10(5):783-791. https://doi.org/10.1109/83.918570

Bas P, Filler T, Pevný T, 2011. "Break our steganographic system": the ins and outs of organizing boss. Proc 13th Int Conf on Information Hiding, p.59-70. https://doi.org/10.1007/978-3-642-24178-9_5

Cheddad A, Condell J, Curran K, et al., 2010. Digital image steganography: survey and analysis of current methods. *Signal Process*, 90(3):727-752. https://doi.org/10.1016/j.sigpro.2009.08.010

Chen BJ, Wang JX, Chen YY, et al., 2020. High-capacity robust image steganography via adversarial network. *KSII Trans Int Inform Syst*, 14(1):366-381. https://doi.org/10.3837/tiis.2020.01.020

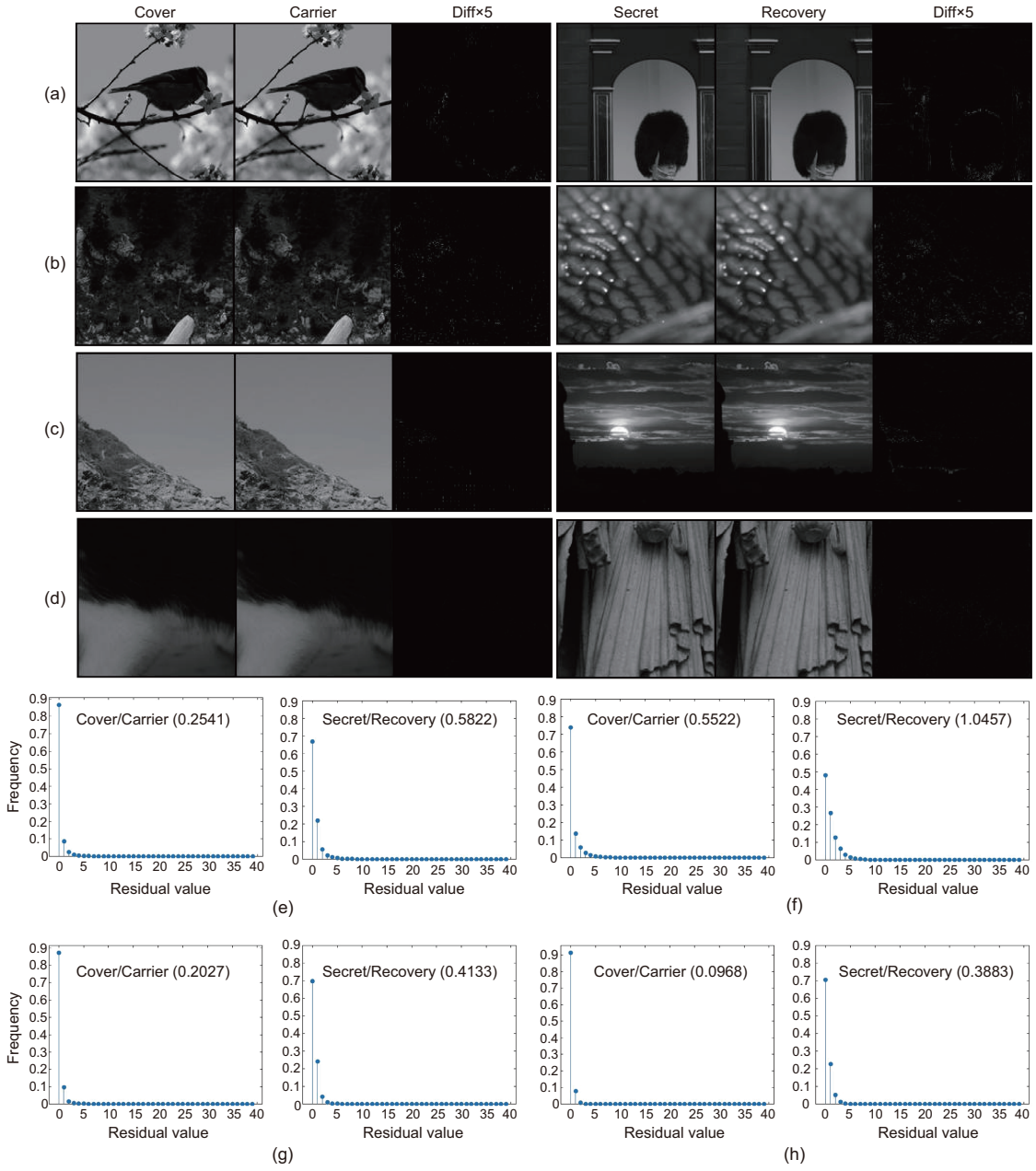


Fig. 8 Four sets of cover/carrier pairs and the secret/recovery pairs generated by our method are shown randomly, corresponding to (a–d). We magnify the residuals of each set of image pairs by a factor of 5 to make the difference almost invisible. We show the residual frequency histograms of the image pairs, corresponding to (e–h). The value in the brackets represents the corresponding average residual value

Denemark T, Fridrich J, Holub V, 2014. Further study on the security of S-UNIWARD. Proc IS&T/SPIE Electronic Imaging, Article 902805. https://doi.org/10.1117/12.2044803

Duan XT, Jia K, Li BX, et al., 2019. Reversible image steganography scheme based on a U-Net structure. *IEEE Access*, 7:9314-9323. https://doi.org/10.1109/ACCESS.2019.2891247

Duan XT, Gou MX, Liu N, et al., 2020a. High-capacity image steganography based on improved Xception. *Sensors*, 20(24):7253. https://doi.org/10.3390/s20247253

Duan XT, Liu N, Gou MX, et al., 2020b. SteganoCNN: image steganography with generalization ability based on convolutional neural network. *Entropy*, 22(10):1140. https://doi.org/10.3390/e22101140

Fridrich J, Kodovsky J, 2012. Rich models for steganalysis of digital images. *IEEE Trans Inform Forens Secur*, 7(3):868-882. https://doi.org/10.1109/TIFS.2012.2190402

Fu ZJ, Wang F, Cheng X, 2020. The secure steganography

for hiding images via GAN. *EURASIP J Image Video Process*, 2020:46. https://doi.org/10.1186/s13640-020-00534-2

Holub V, Fridrich J, Denemark T, 2014. Universal distortion function for steganography in an arbitrary domain. *EURASIP J Inform Secur*, 2014:1. https://doi.org/10.1186/1687-417X-2014-1

Hu DH, Wang L, Jiang WJ, et al., 2018. A novel image steganography method via deep convolutional generative adversarial networks. *IEEE Access*, 6:38303-38314. https://doi.org/10.1109/ACCESS.2018.2852771

Huang JJ, Cheng SY, Lou SH, et al., 2019. Image steganography using texture features and GANs. Proc Int Joint Conf on Neural Networks, p.1-8. https://doi.org/10.1109/IJCNN.2019.8852252

Isola P, Zhu JY, Zhou TH, et al., 2017. Image-to-image translation with conditional adversarial networks. Proc IEEE Conf on Computer Vision and Pattern Recognition, p.1125-1134. https://doi.org/10.1109/CVPR.2017.632

Jing JP, Deng X, Xu M, et al., 2021. HiNet: deep image hiding by invertible network. Proc IEEE/CVF Int Conf on Computer Vision, p.4733-4742. https://doi.org/10.1109/ICCV48922.2021.00469

Johnson J, Alahi A, Li FF, 2016. Perceptual losses for real-time style transfer and super-resolution. Proc 14th European Conf on Computer Vision, p.694-711. https://doi.org/10.1007/978-3-319-46475-6_43

Kodovsky J, Fridrich J, Holub V, 2012. Ensemble classifiers for steganalysis of digital media. *IEEE Trans Inform Forens Secur*, 7(2):432-444. https://doi.org/10.1109/TIFS.2011.2175919

Lai WS, Huang JB, Ahuja N, et al., 2019. Fast and accurate image super-resolution with deep Laplacian pyramid networks. *IEEE Trans Patt Anal Mach Intell*, 41(11):2599-2613. https://doi.org/10.1109/TPAMI.2018.2865304

Li XL, Yang B, Cheng DF, et al., 2009. A generalization of LSB matching. *IEEE Signal Process Lett*, 16(2):69-72. https://doi.org/10.1109/LSP.2008.2008947

Li ZZ, Yang XY, Shen KQ, et al., 2022. Dual branch parallel steganographic framework based on multi-scale distillation in framelet domain. *Neurocomputing*, 514:182-194. https://doi.org/10.1016/j.neucom.2022.09.146

Liu LS, Meng LZ, Wang XL, et al., 2022. An image steganography scheme based on ResNet. *Multim Tools Appl*, 81(27):39803-39820. https://doi.org/10.1007/s11042-022-13206-2

Lu SP, Wang R, Zhong T, et al., 2021. Large-capacity image steganography based on invertible neural networks. Proc IEEE/CVF Conf on Computer Vision and Pattern Recognition, p.10816-10825. https://doi.org/10.1109/CVPR46437.2021.01067

Mao XD, Li Q, Xie HR, et al., 2017. Least squares generative adversarial networks. Proc IEEE Int Conf on Computer Vision, p.2794-2802. https://doi.org/10.1109/ICCV.2017.304

Otazu X, Gonzalez-Audicana M, Fors O, et al., 2005. Introduction of sensor spectral response into image fusion methods. *IEEE Trans Geosci Remote Sens*, 43(10):2376-2385. https://doi.org/10.1109/TGRS.2005.856106

Ren S, Gong H, Zheng SY, 2025. Algorithm for 3D point cloud steganalysis based on composite operator feature enhancement. *Front Inform Technol Electron Eng*, 26(1):62-78. https://doi.org/10.1631/FITEE.2400360

Ruanaidh JJKO, Dowling WJ, Boland FM, 1996. Phase watermarking of digital images. Proc 3rd IEEE Int Conf on Image Processing, p.239-242. https://doi.org/10.1109/ICIP.1996.560428

Shi HC, Dong J, Wang W, et al., 2018. SSGAN: secure steganography based on generative adversarial networks. Proc 18th Pacific Rim Conf on Multimedia, p.534-544. https://doi.org/10.1007/978-3-319-77380-3_51

Shi WZ, Caballero J, Huszár F, et al., 2016. Real-time single image and video super-resolution using an efficient subpixel convolutional neural network. Proc IEEE Conf on Computer Vision and Pattern Recognition, p.1874-1883. https://doi.org/10.1109/CVPR.2016.207

Singh B, Sharma PK, Huddedar SA, et al., 2022. StegGAN: hiding image within image using conditional generative adversarial networks. *Multim Tools Appl*, 81(28):40511-40533. https://doi.org/10.1007/s11042-022-13172-9

Tamimi AA, Abdalla AM, Al-Allaf O, 2013. Hiding an image inside another image using variable-rate steganography. *Int J Adv Comput Sci Appl*, 4(10):18-21. https://doi.org/10.14569/IJACSA.2013.041004

Tancik M, Mildenhall B, Ng R, 2020. StegaStamp: invisible hyperlinks in physical photographs. Proc IEEE/CVF Conf on Computer Vision and Pattern Recognition, p.2117-2126. https://doi.org/10.1109/CVPR42600.2020.00219

ur Rehman A, Rahim R, Nadeem S, et al., 2018. End-to-end trained CNN encoder-decoder networks for image steganography. Proc Computer Vision-ECCV Workshops, p.723-729. https://doi.org/10.1007/978-3-030-11018-5_64

Van TP, Dinh TH, Thanh TM, 2019. Simultaneous convolutional neural network for highly efficient image steganography. Proc 19th Int Symp on Communications and Information Technologies, p.410-415. https://doi.org/10.1109/ISCIT.2019.8905216

Wengrowski E, Dana K, 2019. Light field messaging with deep photographic steganography. Proc IEEE/CVF Conf on Computer Vision and Pattern Recognition, p.1515-1524. https://doi.org/10.1109/CVPR.2019.00161

Wu P, Yang Y, Li XQ, 2018. StegNet: mega image steganography capacity with deep convolutional network. *Fut Int*, 10(6):54. https://doi.org/10.3390/fi10060054

Xu GS, Wu HZ, Shi YQ, 2016. Structural design of convolutional neural networks for steganalysis. *IEEE Signal Process Lett*, 23(5):708-712. https://doi.org/10.1109/LSP.2016.2548421

Xu YM, Mou C, Hu YJ, et al., 2022. Robust invertible image steganography. Proc IEEE/CVF Conf on Computer Vision and Pattern Recognition, p.7875-7884. https://doi.org/10.1109/CVPR52688.2022.00772

Yang H, Xu YT, Liu XH, et al., 2024. PRIS: practical robust invertible network for image steganography. *Eng Appl Artif Intell*, 133:108419. https://doi.org/10.1016/j.engappai.2024.108419

Ye J, Ni JQ, Yi Y, 2017. Deep learning hierarchical representations for image steganalysis. *IEEE Trans Inform Forens Secur*, 12(11):2545-2557. https://doi.org/10.1109/TIFS.2017.2710946

Ying QC, Zhou H, Zeng XH, et al., 2022. Hiding images into images with real-world robustness. Proc IEEE Int Conf on Image Processing, p.111-115. https://doi.org/10.1109/ICIP46576.2022.9897931

Yu C, 2020. Attention based data hiding with generative adversarial networks. Proc AAAI Conf on Artificial Intelligence, p.1120-1128. https://doi.org/10.1609/aaai.v34i01.5463

Zamir SW, Arora A, Khan S, et al., 2022. Restormer: efficient transformer for high-resolution image restoration. Proc IEEE/CVF Conf on Computer Vision and Pattern Recognition, p.5728-5739. https://doi.org/10.1109/CVPR52688.2022.00564

Zhang L, Lu Y, Li J, et al., 2023. Deep adaptive hiding network for image hiding using attentive frequency extraction and gradual depth extraction. *Neur Comput Appl*, 35(15):10909-10927. https://doi.org/10.1007/s00521-023-08274-w

Zhang R, Dong SQ, Liu JY, 2019. Invisible steganography via generative adversarial networks. *Multim Tools Appl*, 78(7):8559-8575. https://doi.org/10.1007/s11042-018-6951-z

Zhang R, Zhu F, Liu JY, et al., 2020. Depth-wise separable convolutions and multi-level pooling for an efficient spatial CNN-based steganalysis. *IEEE Trans Inform Forens Secur*, 15:1138-1150. https://doi.org/10.1109/TIFS.2019.2936913

Zhou DQ, Hou QB, Chen YP, et al., 2020. Rethinking bottleneck structure for efficient mobile network design. Proc 16$^{\text{th}}$ European Conf on Computer Vision, p.680-697. https://doi.org/10.1007/978-3-030-58580-8_40