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Coverless Information Hiding Using Machine Learning: A Next-Generation Approach to Secure Communication

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ABSTRACT

Traditional steganographic techniques embed secret information into a cover medium such as an image, audio, or video, which inevitably introduces distortions and makes the hidden data vulnerable to steganalysis. To address this limitation, **coverless information hiding** has emerged as a novel approach that avoids modifying the cover object, thereby significantly enhancing security and imperceptibility. This paper explores the application of **machine learning (ML) techniques** in coverless information hiding, leveraging their capability for feature extraction, pattern recognition, and content generation. By mapping secret messages to pre-existing media features or generating synthetic covers using deep generative models, such as Generative Adversarial Networks (GANs) and Convolutional Neural Networks (CNNs), the proposed method ensures zero embedding distortion and improved resistance against detection. We review existing ML-driven frameworks for coverless information hiding, analyze their performance in terms of security, robustness, and payload capacity, and discuss potential applications in secure communication and digital watermarking. Furthermore, this work identifies key challenges such as database dependency, computational complexity, and vulnerability to adversarial attacks, providing insights into future research directions for developing more scalable and intelligent coverless hiding systems.

Keywords: Steganography, coverless image steganography, information hiding, information security.

1. INTRODUCTION

The exponential growth of digital communication in recent decades has raised significant concerns regarding data privacy and information security. Traditional methods of securing data, such as encryption, protect content during transmission but still expose the presence of a secret message,

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making them vulnerable to interception and cryptanalysis. To enhance security and conceal the very existence of confidential information, steganography has emerged as a critical technology. Conventional steganographic techniques embed secret messages into digital media—such as images, audio, or video—by slightly altering the cover object. However, these modifications, even when imperceptible to the human eye, often leave detectable statistical artifacts that can be exploited by advanced steganalysis tools, particularly those based on machine learning.

To overcome these limitations, **Coverless Information Hiding (CIH)** has been proposed as a novel paradigm that completely eliminates the need for embedding. Instead of modifying the original cover, CIH techniques map the secret information to pre-existing media elements or generate new media using intelligent models, thereby achieving zero embedding distortion. This approach not only enhances the imperceptibility of hidden communication but also significantly increases security by minimizing the attack surface for detection.

The integration of **Machine Learning (ML)** into CIH systems has further advanced the field by enabling efficient feature extraction, content matching, and media generation. Shallow learning methods, such as clustering and image hashing, initially facilitated message-to-media mapping. However, the advent of deep learning has introduced powerful tools such as Convolutional Neural Networks (CNNs) for high-level feature extraction and Generative Adversarial Networks (GANs) for producing realistic images aligned with secret message features. These models allow for semantic understanding of media content, enabling more robust and flexible mapping strategies while maintaining the visual integrity of the cover.

ML-based CIH techniques generally follow two main approaches: (1) **Database Retrieval**, where large image datasets are indexed using feature descriptors and secret messages are encoded as a sequence of image indexes; and (2) **Generative Modeling**, where neural networks synthesize media on demand based on the secret information. Both methods ensure zero modification of the original cover, making the hidden communication virtually undetectable by current steganalysis algorithms.

Despite these advancements, several challenges remain in the practical deployment of ML-based CIH systems. These include the requirement of large-scale and stable databases, significant computational resources for deep model training, and resilience against adversarial attacks targeting machine learning models. Moreover, the trade-off between payload capacity and communication efficiency continues to be a critical research issue.

This paper explores the state-of-the-art ML-driven techniques for coverless information hiding, evaluates their strengths and weaknesses, and identifies future research directions to build more secure, scalable, and adaptive CIH systems.

Traditionally, steganography for images involves hiding messages within images. The traditional process of concealment is carried out by hiding the message inside the graphics, that is, inside the image, for example, in a way that is not visible to the human eye. This results in unauthorized persons being unable to obtain the hidden message. This process can be implemented by following one of two methods, which are either spatial masking or frequency masking, and both methods are subject to masking. The traditional method: The first method is characterized by changing the pixels of the image

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for the purpose of inserting the hidden message. This is achieved by changing the color pixel values or spatial arrangement. On the other hand, manipulating high frequencies is another method [1]. The second method of traditional concealment, as mentioned previously, is a change in the frequency of the image for the purpose of hiding the secret message through a change in the values of the contrast or brightness of the image. It is possible to benefit from this technique to protect secret communications by including the message in the images, after which the image that is hidden is sent. It contains the secret message, and thus messages are transmitted without worrying about being exposed to eavesdropping, or for the purpose of protecting copyright and printing, that is, to protect intellectual property, which leads to preventing some malicious parties from unauthorized copying and re-publishing [2]. Another method used in the concealment process is the use of a watermark, which is used as a secret addition to images. It is implemented using a single identifier that is integrated into the images for the purpose of easy tracking. It is considered one of the traditional methods for hiding messages inside images or texts. Messages hidden within images can be discovered through special analysis techniques. By hiding information, therefore, these methods must be used with caution because they are vulnerable to detection, which has led to a recent reduction in the use of these traditional methods [3]. For the purpose of thwarting the process of analyzing information hidden inside images, we use steganography coverless. This approach relies on generative models, which enable us to hide the secret message inside the carrier, and thus there is no change in the carrier. Therefore, the ability to hide a greater amount of information has been enhanced in a secure manner from attacks. Many works based on generative models provide different techniques to hide information without being detected. Liu et al. Providing a technique that creates a hidden image by replacing secret information with the name Generative Adversarial Networks class [4] . Duan and Song provide a technique that transmits data without encoding any information by using generative models to create visually identical pictures to the secret image [5]. In order to greatly increase the hidden capacity, Cao et al. offer a technique that directly generates anime characters based on attribute labels using generative adversarial networks [6]. n a another study, Duan et al. increase security and capacity by creating visually comparable pictures to the secret image using an enhanced Wasserstein GAN model [7].

2. BACKGROUND

Significantadvancementshavebeenmadeinthecreationofgenerativemodelsinrecentyears.Many fields,includingcomputervisionandnaturallanguageprocessing,areveryinterestedingenerativemodels. Generativemodelsareveryusefulforhidinginformation,whichistheactofenclosingprivateinformation behind a cover object. In particular, a coverless technique to information hiding with generative models is presentedinthisstudy.Coverlesssteganographyreferstoatechniqueusedtohidemessageswithoutusing acover,suchasimages.Unliketraditionaltechniques,inwhichthecoverisanimportantelement,withthis technique, there is no need for that cover [8]. Recently, with the emergence of generative models, the security of not discovering hidden secret information has increased through a new approach called concealment without cover, meaning this technique works to identify specific locations for secret information and is crammed instead of using traditional methods, which is concealment with cover [9], as ithasbeenwidelyused,suchasimagesandmultimedia.Withthedevelopmentoftechnologyindatasharing aswellascloudcomputing,steganographymethodsbasedongenerativemodelshavebecomecharacterized by high rates of concealment compared to traditional methods and an increase in security, which is considered the most important characteristic of this approach, which leads to resistance to

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steganography analysistoolsbecausetheydonotusecover[10].Thisapproachrequiresstoringandprocessingdata,which has become possible due to the rapid development of this technology.

3. STEGANGRAPHY

Steganography is oneof themethods used to maintain theconfidentiality ofdata, eitherby making it hidden from view, which is called steganography, or encoding it in a way that is difficult to read, which is called encryption. In both cases, we are able to transfer and share that information only between the people concerned with it. It can be implemented using traditional methods or modern methods such as generativemodels.Itispossibletoembedandextractprivateinformationfrommediausingsteganography. Steganography's objective is to prevent suspicion from being raised about the transmission of a secret message[11].Thebasictenetofthissystemisthatthestego-object(i.e.,theobjectcarryingsecretsignals) mustbeperceptuallyindistinguishabletotheextentthatsuspicionisnotaroused.Steganalysismakesuse of the fact that hiding information in digital media alters the carrier's characteristics and distorts the informationasimages(i.e.,theimagesthatdon'tcontainanyhiddenmessages).Thefoundationforlocating the secret message is steganography [12]. An asteganalysis system is created to detect hidden data by examining the various aspects of stego-images and covering a collection of techniques for embedding informationusingmultimediadata,includingimages,text,audio,video,etc.[13].Imagesteganographyhas sparkedalotofattentionsincepeopleuseimagessofrequentlyandbecausetheyareoneofthemostpopular forms of media [14].

3.1. IMAGESTEGANOGRAPHY

Imagesteganographyisamethodforcommunicationthatinvolvesconcealinginformationinanimage[15]. Secretmessageinsertioncouldbeusedtoconcealdatabyencodingitforeachbitintheimageorprimarily inserting it as a message in the noisy parts that reflect places with less observation, such as those where there is a lot of natural color variation. Additionally, because covert data cover, images have grown to be the may disperse randomly throughout an entire most frequent Steganography cover objects. The present research's subsequent sections will therefore concentrate on concealing information in images [16].

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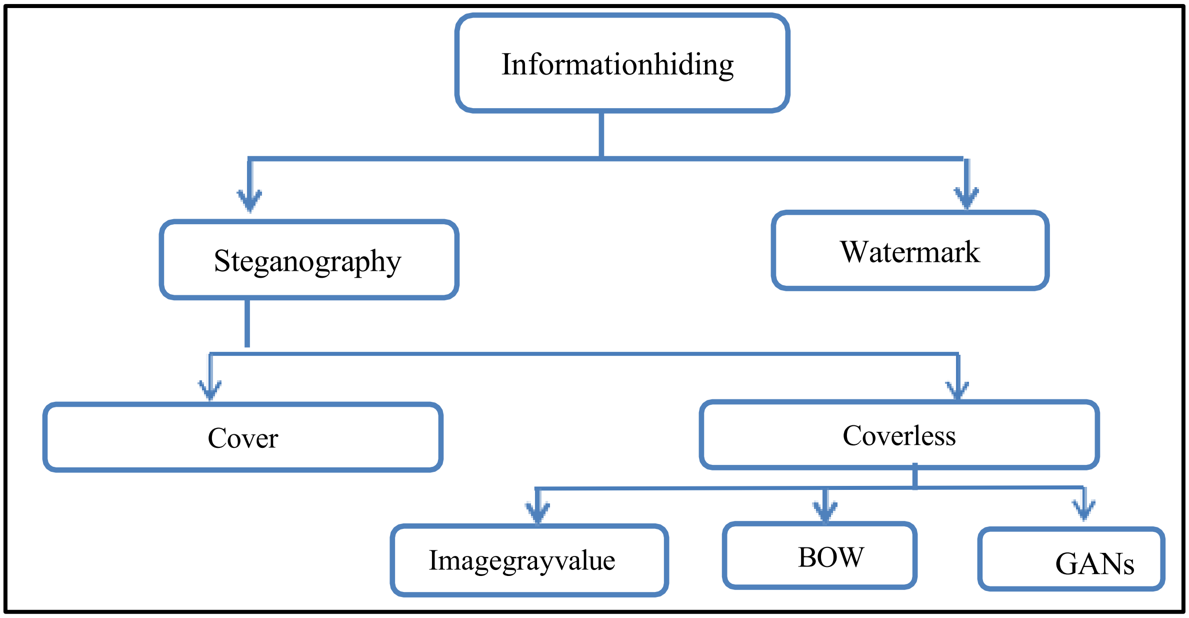

Fig.1. ClassificationOfInformationhidingtechniques

3.2. TRADITIONALIMAGESTEGANOGRAPHY

Traditional image steganography involves embedding secret information within an image without altering its visual appearance, thus allowing for covert communication or concealment of sensitive data. This technique utilizes the principle of imperceptibility, ensuring that the embedded information remains undetectabletothehumaneye.Theblockdiagramofthegeneraltraditionalimagesteganographyisshown inFigure(2).Theapproachthatisfrequentlyemployedinthisprocedureentailsdirectlyencodingthesecret dataintothecarriers.Theterm"secretdata"referstoinformationwherethesender'smessageswerekept private) [17]. The image that is used to communicate the secret message is referred to as the cover image. When images are used for the purpose of concealment, these images are called stego images, in which we canincludethesecretinformationintheseimagesandthecovertogether,ortheyarecreatedfromthesame images. This is on the sending side, but on the receiving side of hidden images, the secret information is extracted through devices that use special decryption algorithms for coding. [18].

3.2.1. LEASTSIGNIFICANTBIT (LSB)

LSB steganography Previously, this technology was one of the most widespread techniques for hidingsecretinformationinsideimages.Theprincipleofitsoperationistousetheleastimportantbitinthe image pixel values and replace it with the bits of the secret message, so that the secret information is not revealed, and the eye cannot perceive it directly inside the image. It has two methods of application, depending on the field. In the spatial or frequency domain, one of the spatial or frequency

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transforms is used, and then the values of the least important bits in the image are manipulated in order to include the secretmessage.Therearemanytransforms,includingwavelets,etc. [19]. TheLSBtechniqueisoneofthe techniques that is easy to implement and clear to use because it only changes the least significant bit and provides good storage capabilities compared to other transformation techniques. LSB information hiding has limited capabilities in the direction of statistical analysis attacks because it works to analyze and examine whether there is hidden information or not [20].

4. COVERIMAGE STEGANOGRAPHY

Cover Image Steganography is a technique used to hide secret information (text, image, audio, or video) inside a digital image called the cover image. The result is known as the stego image, which looks visually similar to the original cover image to prevent detection. Unlike encryption, which only scrambles data, steganography hides the very existence of the message.

Hidingthroughcoverisoneofthewaystohidesecretdatainsidedigitalimageswithoutthehuman eye being able to perceive that secret data because that data will be merged with the pixels of the cover image, so the cover image will be observed as if it were the original image. Due to the great diversity of digitalmediaandthegreatrepetitionoftheseimages,therehasbeenawidespreaddemandforhidingimages inallfields,suchascombatingcrimesandthemilitaryfield,aswellaselectroniccommercialtransactions, and electronic development has contributed to the development of this technology [21]. One of the most important benefits of hiding secret photos is the ability to transfer confidential data without detection by unauthorizedpersons.Thisfeatureisimportantforthesecurityofgovernments,inadditiontothepossibility of hiding them in the cover photo and not revealing that identity in communications, for example, during voting processes, for the purpose of not revealing their identities [22].

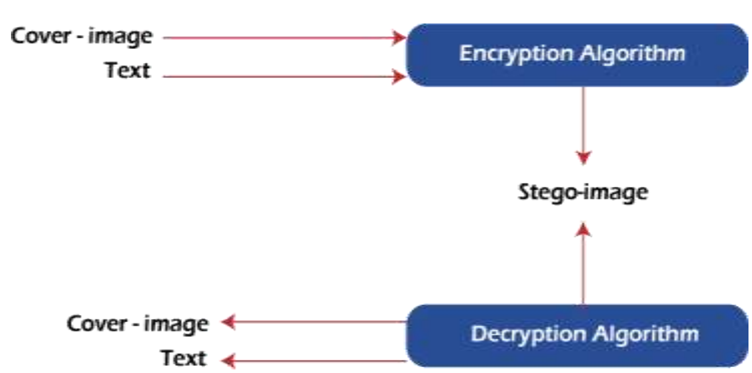

Fig.2. TraditionalImageSteganography[23]

5. COVERLESSIMAGESTEGANOGRAPHY(CIS)

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In the digital age, the exponential growth of information exchange has amplified the need for secure communication methods. Traditional security techniques such as encryption, while effective at protecting data content, fail to hide the existence of confidential communication, making encrypted data vulnerable to interception and cryptanalysis. Steganography addresses this limitation by concealing secret information within a cover medium—commonly an image—such that the hidden communication remains imperceptible to unintended observers. However, conventional image steganography techniques rely on modifying the cover image, even if only slightly, to embed the secret data. These alterations, though often invisible to the human eye, introduce statistical anomalies that can be detected by advanced steganalysis tools, especially those leveraging machine learning.

To overcome the inherent vulnerabilities of modification-based methods, **Coverless Image Steganography (CIS)** has emerged as an innovative solution. Unlike traditional steganography, CIS completely eliminates the process of embedding secret information into a cover object. Instead, it achieves secrecy by representing or conveying the message using unaltered images from a pre-constructed database or through on-demand image generation using intelligent models. This approach ensures **zero modification**, thereby making the detection of hidden communication by steganalysis extremely difficult, if not impossible.

CIS techniques are broadly classified into two categories: **image retrieval-based** and **generative model-based** approaches. Retrieval-based methods encode the secret message as a sequence of indexes corresponding to pre-existing images in a database. These images are then transmitted as cover images without any alteration. In contrast, generative approaches leverage advanced deep learning models such as **Convolutional Neural Networks (CNNs)** and **Generative Adversarial Networks (GANs)** to create new images that are semantically or statistically correlated with the secret message. With the advent of powerful models like GANs, Variational Autoencoders (VAEs), and Diffusion Models, CIS has seen significant improvements in image realism, scalability, and security.

The primary advantage of CIS lies in its undetectability. Since no modification occurs in the transmitted image, statistical and ML-based steganalysis methods designed to detect pixel-level alterations fail to identify the hidden communication. However, the approach is not without challenges. CIS methods often require **large image databases**, **efficient indexing strategies**, or **complex generative models**, which introduce issues related to scalability, storage, computational cost, and resistance to adversarial attacks.

Coverlesssteganography isanimagesteganographyframeworkforhidingsecretdatabysearching foracceptableimagesthatcontainthesedata.Theseimagesareconsideredstego-images.Whilethecarrier isstillutilizedincoverlessimagesteganography,itisnotaltered.Thehiddeninformationisrepresentedby itsownattributes,includingpixelbrightnessvalue,color,texture,edge,contour,andhigh-levelsemantics. The carrier is passed without going through the standard steganography method's construction of the camouflage carrier (the secret information) [24]. In terms of resistance to well-known attacks, including brightness change, rescaling, JPEG compression, and contrast enhancement, enhancing the privacy of information'ssecurityoftheCISframeworkoutperformsearliersteganographytechniques.Duetothefact

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thatitisinvisibleandcannotberead,theCIShasalotofdevelopmentpotential.Thefundamentalconcept ofcoverlessimagesteganographyistoexaminethecarrier'squalitiesandmapthemtothesecretinformation in accordance with predetermined rules based on the attributes' properties. The secret information can be directly represented by the carrier in this way. The stego cover is directly generated or acquired using the secret information. Despite the fact that an image just consists of pixels, the information they hold is very different.Theimagecanexpressmorethantheimageitself,whichisnotavailableinthetext,accordingto previous research on the subject [25].

5.1 Three Challenges Faces CIS:

A. Capacity

Itisthefirstparameterthatreflectsthemostinformationthatcanbeeffectivelyburiedandretrieved. Compared with watermarks, which only need little embedding of copyright information, since steganography is used for communication transmission, high embedding capacity is necessary [26]. Capacity,sometimesexpressedinbitsperpixel,referstothetypicalnumberofbitshiddenwithineachpixel ofthecoverimage.Thenumberofhiddenmessagesthatcanbesentthroughthemediumincreaseswiththe number of bits that can be hidden in the cover image.

B. Robustness

The second parameter evaluates the extent to which steganography technology resists attempts to remove or change hidden information, because when a hidden image is communicated through trusted systems, an active observer can see the image and change it in an attempt to eliminate any hidden information [27].

C. Security

Tohideinformationbecausethetechnologymustbeabletowithstandsteganographyanalysistools [28]. Steganography is considered secure if the precision value of the classifier is a random guess,making itdifficultforanattackertodecryptthesecretmessagefromtheshellmedium,andsecuritydependsonthe secret key and knowledge of the algorithm [29].

6. METHODSOFINFORMATIONHIDINGTHATISBASEDONDEEP LEARNING

Information can be hidden through unsupervised deep learning via auto encoders, where a neural networkequippedwithautoencodersisusedforthepurposeofencryptinganddecryptingtherequireddata. Theautoencoderpartisresponsibleforthe inputdataforthepurposeofrepresentingitinanencodedform containing important information about the original data. The decoding part undertakes the task of reconstructing the original information before encrypting it. By using this method of data hiding, it has becomepossibletoextracthiddeninformationandcombineitwithvariousotherinformationcarriers,such as images, a framework for a coverless image information steganography strategy based on generative modelswasfirstpresentedinthemethodin.Thehiddenimageofthegenerativemodeldatabaseisusedto generateregular,independentimageswithasetofassociations.Theproducedimageisthendeliveredtothe

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recipient and entered into the model database to produce a second image identical to the secret image. The parameters and data set are the same for the sender and receiver. Sending the typical standard image, unrelatedtothesecretimage,toachievethesameresultassendingthesecretimage[30].Anothertechnique forhidingusinggraphs,wherethesecretmessageisincludedinthedesignofthegraphandisimplemented by convolutional neural networks [31]. An autoencoder is a type of artificial neural network used to learn efficient encodings for unlabeled data and is a very useful tool for network embedding. The encoding is validated and refined by attempting to reconstruct the input from the encoding. Autoencoder is an unsupervised learning method [32]. Using autoencoders is one of the methods used to reduce noise for learning text embeddings. It learns the representation (encoding) of effective data by training the neural network to ignore the noise signal [33]. Generative Adversarial Networks are another deep learning-based technique for hiding information. Discriminative and Generative Neural Network play a game-theoretic framework. The Generator aims to generate realistic data samples, while the Discriminator aims to distinguish between real and generated data. By taking advantage of autoencoders within generative adversarial networks, scientists were able to generate realistic data in addition to making a clear meaning of that data through these networks. Therefore, generative adversarial networks became an important field in hiding secret data coverless [34]. This article provides a brief, high-level overview of coverless information hiding and offerssolutions to typical challenges, such as theneed forseparatedcoversamples and real-world applicability. The advent of deep learning (DL) based models has shown an encouraging performancewithtypicalmeta-problems,suchassteganography,security,capacity,andmodelcomplexity, faced by traditional CIH methods. These have been corroborated by applications in real-world scenarios. So,thisnewkindofhiddencommunicationframeworkappearstobenotonlyofacademicinterestbutalso of practical importance. Methods for information hiding that are based on deep learning shown in table 1 below:

Table1.-TheCoverlessImageSteganographythatBasedonDeepLearning

Year	Author(s)	Technique / Model	Key Idea	Advantages	Limitations
2017	Zhou et al.	Hash-based CNN feature mapping	Use CNN features to map secret messages to pre-existing images in a database	No image modification; high security	Requires large image database
2018	Li et al.	GAN-based Image Generation	Use GANs to generate new images conditioned on secret data	Zero embedding distortion; realistic images	High computational cost; GAN instability
2019	Hu et al.	Deep Hashing + Semantic Retrieval	Convert messages into hash codes and retrieve semantically similar images from a database	Faster retrieval; scalable	Sensitive to hash collisions
2020	Luo et al.	VAE-GAN Hybrid Model	Variational Autoencoder + GAN for generating cover images based on hidden information	High quality image generation	Complex architecture; slow training
2021	Zhang et al.	Attention-based	Use attention mechanisms	Better image	Requires large training

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Year	Author(s)	Technique / Model	Key Idea	Advantages	Limitations
		GAN	to improve GAN-generated image quality and robustness	realism; robust to noise	datasets
2022	Liu et al.	Transformer-based Image Generation	Leverage Vision Transformers (ViT) for semantic feature extraction and cover image synthesis	State-of-the-art generation quality	High hardware requirements
2023	Chen et al.	Multi-modal GAN	Combine text and image features to improve semantic consistency in cover image generation	Supports text-image mapping for CIH	Increased complexity; limited datasets

CONCLUSION

Continuing progress in the development of traditional steganography analysis methods degrades the performance of public classified communications systems and makes them vulnerable to detection and hacking.Steganographyisthepracticeofhidingamessagewithinamedium,suchasadigitalimage,audio file, or other types of media. It serves as an important means of confidential communication with a wide range of applications. According to the range of applications, information hiding can be divided into communication security, copy restriction, fingerprint protection, ownership protection, and some other fields.Ontheonehand,theubiquityofthenetworkandtherapiddevelopmentofcomputercommunication makeinformationtransmissionmoreandmoreconvenientandvast,andtheyalsoletthecarriermediumof steganography have higher concealment. On the other hand, as a product and application of ideal mathematicaltechnology,especiallytheapplicationofdigitaltechnology,steganographyemerges accordingly. It is crucial to develop new methods to protect private digital content. Using neural network models to achieve coverless communication is a new concept of information security. The experimental results of the mentioned methods show that the coverless steganography system has good performance in the experimental environment in which the most intuitive and original features of steganography are described,andtheapplicationofsteganographyis analyzed.Theideaofcoverlesssteganographyistohide theedgesthatcarryinformationortoextractthebasicpropertiesoftheinformationandrepresentit.Inother words, although the image itself does not contain secret information, the behavior and nature of the algorithm used still contain the property of hiding information.

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