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Applications and prospects of artificial intelligence in covert satellite communication: a review

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Abstract Satellite communication has the characteristics of wide coverage and large communication capacity, and is not easily affected by land disasters. It is quite suitable as a supplement to terrestrial communication networks and has been widely used in education, navigation, emergency relief, military, etc. However, due to the openness of the channel of satellite communication systems, satellite communication signals are easily eavesdropped on by eavesdroppers. This greatly threatens the privacy and security of countries and individuals. Covert satellite communication can effectively improve the covertness of satellite communication systems and greatly reduce the probability of detection by eavesdroppers. So, it has attracted more and more attention. In addition, with the development of artificial intelligence (AI), AI has been applied in many technics of covert satellite communication, which has achieved higher reliability and stronger concealment in covert satellite communication systems. The research status of key technics in covert satellite communication is discussed in this study, and the applications of AI in covert satellite communication are shown. Finally, future research directions of covert satellite communication are looked forward to. In the future, covert satellite communication technology will be an indispensable part of satellite communication systems.

Keywords satellite communication, covert communication, secure communication, low probability of detection (LPD), artificial intelligence (AI), machine learning (ML)

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1 Introduction

In recent decades, the speed and range of communication are increasingly required [1, 2]. Satellite communication has many advantages, such as wide coverage and large communication capacity, and it is not easily affected by land disasters. Compared with the terrestrial communication network, the satellite network has stronger stability and security, so it is quite suitable as a supplement to terrestrial communication networks. Satellite communication has been widely used in education, navigation, emergency relief, military, etc. However, due to the openness of the channel, the security of satellite communication systems is seriously threatened [3, 4]. The signal of satellite communication systems can be received by any equipment covered by the satellite beam which is a huge threat to both personal privacy and national privacy [5]. What's more, the receiver will also sustain interferences, which may reduce the performance of satellite communication systems. Covert satellite communication is a technology that is able to improve the covertness and security of satellite communication. It can reduce the possibility of communication signals being discovered while ensuring communication reliability. In sum, the development of covert satellite communication technology is crucial to the security of satellite communication systems. The scenario of covert satellite communication described above is shown in Figure 1. Covert users convey information to ground stations through satellites, and eavesdroppers are also under the coverage of satellite beams or are close to the covert users. At the same time, covert users are also faced with unintentional or malicious interference. So, covert users need to take some methods to make the

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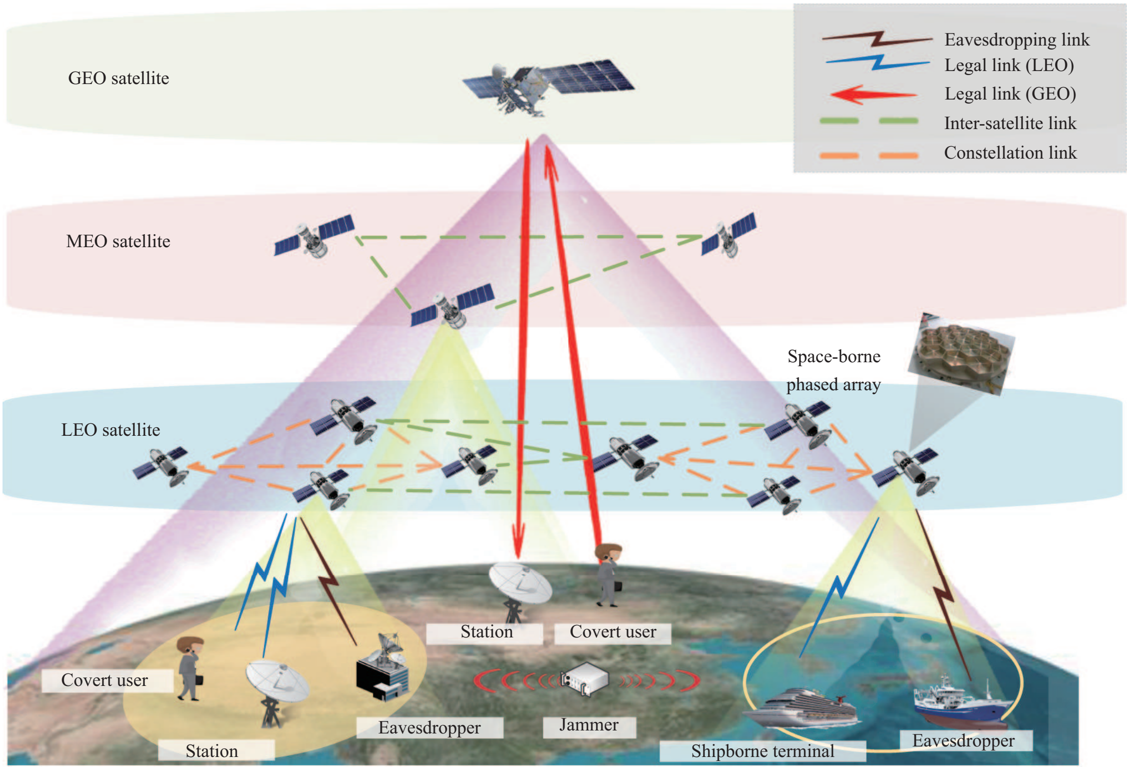

Figure 1 (Color online) The scenario of covert satellite communication.

signal evade the detection of eavesdroppers, and ensure the reliability and security of the communication at the same time.

The research on covert communication technology started in the 20th century [6]. In the beginning, researchers mainly used short-frame burst communication [7] and spread spectrum (SS) [8] to improve the covertness of communication. The SS technology mainly includes direct sequence spread spectrum (DSSS) [9, 10] and frequency hopping spread spectrum (FHSS) [11]. It is a kind of signal structuring method by which a signal can be generated with a much wider bandwidth than the original information. This abuse of spectrum resources can be rewarded with both the lower power density in the frequency domain and noise-like waveform in the time domain, thus significantly improving the covertness of the communication system [12]. Later, the satellite overlap communication was proposed based on DSSS technology. In this way, the DSSS signal is added to the general user signal of the satellite to share the same channel [13, 14]. Because of the low probability of detection (LPD) of the DSSS signal, overlapping communication will not affect the performance of the general user signal. This method not only enhances the covertness of the DSSS signal but also effectively improves the utilization of spectrum resources [15].

However, with the development of communication reconnaissance technology, a large number of methods have been proposed to effectively detect and estimate the key parameters of periodic short code DSSS signal [16]. These parameters include carrier frequency, spread rate, spread code period, bit rate and modulation mode [17, 18]. Therefore, the DSSS technology cannot meet the current requirements of satellite communication for covertness performance. In order to carry out the research on covert communication more scientifically, Wyner [19] proposed the classic prisoner communication model of covert communication in 1975. The model consists of Alice, Bob, and Willie. For successful covert communication, Alice needs to successfully send the message to Bob without Willie detecting the communication behavior. Based on this model, a set of LPD theories had been developed [20], which realized theoretical analysis of the performance of covert communication systems.

Obviously, according to the LPD theory, both reliability and covertness are indispensable in the covert satellite communication system, which are the two we are most concerned about. The methods to improve the performance of covert satellite communication systems are discussed from the aspect of technical application.

First of all, from the process of transmitting, propagating, and receiving, the methods to improve the performance of covert satellite communication are considered.

The direct way to improve the covertness of communication is to reduce the transmission power and let the eavesdropper cannot detect the signal. However, too low transmit power may lead to a too low signal-to-noise ratio (SNR) and reduce the performance of modulation. So, how to control transmit power [21] is a key technique in covert satellite communication.

In the propagation process of covert satellite communication signals, the large dynamic characteristics between the satellite and the ground [22], especially in the low earth orbit (LEO) satellite communication system, make it difficult for the satellite antenna to target the terrestrial user. When the angle error of the antenna is too large, the user signal will fall in the sidelobe of the antenna beam. So, the transmit power must be increased to ensure the SNR of the receiver is big enough for modulation, which will result in reducing the covertness and introducing unnecessary interference in the space. In order to solve this problem, the phased array antenna technique [23, 24] is applied, which can flexibly adjust the direction diagram of the antenna by controlling the weighted value of radiation elements in the array antenna. By using the phased array antenna technique, the angle error of the antenna is greatly decreased and the reliability and concealment of covert satellite communication systems are effectively improved.

In general, the effective signal power is awfully low at the receiver of covert satellite communication systems. What's more, because of the openness of the covert satellite communication channel, the effective signal received by the receiver will be superimposed on by the intentional and unintentional interference in the surrounding environment. This will make the receiver work under a low signal-to-interference ratio. Although SS techniques that are mostly used in covert satellite communication have certain anti-interference capabilities, too much interference will still have a serious impact on the performance of covert satellite communication systems [25]. Therefore, the anti-interference technique which can reduce the effect of interference is necessary to improve the reliability of covert satellite communication systems.

In the above, the key techniques of covert satellite communication are discussed from the process of signal propagation. Next, we will discuss the key techniques of the covert satellite communication system itself.

Most of the time, the channel state information (CSI) of the covert satellite communication changes rapidly. For different CSI, researchers hope to choose a proper communication system that can improve the effective communication rate as much as possible on the premise of ensuring concealment. Spectrum prediction and adaptive modulation and coding (AMC) can help us achieve this destination. Spectrum prediction [26] can effectively predict the future spectrum occupation, and then guide the transmitter to adjust the frequency and bandwidth in real time. In this way, the surrounding spectrum environment will be effectively used to maximize the covertness. After the CSI is confirmed, AMC will be applied to determine which coding algorithm and modulation mode to choose in time, so that the performance of the covert satellite communication system can be optimized.

It can be seen from the above discussion that LPD communication, transmit power control, phased array antenna, anti-interference, spectrum prediction, and AMC are effective means to improve the performance of covert satellite communication. Figure 2 shows where these key techniques are employed in a typical covert satellite communication system, in which the satellite is used as the relay.

Many achievements of artificial intelligence (AI) have been made in recent years. AI includes machine learning (ML) [27], deep learning (DL) [28], reinforcement learning (RL) [29], etc., and has been widely applied in electrical engineering, communication engineering [30, 31], software engineering, biological engineering, medical engineering [32], and financial fields. AI is usually used to complete tasks such as clustering, classification, optimization, and regression [33]. Therefore, many researchers apply AI to solve some complex problems in their field [34]. The field of communication has received many successful applications based on AI. Wang et al. [35] reviewed the achievements of ML algorithms in wireless networks in the past decades. Du et al. [36] introduced and surveyed some state-of-the-art techniques based on AI/ML and their applications in 6G. AI has also made great progress in the key techniques in covert satellite communication. We are going to introduce the six key technologies including LPD communication, transmit power control, phased array antenna, anti-interference, and spectrum prediction in detail, at the same time the application of AI technology in them will be shown.

In recent years, some studies related to this paper have been published. Fourati et al. [37] proposed some limitations of satellite communications and discussed their proposed and potential AI-based solutions, and the application of AI showed great results in a wide variety of satellite communication aspects. Yue et al. [5] summarized the unique security vulnerabilities of LEO satellite communication systems, including the issues of passive and active eavesdropping attacks, interference scenarios, single event upsets, and

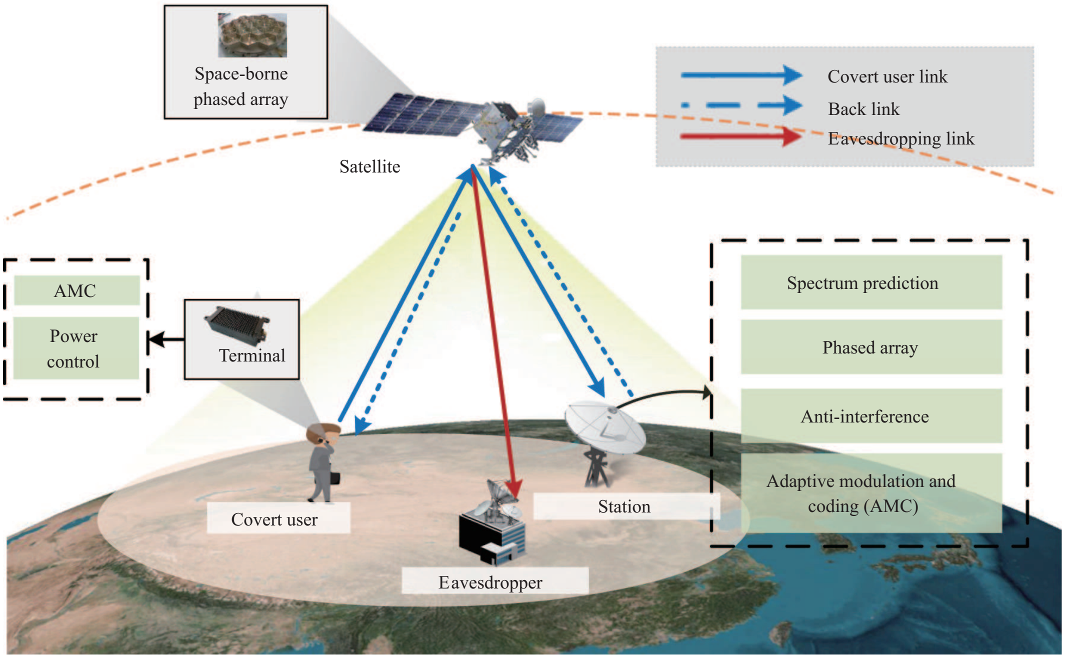

Figure 2 (Color online) Application of key technologies in covert satellite communication.

space debris. And they discussed the corresponding active and passive security countermeasures. Wang et al. [3] presented a comprehensive overview of the protected satellite communication systems, and they investigated and compared the critical technologies used in the protected satellite communication systems. In the research of covert communication theory, Yan et al. [20] reviewed the related research on LPD communication, and discussed the optimal signaling strategies for transmitting the message-carrying signal and artificial noise signal for LPD communication from an information-theoretic point of view. However, these articles are only reviews of satellite security communication, and there is a paucity of literature on a detailed summary of AI applications in covert satellite communication. In order to fill this knowledge gap, this study summarizes covert satellite communication from seven key technical points, introduces the application of AI technology, and finally looks forward to the future development trend.

The rest of this paper is organized as follows. Section 1 introduces the background and key techniques of covert satellite communication systems, and gives an overview of the development of AI. Section 2 talks about some AI techniques used in covert satellite communication. Section 3 discusses six key techniques including LPD communication, transmit power control, phased array antenna, anti-interference, spectrum prediction, and AMC, and introduces their development statuses based on AI. Section 4 looks forward to the future development of AI in covert satellite communication. Section 5 summarizes the full text. The acronyms used in this paper can be found in Table A1.

2 Related artificial intelligence methods

AI was first proposed at the Dartmouth Institute in 1956. It is the technology that presents human intelligence through ordinary computer programs. This technology aims to make machines smarter by following some rules or by facilitating guided learning. With the development of computer science, the theoretical methods of AI are gradually enriched. Researchers are beginning to apply AI methods to various fields [1, 38, 39]. Four AI methods will be introduced: convolutional neural network (CNN), long short-term memory (LSTM), Q-learning, and generative adversarial network (GAN). These are four classical AI techniques, and their research has obtained rich achievements and wide applications.

2.1 Convolutional neural network

CNN is a kind of feedforward neural network with convolution calculation and deep structure, and it is one of the representative algorithms of DL. The structure of CNN is also divided into the input layer, hidden

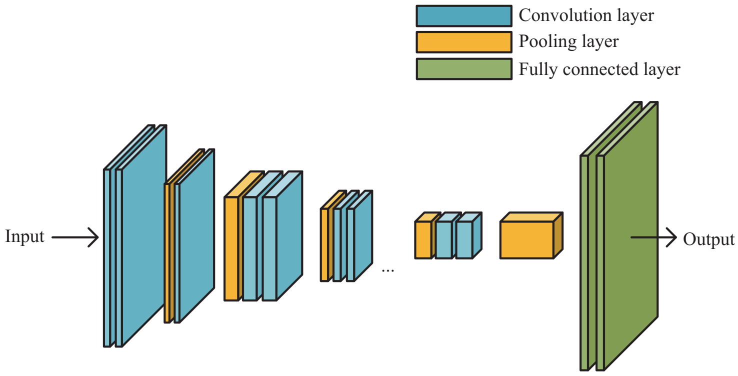

Figure 3 (Color online) The structure diagram of CNN.

layer, and output layer, which is the same as other DL networks. The convolutional layer, pooling layer, and fully connected layer are included commonly in the hidden layer according to different algorithms, while the convolutional layer and pooling layer are unique to CNN. Its structure diagram is shown in Figure 3. In addition to the differences in the structure of each layer itself, with the development of modern algorithms, people have invented complex network structures such as the inception block, the residual block, the dense block, and the attention mechanism. The structures are used to solve various problems encountered by deep CNN models.

The good local connectivity of the CNN algorithm can extract local features of objects and effectively retain useful information. And the feature of weight sharing greatly reduces the number of parameters and thus reduces the difficulty of training. More and more researchers have combined the CNN algorithm with satellite communication technology in recent years. For example, CNN is used to identify and classify interference in satellite communication scenarios [40, 41], or to extract and separate effective signals from interference [42]. Automatically identify the modulation format in terms of satellite modulation technology so that the receiver can perform adaptive demodulation [43, 44]. And also the construction and synthesis of phased array antennas for satellite communication transmitting equipment [45], the prediction of the future spectrum in communication environments [46], the control of the transmit power strategy in power control to maximize spectral efficiency (SE) [47, 48] and so on. There will also be more in-depth research directions and broader application fields in the field of satellite covert communication.

2.2 Long short term memory

A recurrent neural network (RNN) is an algorithm used to process sequential data. Compared to a normal neural network, it can process changing data. However, RNN can only memorize short time-series data. As the number of data and the time interval increase, RNN will lose the important information previously input, causing the gradient to disappear and leading to the failure of the prediction model [49].

LSTM is a special RNN proposed by Hochreiter et al. [50] in 1997. LSTM network is suitable for processing and predicting important events with relatively long intervals and delays in time series. Compared with ordinary RNN, LSTM can perform better in longer sequences. Therefore, LSTM can solve the problems of gradient disappearance and gradient explosion in the long sequence training process of the RNN algorithm. The LSTM network processes the input time series by transferring the transfer function, and Figure 4 shows the structure of a memory cell in the LSTM network. LSTM has three gates in one cell, which are called input gate, forget gate, and output gate, respectively. The input gate determines whether the hidden layer information is updated. The forget gate determines whether the updated information contains information from the previous moment. The output gate determines which part of the updated information to output. When a message enters the LSTM network, it can be determined whether it is useful or not according to the rules. Only the information conforming to algorithm authentication will be left behind, and the inconsistent information will be forgotten through the oblivion gate.

In recent years, LSTM has been widely applied in the field of satellite communication. Gunn et al. [51] used the LSTM algorithm to predict errors in satellite communication monitoring, and the results show that this method has better performance than the simple threshold model. Lee et al. [52] applied LSTM to the synchronization of frequency-hopping signals in a tactical satellite communication system. The

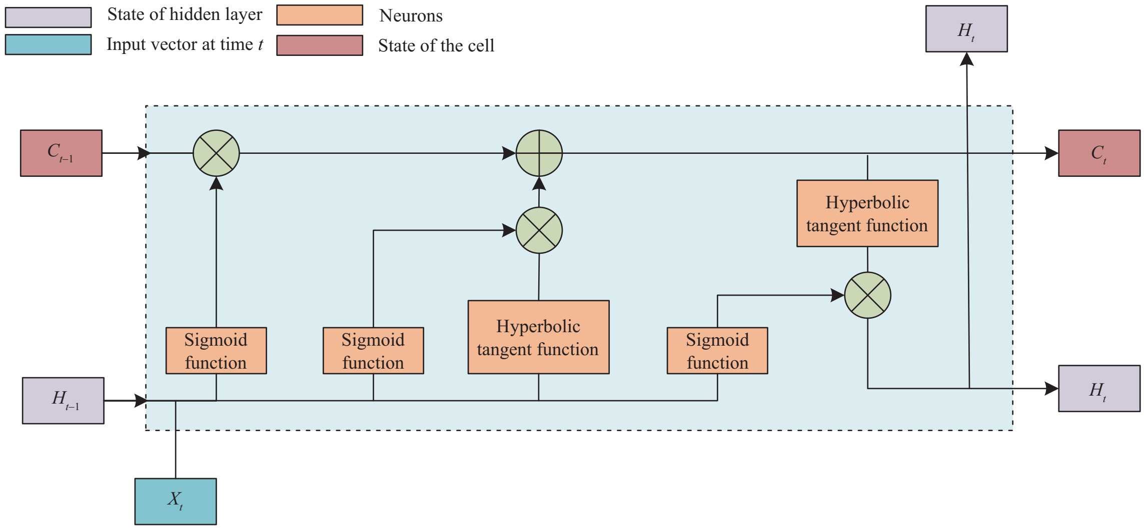

Figure 4 (Color online) The structure of the memory cell.

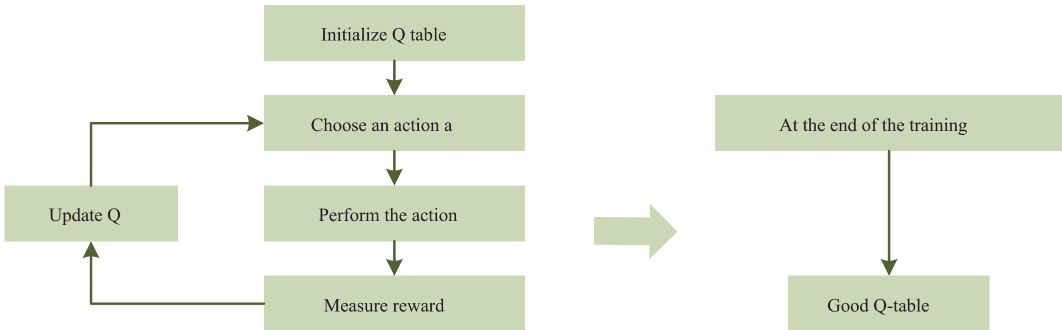

Figure 5 (Color online) The flow chart of Q-learning.

LSTM network is used to learn the trend of energy signals for fine acquisition. With the development of covert satellite communication, some scholars have combined the LSTM network with covert satellite communication technology and achieved a lot of research results [53–56].

2.3 Q-learning

RL describes the process by which an agent interacts with the environment. Maximize the returns or achieve specific goals through certain learning strategies. Q-learning is a value-based algorithm in RL algorithms, which is a decision-making process. Q is Q(s, a), which is the expectation of the reward that the action a can obtain at a certain moment in the state. The environment will feedback corresponding rewards according to the actions of the agent. So the main idea of the algorithm is to build state and action into a Q-table. Each row of the Q-table represents each state, each column represents each action, and the Q value (Quality) is stored in the middle. According to the Q value, the action that can obtain the maximum benefit will be selected. The algorithm continuously updates the Q value during the process and the flow chart of this algorithm is shown in Figure 5.

Q-learning uses the time difference method, and integrates Monte Carlo and dynamic programming. It has the ability to perform off-policy learning and the optimal strategy for the Markov process can be solved by the bellman equation. It is a typical model-independent algorithm that can perform operations without establishing an environment model, making it highly versatile. And it is not limited to episode tasks, requiring fewer parameters. Any task that can build a Q-table can use the Q-learning method for modeling, which makes Q-learning widely used in various strategies and games.

Tsuchida et al. [57] applied Q-learning to the problem of power distribution in satellite-ground communication of LEO satellites, and the results show that the proposed method can prolong the battery life of LEO satellites. To solve the high handoff dropping probability caused by the long transmission delay of satellite links, Xiong et al. [58] proposed a novel handoff decision strategy based on the predictive

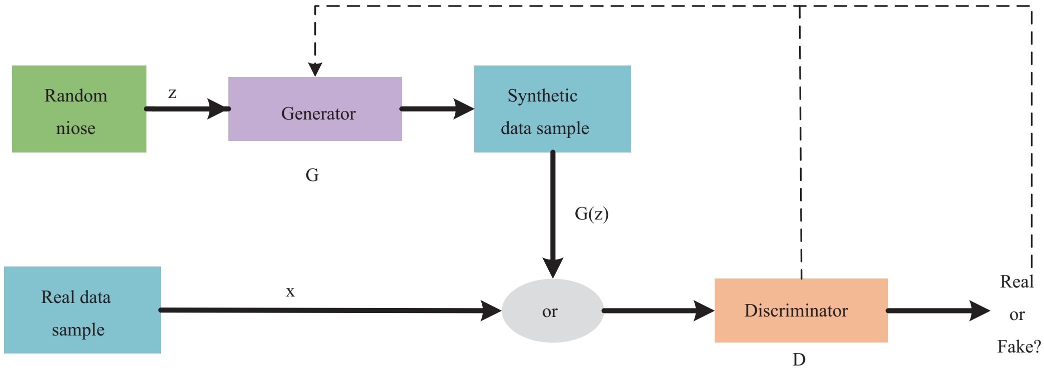

Figure 6 (Color online) The basic model structure of GAN.

received signal strength (RSS) and Q-learning algorithm. In covert satellite communication technology, Q-learning also plays an important role in some aspects. For example, the problem of channel selection in the complex environment of satellite communication systems [59], the optimal game problem between the interferer and the interfered [60, 61], etc., effectively reduce the interference in space impact on effective communication. Or under the needs of complex communication networks, use Q-learning to achieve optimal real-time power allocation [62]. It can be seen that the combination of RL up to Q-learning and satellite communication has great research potential.

2.4 Generative adversarial network

ML can be divided into supervised learning and unsupervised learning. Although supervised learning has achieved good performance, it needs to rely on known labeled data, and the algorithm cost is high. In order to reduce the cost of learning, unsupervised learning has received more and more attention, and generative models are one of the most promising techniques [63]. Early generative models, such as restricted Boltzmann machines, deep belief networks, and deep Boltzmann machines, have poor performance in generalization. In response to this problem, in 2014, Goodfellow et al. [64] introduced the concept of GAN. By 2016, researchers began to discover the great potential of GAN, and GAN broke through the bottleneck that previously limited the development of DL [65].

The ultimate goal of GAN is to understand the appearance of real data, estimate the distribution or density of real data, and finally generate new data based on the learned knowledge. GAN is inspired by the two-person zero-sum game in game theory, in which the sum of the interests of both parties is 0 or remains the same, so one party gains while the other party must lose. In this way, the two neural networks are constantly learning and optimizing in the process of playing against each other, and finally, the optimal model will be achieved.

The basic model structure of GAN is shown in Figure 6. It mainly consists of two important parts, that is, the discriminator D and the generator G. Among them, the generator takes random noise as input and learns the distribution of real samples, so as to be able to generate sample data close to the real. The discriminator takes real data or the generated data of the generator as input and tries to determine whether the input data is real data or generated data. These two parts iteratively optimize their performance through continuous adversarial training. When the data generated by the generator G are as close to the real data as possible and the probability of the discriminator's output is close to 1/2 each time, the GAN reaches the Nash equilibrium.

GAN has many advantages. It can learn the true distribution of samples and achieve strong predictive ability according to the distribution of samples. Moreover, GAN is very robust in generating samples, which is unattainable in many ML models. The most direct application of GAN is data modeling, which generates samples that are consistent with the real data distribution, and it is widely used in image generation, image classification, target detection, etc. [66]. Due to the powerful prediction generation ability of GAN, it has also received extensive attention in the field of covert satellite communication. Guan et al. [67] proposed a satellite downlink signal detection method based on GAN. Davaslioglu et al. [68] and Lin et al. [69] used GANs to enhance sparse historical data for more stable and robust spectral predictions. Liao et al. [70] proposed a GAN-based power allocation algorithm to solve the power allocation problem of a cooperative cognitive covert communication system.

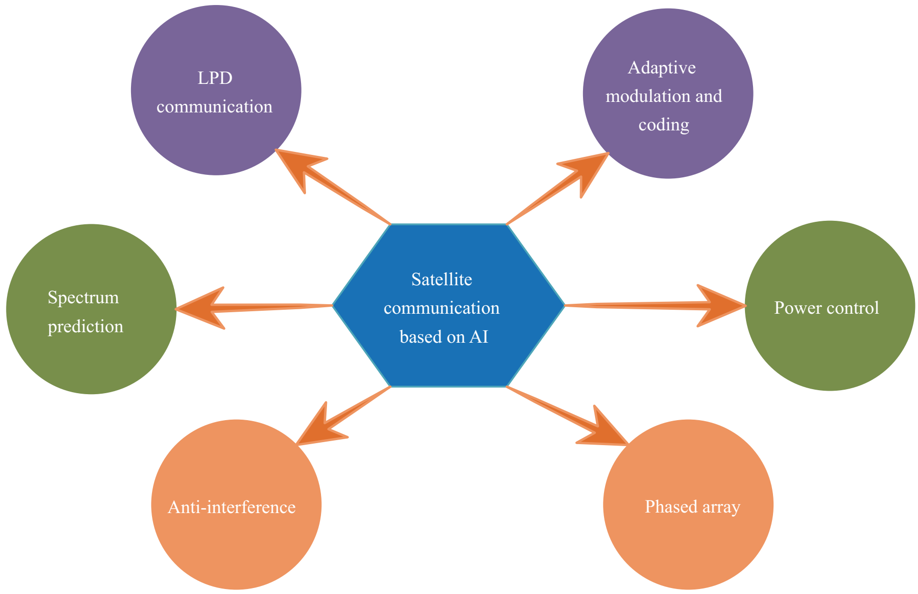

Figure 7 (Color online) Key techniques for covert satellite communication based on AI.

3 Applications of AI in covert satellite communication

In this section, the applications of AI in six key techniques for covert satellite communication are discussed, including LPD communication, transmit power control, phased array antenna, anti-interference, spectrum prediction, and adaptive modulation and coding. Figure 7 shows these six key techniques in covert satellite communication. Next, they will be discussed separately.

3.1 Low probability of detection communication

3.1.1 *Definition & limitations*

Because of the openness of the wireless communication system, the transmitted information is easy to be intercepted or attacked maliciously. Therefore, information security has always been the hotspot of research in wireless communication. LPD communication is a technique that ensures wireless security at the physical layer through covert signals. It can greatly reduce the detection of communication signals by the eavesdropper and achieve the purpose of concealing signals by coding, modulating, designing waveform, and other methods [71].

Figure 8 describes the scenario of a covert satellite communication system, which consists of a satellite, covert users, stations, and eavesdroppers. Covert satellite communication is expected to reduce the probability of communication being detected by the eavesdropper on the premise of ensuring the stable transmission of information between the station and the covert user. Especially in some military communication scenarios, communication signals are extremely undesirable to be detected by the enemy. So higher requirements for information security are put forward. LPD technique can fundamentally solve the malicious behavior of signals, so the study of LPD has become an important technical support for the realization of covert satellite communication. The problems and solutions of LPD communication are described as follows.

The basic model of the LPD problem is shown in Figure 9. This classic prisoner communication model was first proposed by Wyner in 1975 [19], which consists of three basic components: Alice (the signal sender), Bob (the legal receiver), and Willie (the illegal monitor). Prisoner Alice needs to transmit critical information to Bob. And in the meantime, their communication process cannot be detected by Willie. Willie does not need to pay attention to the contents of communication, but only to whether communication occurs. Therefore, the goal of LPD is to ensure the reliable transmission of information between two users while ensuring that the probability of the information being detected by the monitoring party is low enough [20].

Traditional LPD communication mainly relies on SS communication technologies, including DSSS [72] and FHSS [73–77]. The schematic diagrams of the two techniques are shown in Figure 10. SS communi-

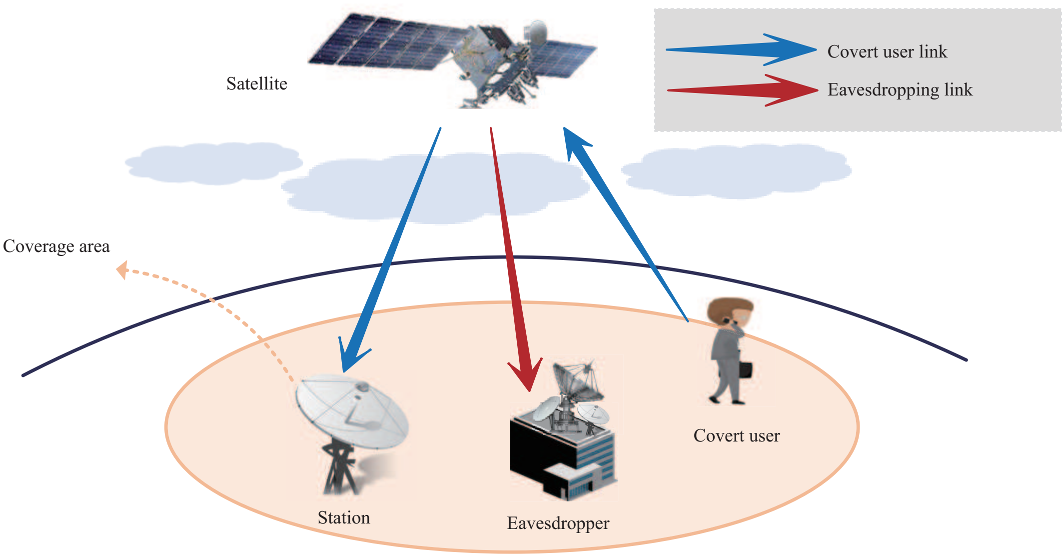

Figure 8 (Color online) LPD satellite communication model.

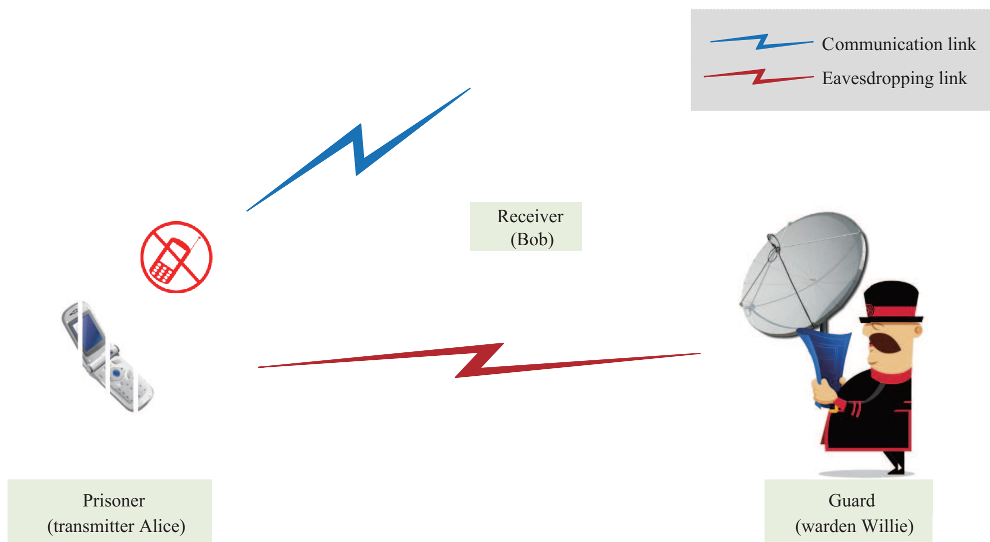

Figure 9 (Color online) The basic model of the LPD communication.

cation keeps the signal power unchanged and reduces the signal power spectrum density to below noise by expanding the signal spectrum bandwidth, so that it cannot be noticed. Therefore, SS communication can realize covert communication in a low SNR environment. However, the SS technique is mostly used in engineering practice, and there is no theoretical limit on the system capacity of this method. Therefore, the security performance of SS communication cannot be quantified. With the development of wireless techniques, many detection methods for SS communication have been proposed [78, 79]. The current research on LPD mainly focuses on LPD information theory, implementation methods, constant rate covert communication, and so on.

3.1.2 *Main challenges and solutions*

The information theory of LPD communication has achieved a lot of progress. In 2013, Bash et al. [80] studied LPD communication from the perspective of information theory and proposed the concept of covert communication. The results showed that the communication capabilities that can be reliably transmitted over an additive white Gaussian noise (AWGN) channel are limited by the square root law (SRL) for LPD communication. SRL says that covert communication can transmit $O\sqrt{n}$ bits information for blocks of length N. The communication rate decreases with the increase of the code length,

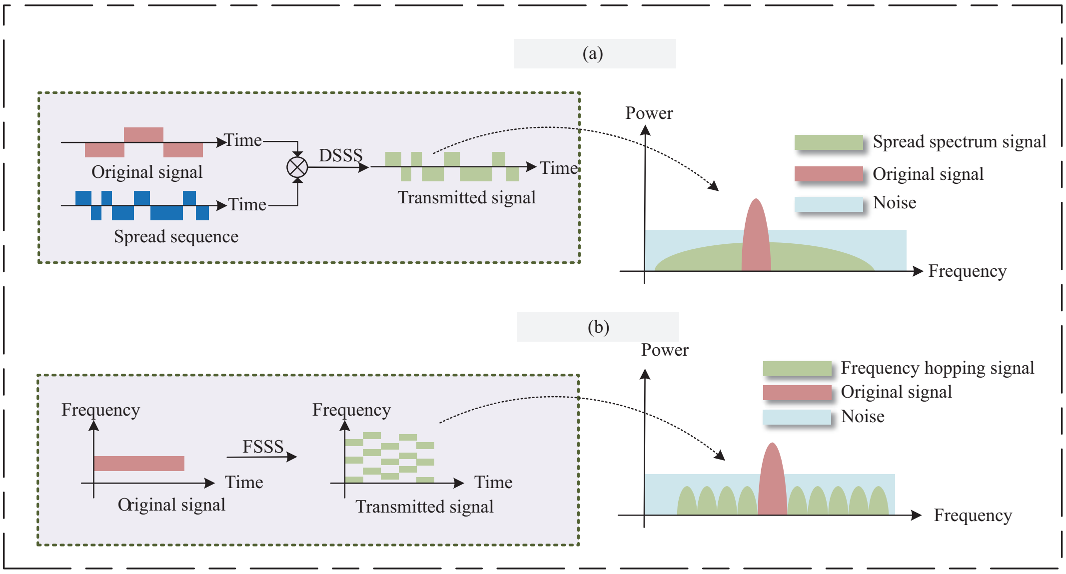

Figure 10 (Color online) Spread spectrum techniques. (a) DSSS; (b) FHSS.

and the traditional Shannon capacity tends to zero when the transmission code length tends to be infinite. Subsequent studies showed that SRL is suitable for LPD problems of various channels. Abdelaziz et al. [81] proved that SRL is suitable for the MIMO Gaussian channel and the number of bits that can be transmitted covertly has an exponential relationship with the number of transmitting antennas. Wang et al. [82] considered the LPD problem over a discrete memoryless channel (DMC), and gave the maximum information and block length that can be transmitted under SRL conditions. Tahmasbi et al. [83] clarified how the choice of imperceptibility measure affects the information theory constraints of covert communication over DMC. Bloch [84] developed an encoding scheme for a binary symmetric channel (BSC) based on the principle of channel resolvability. Che et al. [85] proved that if the legal channel environment is superior to the monitoring channel, the effect of covert communication can be achieved even if both parties communicate by using public codes instead of common keys, which is also a communication model based on BSC.

Based on the support of theoretical research, a lot of research has been made on the implementation of the LPD technique. Bloch et al. [86] used a random m-element external code and an m-order pulse position modulation (PPM) internal code cascade, which implements the information-theoretical limits of covert communication. Kadampot et al. [87] proposed a combination of PPM and multi-level coding, which is a low-complexity coding scheme. Li et al. [88] made a joint optimization of the modulation order L and transmitted power P of PPM in covert communication. Yan et al. [20] studied AWGN channel covert communication with short delay constraints and proved that effective throughput of the system can be improved if all available channels were utilized by transmitters.

A lot of research achievements have also been achieved in the constant rate of covert communication. This method makes use of the uncertainty of the communication system or human interference to produce detection errors, which reduces the monitoring ability of the monitor but does not affect the legitimate communication performance too much.

There are many uncertainty factors in communication systems, such as noise uncertainty, communication transmission time uncertainty, and channel uncertainty. Considering the communication with noise uncertainty distribution, He et al. [89] proposed the maximum realizable communication rates under bounded or unbounded noise uncertainty models. Ta et al. [90] analyzed the combined effects of channel uncertainty and noise uncertainty on the average detection error probability and throughput of the monitor. It is proved that channel fading is very important for covert communication. Bash et al. [91] proposed that constant rate covert communication can be achieved by selecting a random time slot communication known by both communicators and unknown to the monitor, but a sufficient number of alternative time slots are required.

Some scholars considered adding artificial noise to the original LPD communication model. This approach weakens the administrator's ability to detect traffic by confusing eavesdroppers. Sobers et al. [92, 93] proposed that the LPD communication model consists of transmitters, receivers, and friendly jammers, and the jammers produce artificial noise. The jamming activity is independent of the legitimate communication process so the monitor cannot detect the transmission by listening to the jammer. Shahzad et al. [94] studied the duplex wireless communication system in fading channel, which generated artificial noise of different powers, resulting in the uncertainty of the statistical data of the received signal by the monitor. At the same time, the best choices of power range of artificial noise and the best transmission probability of covert information were given. Yang et al. [95] achieved covert communication by using a full-duplex multi-antenna receiver with random transmit power, and they demonstrated that increasing the number of antennas increases the ability to perform covert communications. He et al. [96] studied the effects of density and transmit power of concurrent interference sources on covert throughput. It is proved that when the interference is small enough and is equivalent to the receiver noise, the throughput of the system increases with the increase of the density and transmission power of the concurrent interference source.

3.1.3 *AI-based solutions*

With the advent of AI, some researchers began to consider applying ML to LPD communication scenarios. Yang et al. [97] constructed a burst communication model with low intercept probability based on conditional maximum entropy. In this model, hybrid chaotic particle swarm optimization (HCPSO) is used to optimize the objective function to obtain the conditional maximum entropy model, which makes the covert communication performance better. Shakeel [98] proposed using ML to generate synchronized featureless signals, which has better LPD performance than the DSSS system. Zhou et al. [99] proposed a low probability of intercept (LPI) communication system based on ML, which has low interception accuracy. The combination of ML and LPI/LPD communication is a very novel direction. Few research achievements have been made so far, and we expect there will be more important progress in the future.

3.2 Transmit power control

3.2.1 *Definition & limitations*

Transmit power control refers to the technology that timely adjusts the transmit power of the transmitter according to the functional requirements of the communication system. In a communication system, if the transmit power is too low, the receiver cannot demodulate correctly, which will reduce the system performance. On the contrary, if the transmit power is too high, it will waste the power and spectrum resources of the system, and may cause interference to other communication devices in the same network [100, 101]. It can be seen that power control is extremely important for the performance improvement of communication systems, and this technique has been widely used in mobile communication networks [102–104], Internet of Things (IoT) [105], and satellite communications [106].

In covert satellite communication, if the warden (Willie) tries to identify the presence of effective communication by standard methods (such as energy detection in each spectrum band), we have a motivation to reduce the transmit power in each band to the minimum value, to hide the behavior of communication [107]. As known from the noisy channel coding theorem [108], even at extremely low signal-to-noise ratios, a reliable communication channel can be established at the expense of reducing the transmission rate to be lower than the channel capacity. Reasonable control of the transmit power can not only enhance the throughput and robustness of the covert satellite communication but also reduce the probability of detection of the warden. In sum, transmit power control is crucial for improving the reliability and covertness of covert satellite communication.

3.2.2 *Main challenges and solutions*

At present, the research on transmit power control in satellite communication can be divided into the following three categories.

One is to maximize the rate or throughput of the network by allocating and controlling the power of each node in the network [106, 109, 110]. Zou et al. [109] studied the optimization of power control in cognitive satellite-terrestrial networks under hybrid interweave-underlay to maximize network throughput. Based on the cognitive model of CSMA/CA (carrier sense multiple access with collision avoid), the strong interference of secondary users to primary users is limited from the two dimensions of space and time. In order to ensure the communication QoS of terrestrial primary users who have both delay-sensitive and delay-insensitive communication service requirements, Gao et al. [110] proposed a satellite uplink power control algorithm based on the alternating direction method of multipliers (ADMM). Wang et al. [106] studied a distributed spectrum access and power control scheme based on ML for multi-beam satellites in a non-cooperative game cognitive mode to maximize the achievable rate of the communication network.

The second category is to improve the robustness of the network under non-ideal conditions such as large dynamics, interference, and jammer, to minimize the probability of interruption [111–113]. Vassaki et al. [111] modeled with the constraints of the quality of service (QoS) requirements of the terrestrial network and the interruption probability of satellite communication. Then, based on the constraints, they proposed an optimal power control scheme for the terrestrial network as a secondary user (SU). Considering the influence of inaccurate CSI estimation for satellite communication links and terrestrial interference links, Shi et al. [112] proposed a power control scheme that maximizes outage capacity. Based on the dynamic characteristics of LEO satellites, Hu et al. [113] proposed a mathematical model for satellite-to-earth cognitive scenarios based on LEO constellations and terrestrial networks. They proposed a power control scheme to maximize delay-limited capacity and minimize interruption probability.

The third category is to minimize the delay of the control network under the condition of long distance between satellites and the terrestrial user [114, 115]. Aiming at the problem of interference management in the terrestrial primary network, Shi et al. [114] proposed two power control schemes suitable for real-time communication scenarios. They adopted the average interference power constraint and the peak interference power constraint to maximize the system delay-limited capacity. To solve the problem of unsatisfactory spectrum sensing and the delay caused by the mobility between the satellite and the terrestrial user, Wang et al. [115] proposed a distributed joint resource optimization scheme, which minimizes end-to-end data transmission delay for the SU.

For the problem of transmit power control in covert communication systems, a lot of research has been done, and the main problem is to maximize the sum of the effective communication rates of the network under the constraints of covertness. Different from the traditional communication network, the goal of covert communication is not only to improve the communication performance but also to reduce the detection performance of the warden. So, the covert communication system is unique in resource optimization. Considering the communication over parallel Gaussian channels under an LPD constraint, Letzepis et al. [116] analyzed the optimal power allocation strategy that can maximize the achievable number of transmitted information bits per codeword under constraints on the receiver's decoding error probability and the adversary's detection probability. Dvorkind [107] considered the problem of spectral power allocation under the condition of ensuring that the warden's SNR is below a certain threshold. Forouzesh et al. [117] and Hu et al. [118] studied covert communication transmit power control in relay network scenarios. Zheng et al. [119] considered the multi-antenna and multi-jammer scenarios and determined the optimal detection threshold from the perspective of wardens. They obtained the maximum covert throughput by jointly optimizing the transmit power and transmission rate under this condition.

Recently, some scholars have studied the channel inversion power control (CIPC) technology, which can effectively improve the covertness of communication systems [105, 120–122]. Hu et al. [120] studied CIPC-based covert communication under Rayleigh fading. Specifically, the transmitter varies the power and phase of transmitted signals as per the channel to the receiver, such that the receiver can decode these signals without knowing the CSI. Then, they applied it to IoT [105]. Ma et al. [121] studied covert communication with finite blocklength under the CIPC scheme, which allows the transmitter to communicate with the receiver without transmitting a pilot signal and can improve the effective covert throughput. Wang et al. [122] proposed a scheme based on CIPC, which instructs public users as a random transmit power jammer to interfere with the warden's detection.

The classification of the above research on power control is shown in Figure 11.

3.2.3 *AI-based solutions*

With the development of DL, more and more people began to research applying the deep neural network (DNN) to optimize power control in wireless communication. According to the universal approximation theorem of DNN [123], any continuous function can be approximated by DNN. So, DNN tried to approximate the optimal transmit power control parameters that could not be reached before. What's more, it can also reduce the calculating time. Sun et al. [124] used DNN to approximate the near-optimal transmit power control of the weighted minimum mean square error (WMMSE), resulting in a reduction in computation time. Lee et al. [47] proposed the first CNN-based transmission power control framework,

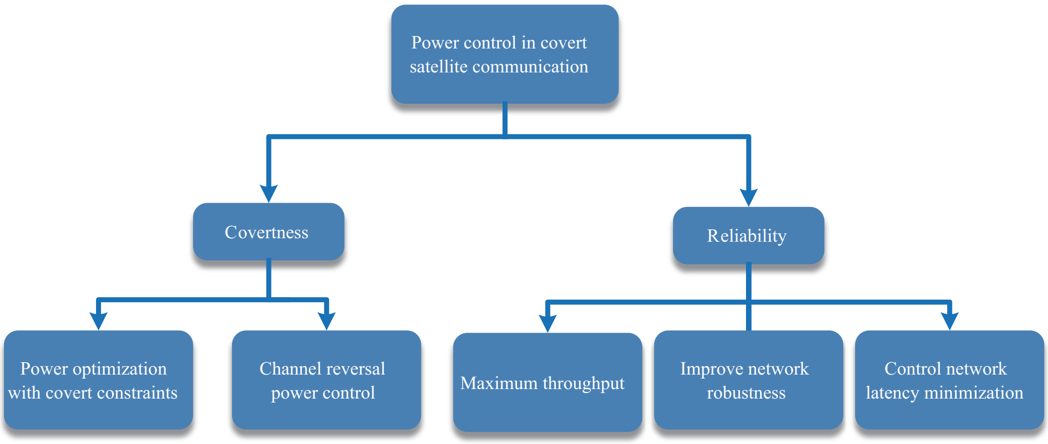

Figure 11 (Color online) Application classification of transmit power control technologies.

deep power control (DPC), in which the transmit power control strategy to maximize the SE or energy efficiency (EE) can be achieved through CNN learning. The proposed DPC form can achieve almost the same or even higher SE and EE compared with the traditional power control scheme, and a lower computation time is also achieved. Then they used DNN to design a multi-channel underlay cognitive radio network (CRN) power allocation scheme [125]. They also put QoS into constraints and proposed DNN-based transmit power control strategies [126, 127]. Lee et al. [48] used CNN to investigate the joint optimization of transmit power and time switching ratio. As a result, the EE of a wireless-powered network with co-channel interference was maximized.

Although DNN-based power control methods have been extensively studied, the above methods are almost all proposed under the assumption that the global CSI is well known. However, it is extremely difficult and unrealistic to obtain accurate global CSI in time in practice. In response to this problem, Lee et al. [128] proposed a distributed DNN-based underlay CRN transmit power control scheme. In this scheme, each SU can determine a near-optimal transmit power policy based only on its local CSI, and compared to centralized DNN-based schemes this one can greatly reduce operational overhead while maintaining high performance.

To meet the demands of more and more complex communication networks, deep reinforcement learning (DRL) began to be introduced into power control algorithms. Considering the practical scenarios where the system model is inaccurate and the CSI delay cannot be ignored, Nasir et al. [62] proposed a distributed dynamic power allocation scheme based on model-free DRL, which can achieve near-optimal real-time power allocation based on delayed CSI measurement data. To solve the high-dimensional problem in transmit power control, Zhang et al. [129] proposed a power control method by asynchronous advantage actor critic (A3C) based on RL and DNN, which achieved great performance in power efficiency and network convergence. For overcoming the difficulties caused by the random variation of the RSS collected by the sensor, Li et al. [130] used DRL to assist the transmit power control and ensure the QoS of users in the network. Tan et al. [131] developed a distributed DRL-based power allocation scheme in an overlay device-to-device network scenario, which achieves better scalability compared to FP-based schemes.

For AI-based methods to improve the covertness of communication systems, Liao et al. [70] studied the power allocation problem of a cooperative cognitive covert communication system with a relay station, and proposed a power allocation algorithm based on a GAN. This is the first time that GAN has been used as a transmit power control method to improve covertness. The current AI technology is mostly applied to the optimization of the maximum transmission rate and throughput of the communication network, and further research is needed to improve the covertness.

3.3 Phased array antenna

3.3.1 *Definition & limitations*

The phased array antenna has multiple radiating elements arranged and combined. By controlling the weighted value of the radiating elements in the array antenna, the direction of the maximum value of the pattern can be changed to achieve the purpose of beam scanning [132, 133].

In covert satellite communication, how to hide the communication process is very important. The most common method is to reduce the power of the transmitted signal so that the signal drowns in the noise. In order to improve the receiving reliability, it is necessary to design a receiver system with strong anti-interference ability. The phased array antenna can accomplish this task well. In current satellite communication systems, the high speed and complex motion of the ground terminal bring great difficulties to the efficient and stable communication of the system. Beamforming technology forms an ideal signal in the specified direction, improving the efficiency of spectrum utilization. Therefore, the phased array antenna system has automatic tracking technology and can realize fast acquisition through a smart antenna. It provides important technical support for the satellite communication system [134]. When the phased array antenna is transmitting, it can generate beams with high gain and low sidelobe level by its flexible beamforming technology, so that the satellite signal is not easy to be intercepted by the enemy. For the receiver, the zero point of the antenna pattern can be adaptively aligned with the direction of interference to ensure that the gain of the useful signal is almost unaffected. Therefore, the interference and error of the received signal are controlled to the minimum, so that the satellite transponder can still work normally in the interference environment [135].

3.3.2 *Main challenges and solutions*

A good antenna array arrangement is the basis of a phased array antenna system. In order to adapt to different satellite communication scenarios, the phased array has unique characteristics in hardware design. Kapusuz et al. [136] proposed a design scheme of an 8×8 phased array antenna for Ku-band mobile satellite communication. The array had the characteristics of low profile, high gain, and wide-angle scanning so that the satellite communication terminal would have a relatively compact size. Simulation results showed that the phased array antenna can scan 50 degrees in both axes without generating any grating lobes. Rao et al. [137] proposed a unique phased array concept of a planar array antenna, which can generate multiple independent beams to communicate with multiple geostationary satellites simultaneously. It has the capability of omnidirectional electronic beam scanning which can reduce the cost and complexity of phased array antennas. Zhang et al. [138] proposed an active phased array antenna (APAA) for Ka-band broadband mobile satellite communications. They discussed a highly integrated antenna module that combines the antenna, radio frequency (RF) circuitry, and cooling system. The results showed that the axial ratio of a single element is about 4 dB on the boresight, the cross-polarized lobe that appears is only 7 dB below the main beam level, and in the steering beam, the axial ratio is less than 2.0 dB.

In order to meet the requirements of signal transmission, the phased array antenna as a transmitting device needs to design a signal transmission algorithm and control beam configuration to cope with the rapid growth of satellite communication throughput. Kumar et al. [139] used the spherical phased array antenna for systems with small beam directivity changes. By combining different output amplifiers to accommodate information transmission at different data rates, there is enough equivalent isotropic radiated power (EIRP) to meet link requirements. Moon et al. [140] proposed a beamforming technology based on enhanced beam steering, which can support enhanced mode under any weather conditions to meet the high-power signal of communication. To achieve effective satellite tracking, Raj et al. [141] utilized a hexagonal 7×7 antenna array consisting of built-in phase shifters. A structured beam in the desired direction is obtained by eliminating the beam in the unwanted direction with rear lobe suppression.

The phase and amplitude imbalance of the radiation antenna elements is caused by the mode difference of the embedded elements, the gain and phase offset of the RF electronic devices, and the temperature change of the aperture. For the normal use of phased array antennas, most systems need to be calibrated during operation. Calibration can achieve accurate beam pointing and reduce the error of the hardware system. Lin et al. [142] proposed an online phased array antenna calibration method based on partial parallel interference cancellation multi-user detection, which would not interrupt normal communication. This method sends the modulation low power calibration signal and the normal communication signal at the same time, the existence of the calibration signal can maintain the reliability of the normal communication. The simulation results showed that the calibration accuracy of the calibration algorithm can achieve near-linear multiuser (LMU) calibration accuracy with low computational complexity. Ghaffarian et al. [143] used a planar near-field probe set up in an APAA environment for external calibration. They validated a phased array antenna consisting of 1024 radiating elements over a wide scan angle of

18–21 GHz (0°–70°).

3.3.3 *AI-based solutions*

With the rise of AI, research on the combination of AI and phased array antennas has also attracted widespread attention in the industry. For the three scenarios mentioned above, the addition of AI technology has led to technological innovation to a certain extent.

For the construction and synthesis of transmitting active phased array antennas, Mishchenko et al. [144] created an antenna algorithm that can combine multiple continuous stages. A neural network structure consisting of a classified neural network and several approximate neural networks is constructed to solve the structural synthesis problem of the transmitting active phased antenna array. Elbir et al. [45] proposed an antenna element selection method based on CNN to find the optimal subarray. This method does not need to compute analog and baseband beamformers, but only needs to feed the estimated channel matrix back to the network. Considering the time-varying of channel and user parameters during simulation, training the network with a large amount of training data (240000 input samples), and a noisy channel matrix, the classification accuracy quickly reached 100%.

For the design of the beamforming algorithm, Lovato et al. [145] combined AI with electromagnetics. Given the required two-dimensional radiation pattern, the neural network is used to calculate the phase of the antenna array in complex radiation mode. Simulation verified that it can accurately calculate the phase value of array beamforming. Fournier et al. [146] implemented a neural network-controlled beamforming network on field-programmable gate array (FPGA) to achieve a more flexible, faster, and more reliable control method. Hameed et al. [147] used the DNN algorithm to find the optimal solution for the energy beamforming vector in multi-antenna non-communication networks. Offline training can be more efficient and less complex. The simulation results proved that the DNN scheme has lower computational complexity and time complexity than the traditional sequential parametric convex approximation method.

For phased array antenna calibration, Sarayloo et al. [148] proposed a calibration method based on amplitude measurement and DL for phased array calibration. Under different SNR conditions, the phase calibration coefficients of each RF path of the phased array receiver are estimated by convolution and multilayer perceptron neural network. Thus, the errors affecting the phased array performance can be reduced with higher speed and accuracy. Southall et al. [149] proposed a neural network algorithm for digital beamforming in the case of uncalibrated antennas or poor performance due to unknown degradation. The proposed adaptive radial basis function artificial neural network (ANN) architecture can learn single-source direction finding functions for octa-element X-band arrays with multiple unknown failures and degradations.

3.4 Anti-interference

3.4.1 *Definition & limitations*

Interference signals can be roughly divided into man-made Interference and non-man-made Interference, both of which will reduce the communication quality to a certain extent. Man-made interference is divided into intentional and unintentional. Generally speaking, intentional interference is a malicious signal sent by attackers to jam with the communication process. Unintentional interference is intra-system interference or inter-system interference which is caused by insufficient system design or improper frequency management between systems [5].

The scattering of electromagnetic waves by the atmosphere, the reflection and refraction of electromagnetic waves by the ionosphere, the reflection of electromagnetic waves by surface objects such as mountains and buildings, and the influence of bad weather will all cause multipath propagation, resulting in signal attenuation and phase shift. Therefore, non-human interference mainly includes multi-path interference, atmospheric scintillation or fading, which are mostly caused by nature. The schematic diagram of interference classification is shown in Figure 12.

The covert satellite communication environment has a large dynamic change, and there are many interference factors, such as common multipath, intra-system interference, inter-system interference, and false signals emitted by some devices, etc. [150]. Generally, the covert satellite communication system has higher requirements on the reliability, accuracy, and security of the transmitted information, so the

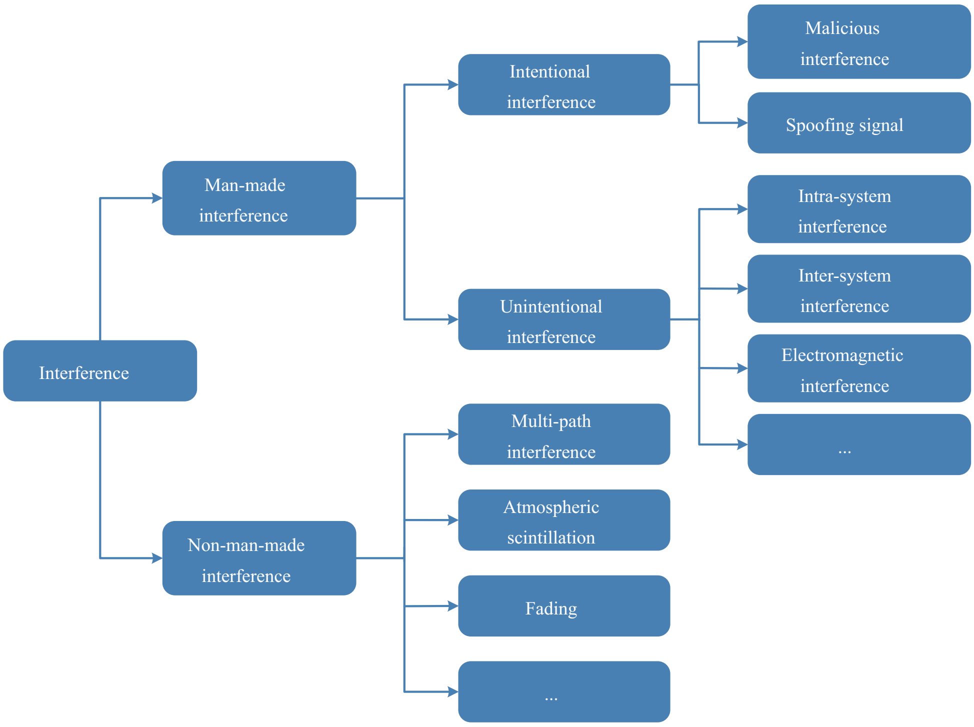

Figure 12 (Color online) The schematic diagram of interference classification.

system needs to have an excellent anti-interference performance to ensure the success of the covert satellite communication process. However, a considerable part of covert satellite communication systems is built on the background of the SS communication technique, which consumes frequency band resources in exchange for better anti-interference and anti-noise performance. Therefore, the spread-spectrum system has a certain capability to be immune from interference, as shown in Figure 13(a). But when the strength of the jamming source exceeds the anti-interference ability of the system, the system performance will be seriously degraded, and even lead to the paralysis of the system [151]. The existence of interference is unavoidable, so it is very necessary to adopt some technologies to protect the covert satellite communication system in the interference environment.

3.4.2 *Main challenges and solutions*

At present, for the detection and suppression of interference, there are many anti-interference processing technologies widely used in the scenario of covert satellite communication, which can be divided into the time domain, transform domain, time-frequency domain, time-space domain, and so on.

Among the time-domain methods, adaptive filtering techniques using finite impulse response (FIR) and infinite impulse response (IIR) filters are superior filtering methods to eliminate interference and have attracted extensive attention. Figure 13(b) vividly describes the signal-changing process under the time-domain adaptive filtering. An adaptive IIR notch filter requires considerably fewer filter coefficients compared with FIR for the same notch bandwidth while demonstrating quite similar performance to that of the FIR [151]. For continuous wave interference (CWI), Chien [152] and Lv et al. [151] used an adaptive notch filter (ANF) to estimate the power of the detected CWI by exploiting the statistics and internal states associated with the IIR filter and the CWI signal in the time domain was effectively detected and mitigated. Mao et al. [153] discussed the application of the adaptive all-pass-based notch filter (ANFA) in the improved adaptive Gauss-Newton (MAGN) algorithm for four kinds of continuous-wave interference signals. ANFA has a higher SNR and lowers residual interference level, which is superior to the traditional adaptive filter.

Among the transform domain methods, techniques used are usually based on the spectral estimation of the incident signal to track the rapidly changing interference. Figure 13(c) is a schematic diagram of the process of real-time interference elimination in the transform domain by using an adaptive threshold. Wang et al. [154] designed a partial coefficient update least mean square adaptive algorithm with local

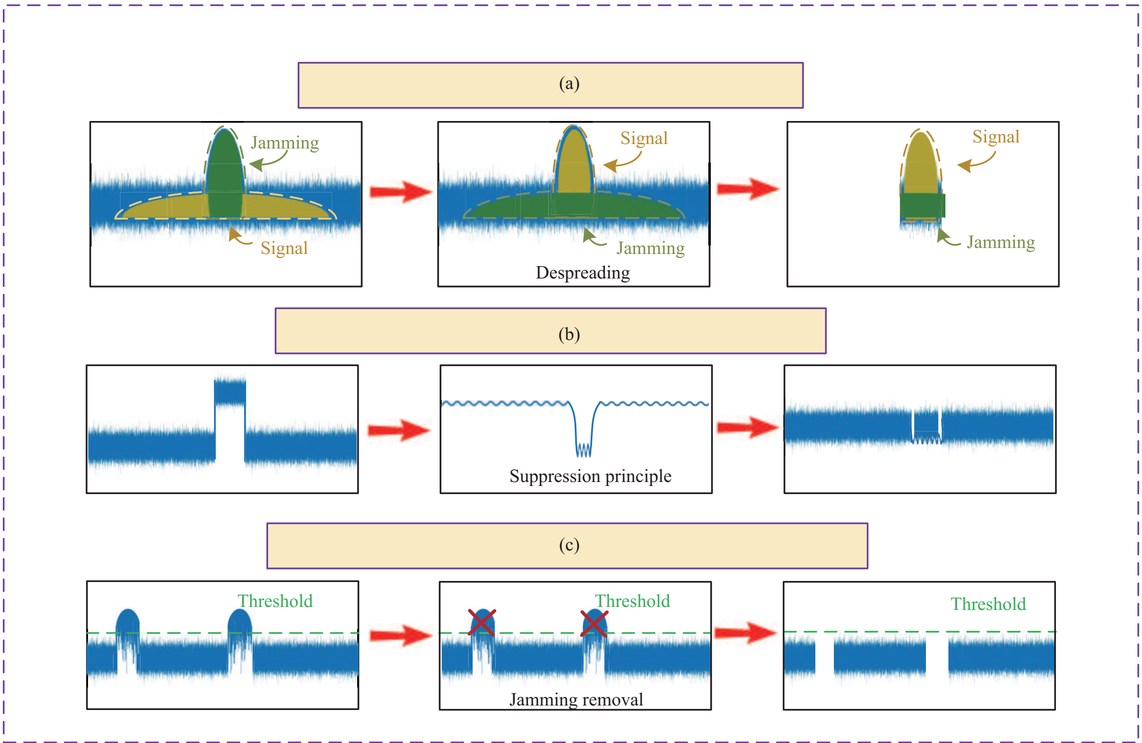

Figure 13 (Color online) Three ways for anti-jamming by filtering. (a) Spread spectrum receiver; (b) time-domain adaptive filtering; (c) frequency-domain adaptive filtering.

coefficients update to suppress narrowband interference, which could adaptively update N groups of interference blocks in the frequency domain. Zhang et al. [155] proposed an interference suppression method combining wavelet transform and frequency shift for the CWI signal that had a great influence on the satellite communication system. It could not only effectively suppress narrowband interference, but also reduce noise and reduce the time of a single stop of acquisition.

Time-frequency domain techniques allow people to observe received signals in a joint domain. Interfering signals are usually concentrated in a limited area of the two-dimensional time-frequency plane, while noise is distributed over the entire plane [150]. Djukanovic et al. [156] used local polynomial Fourier transform to eliminate single-component non-stationary interference. A binary mask was used to remove interference through a time-varying filtering process and modified the receiver to maximize the output SNR. Savasta et al. [150] used a synthesis technique based on orthogonal Gabor expansion. In this method, the interference signal in the time domain is recovered from the Gabor coefficient of the input signal and then subtracted from the input signal to reduce the influence of interference on the required signal in the time-frequency domain.

Among the space domain methods, antenna arrays are usually used to suppress broadband and narrowband interference, which adds a significant anti-interference capability to satellite communication systems. Amin et al. [157] discussed the application of sparse arrays and sparse signal processing for interference suppression and direction of arrival estimation. For multipath interference design, Heng et al. [158] proposed the high mask angle antenna to suppress the interference and signal from the low elevation Angle for multi-path interference design. The optimal mask angles are obtained by different constellation settings, accuracy dilution of precision indices, and range accuracy assumptions. Simulation results showed that the proposed method is beneficial to reduce multipath interference for multi-constellation global navigation satellite system (GNSS) users. Space-time adaptive processing (STAP) combines spatial and temporal information to provide joint spatiotemporal processing to suppress multipath and narrowband and wideband interference. Zhao et al. [159] proposed a scheme to use the STAP algorithm to improve the anti-jamming performance of the antenna array. It was proved by simulation that STAP is superior to spatial adaptive processing in the case of multiple jamming signals.

In addition, we summarize three methods of interference suppression in the communication process in Figure 13. Figure 13 shows three ways of eliminating interference: time-domain adaptive filtering, frequency-domain adaptive filtering, and SS receiver. The signal condition after anti-interference is given, which proves that the bad influence of interference can be removed under the condition of protecting the original signal information as much as possible.

3.4.3 *AI-based solutions*

The vigorous development of AI has provided many new ideas and methods for the identification and classification and the suppression and elimination of interference. First, AI can assist in identifying the type or characteristics of interference. Second, AI can be applied to the game selection between the interferer and the interfered in a dynamic environment. Third, AI can efficiently adjust the adaptive parameters required by the system.

For the identification and classification of interference, accurate and reliable identification of the type of interference is a necessary prerequisite for the use of targeted anti-interference methods. Refs. [40] and [160] both proposed methods for classifying interference types in satellite communication systems. Ferre et al. [40] proposed an efficient jammer classifier based on support vector machine (SVM) and CNN. First, the spectrogram is calculated from the intermediate frequency (IF) sample, and the jammer classification problem is transformed into a black and white image classification problem. When an ML algorithm is applied to this problem, the classification accuracy can reach more than 90%. Xu et al. [160] proposed a jamming recognition algorithm based on the DNN, which extracts a set of low-complexity and high-resolution jamming features in the time domain, frequency domain, and transform domain, and constructs the disturbance classifier based on the decision tree and DNN, respectively. The simulation comparison results showed that when the jamming SNR is 0 dB, the recognition rate of the typically suppressed jamming by the DNN-based classifier can reach 99%. When the jamming SNR is 10 dB, the recognition rate of the DNN-based classifier for all 10 kinds of composite jamming can reach more than 85%.

In the complex electromagnetic dynamic environment of the satellite communication system, the channel selection problem and the optimization game between the interferer and the interfered are the keys to maintaining the performance of the communication system. Yao et al. [59] defined the channel selection problem of anti-jamming defense as Stackelberg game, and based on stochastic learning theory, established a hierarchical learning framework and proposed a hierarchical and learning-based channel selection algorithm. Erpek et al. [161] designed an intelligent jamming attack system and gave a corresponding defense scheme, where the transmitter senses the channel and applies a pre-trained ML algorithm to detect the idle channel of transmission for data transmission. Noori et al. [60] studied a stochastic game method between jamming and anti-jamming in jamming channels. Combining game theory with RL, Han et al. [61] proposed a distributed dynamic anti-jamming scheme that reduced energy consumption in jammed environments. Lu et al. [162] proposed a relay technique against intelligent jamming, which combines RL with a function approximation approach named tile coding. Based on game theory, the mobility and relay strategies of the robot are adaptively selected. The simulation results showed that the performance of the scheme is better than the existing scheme in terms of bit error rate, energy consumption, and efficiency.

In addition, accurate real-time adjustment of system adaptive parameters is also a condition for maintaining system stability and efficiency. For the CWI mentioned in [151–153], Abbasi et al. [163] used an adaptive filtering method. Its ANF needs to follow the interference, and it is a system that can find its coefficients according to the environment and the input signal. It uses a single neural network to predict filter coefficients, which is faster than traditional methods and improves the SNR significantly. Shi et al. [164] improved two algorithms, power distribution panel wavelet packet transform (PDP-WPT) and extended BP neural network (EBPNN), and used the adaptive TISI neural network to identify information in the transform domain. Compared with the traditional method, the capability of interference suppression can be improved by 32%.

3.5 Spectrum prediction

3.5.1 *Definition & limitations*

Spectrum prediction refers to the effective use of known spectrum data to predict the occupancy or idle situation in the spectrum at future moments [165]. It performs feature learning and summarizes experience to make reasonable predictions about the spectrum occupancy status of the future time slots.

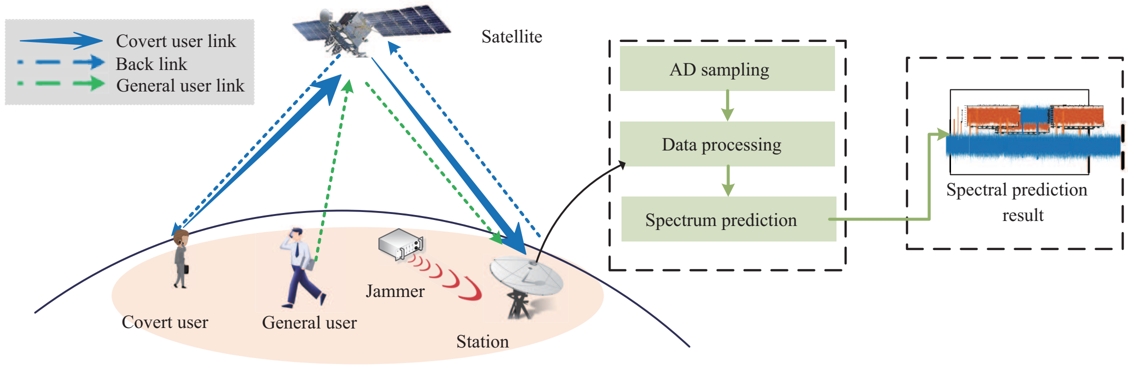

Figure 14 (Color online) Spectrum prediction in covert satellite communication scenario.

Spectrum prediction is a complementary technique to spectrum sensing. A general spectrum prediction model is designed to provide accurate spectrum occupancy predictions for communication networks, which can allow SU to discover and access current spectrum holes. By use of spectrum prediction, the SE of the network will be maximized without interfering with primary user (PU) communications [166]. Spectrum prediction is also widely used in satellite communication, and can provide an effective solution for real-time spectrum resource allocation in large-scale satellite internet [167].

In covert satellite communication systems, the knowledge of the current spectrum is critically important. Because covert satellite communication is in an open space, the spectrum occupancy in the corresponding frequency band will greatly affect the reliability and covertness of the covert satellite communication system. By using spectrum prediction technology, users can flexibly select the frequency, bandwidth, and hopping spread spectrum mode of their own communication according to the current spectrum background, so as to actively bypass channels that may seriously interfere with communication performance. Signals that are currently occupied in the spectrum can also be used effectively as bunker signals. In this way, on the basis of ensuring the reliability of the communication, the covertness of the communication is also improved. Spectrum sensing is another way to realize the cognition of the current spectrum state. However, for the reason that the communication delay between the satellite and the terrestrial station in the covert satellite communication system is much larger than that of the terrestrial communication system, the real-time performance of the cognition obtained spectrum has been seriously damaged [168]. Therefore, the satellite communication system needs to adopt spectrum prediction technology to predict the spectrum state in advance and improve the accuracy of perception. Figure 14 shows the spectrum prediction technique in the covert satellite communication scenario.

3.5.2 *Main challenges and solutions*

In the earliest days, most spectrum predictions were based on linear models, that was, by linearly changing and modeling the obtained historical spectrum data to obtain the future predicted values [26, 169–176]. For example, Huang et al. [171] proposed a spectrum prediction model based on partial periodic pattern mining, which improves the prediction performance under the conditions of sensing error and spectrum irregularity. Nguyen et al. [172] given a collaborative model based on spectrum prediction and spectrum sensing. In order to augment incomplete or corrupted historical observation data, Ding et al. [173] established a robust online spectrum prediction framework, and analyzed the impact of abnormal data on the rank distribution.

However, the methods above were limited to only solving linear problems. Most of the models in practice were nonlinear, and the predicted performance cannot be guaranteed in more complex scenarios. To adapt to the complex environments, Akbar et al. [177] proposed the use of the hidden Markov model (HMM) to model and predict spectrum occupancy. But, when the first-order hidden Markov model is applied to make predictions, the state of the current moment is only related to the previous moment, and the historical spectrum information is not fully utilized. Therefore, Chen et al. [178] proposed a higher-order hidden Markov model (HOHMM), which achieved better prediction performance. Noticing that cooperative spectrum prediction has the potential to improve prediction accuracy, Eltom et al. [179] proposed an HMM-based collaborative soft-fusion spectral prediction method, which can significantly reduce the prediction error.

However, the spectrum prediction method based on HMM also has some limitations. It needs to know the prior knowledge in the spectrum, and there are many parameters to be modified during learning and training, which results in large system loss.

3.5.3 *AI-based solutions*

In recent years, with the development of AI, more and more researchers apply AI to assist spectrum prediction techniques.

The neural network in DL is the first technique to be widely used in spectrum prediction. Zhang et al. [180] proposed a radial basis function (RBF) neural network spectrum prediction algorithm based on the K-means clustering algorithm (K-RBF). Lan et al. [181] designed a three-step advanced spectrum prediction framework based on a neural network. Mennes et al. [46] used a CNN to predict future spectrum usage. Zhang et al. [182] designed a multi-layer neural network predictor.

RNNs and their improved models such as LSTM have a strong ability to mine potential temporal correlations between input data. Yu et al. [53, 54] first applied the LSTM network to spectrum prediction, the purpose of which was to better extract long-term features in time series spectrum data without using any prior information about the device. By learning from the past spectrum availability data, they exploited the inherent time-frequency correlation between the data to predict future spectrum availability. Applying the LSTM neural network for spectrum prediction, Yu et al. [55] effectively reduced the optimization time and consumed resources by using the Taguchi method instead of the grid search method. And in order to improve the timeliness of spectral prediction, they adopted the deep time spectral residual network (DTS-ResNet) [183]. By introducing advanced residual units, they constructed multiple residual network modules to capture the characteristics of these data at different time scales and predict multiple time series at the same time. For the problem of unreliable local spectrum prediction of a single user under harsh channel conditions, Shawel et al. [56] proposed a soft collaborative fusion model based on LSTM, which improves the prediction accuracy and optimizes the energy consumption.

However, the ability of only one kind of neural network was limited, so some researchers began to study multi-layer fusion neural networks. Yu et al. [184] designed a hierarchical spectrum learning system, and using fine-tuned CNN and gated recurrent unit network they proposed a DCG model for local spectral availability prediction. This hierarchical model combines the advantages of CNN and RNN at the same time, and has a strong ability to find correlations in the spatial and temporal domains of signals. Ding et al. [168] also proposed a CNN and bidirectional LSTM (CNN-BiLSTM) model, which was used on LEO to characterize the spectrum utilization law of geosynchronous earth orbit (GEO) satellites, and a fusion network was designed to effectively combine multiple prediction results.

The above-mentioned DL-based spectrum prediction studies all have an explicit or implicit assumption, that is, the historical data of the target frequency band are abundant. However, when the equipment for spectrum prediction switches to a new band or when the spectrum environment changes, traditional DL models will be limited by the timeliness and scarcity of required historical data. To overcome this issue, Davaslioglu et al. [68] used a GAN with a DL architecture to generate additional synthetic training data for spectral prediction. Lin et al. [185] proposed a cross-band spectrum prediction model based on transfer learning, and in the case of limited historical spectrum data, the performance was improved compared with the existing model. In order to further enhance the sparse spectral historical data, they proposed a cross-band spectral data enhancement framework DA-DTS-ResNet based on GAN and deep transfer learning [69]. Compared with the method in [68], this framework is simpler, more stable, easier to train, and can make the spectral prediction model more robust when data is scarce.

3.6 Adaptive modulation and coding

3.6.1 *Definition & limitations*

AMC is to get the current channel state by analyzing the information received by the receiver, and adaptively adjusting the modulation scheme and coding scheme of the sender at the next moment. AMC uses dynamically varying bit rate and modulation sequence to adapt to time-varying channels, thereby increasing capacity and reducing the bit error rate. With fixed code modulation, the system needs to be designed with link margin reserved for worst-case communication [186].

Covert satellite communication needs to work properly in the presence of a lot of interference. Therefore, the previous communication system would adopt the link allowance. By using low order modulation

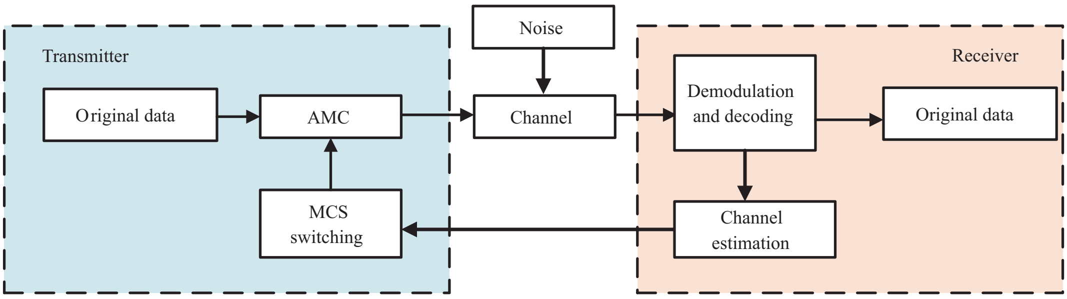

Figure 15 (Color online) The system framework for AMC technology.

mode, low bit rate, and high transmit power, the system can still work normally under bad communication conditions. This method is relatively simple, but it wastes satellite power and spectrum resources. With the development of adaptive techniques, scholars began to consider the application of adaptive technology in satellite communication to overcome the above problems. AMC can compensate for the change of link-state caused by channel fading and environmental interference, and it has become a research hotspot in covert satellite communication. For the power-limited system such as covert satellite communication, AMC can effectively overcome the deficiency of power limitations. For a multi-beam system, different users can effectively match different link performances to maximize the overall throughput of the system. In covert satellite communication, the purpose of AMC is to dynamically adjust the coding rate and modulation mode to achieve higher data throughput and SE on the premise of ensuring the concealment of transmitted signals. In short, a high-order modulation mode and a high bit rate can be selected to improve the link throughput when the link condition is good. And in the case of poor link conditions, using low modulation mode and low bit rate can prevent the system from being affected.

Hayes [187] first proposed an adaptive receiver and feedback channel in 1968. In this method, the channel information obtained at the receiver is fed back to the transmitter, which adjusts the transmitted data through the feedback information. In 1992, Webb et al. [188] proposed a variable rate adaptive QAM modulation system. Simulation proved that under the same conditions, the channel SNR of the variable rate system is about 5 dB higher than that of the fixed 16-level QAM system. In 1999, considering that different levels of services are provided for different users in the cellular system, Qiu et al. [189] combined adaptive modulation and power control to improve the throughput of the whole communication system. In 2004, AMC was included in the DVB-S2 standard, which can increase the capacity gain by about 30% compared with the DVB-S standard [190]. In the same year, Rinaldo et al. [191] proposed an AMC scheme for multi-beam wideband satellite downlink, and they proved that compared with the traditional non-adaptive TDM system under the same conditions, the capacity of the proposed system increases by 2.5 times. In 2010, Ahn et al. [192] used irregularly modulated LDPC coding to reduce the system complexity of AMC and control the transmission rate. In 2021, based on the satellite DVB-S2/S2X standard, Tropea et al. [193] proposed a two-layer packet scheduling mechanism for AMC, which can support different QoS levels to monitor propagation and channel conditions, and the simulation results showed that the overall system performance is improved.

The system framework for AMC technology is shown in Figure 15. The receiver decodes the received information and estimates the transmission channel at the same time. Then the channel status information is fed back to the sender. According to the received channel status information, the sender determines the modulation and coding scheme (MCS) to be used for communication at the next moment, and sends the data according to the modulation and coding of the scheme.

3.6.2 *Main challenges and solutions*

In recent years, AMC has made remarkable progress in all aspects of research. According to the AMC technical structure, it can be roughly divided into the following directions. The first is to estimate the channel state. In the channel estimation of link adaptive technology, there are a lot of studies that use SNR as an indicator of channel evaluation. Traditional SNR estimation methods include maximum likelihood estimation, spectral estimation, statistics-based estimation, and so on [194]. It maps the current CSI to an SNR, which will be fed back to the sender for subsequent MCS switching. The second step is the selection and switch of the MCS scheme. The sender selects the encoding modulation scheme which is suitable for the current environment according to the MSC selection strategy.

Some advances in AMC technology in recent years are described as follows. The ultimate purpose of these studies is to optimize performance and improve spectrum utilization. The effectiveness of the AMC scheme depends on the accuracy of channel estimation. So channel estimation plays a key role in the AMC scheme. Weerackody [195] proposed a channel SNR estimation technique, in which the possible errors caused by channel estimation are considered and the performance of AMC is improved. Considering that rainfall and ground movement environment would cause serious attenuation to Ka-band signal communication, Yu et al. [196] derived a rain failure probability density function based on satellite elevation changes and calculated the channel parameters. Then they select the best MCS according to the adaptive coding algorithm and the simulation results showed that the proposed scheme can effectively compensate for attenuation. Wan et al. [197] proposed the effective signal-to-noise ratio (ESNR) as a new performance indicator for mode switching, and the simulation and experimental results verified the advantages of ESNR over other SNR definitions. Zeng et al. [198] have focused on fast-moving scenarios, which can enhance the time-domain equivalent wireless channel parameter correlation and reduce the channel quality indicator (CQI) mapping mismatch level in the communication environment with large feedback delay.

The switch and selection of the MCS scheme is also the key research. Meng et al. [199] studied the problem of constellation and channel coding rate selection in AMC for multiple-input multiple-output (MIMO) systems. They proposed a new selection rule for narrowband MIMO systems which selects constellation and coding rate by comparing throughput, and the rule was further promoted to broadband MIMO orthogonal frequency division multiplexing (OFDM) system. Farrokh et al. [200] expressed the MCS selection problem as a Markov decision problem approaching an infinite level, and the experiments proved that the optimal MCS selection strategy has a monotone structure under some sufficient conditions. Considering that channels fluctuate under the influence of shadow, multipath fading, and mobility, Kojima et al. [201] proposed AMC and frequency symbol extension (FSS) adaptive switching strategies for OFDM systems to improve throughput performance by using a mixture of FSS and traditional AMC. There are also some other scholars focusing on the improvement of channel coding [192] and channel prediction [202].

3.6.3 *AI-based solutions*

With the development of AI, more and more scholars began to consider the combination of ML and AMC to improve throughput, spectrum efficiency, and the accuracy of CSI estimation while reducing computational complexity. Elwekeil et al. [203] compared the performance of K-nearest Neighbor, SVM, and DL when they were respectively applied to AMC, and analyzed the system throughput and algorithm complexity of the three schemes. Ferreira et al. [204] integrated multi-objective RL and ANN to achieve the management of available resources and task-based conflict objectives, which can be used in the flexible and changeable satellite communication environment. The simulation results proved that the algorithm can improve system capacity.

Some scholars optimize AMC by improving the accuracy of channel estimation. AbdelMoniem et al. [205] proposed an efficient channel estimation algorithm based on LSTM neural network. Compared with the traditional non-orthogonal multiple access system, this channel estimation algorithm reduces the interrupt probability by 10% on average. Kojima et al. [206] combined an ANN with SNR estimation and established the mapping relationship between the power spectral density value and different MCS through training. They improved the system throughput and reduced the computational complexity by 97.5% compared with using the traditional EVM-based AMC scheme. Tato et al. [207] selected modulation schemes using a multilayer feedforward neural network-assisted with SNR estimation.

There are also many research achievements in the switching and selection of MCS. Zhang et al. [208] utilized DRL and proposed an intelligent MCS selection algorithm for master transmission. The simulation results showed that without considering the cost, the primary transmission rate of the proposed algorithm is 90%-100% of the optimal MCS selection scheme. Subsequently, they applied supervised learning and RL to AMC technology respectively [209] to meet the contradictory requirements of high data rate and high reliability by adjusting modulation sequence and coding rate. Zhang et al. [43] used a CNN to identify modulation formats, which avoids artificial feature selection and provides good classification accuracy. In addition, AI has been combined with research on channel decoding [210] and CSI [211] prediction.

The key to AMC is the assumption that real-time channel parameter estimates can be received. But channel changes rapidly in satellite communication, which poses a challenge to the accuracy of AMC.

AMC based on ML is a novel direction, and the neural network algorithm shows great advantages in prediction. Therefore, with the continuous breakthrough of AI algorithms, it is believed that there will be more algorithms with excellent performance combined with traditional AMC techniques.

4 Future trends

In this section, future development trends will be discussed based on the above research and discussion about key techniques in covert satellite communication.

(1) LPD communication. At present, the research on LPD communication mainly focuses on LPD information theory, implementation scheme, constant rate covert communication, and so on. However, AI is seldom used in LPD communication. The future development trend of LPD communication can be considered as follows. (a) Generate more featureless signals with good performance through ML and optimize the LPD model by using optimization algorithms. (b) Consider key generation in communication through training networks. At present, there is a lot of theoretical analysis on key length and usage, but there is still a lack of practical application on how to generate keys using actual channel characteristics. (c) The eavesdropper and communication parties present a game relationship and consider the combination of game theory and LPD communication. Especially in the multi-user communication network, multiple communication parties can jointly fight against the monitor and get higher system throughput.

(2) Transmit power control. Recently, the transmit power control technique in covert satellite communication mainly focuses on four problems: improving network throughput, enhancing network robustness, reducing control delay, and enhancing covertness. AI applications are limited to solving the first three problems to improve the reliability of covert satellite communication. Research on the power control of AI to improve covertness is yet to be carried out. The use of satellite-ground networks will increase in the future, and in this scenario, it will be an important topic to consider the reliability and covertness of network node communication. AI will play an irreplaceable role.

(3) Phased array antenna. At present, AI algorithms have achieved good results in beamforming and antenna calibration. In terms of calibration accuracy and transmitting beam performance, the AI algorithm continues to surpass traditional algorithms. However, there is still some research on hardware design, and the antenna is mainly designed by manual work. How to use AI to design the antenna system with the best performance according to the application scenarios and environmental parameters is a major research direction in the future. In addition, new application directions such as AI fault detection also need to be more developed and mined to build a complete intelligent phased array antenna system.

(4) Anti-interference. The intelligence of interference detection and anti-interference decision has become a developing trend. However, most existing research related to AI has high implementation complexity and is not suitable to complete relevant operations on the satellite. Algorithm optimization and complexity reduction are important to research direction in the future. In addition, most of the communication channels considered at present are Gaussian white noise channels, and non-human interference such as adjacent satellites and solar wind is hardly considered. In the future, more research is needed on interference identification and anti-interference decision in complex environments.

(5) Spectrum prediction. Spectrum prediction has been widely used, which greatly improves spectrum utilization. Future research on spectrum prediction will more concentrate on large-scale MIMO. How to use multi-node cooperative prediction in AI coordination communication networks to improve prediction accuracy is an important research direction. On the other hand, using AI data enhancement to make faster predictions with fewer data is also a promising direction.

(6) Adaptive modulation and coding. In covert satellite communication systems, AMC techniques based on AI have gradually matured. But current AMC techniques based on ML mostly use a single AI algorithm. One of the future research trends is based on combinatorial ML. In addition, the performance of the AMC technique is poor in high-speed channel environments. It is a hot issue that needs further study in the future to use AI to learn and classify scenarios with rapid channel changes. AI can also be used to achieve more accurate channel state prediction and higher robustness.

In the future, with the continuous deepening of the urbanization process around the world, there will be more and more demands for covert satellite communication in complex urban environments. The covert satellite communication scene in the urban environment is shown in Figure 16. In the urban environment, the space is filled with signals of various forms and various frequency bands. This complex electromagnetic environment is both an opportunity and a challenge for covert satellite communication.

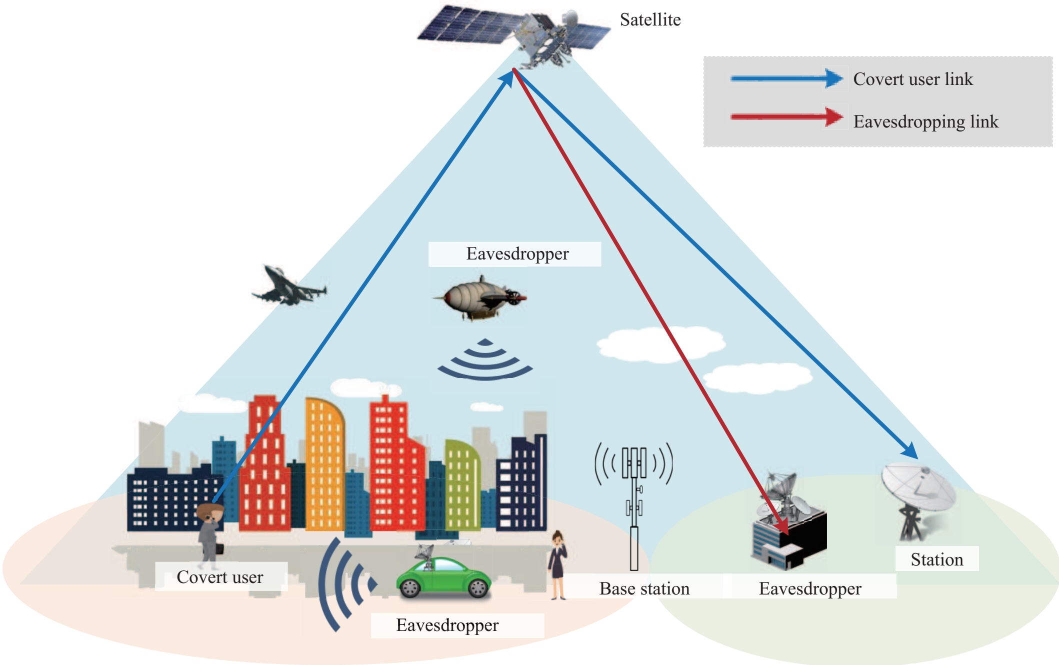

Figure 16 (Color online) The covert satellite communication scene in the urban environment.

How to use the complex electromagnetic environment to improve the covertness of communication while keeping the reliability unaffected by it will be an important topic in the future. At the same time, in the city, hidden users will face the threat of close detection, that is to say, eavesdroppers may exist in any corner of the city, and may be very close to the covert users, which will lead to a very high SNR at the Eavesdroppers. In that case, the traditional methods of hiding communication signals below the noise floor are no longer realistic, and new covert communication mechanisms must be studied.

5 Conclusion

In this study, a comprehensive overview of the application of AI in covert satellite communication systems was presented. This study summarized the background and applications of covert satellite communication and clarified the importance of the six key techniques in covert satellite communication systems, including LPD communication, transmit power control, phased array antenna, anti-interference, spectrum prediction, and AMC. In particular, the research status of these techniques and the application of AI in them were introduced in detail. Finally, the existing problems and future research directions of these techniques were pointed out. Obviously, covert satellite communication will be an important part of future satellite communication, and it has broad prospects in both commercial and military fields.

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Appendix A

Table A1 List of acronyms

Acronyms	Definition	Acronyms	Definition
ADMM	Alternating direction method of multipliers	HMM	Hidden Markov model
AI	Artificial intelligence	HOHMM	Higher-order hidden Markov model
AMC	Adaptive modulation and coding	IF	Intermediate frequency
ANF	Adaptive notch filter	IIR	Infinite impulse response
ANFA	All-pass based notch filter	IoT	Internet of things
ANN	Artificial neural network	LEO	Low earth orbit
APAA	Active phased array antenna	LPD	Low probability of detection
AWGN	Additive white Gaussian noise	LPI	Low probability of intercept
BSC	Binary symmetric channel	LSTM	Long short-term memory
CIPC	Channel inversion power control	MCS	Modulation and coding scheme
CNN	Convolutional neural network	MIMO	Multiple-input multiple-output
CRN	Cognitive radio network	ML	Machine learning
CSI	Channel state information	OFDM	Orthogonal frequency division multiplexing
CWI	Continuous wave interference	PPM	Pulse position modulation
DL	Deep learning	PU	Primary user
DMC	Discrete memoryless channel	QoS	Quality of service
DNN	Deep neural network	RBF	Radial basis function
DPC	Deep power control	RL	Reinforcement learning
DRL	Deep reinforcement learning	RNN	Recurrent neural network
DSSS	Direct sequence spread spectrum	RSS	Received signal strength
EE	Energy efficiency	SE	Spectral efficiency
EIRP	Equivalent isotropic radiated power	SNR	Signal-to-noise ratio
ESNR	Effective signal-to-noise ratio	SRL	Square root law
FHSS	Frequency hopping spread spectrum	SS	Spread spectrum
FIR	Finite impulse response	STAP	Space-time adaptive processing
FSS	Frequency symbol extension	SU	Secondary user
GAN	Generative adversarial network	SVM	Support vector machine
GEO	Geosynchronous earth orbit	WMMSE	Weighted minimum mean square error