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Overview of commonly used spread spectrum techniques

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Abstract: *Spread spectrum communication technology is characterised by strong anti-interference, strong concealment, multipath resistance and low power spectral density. In recent times, it has been widely used in aerospace measurement and control, military communication, hydroacoustic communication, optics and other fields for the purpose of realising high quality and high speed transmission of signals and completing the purpose of information transfer. In recent years, along with the development of 5G and other communication methods, spread spectrum technology has been introduced into the public's field of view, and it is the focus of future spread spectrum technology to consider how to achieve high speed rate and high applicable communication quality. Firstly, the working principle, composition and development direction of basic spread spectrum technology, hybrid spread spectrum technology and other spread spectrum methods are introduced, such as summarising the fuzzy problems of BOC signals and introducing the improvement of direct sequence spread spectrum technology after the introduction of chaotic sequences. The advantages and limitations of each of the different spread spectrum techniques are analysed for the advantages and disadvantages at the end.*

Keywords: *basic spread spectrum technique; hybrid spread spectrum; other spread spectrum methods*

1. Introduction

SPREAD SPECTRUM COMMUNICATION SYSTEM (SSCS) is a communication system that uses a specific spread spectrum function to expand the spectrum of the signal to be transmitted into a wide-band signal, and then transmits it in a channel while compressing the transmitted signal, and then gets the transmitted information at the receiving end [1].

The theory of spread spectrum communication technology comes from the channel capacity summarised by Shannon's formula in information theory research:

$$C = W \log_2(1 + \frac{S}{N}) \tag{1}$$

It is the transmission rate of data information, the bandwidth, the useful signal power and the noise power.

Spread spectrum communication has strong anti-jamming ability, and it has especially outstanding anti-jamming ability for narrowband interference. Spread spectrum communication is easy to realise code division multiple access (CDMA) technology, with good security and confidentiality. Spread spectrum communication has strong anti-frequency selective fading performance and high spectrum utilisation. The spread spectrum code used in spread spectrum communication is not easy to be eavesdropped and deciphered, and the confidentiality is excellent. At the same time, the wider the width of the spectrum expansion of spread spectrum communication, the stronger the anti-interference ability [2].

There are four basic types of spread spectrum technology, classified by system operation and principle: direct sequence spread spectrum (DS), time-hopping spread spectrum (TH), frequency-hopping spread spectrum (FH), and linear frequency modulation (Chirp). Originally used in military communications, in recent years spread spectrum technology has moved into commercial and civilian applications in everyday communication situations. In addition, there are two or more hybrid spread spectrum technology combinations, such as: hopping spread spectrum technology (FH/DS), TH/FH, TH/DS and other spread spectrum technology. Along with the increase of signal complexity, there are many other types of spreading methods, such as: slow quadrature spreading technology, BOC spreading technology,

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soft spreading technology and so on.

2. Basic spread spectrum technology

2.1 Direct spread spectrum technique (DDS)

The earliest developed spread spectrum technology is Direct Sequence Spread Spectrum (Direct Sequence Spread Spectrum, DSSS), which is the basis of modern spread spectrum technology.

The direct spread spectrum signal expression is:

$$s(t) = \sqrt{2P} \bullet d(t)c(t)\cos(2\pi f_0 t + \varphi) \tag{2}$$

Where $d(t)$ is the data signal, $c(t)$ is the spread spectrum signal, f_0 is the carrier frequency, φ is the carrier phase and P is the transmitted signal power [2].

Usually, the direct sequence spread spectrum communication system model is mainly divided into two parts: the transmitter and the receiver. As shown in figure 1, the transmitter first differentially encodes the original digital baseband signal from the source, then uses the spread spectrum code generated by the spread spectrum code generator to broaden the spectrum of the digital signal, then reduces the inter-code crosstalk through the shaping filter, and then sends it out through the carrier modulation. The receiving end decodes the received signal with the local pseudo-code, and recovers the original baseband information after demodulation.

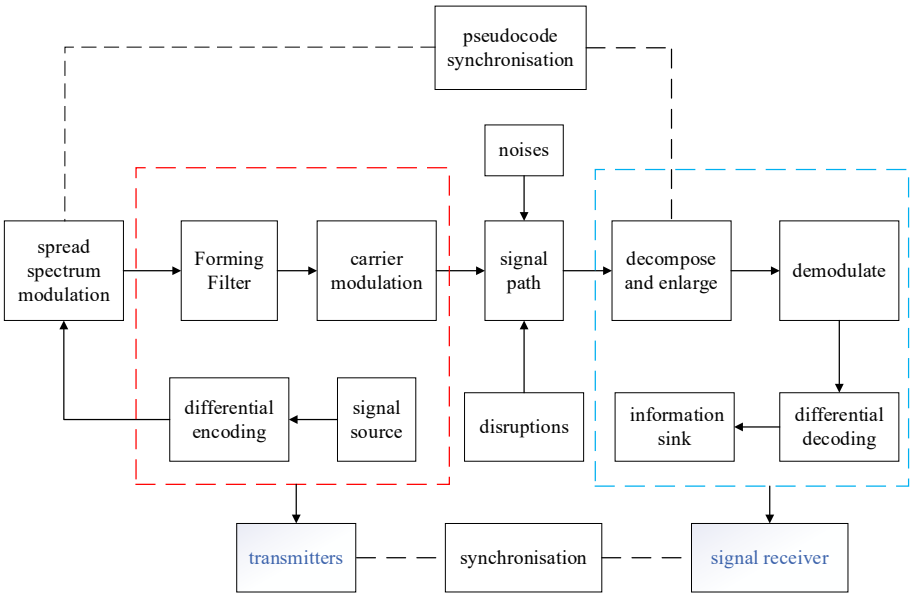

Figure 1: Direct expansion system

In order to further improve the frequency band utilization and information transmission efficiency, Fang Xu also proposed parallel combined spread spectrum, code index modulation technique and time-shift position modulation[3].

The DS-SS system that develops pseudo-chaotic sequences as spreading sequences from chaotic sequences is significantly better than the traditional PN sequences, e.g., Mahalinga V. Mandi" et al. proposed the pseudo chaotic sequence (PCS) spread spectrum communication system. Possessing good correlation properties over conventional m-sequences, it reduces the BER of the direct spreading system and improves the communication efficiency[4]. Literature[5]improves more security features in Direct Sequence Spread Spectrum (DS/SS) tapered system by using chaotic sequences as spectral diffusion sequences, stealthy. Yuzhen Li proposed a chaotic spread spectrum sequence based on Chebyshev mapping and Hybrid mapping novel cascade. It improves the system secrecy and good anti-interference performance. The new chaotic sequence replaces the traditional chaotic sequence, which lays the foundation for designing chaotic spread spectrum sequences with a large number of non-periodicity and good statistical characteristics. Zhi Zhang proposed a non-coherent chaotic spread spectrum

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communication system (MIMO-MC-CSK) combined with MIMO technology, whose performance is significantly better than other non-coherent chaotic spread spectrum communication systems under different channels[6].

2.2 Time-hopping spread spectrum technique

The principle of time-hopping spread spectrum is to divide the time axis into many time slots within a frame which time slots transmit signals controlled by time-hopping code sequences[7]. The traditional time-hopping communication focus gradually changed from enhancing the signal's anti-jamming and anti-interception capabilities to signal concealment issues. Time hopping spread spectrum is used to open and close a keyed transmitter with a spread spectrum code slice to split the duration of a signal code into a number of time slots, and the spread spectrum code slice controls in which time slot a signal code is transmitted[8].

Time-hopping spread spectrum technology is mainly used in the following two aspects, the first aspect is UWB (Ultra Wide Band Communication) and the second aspect is in military encrypted communication. Zhi-Ying Gao proposes the UWB time-hopping spread spectrum communication system with BPSK modulation, and uses the error bit rate as an index to derive the general law of TH-BPSK time-hopping spread spectrum communication system performance. In order to improve the security performance of encrypted communication, Liu Nan draws on cryptography, software simulation of primary time-hopping sequence (pseudo-random sequence) and secondary time-hopping sequence, and concludes that the capacity in the time-hopping spread-spectrum communication system and the reliability of the system's data transmission will produce a contradiction.

2.3 Frequency hopping spread spectrum technology

Frequency hopping is a spread spectrum technique that extends a signal to a wide bandwidth by rapidly changing the carrier frequency[9]. The transmitter and receiver ends of the FH system are shown in Figure 2 below.

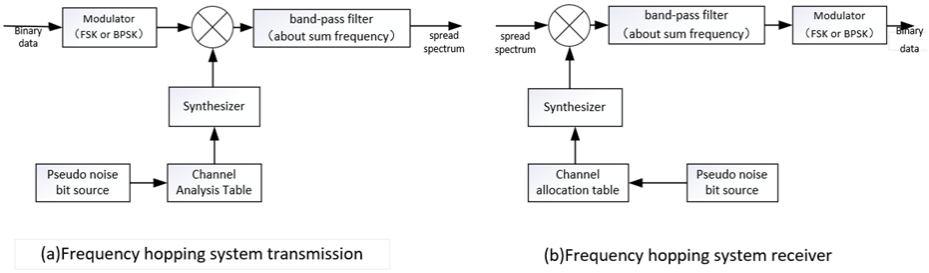

Figure 2: Frequency hopping system[8]

Relative to the traditional fixed-frequency communication form, frequency hopping system has many fixed-frequency system can not be comparable to the advantages: the first one is strong anti-jamming ability: frequency hopping system using random frequency fast switching and long periodicity, high randomness of the pseudo-random code generated by a large number of different frequency combinations, so that its frequency hopping law can not be interfered with by the interference party to grasp the accuracy, thus making frequency hopping signal is more difficult to be captured and interference, so it has a very strong anti-jamming ability. The second one is high spectrum utilization rate: spectrum utilization rate is one of the basic requirements of modern communication, because spectrum resources are very valuable. In order to improve spectrum utilization, frequency hopping communication adopts different frequency hopping schemes or clocks to simultaneously accommodate multiple frequency hopping communication systems to work within a certain bandwidth, so as to achieve the goal of spectrum resource sharing and utilization improvement. The third is easy to realize code division multiple access: frequency hopping communication can easily build multiple access communication network, each user is assigned a unique address code, only to receive the signal sent according to its address code, the user can identify the useful signal for demodulation. The fourth one is strong compatibility: frequency hopping communication system can establish communication with non-frequency hopping communication system on fixed frequency, realizing the interoperability between advanced frequency hopping radio and traditional fixed frequency radio, so as to realize the effective and full use of resources[10].

In conclusion, frequency hopping (FH) system effectively improves the immunity to interference and

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confidentiality of the communication system by frequently hopping the channel frequency. However, the FH technology is still facing some problems and challenges, such as the synchronization under the high-frequency switching of transceiver and receiver double-end, the limitation of the spectral resources, the multipath interaction interference and the adaptive frequency hopping under the high dynamic environment, etc., which are the urgent issues to be solved for the frequency hopping communication[11].

The future frequency hopping system will be oriented to the following aspects of development: first, the pursuit of higher speed data transmission speed: with the increasing applications of wireless communication systems and data demand[12], frequency hopping system will be oriented to new modulation and demodulation technology, higher utilization of spectrum bandwidth and faster hopping rate innovation and improvement to meet the needs of higher data transmission, and the second is the stronger security and confidentiality, to protect the communication. The security of the system has been the focus of the development of frequency hopping systems, and continue to improve the defense capability against interference, eavesdropping and spoofing attacks in the future, for example, in 2020 Park W J proposed a BPSK-QPSK hybrid modulation frequency hopping spread spectrum system to increase the complexity of the interceptor[13], which provides a higher level of security for frequency hopping systems. Thirdly for example Kathirvel N in 2022 proposed is a way to get higher data transmission speed[14].

2.4 Chirp Linear Modulation Spread Spectrum

Chirp spread spectrum technology, also referred to as linear FM spread spectrum, differs from other spread spectrum techniques in that it does not require pseudo-noise sequences for signal modulation. Instead, it relies on the spread spectrum communication method through its inherent frequency linear changes. This approach offers unique advantages, including broadband characteristics introduced by the anti-Doppler effect, resistance to multiple paths, and resilience against noise interference. While improving the anti-jamming ability, the data rate of this communication method will be limited, so the Chirp spread spectrum communication is generally used in the scenario where the data rate requirement is not high[15].

Chirp spread spectrum technology is widely used in underwater acoustic spread spectrum communication and airborne acoustic spread spectrum communication compared to traditional spread spectrum technology, chirp linear pulse FM signal. The traditional Chirp spread spectrum application is mainly two aspects, orthogonal key control and direct modulation; the multiple access technology is divided into slope interleaving, frequency interleaving and time interleaving techniques[16].

Yi-Qi Bai proposed an orthogonal Chirp signaling (OCDM), which greatly improves the transmission efficiency of conventional CSS systems, and the comparison with conventional OFDM yields a great BER performance improvement by sacrificing the transmission rate[30].

3. Hybrid spread spectrum technology

3.1 FH/DS spread spectrum

Frequency hopping spread spectrum (FH/DSSS) spread spectrum communication technology is a combination of direct sequence spread spectrum and frequency hopping spread spectrum technology, with communication covertness, security and anti-noise, anti-fading, anti-multipath, communication confidentiality.

Hybrid hopping spread spectrum system transmit signal expression:

$$s(t) = \sqrt{2P} \bullet d(t)c(t) \bullet \sum_{k=0}^{\infty} \cos(2\pi f_1 t + \varphi) g(t - kT_h) \tag{3}$$

f_1 is the frequency hopping carrier frequency, $g(t)$ is the gate function, φ_i is the frequency hopping carrier phase, $c(t)$ is the pseudo-random code, and T_c is the code slice width.

First of all, the signal will be directly expanded modulation, and then after the mixing process, and then once again for frequency hopping spread spectrum modulation, after two spread spectrum modulation, the signal can ultimately be used as a transmitting letter. Receiving process and the opposite

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of the launch process, demodulation of the received signal, the demodulation process, and ultimately complete the process of transmitting and receiving spread-spectrum signals.

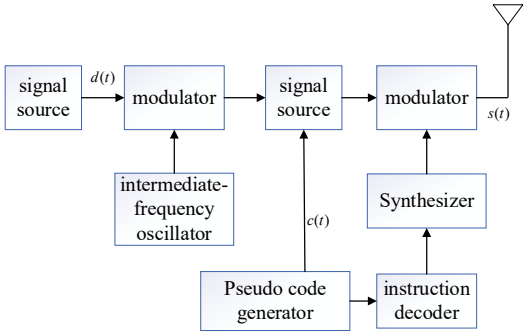

Figure 3: Launchers[36]

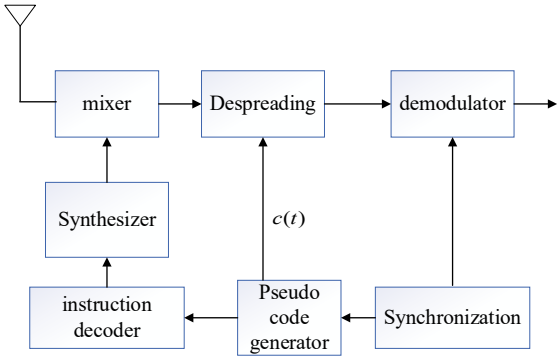

Figure 4: Receive end[36]

As shown in Figures 3 and 4 above, the transmitter and receiver of the hopping expansion system. In order to improve the reliability of civil/military transmission of electromagnetic information, Yunzhang Du proposed a low-complexity dual-multiple quadrature spread spectrum and DQPSK composite modulation scheme based on the weapon datalink system with FPGA code implementation[17]. Chen Rui proposed a hopping spread spectrum communication system with DQPSK modulation and direct spread spectrum in the baseband, which improves the noise processing capability of the received signal, and at the same time enhances the anti-jamming capability and the confidentiality of communication[18].

The synchronization of hopping spread spectrum pseudocode has always been a difficult point in hopping technology, in order to solve this difficulty, Hong Wei proposed a FH / DS hybrid spread spectrum regime receive synchronization algorithm[19]. Tao Wang proposed a hybrid hopping spread spectrum tracking synchronization method based on Coordinate Rotation Digital Computer (CORDIC)[20]. Under the condition of large Doppler shift, Hanqing Dong proposed the hopping spread spectrum pseudo-code synchronization algorithm to improve the phase recovery speed of the received information.

3.2 Multi-Binary Spread Spectrum

A multigraded spread spectrum communication system is a communication system that transmits only spread spectrum codes. It uses a multicode representation in which a binary information code has M=2^m states, each corresponding to a pseudo-random code. Therefore, the multicomponent spread spectrum system is also known as the M-component spread spectrum system. This system utilizes M mutually orthogonal pseudo-random codes $Cj(j=0,1,2,\ldots,M-1)$ of length L[21].

Multi-binary spread spectrum transmission system effectively solves the contradiction between tight spectrum resources and limited transmission rate, and compared with the traditional spread spectrum system, multi-binary spread spectrum transmission system has many advantages, such as low spectral density, high spectrum utilization, strong multipath resistance, high information transmission rate, small inter-code interference, low bit error rate, and long-distance communication, etc[22]. These advantages can enhance the overall communication effectiveness of the spread spectrum communication system and constitute an effective method to realize efficient direct spreading communication.

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Xingyuan Wang proposed a multi-digital communication system based on a 6th order CNN hyper chaotic system[23], which can transmit arbitrary progression signals. It solves the problem that most chaotic communication schemes based on chaotic systems can only transmit binary signals[24] and cannot transmit multiplexed signals.

4. Other spread spectrum technologies

4.1 M element spread spectrum

Soft spread spectrum technology is also known as M element spread spectrum, slow spread spectrum technology. It is a new spread spectrum generated by the organic combination of direct spreading technology and coding technology, and the difference between the basic spread spectrum technology is that the purpose of spectrum expansion is achieved by coding[25].

In order to solve the problem of high BER and unsatisfactory capture effect in aerospace measurement and control communication, Song Qingping proposed an improved soft spread spectrum leading sequence, which improves the signal capture sensitivity and transmission reliability[26].

For signal transmission in special environments, Wang Hongrui proposed a high-performance M-element orthogonal spread spectrum communication, and the signal concealment as well as the BER were significantly improved[27].

Along with the development of soft spread spectrum (M-ary spread spectrum), parallel combined spread spectrum evolved, which is an efficient spread spectrum communication method. In order to improve the communication performance of multicarrier parallel combining spread spectrum, J. Ding proposed adaptive multicarrier parallel combining spread spectrum (PCSS-OFDM) communication system, multicarrier differential multiphase parallel combining spread spectrum (DMP-PCSS-OFDM) communication system, and a new multicarrier parallel combining spread spectrum communication technique[28,29].

4.2 BOC modulation techniques

Along with the development of communication information technology, global satellite navigation and positioning systems, which have the characteristics of wide coverage, all-weather and high accuracy, are used in electronic warfare or civilian fields. For example, the modern GPS, Galileo and Beidou satellite navigation systems. Binary Offset Carrier (BOC) signals with positioning accuracy, anti-jamming and anti-multipath performance have been continuously used as navigation signals under the main new system, improving the shortcomings of the traditional modulation method, and solving the problem of aerospace navigation frequency band congestion and communication interference.

The BOC baseband signal is composed of three parts: navigation message, spreading code, and subcarrier, and the expression is:

$$r(t) = d(t) \bullet c(t) \bullet c^{'}(t) \tag{4}$$

$d(t)$, $c(t)$, $c^{'}(t)$ are the navigation message, spread spectrum code, and BOC modulation subcarrier, respectively.

The generation principle of BOC signal modulation is shown in Figure 5 below:

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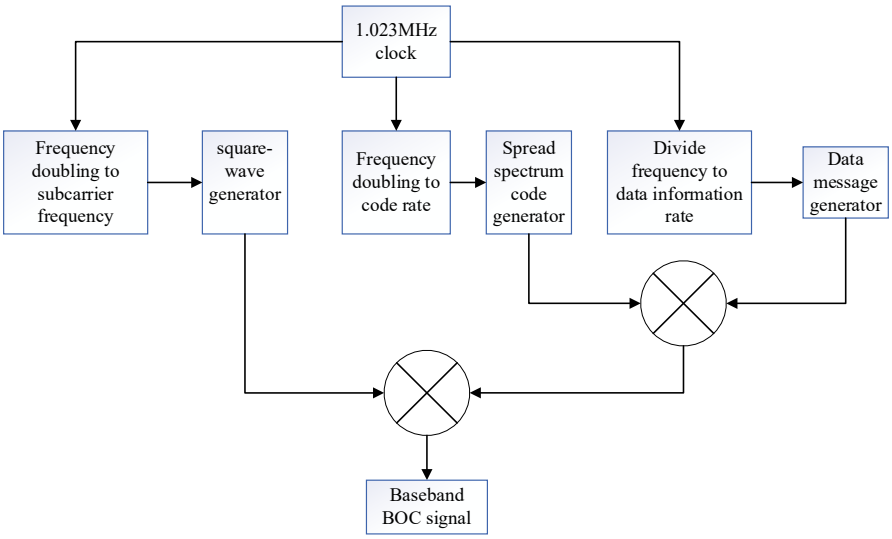

Figure 5: Diagram of the BOC modulation process[30]

The common BOC spreading techniques are SinBOC spreading, CosBOC spreading, AltBOC spreading, and MBOC spreading, and the following is an example of MBOC spreading. Essentially, MBOC spread spectrum is not a specific expression or spread spectrum principle, it is a unified modulation method constrained to have the same power spectral density. Its normalised spectral density formula is:

$$G_{MBOC}(f) = (1-\gamma)G_{BOC(n,n)}(f) + \gamma G_{BOC(m,n)}(f) \tag{5}$$

From Eq. 6, the MBOC signal is calculated by proportioning the $BOC(n,n)$ signal to the $BOC(m,n)$ signal with a weighting of $(1-\gamma)$: γ. Therefore, MBOC can also be regarded as a composite signal of the two signals.

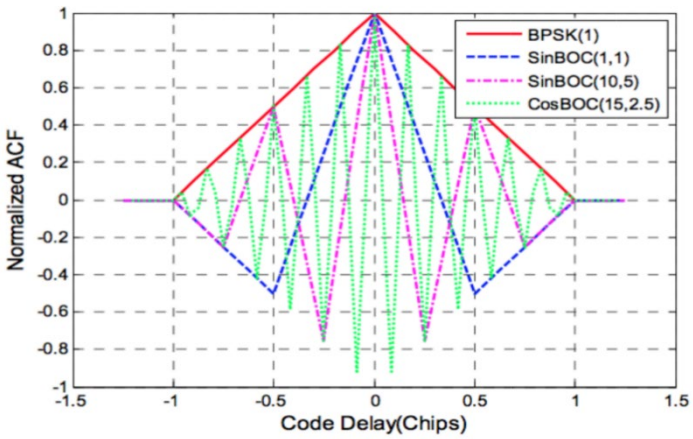

Figure 6: Autocorrelation function of BOC signal with different parameters[31]

The Figure 6 shows the comparison between the BOC signal under three different parameters and the conventional BPSK modulated signal (which has a spread spectrum code rate of 1.023 Mchips/s), and it can be seen that the BOC signal in the figure shows multiple peaks, which leads to the ambiguity problem of the BOC signal[31].

4.3 Multi-Carrier Spread Spectrum

Multi-Carrier Spread Spectrum System (MC-SS) is a communication technology for spread spectrum modulation through multiple subcarriers with high spectral efficiency, interference immunity and flexibility.

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According to different signal transmission requirements, researchers have proposed different MCSS schemes: e.g., Discrete Fourier Transform-based MCSS (DFT-MCSS), Wavelet and Wavelet Packet-based MCSS (WP-MCSS), etc. Xiaofan Y proposes a Wavelet Packet-based multipath MCSS scheme, which has a better performance than the DFT-based multipath MCSS in multipath channels. Scheme with better performance in multipath channels than the DFT-based multipath MCSS scheme.

In order to solve the high BER caused by the strong fading of some carriers, Steendam investigated the combination of orthogonal MC systems with code division multiple access (CDMA), and proposed a flexible MC-CDMA system in which the number of chips per symbol Nchip can be selected independently of the number of carriers Ncam[32], with more efficient utilization of the available resources to reduce the BER.

The advantages and disadvantages of various spread spectrum communication methods are summarised in Table 1 below.

Table 1: Spread Spectrum Analysis of the advantages and disadvantages of the technology

form	advantages	disadvantages	references
Direct Spread Spectrum (DS)	1. Strong anti-interference, good concealment 2. Easy to achieve code division multiple access (CDMA) 3. Strong multipath resistance	1. Mobile environment, the existence of the near and far effect increases the complexity of the application 2. Limited processing gain, anti-jamming ability and multi-access ability are restricted	[1,33,34]
Time Hopping Spread Spectrum (TH)	1. Compared with direct spread spectrum, reduce the duty cycle of the working time 2. No near or far effect 3. can be used in time division multiple access TDMA systems	1. Extremely strict requirements for time synchronisation 2. Cannot resist continuous wave interference of the same frequency. 3. Poor concealment	[29,34]
Frequency Hopping Spread Spectrum (FH)	1. No near or far effect 2. Faster capture (ms level) 3. Good multi-access capability, easy to network, high spectrum utilisation, easy compatibility	1. Poor anti-tracking interference ability, and the system's resistance to part of the frequency band interference performance is limited 2. Low signal concealment	[1,20,34]
Chirp Linear Modulation Spread Spectrum (CSS)	1. Chirp spread spectrum can effectively resist Doppler shift and deep fading. 2. Compared with direct spread spectrum and frequency hopping spread spectrum, it has the advantage of anti-Doppler shift for mobile object communication.	1. Poor multipath resolution as well as measurement accuracy	[29,35,34]
DS/FH technique	1. Resist broadband and narrowband interference within a certain range, and have a good ability to avoid tracking interference. 2. Confidentiality is enhanced compared to single spread spectrum technology	1. Demanding and complex to realise	[4,34]
M-element spread spectrum	1. With the advantages of general direct sequence spread spectrum 2. Anti-white noise, anti-polygon, code division multiple access capabilities	1. Low capture rate and high BER under strong interference conditions	[34]
BOC modulation technology	1. Low complexity and easy to implement 2. Better ranging performance and anti-multipath capability than BPSK modulation	1. There are fuzzy capture and tracking problems 2. Poor accuracy of ranging film due to multi-peak characteristics	[35]

5. Summary

Spread spectrum communication technology is a communication technology applied in different scenarios. According to its principle, spread spectrum technology can be divided into basic spread

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spectrum technology and new spread spectrum technology, in which the basic spread spectrum technology includes direct spreading technology, frequency hopping technology, time hopping technology and linear Chirp spread spectrum technology. The direct spreading technology extends the frequency band of the signal to a wider one by multiplying the signal with the spreading code; the frequency hopping technology achieves the effect of spreading the frequency by stipulating the frequency hopping sequence and sending the data in different time slices; the time-hopping technology spreads the signal in the time domain, and extends the frequency band by sending multiple transient signals within a short period of time; and the linear Chirp spreading technology realizes the spreading effect by modulating the carrier frequency linearly effect.

In addition to the basic spread spectrum technology, there are also some new spread spectrum technologies, which are designed to meet the requirements of higher spectral efficiency, anti-interference performance and security. These new technologies are widely used in wireless communication, radar, satellite communication and other fields, and continuously promote the development of wireless communication technology. In addition, there are also some hybrid spread spectrum methods, such as multi-degree spread spectrum and hopping spread spectrum technology, which combine the characteristics of different spread spectrum technologies and can be more adaptable to the communication needs in various scenarios. Different types of spread spectrum communication technologies include basic spread spectrum technology and new spread spectrum technology, as well as some hybrid spread spectrum methods. Their applications cover wireless communications, radar, satellite communications, and other fields, and play an important role in promoting the development of wireless communications technology.

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