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Performance Evaluation of a Tactical Data-Link System Based on MSK and 16QAM

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ABSTRACT Tactical data links are becoming more widely used in the military, as they can greatly improve the efficiency of various combat units. Such tactical data links must be able to transmit large volumes of data at high speed in complex communication environments while ensuring reliability. This paper studies the influence of 16-ary Quadrature Amplitude Modulation (16QAM) and Minimum Frequency-shift Keying(MSK) modulation on the transmission performance of data chain system. The simulation results show that 16QAM modulation can meet the requirements of tactical data link system for BER and data transmission rate, and the technical complexity is in the middle; the system BER of MSK modulation is lower, and a large number of data transmission can be realized at high speed. When the SNR reaches 50dB, the BER of MSK modulation can be reduced to 10^{-4} order of magnitude, which is better than Quadrature Phase Shift Keying (QPSK) modulation, that is, the data chain system based on MSK modulation can meet the transmission requirements of data chain when the signal-to-noise ratio is large.

INDEX TERMS Tactical Data-Link, OFDM, OCML, MSK, 16QAM.

I. INTRODUCTION

Tactical data links are systems that transmit, exchange, and process tactical information in real time according to standard message formats and communication protocols [1], [2]. They enable combat units that serve the same tactical purpose but are geographically dispersed to form a cohesive tactical community [3]. Combat units with tactical data links connections can share intelligence and weapon resources in the tactical community to achieve the same tactical purpose, thereby achieving maximum combat effectiveness [4]–[8]. Tactical data links have been used increasingly widely in the military. They can be used to quickly understand combat situations through the transmission of information between combat units, helping to control the overall battle situation [9], [10].

Tactical data links are an important means of transmitting information, but the communication channel is complicated during the transmission process, and the reliability of the data transmission is considerably affected by the surrounding environment [11]. It is therefore critical to ensure the accuracy of the data while transmitting at high speed in a complex environment. Previous studies have generally used soft spread spectrum technology and quadrature phase shift keying (QPSK) modulation technology based on pseudo-random sequences [12], [13]. However, due to the demand for higher data transmission rates, new technologies are still needed. In order to transmit information in real time, the transmission requirements of the system are getting higher and higher. When the bandwidth of the channel is certain, how to transmit a large amount of data more efficiently has become the focus of research nowadays. In order to solve the contradiction between the transmission of large amount of data and limited bandwidth, scientists have proposed various modulation methods. This article introduces an investigation on this issue and analyzes the influence of QAM and MSK modulation on the system data transmission performance. QAM modulation is a double-sideband modulation method that suppresses the carrier [14]. It has the advantages of high-frequency band utilization and strong anti-interference ability [15]. It combines the advantages of PSK and ASK modulation and increases the effective rate of information transmission by multi-decimal, so it has

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significant superiority in decoding rate and band utilization at the receiver side compared with single modulation, and its equipment is also more complex than single modulation. However, with the development of science and technology, its equipment complexity is getting lower and lower. Therefore, QAM-based modulation is a better choice for high-speed transmission systems at present. Minimum frequency-shift keying (MSK) is an improvement over binary frequency-shift keying (2FSK) [16], [17]. The conventional FSK system has been widely used, but its performance is poor in many aspects. FSK not only has a much lower band utilization than 2PSK, but also has a high probability of abrupt phase changes of adjacent code elements, resulting in the modulated signal being transmitted in the band channel with an unstable envelope and undulations. And this kind of undulation is not desired. In general, the two code-element waveforms of a signal are not necessarily strictly orthogonal. However, if the two code elements of a binary signal are orthogonal to each other, the BER performance will be better. In order to overcome the above disadvantages, the FSK signal has been improved and the MSK signal has been developed. As a constant envelope modulation, it has the characteristics of phase continuity, narrow bandwidth, concentrated energy of the main flap of the spectrum, fast decay of the side flap, high spectrum utilization, which makes it have better BER performance in the same bandwidth [18]. Due to its signal characteristics, this type of modulation method is widely used in military communication systems.

II. THEORETICAL BASIS

A. TACTICALDATA LINKS PRINCIPLE

The tactical data link is a transmission system that transmits large-capacity and high-speed information between air and ground. It can ensure that the army can exchange information in real time under the battlefield environment's harsh conditions [6]. Specifically, it provides anti-interference, high-secure voice, and data interaction functions in harsh environments, thereby greatly improving the military's flexibility and operability.

The architecture of the commonly used tactical data link is shown in Figure 1. The components of the data-link system include a data link processor (DLP), a system network controller (SNC), link-level COMSEC, link level communication (LLC), a signal processing controller (SPC), a radiofrequency terminal (radio), and a human-machine interface (HMI) [8], [9]. Among them, the tactical data link processor works at the presentation layer, providing users with data conversion, formatting, and grammar selection. And the tactical data link processor also serves as the interface of the data link SNC. DLP provides the tactical data link system and the tactical data system (TDS) or the common channel signaling (CCS) and the ability to interact with other tactical data links to perform data forwarding. The purpose of the latter is to transmit tactical messages from the transmitting party to one or more destinations and each

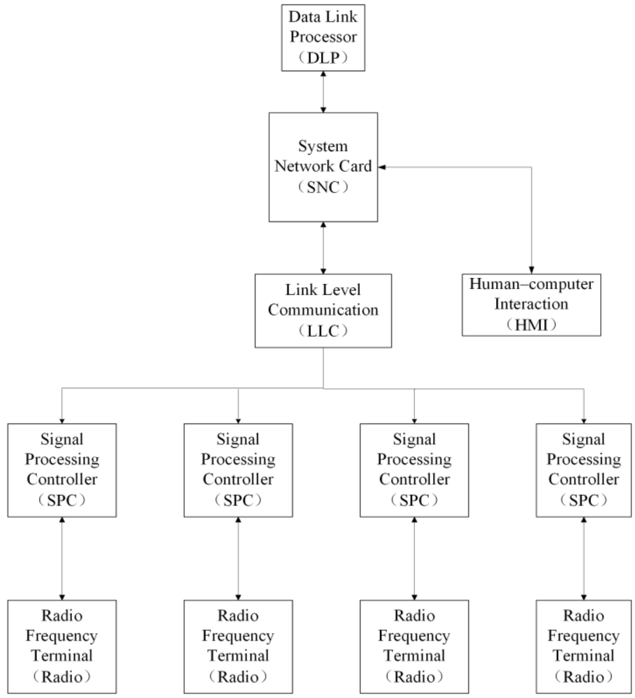

FIGURE 1. Radar data link architecture.

message independent of other messages of the system. The SNC works at the transport layer and the network layer, which provides end-to-end links, and its main function is to act as a messaging service provider to communicate tactical messages. The link-level communication security unit mainly works at the tactical data link layer and the physical layer. It provides point-to-point link connections for the control and data interface between SNCs and no more than four SPCs. Because the four parts of SNC, LLC, SPC, and Radio are encapsulated as a joint tactical radio system, this article only focuses on the DLP module [11].

The main block diagram of the tactical data link studied in this paper is shown in Figure 2. In this system, the technologies used are RS coding, interleaving coding, soft spread spectrum CCSK technology, 16-QAM modulation and demodulation technology, frequency hopping technology, and orthogonal frequency division multiplexing (OFDM) technology. Among them, RS coding and interleaving coding are used to correct random errors and burst errors that occur during transmission. The purpose of soft spreading is to ensure the reliability of transmission through the base sequence and the communication quality during transmission; Frequency hopping is also a spread spectrum technology that can quickly change the frequency to greatly improve the reliability of data transmission. OFDM technology is used to achieve the transmission requirements of large data volumes and a high transmission rate in the data chain.

B. CCSK SPREAD SPECTRUM PRINCIPLE

Cyclic code shift keying (CCSK) is an M-ary soft spreading technique used to select a set of sequences with good

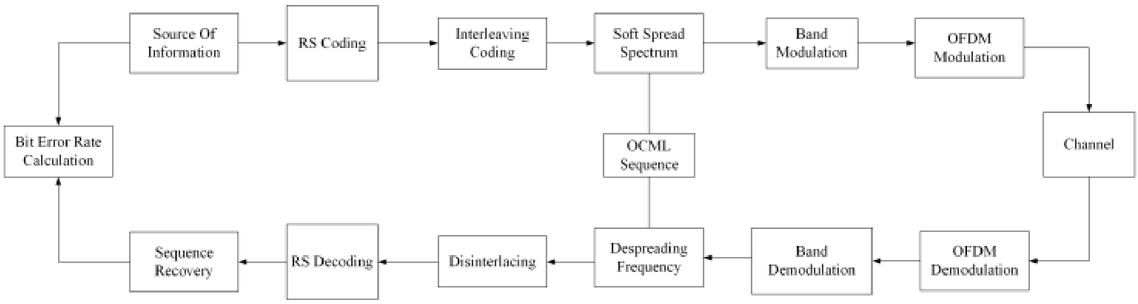

FIGURE 2. Block diagram of air-to-ground radar data-link system.

autocorrelation as the base sequence for spreading [8]. At the same time, the sequence $S_1, S_2, \cdots, S_n$ obtained from S_0 and its cyclic shift is used as a different data information bit, and the information bit also maps the data information sequence to the cyclic shift sequence set. CCSK is an (M, k) coded soft spread spectrum signal, where k represents the spread of k-bit information code each time, M represents the length of the information code after spreading, and the k-bit information code corresponds to 2^k states [19], [20]. Each **k**-bit information code requires 2^k pseudo-random sequences of length M in a one-to-one correspondence. Its spreading frequency is M/K:

$$\frac{R_c}{R_b} = \frac{1}{T_c}\Big/\frac{k}{MT_c} = \frac{M}{K}$$

Among them are the spectrum width of the spread-spectrum signal, the information bit rate, and the symbol width. M is the pseudo-random sequence length, and k is the number of bits of the symbol before the spread spectrum.

As

$$\mathrm{k} = \log_2 M$$

$$G_p = \frac{M}{\log_2 M} = 10\lg\left(\frac{M}{\log_2 M}\right)$$

Among them, G_p is the spreading frequency.

CCSK encoding is a kind of M-ary encoding [21]. When the pseudo-random spreading code and system bandwidth are the same, CCSK dramatically improves the transmission rate of symbol information compared to the binary direct sequence spreading method, and its transmission rate is binary. The k times of the direct sequence spread spectrum significantly improves channel utilization. Simultaneously, under the condition of the same spreading gain, CCSK shows better performance than the binary direct sequence spreading method [22]. When the information transmission rate and system bandwidth are the same, CCSK uses coding to reduce the symbol rate and longer spreading sequences to improve signal detectability [23].

C. THE PRINCIPLE OF ONE-WAY COUPLED MAPPING LATTICE MODEL (OCML)

At present, most of the scrambling code sequences used in tactical data link communication are pseudo-random

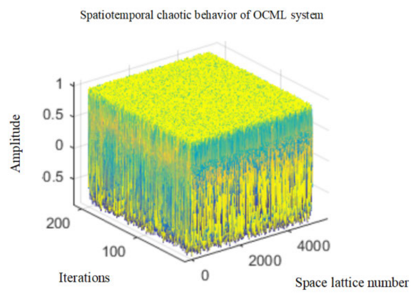

FIGURE 3. Spatiotemporal chaotic behavior of OCML system.

sequences (PN sequences). Still, the CCSK in the research model illustrated in this article requires its base sequence to have proper autocorrelation, and the PN sequence has poor correlation and low sequence complexity [20]. Its security is not high and cannot meet the requirements of CCSK for the base sequence. Therefore, this paper proposes to use OCML spatiotemporal chaotic sequence to improve the CCSK spread-spectrum coding module to enhance the autocorrelation and security of its base sequence.

One-way couple map lattices (OCML) is a higher-dimensional spatiotemporal chaos. It has the advantages of good orthogonality and autocorrelation, invariant distribution, and a large number of sequences [23]. Furthermore, the interaction between its grid points is directional, and there is no mutual influence between adjacent grid points [21]. Finally, its sequence complexity and randomness are higher than other sequences, and it has the advantages of high computational parallelism and fast computational efficiency. For this study's convenience, the OCML state value was mapped in a two-dimensional plane; the state value can be regarded as a matrix with N rows and $\underline{I}$ columns, as shown in Figure 4.

The state values corresponding to different iteration times n and different grid points i selected in the matrix are different, and the corresponding chaotic performance is also uneven. Generally, a chaotic sequence with a large number of iterations and at the upper limit of the iteration has better chaotic characteristics, with better orthogonality and randomness; a chaotic sequence with a small number of iterations and at the beginning of the iteration has better chaotic features [24]–[26].

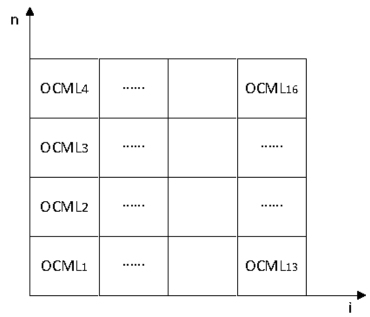

FIGURE 4. OCML two-dimensional plan.

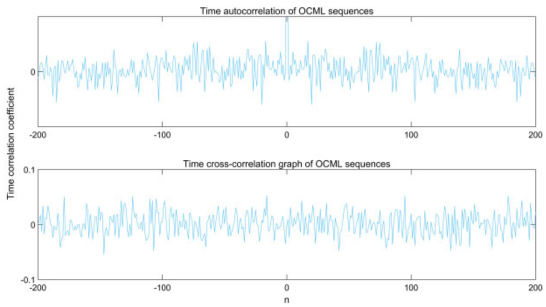

FIGURE 5. OCML correlation result diagram.

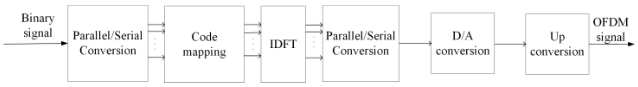

FIGURE 6. Block diagram of OFDM modulation principle.

Figure 5 shows that the autocorrelation of the OCML sequence has an impact at $n = 0$, and the cross-correlation is around 0, which indicates that OCML has good temporal autocorrelation. Furthermore, the sequences are orthogonal to each other, with good orthogonality.

D. OFDM MODULATION PRINCIPLE

The idea of OFDM modulation is to divide a given channel into several orthogonal sub-channels in the frequency domain and use one sub-carrier for modulation on each sub-channel [27]. Each sub-carrier uses parallel transmission, which converts high-speed data signals into parallel low-speed sub-data streams. The frequency spectrum of each sub-carrier is only 1/N of the signal bandwidth, and parallel data stream also ensures that the sub-carriers maintain orthogonality within the OFDM period T. OFDM uses discrete Fourier transform and its inverse transform to solve the problem of generating multiple orthogonal sub-carriers and recovering the original signal from the sub-carriers, which greatly reduces the complexity of the multi-carrier transmission system [21], [28], [29]. The modulation principle is shown in Figure 6.

E. QAM MODULATION PRINCIPLE

QAM modulation is a double-sideband modulation method that suppresses the carrier. It has the advantages of high-frequency band utilization and strong anti-interference ability. QAM modulation includes 16-QAM, 64-QAM,

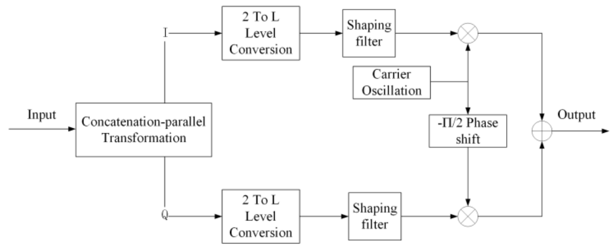

FIGURE 7. Modulation principle diagram of QAM quadrature amplitude modulation method.

256-QAM, and other modulation methods. There are two main ways to generate QAM modulated signals: the compound phase shift method and the quadrature amplitude modulation method [30]–[32]. The modulation principle diagram of the quadrature amplitude modulation method is shown in Figure 7.

It can be seen from the figure 7 that the principle is to divide the input signal into I and Q signals through serial/parallel conversion. After the I and Q signals pass through the level conversion module and shaping filter module, the two channels are divided by a multiplier. The signal is modulated to the carrier frequency. The only difference between the two signals is that their phase difference is 90°. Finally, the two signals are superimposed by the adder to obtain the QAM modulated output signal.

In the 16-QAM modulation mode, there are 16 possible states, which means that every four states of I and Q can be switched from one to the other within each symbol time. When $M = 16$, each symbol is represented by four bits of data (two bits each for I and Q), and its symbol rate is equal to 1/4 of the bit rate.

The expression of QAM modulation is:

$$S_{MQAM}(t) = \sum_n A_n \delta(t - nT_s) \cos(\omega_c t + \varphi_n)$$

Among them, A_n is the amplitude of the baseband signal, $\delta(t - nT_s)$ is a baseband waveform T_s of width, and the orthogonal expression of this formula is

$$\begin{aligned} S_{MQAM}(t) = & \left[\sum_n A_n \delta(t - nT_s) \cos(\omega_c t + \varphi_n)\right] \cos \omega_c t \\ & + \left[\sum_n A_n \delta(t - nT_s) \sin(\omega_c t + \varphi_n)\right] \sin \omega_c t \end{aligned}$$

Make

$$\begin{cases} X_n = A_n \cos \varphi_n \\ Y_n = A_n \sin \varphi_n \end{cases}$$

Bring this formula into the above formula to get:

$$\begin{aligned} S_{MQAM}(t) = & \left[\sum_n X_n \delta(t - nT_s)\right] \cos \omega_c t \\ & + \left[\sum_n Y_n \delta(t - nT_s)\right] \sin \omega_c t \\ = & X(t) \cos \omega_c t + Y(t) \sin \omega_c t \end{aligned}$$

Among them, amplitude X_n and Y_n can also be expressed as

$$\begin{cases} X_n = c_n A \\ Y_n = d_n A \end{cases}$$

where A is a fixed amplitude, c_n and d_n determine the position of the modulated signal in space.

F. MSK MODULATION PRINCIPLE

The simplest type of frequency modulation is 2FSK. It is divided into two types: phase continuous and phase discontinuous. If the phase of 2FSK is continuous and the interval between the two carrier frequencies is 1 / 2 symbol rate, the phase continuous 2FSK is called minimum frequency shift keying (MSK) [31]–[33]. MSK is an orthogonal signals with minimum modulation index ($h = 0.5$), which has a higher bit rate than FSK. The time domain signal corresponding to the K^{th} symbol of the MSK signal can be expressed as

$$S_{MSK}(t) = A\cos\left(\omega_c t + \frac{\pi a_k}{2T_s} t + \varphi_k\right)$$

where ω_c represents the carrier angular frequency; A is the carrier amplitude; a_k stands for bit K information code; T_s represents the symbol width; and φ_k is the phase constant of the k code element, which remains unchanged in time $(k-1)T_s \leq t \leq kT_s$. The function of φ_k is to ensure the signal phase continuity at time $t = kT_s$.

Since the MSK signal has no interruption point in the time domain and the phase is continuous at the moment of code element conversion, its total phase relationship at the time point between the $k-1^{\text{st}}$ symbol and the K^{th} symbol interval should satisfy the following equation:

$$\omega_c t + \frac{\pi a_{k-1}}{2T_s} t + \varphi_{k-1} = \omega_c t + \frac{\pi a_k}{2T_s} t + \varphi_k$$

Furthermore, the expression of the phase constant φ_k can be obtained by simplifying the equation above:

$$\begin{aligned} \varphi_k &= \varphi_{k-1} + \frac{k\pi}{2}(a_{k-1} - \varphi_k) \\ &= \begin{cases} \varphi_{k-1}, & a_k = a_{k-1} \\ \varphi_{k-1} \pm k\pi, & a_k \neq a_{k-1} \end{cases} \end{aligned}$$

The phase constant of the k^{th} symbol depends on the k^{th} information code, the $k-1^{\text{st}}$ information code, and their phase constants. The symbols before and after the MSK signal are therefore strongly correlated [16].

If $\cos\varphi_k = I_k$, $a_k \cos\varphi_k = Q_k$, then the orthogonal expression of MSK signal is as follows:

$$S_{MSK}(t) = I_k A\cos\left(\frac{\pi t}{2T_s}\right)\cos\omega_c t - Q_k A\sin\left(\frac{\pi t}{2T_s}\right)\sin\omega_c t$$

From the structure above, a block diagram of MSK signal quadrature modulation can be obtained, as shown in Figure 8. The MSK signal can be obtained by sequentially performing differential encoding, serial–parallel conversion, two-level modulation, and differentiation of the input information sequence a_k.

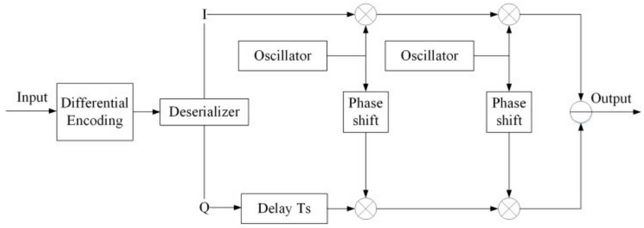

FIGURE 8. Block diagram of MSK orthogonal modulation.

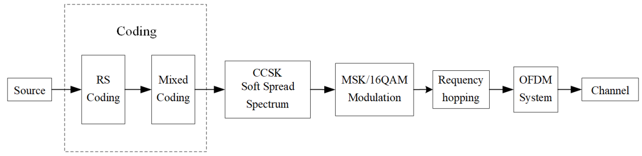

FIGURE 9. Block diagram of data-link system based on MSK&16QAM modulation.

III. SIMULATION OF MSK-BASED DATA LINK

Figure 9 shows a block diagram of the transmitting end of a tactical data link system based on MSK and 16QAM modulation. In this system, the transmitter source sends a Bernoulli signal, which is first encoded using Reed–Solomon (RS) encoding and interleaving encoding. The RS coding provides supervision symbols. When the RS coding rate is smaller, the anti-interference ability of the system is stronger, and the reliability of data transmission is higher [6]. If the RS coding efficiency is too low, however, the data transmission rate decreases, which affects the timeliness of information transmission in the battlefield. So, the simulation in this study used the coding method of RS (15,11).

The receiving end can correct a certain percentage of random errors through RS decoding, thereby increasing the reliability and transmission rate of the data link. The RS-encoded signal is then interleaved and coded. After the RS encoded signal is interleaved, the channel with memory is transformed into the channel without memory. When interleaving is performed at the receiver side, the interleaved code element sequence is restored to the original code element sequence so that the consecutive erroneous code elements can be dispersed, thus correcting the burst errors and further increasing the reliability of the system. The combination of RS coding and interleaving coding can correct the random error and burst error in the transmission process better than using a single encoding method, thus greatly reducing the probability of erroneous code elements during the transmission of signals.

The communication bandwidth used in tactical data links is several hundred megahertz, and so cyclic code-shift keying (CCSK) soft spread spectrum technology was used in the simulation. CCSK coding is an M-decimal coding, and when the pseudo-random spreading codes as well as the system bandwidth are the same, CCSK greatly improves the transmission rate of the code element information compared to the binary direct sequence spreading method, and its transmission rate is k times higher than the binary direct sequence spreading, which improves the channel utilization very well.

The signal undergoes CCSK soft spreading, which maps the shorter sequence to the longer sequence and increases the randomness of the mapping code, which greatly improves the confidentiality of the signal. The reliability of transmission is therefore guaranteed.

Compared to direct spread spectrum technology, CCSK spread spectrum can more effectively expand the sampling rate and increase the transmission rate when the frequency band is narrower and the pseudo-random code rate is lower. The multiple of its expansion can be a non-integer multiple, thus making the spread spectrum more flexible and convenient. CCSK soft spread spectrum has the characteristics of high spectrum efficiency, low detection, low interception, which can greatly improve the reliability and security of the tactical data link. If the channel bandwidth is small, the channel-utilization rate can be improved, enabling large volumes of data to be transmitted.

The signal after CCSK soft spread spectrum is subjected to modulation technology. The most common modulation methods in air–ground radar data links are QAM and QPSK. In the simulation in this work, the MSK modulation method was used to shift the signal to a carrier frequency suitable for channel propagation. The modulation index of the MSK signal is $h = 0.5$. The MSK modulated signal is strictly orthogonal and has a constant envelope, continuous phase, narrow bandwidth, concentrated energy of the main flap of the spectrum, roll-off of the side flap decay quickly, and high spectrum utilization. Due to its signal characteristics, this type of modulation is widely used in military communication systems and can better meet the requirements of air–ground tactical data link signals (high-speed transmission of large volumes of data with limited bandwidth).

Frequency hopping is also a spread spectrum technology. In this simulation, after the signal is modulated by MSK, it is multiplied by the frequency-hopping synthesizer to obtain the frequency-hopping modulated signal. In the tactical data link system based on MSK modulation, the frequency-hopping part uses pseudo-random binary code to control the output frequency of the carrier frequency oscillator. In the frequency-hopping communication system, tens of millions of discrete frequencies can be selected at will, and the selected frequency is determined by the pseudo-random code.

The signal finally passes through the OFDM system. The serial–parallel conversion module in the OFDM system converts the high-speed serial data into a low-speed parallel data stream for transmission and modulates the stream on n sub-carriers with strict orthogonality, thereby reducing the signal rate transmitted on each sub-carrier to the original 1/n. The OFDM system reduces the transmission rate of the signal on each sub-carrier, thereby meeting the transmission requirements of high speed and large data volumes in the air-to-ground radar data chain. Moreover, the OFDM technology can combat interference between signal waveforms and is suitable for high-speed data transmission in multipath environments and fading channels. When frequency selective fading occurs in the channel due to multipath transmission, only the sub-carriers falling in the band recess and the information they carry are affected, and other sub-carriers are not damaged, so the overall bit error rate (BER) of the system is greatly reduced.

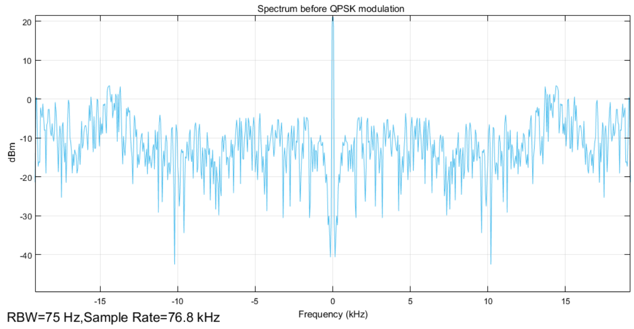

FIGURE 10. Spectrum diagram before QPSK modulation.

The simulation of the tactical data link system based on MSK and 16-QAM modulation was performed using Simulink in MATLAB 2019a. To simulate the influence of external noise interference on the transmission signal, Rayleigh fading and Gaussian white noise were added to the simulation. To compare the impact of the transmission error rate under different conditions, a model of the receiving end was added to the simulation.

IV. SIMULATION PERFORMANCE ANALYSIS

For the 16-QAM modulation tactical data link system, in the process of tactical data link transmission, the frequency bands used are high frequency (HF) and ultra-high frequency (UHF), and the frequency resources are minimal. Therefore, the modulation technology is used to improve its frequency band utilization. In order to compare the effects of different modulation methods on the transmission performance of the tactical data link, this article compares the two modulation methods QPSK and 16-QAM under the same simulation conditions and based on the soft spread spectrum technology of OCML. The specific parameters are set as follows: the initial sampling rate of the simulation is 8.8KHz, the simulation time is 10 seconds, and Rayleigh fading and Gaussian white noise are added in the simulation process.

Figure 10–13 respectively show the spectrum before and after QPSK and 16-QAM modulation.

The figures show that when the initial sampling rate is 8.8kHz, the sampling rate after QPSK modulation is 38.4kHz. The sampling rate after 16-QAM modulation is 19.2kHz, which is the sampling rate after 16-QAM modulation is smaller, therefore, the bandwidth required is also smaller, that is, when transmitting the same amount of data with limited bandwidth, the 16-QAM transmission rate is twice that of QPSK.

As can be seen in Figure 14–16, the waveforms before and after CCSK spreading based on OCML are still 5bit symbols and 32bit symbols in addition to the 5bit delay, indicating that OCML-based CCSK soft spreading can still achieve spread spectrum characteristics. At the same time, the use of

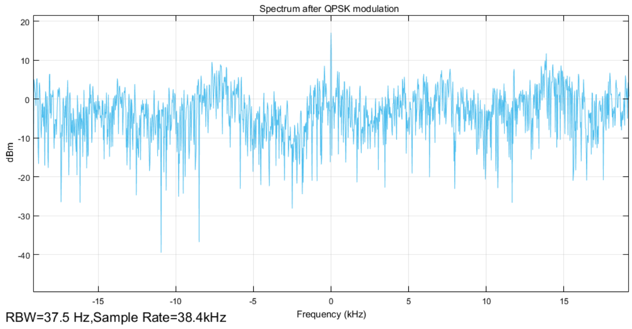

FIGURE 11. Spectrum diagram after QPSK modulation.

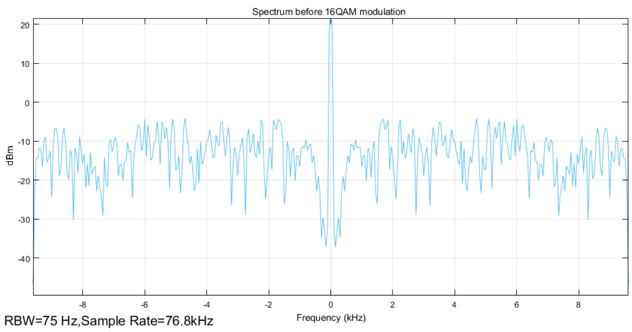

FIGURE 12. Spectrum diagram before 16-QAM modulation.

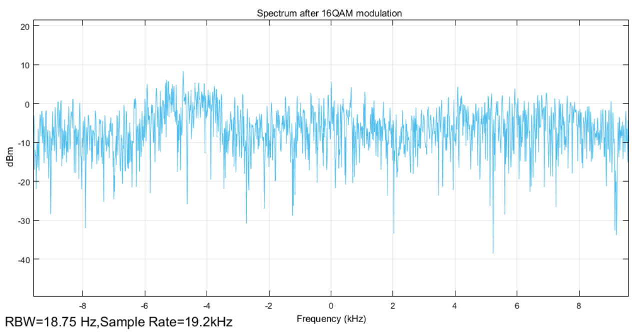

FIGURE 13. Spectrum diagram after 16-QAM modulation.

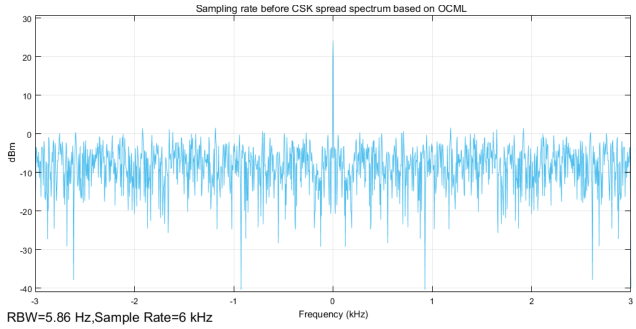

FIGURE 14. Spectrum diagram before CCSK sampling rate based on OCML.

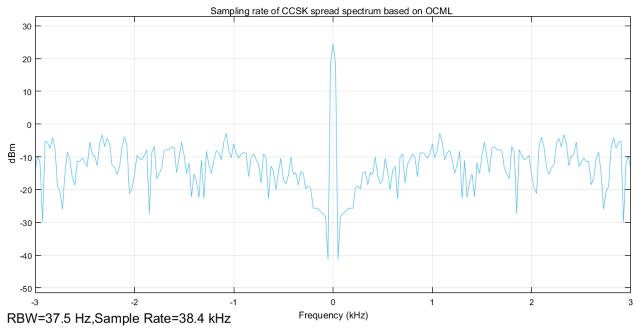

FIGURE 15. Spectrum diagram after CCSK sampling rate based on OCML.

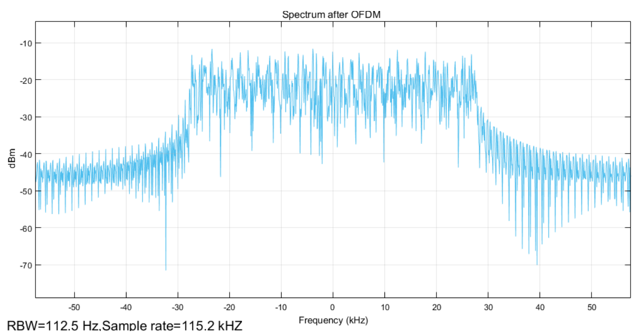

FIGURE 16. Spectrum after OFDM.

OCML sequence did not destroy its spread spectrum capability. In Figure 10, the upper graph illustrates the sampling rate before spreading, showing that the sampling rate is 6KHz, and the lower graph is the sampling rate after spreading; its sampling rate is 38.4KHz. The sampling rate after spreading is still not 32/5 times that before spreading. Therefore, using OCML as the base sequence of CCSK will not destroy its spread spectrum performance.

As shown in Figure 17, the signal waveform at the transmitter side and the signal waveform at the receiver side are randomly intercepted. It can be seen that the signal at the receiving end is basically the same as the signal waveform at the transmitting end. After comparing and analyzing, it can be known that this data chain model system can transmit data information reliably.

Figure 18 and Figure 19 respectively show the relationship between the bit error rate of the tactical data link and the signal-to-noise ratio based on the PN sequence and the OCML sequence.

Figure 18 shows that when based on the PN sequence, the two modulation methods' error conditions are pretty different, and the system based on the 16-QAM modulation method has poor error performance. For example, when the signal to noise ratio is 20dB, the error code rate is 0.13. When it is changed to OCML sequence and the signal-to-noise ratio is 20dB, the bit error rate is reduced to 0.0036, which is reduced by 15.56dB, as shown in Figure 19. The bit error performance of the 16-QAM modulation method has been significantly improved and is close to that of QPSK modulation.

For the simulation based on MSK modulation, the sampling time was set to 0.01/44 s, the sampling number to 44 bit, and the initial sampling rate to 4.4 kHz.

Figures 20–22 show the spectrum before and after MSK modulation and the spectrum after OFDM modulation,

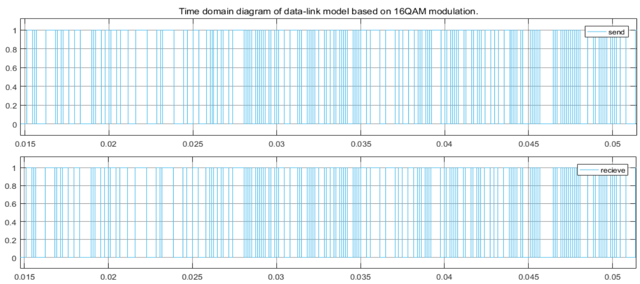

FIGURE 17. Time domain diagram of data-link model based on 16-QAM modulation.

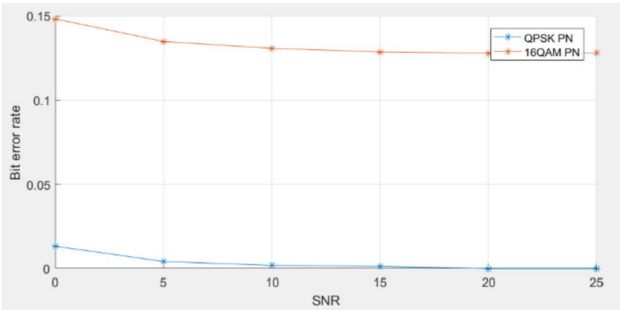

FIGURE 18. Variation of bit error rate with SNR under different modulation methods based on PN sequence.

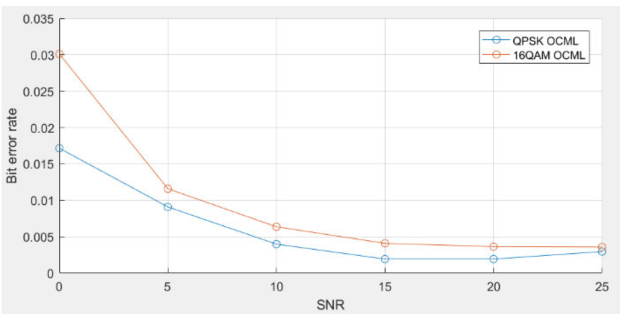

FIGURE 19. Variation of bit error rate with SNR under different modulation methods based on OCML sequence.

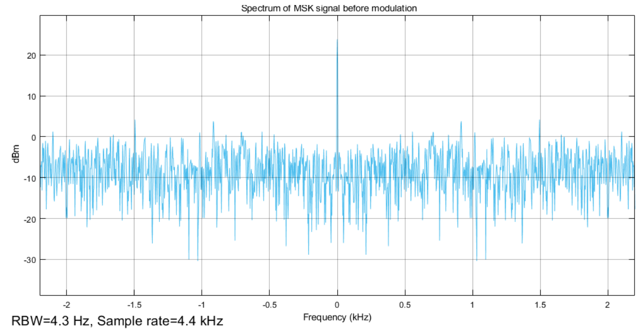

FIGURE 20. Spectrum of MSK signal before modulation.

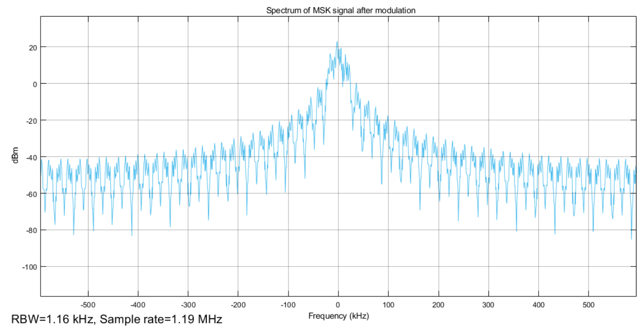

FIGURE 21. Spectrum of MSK signal after modulation.

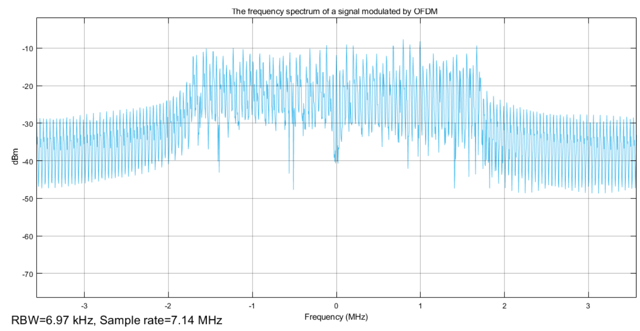

FIGURE 22. The frequency spectrum of a signal modulated by OFDM.

respectively. Before MSK modulation, the signal transmission rate was 38.4 kHz. After passing through the MSK modulator, the sampling rate was 1.19 MHz. After the signal was modulated by OFDM, the transmission rate reached 7.14 MHz. The use of MSK modulation can help the system to transmit large volumes of data at high speed. The spectrum after MSK modulation shows that almost all the signal energy is within 1.5 times the bandwidth of the transmission rate. The out-of-band interference generated by the MSK modulated signal is very small, which makes the transmission reliability of the system higher.

As shown in Figure 23, the signal waveform at the transmitter side and the signal waveform at the receiver side are randomly intercepted. It can be seen that the signal at the receiving end is basically the same as the signal waveform at the transmitting end. After comparing and analyzing, it can be known that this data chain model system can transmit data information reliably.

Finally, the variation of the system BER with the signal-to-noise ratio (SNR) was compared under MSK modulation and QPSK modulation, as shown in Figure 24. Figure 24 shows that the BER of the system decreases as the SNR increases. The BER of the MSK system was about 4.9×10^{-2} when the SNR was 20 dB and about 5.27×10^{-4} when the SNR was 50 dB. As the SNR increased from 20 dB to 50 dB, the BER of the system reduced by 10700 percent. The BER of the QPSK system decreases obviously when the SNR is 0–20dB, but it did not change much when the SNR increased again. The BER was 1.9×10^{-3} when the SNR was 20 dB and 0.8×10^{-3} when the SNR increased to 50 dB. The BER was only reduced by only 50 percent when the SNR increased from 20 dB to 50 dB. As can be seen from the graph, the BER of QPSK modulation method is lower than that of MSK modulation method at 0-45dB, while MSK modulation method is lower than that of QPSK modulation method at greater than 45dB.

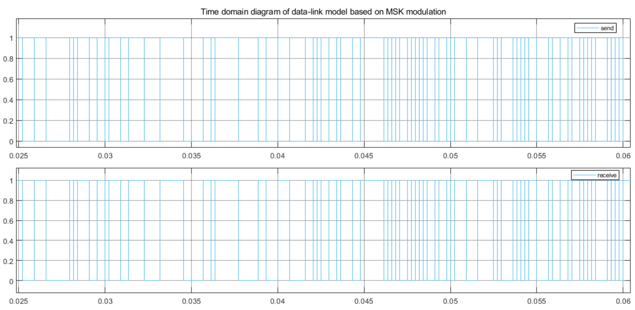

FIGURE 23. Time domain diagram of data-link model based on MSK modulation.

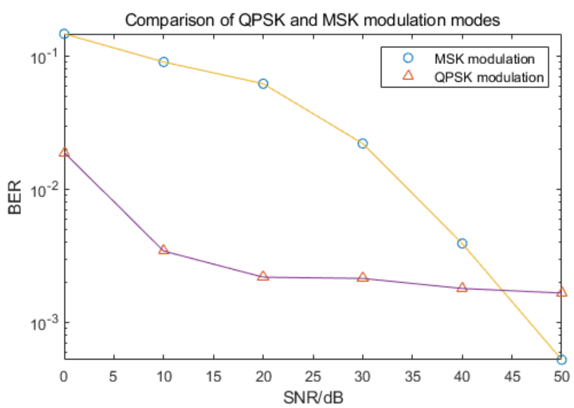

FIGURE 24. Curve of signal-to-noise ratio and bit error rate.

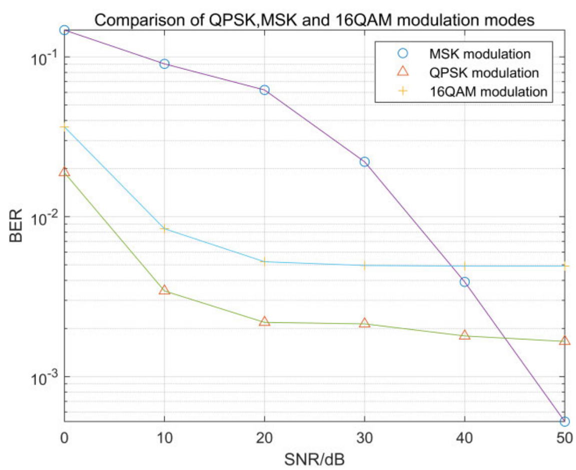

FIGURE 25. SNR and BER curves of three modulation modes.

The simulation results show that in the tactical data link system based on MSK modulation, the information was transmitted at a faster rate after MSK modulation, which can allow large volumes of data to be transmitted at high speed. The SNR curve of the system shows that the BER can be reduced by more than 100 times as the SNR of the system increases. When the SNR is high, the reliability of the data-link system using MSK modulation is significantly higher than that of systems using other modulation methods.

As shown in Figure 25, based on the above two simulation results, the BER of QPSK, MSK and 16-QAM modulation modes under different SNR conditions are compared and analyzed. When SNR is less than 45dB, QPSK modulation has the lowest BER and the best system performance; when SNR is greater than 45dB, MSK modulation has the lowest BER and the best system performance.

Under the harsh conditions where the SNR is small, such as when the SNR is less than 10 dB, the transmission BER of the tactical data link system with 16-QAM modulation is in the range of about $9 \times 10^{-3} - 5 \times 10^{-2}$, while the transmission BER of the tactical data link system with MSK modulation is around 1×10^{-1}, with a large BER. With the increase of SNR, the BER of the tactical data chain system with 16-QAM modulation is basically stable when the SNR is greater than 20 dB, and the BER of the tactical data chain system with MSK modulation decreases rapidly. In summary, the tactical data link system with 16-QAM modulation is more adaptable to the harsh transmission conditions than the tactical data link system with MSK modulation.

V. CONCLUSION

As an important means of information transmission and communication between various units and platforms on the battlefield, tactical data links have become an indispensable part of electronic warfare. It is therefore necessary to investigate how to improve the reliability of tactical data link transmission and ensure the transmission rate of tactical data link.

This paper first introduced some theoretical concepts, such as the tactical data link principle, soft spread spectrum CCSK technology, OCML principle, the OFDM modulation principle, 16-QAM and MSK modulation principle. Through the analysis of the simulation results based on 16-QAM, it can be seen that in order to achieve high-speed data transmission, the 16-QAM modulation based on OCML sequence has significant advantages, which can not only meet the requirements of the tactical data link system for bit error rate, but also meet the requirements of the system for data transmission rate, and the technical complexity is in the middle; Through the analysis of the simulation results based on MSK modulation, it can be seen that when the SNR reached 50 dB, the BER of the MSK modulation-based system can be reduced by 4–10 orders of magnitude, which is better than QPSK modulation. When the SNR is high, the tactical data link system based on MSK modulation can better meet the transmission requirements of tactical data links and has stronger anti-interference, higher security, faster data rate (throughput), more information exchange, and smaller terminal size.

The contribution of this paper is the study of 16-QAM and MSK modulation based on OCML spatiotemporal chaotic sequences for datalink communication. Most of the scrambled sequences used in previous studies of datalink communication systems are pseudo-random sequences (PN sequences), but PN sequences have poor correlation and low sequence complexity and security, and cannot meet the design requirements of the model, while the OCML sequences selected in this paper have several advantages such as good orthogonality and autocorrelation, invariant distribution, and number of sequences, which can make the system have better performance than PN sequences. The performance of the system is better than that of PN sequences. The research in this paper will also continue to play a role in improving the security and transmission efficiency of data chain communication systems of increasing complexity.

REFERENCES

[1] S. Min, "Research on anti-jamming technology of data link transmission waveform," M.S. thesis, Univ. Electron. Sci. Technol. China, Chengdu, China, 2020.

[2] C. Qiang, C. Chen, T. Chen, and M. Cheng, "Simulation of data link communication system and analysis of anti-jamming," *Comput. Simul.*, vol. 32, no. 9, pp. 199–204, 2015.

[3] F. Ling, "Research on signal recognition method of data link-11," Ph.D. dissertation, Dept. Inf. Commun. Eng., Xidian Univ., Xi'an, China, 2014.

[4] X. Li and Z. Li, "Simulation of data link communication system based on simulink," *Modern Electron. Techn.*, vol. 33, no. 3, pp. 29–32, 2010.

[5] Y. Guang, J. Zhou, and P. Luo, "Simulation of data link communication system based on simulink," *J. Syst. Simul.*, vol. 17, no. 17, pp. 4651–4654, 2008.

[6] D. Xie, N. Wu, and C. Wang, "Performance analysis and simulation of RS code in data link system," *J. Microw.*, vol. 2, no. S2, pp. 282–284, 2010.

[7] H. Shen, "The networking research of link11 data link and link11 data link terminal achievement," Ph.D. dissertation, Dept. Commun. Inf., Beijing Univ. Posts Telecommun., Beijing, China, 2014.

[8] W. Zhu, "Research and simulation of JTIDS data link based on CCSK," Ph.D. dissertation, Dept. Electron. Commun. Eng., Xidian Univ., Xi'an, China, 2015.

[9] M. Zhang, "Research on modelling and simulation technology of communication data link," Ph.D. dissertation, Dept. Electron. Commun. Eng., Univ. Electron. Sci. Technol. China, Chengdu, China, 2017.

[10] L. Yan and J. Lu, "Link22-A next generation tactical data link for NATO," *Ship Electron. Eng.*, vol. 1, no. 1, pp. 3–7, 2006.

[11] H. Liu, F. Song, and H. Fang, "Simulation system design of LINK22 network," *Radio Eng.*, vol. 41, no. 6, pp. 1–4, 2011.

[12] B. R. Lee, E. K. Jung, and S. Choe, "Link-16 simulation design over jamming environments and link-16 performance analysis with or without time synchronization," *Telecom Rev.*, vol. 23, no. 2, pp. 261–275, Apr. 2013.

[13] Y. Sun, "Study on properties and applications of pseudo-random sequences," Ph.D. dissertation, Xidian Univ., Xi'an, China, 2013.

[14] F. O. Philip-Kpae and B. O. Omijeh, "Bit error rate and signal to noise ratio performance evaluation of OFDM system with QPSK and QAM M-array modulation scheme in Rayleigh, Rician and AWGN channel using MATLAB/simulink," *Innov. Syst. Des. Eng.*, vol. 8, no. 4, pp. 1–9, 2017.

[15] X. Chen, W. Zhi, and Y. Xiao, "Carrier frequency estimation based on frequency domain and wavelet ridge," *Int. J. Performability Eng.*, vol. 15, no. 8, pp. 2107–2115, 2019.

[16] F. Meng, Z. Teng, and F. Zhou, "Research on modulation recognition method of MSK signals," *Comput. Simul.*, vol. 31, no. 5, pp. 183–186, 2014.

[17] X. Zhao, "The modulation and demodulation of MSK signal," Ph.D. dissertation, Beijing Univ. Posts Telecommun., Beijing, China, 2013.

[18] F. Zhou, S. Fei, and Y. Feng, "Simulation of mechanism and application of quadrature modulated MSK signal in data link," *Fire Control Command Control*, vol. 40, no. 7, pp. 20–23, 2015.

[19] T. Rothman, "Random paths to frequency hopping," *Amer. Scientist*, vol. 107, no. 1, pp. 46–47, 2018.

[20] D. L. Wasden, H. Moradi, and B. Farhang-Boroujeny, "Comparison of direct sequence spread spectrum rake receiver with a maximum ratio combining multicarrier spread spectrum receiver," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2014, pp. 4656–4661.

[21] Z. Danna, N. Wen, Z. Liu, and X. Yang, "Blind separation of soft spread spectrum multiple access signals," *J. Air Fouce Eng. Univ., Natural Sci. Ed.*, vol. 21, no. 4, pp. 49–54, Feb. 2020.

[22] W. Zhu, "Research and simulation of JTIDS data link based on CCSK," Ph.D. dissertation, Dept. Electron. Commun. Eng., Xidian Univ., Xi'an, China, 2015.

[23] S. Rajgopal and O. P. Sahu, "Metrics to define probability of interception of conventional, frequency-hopping, spread spectrum radars," *IETE J. Res.*, vol. 55, no. 6, pp. 304–308, 2009.

[24] P. Wei, "Research on chaotic pseudorandom sequence and its applications," Ph.D. dissertation, Dept. Comput. Softw. Theory, Chongqing Univ., Chongqing, China, 2008.

[25] X.-Y. Wang and X.-M. Bao, "A novel image block cryptosystem based on a spatiotemporal chaotic system and a chaotic neural network," *Chin. Phys. B*, vol. 22, no. 5, May 2013, Art. no. 050508.

[26] A. Qi, "Multiple wings chaotic attractor based on multiple memristors," *Int. J. Performability Eng.*, vol. 16, no. 4, pp. 656–663, 2020.

[27] G. Xuan, Z. Zhang, Z. Bo, and F. Zeng, "Generation of orthogonal sequence sets for M-ary spread spectrum communications with OFDM modulation," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 790, Mar. 2020, Art. no. 012001.

[28] S. Xin and L. Hao, "Principle and key techniques of MIMO-OFDM system for wireless communication," *Foreign Electron. Meas. Technol.*, vol. 29, no. 2, pp. 32–35, 2010.

[29] X. Zhong and X. Wang, "Research on a communication method based on spread spectrum technology," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 252, no. 4, 2019, Art. no. 042070.

[30] M. Xiang, H. Tang, S. Fu, M. Tang, P. Shum, and D. Liu, "Performance comparison of offset-16QAM and 16QAM for nyquist WDM superchannel with digital spectral shaping," *J. Lightw. Technol.*, vol. 33, no. 17, pp. 3623–3629, Sep. 1, 2015.

[31] Z. Dou, X. Zhong, and W. Zhang, "Radar-communication integration based on MSK-LFM spread spectrum signal," *Int. J. Commun., Netw. Syst. Sci.*, vol. 10, no. 8, pp. 108–117, 2017.

[32] J. Zuo, R. Yang, X. Li, and S. Luo, "A study on QAM-OFDM integrated radar and communication signals in radar performance," *Mod. Radar.*, vol. 42, no. 8, pp. 1–5, 2020.

[33] F. I. El-Nahal and N. M. Abualoff, "Coherent optical communication systems based on orthogonal frequency division multiplexing," *Optoelectron. Lett.*, vol. 16, no. 4, pp. 303–305, Jul. 2020.

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