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PAPER

Unconventional Jamming Scheme for Multiple Quadrature Amplitude Modulations

Shaoshuai ZHUANSUN[†a)], **Jun-an YANG**[†], *Nonmembers*, *and* **Cong TANG**[†], *Student Member*

SUMMARY It is generally believed that jamming signals similar to communication signals tend to demonstrate better jamming effects. We believe that the above conclusion only works in certain situations. To select the correct jamming scheme for a multi-level quadrature amplitude modulation (MQAM) signal in a complex environment, an optimal jamming method based on orthogonal decomposition (OD) is proposed. The method solves the jamming problem from the perspective of the in-phase dimension and quadrature dimension and exhibits a better jamming effect than normal methods. The method can construct various unconventional jamming schemes to cope with a complex environment and verify the existing jamming schemes. The Experimental results demonstrate that when the jammer ideally knows the received power at the receiver, the proposed method will always have the optimal jamming effects, and the constructed unconventional jamming scheme has an excellent jamming effect compared with normal schemes in the case of a constellation distortion.

key words: *multi-level quadrature amplitude modulation, orthogonal decomposition, optimal jamming, in-phase, quadrature phase, constellation distortion*

1. Introduction

Multi-level quadrature amplitude modulation (MQAM) is a carrier control scheme that is widely used in medium and large-capacity digital microwave communication systems [1]. This scheme has a high spectrum utilization and a better bit error rate performance than multiple phase shift keying (MPSK). When the modulation order is high, the distribution of the signal vector sets is still reasonable, and it is easy to implement. At present, this modulation scheme is used in large-capacity digital microwave communication systems such as synchronous digital hierarchy (SDH) technology, local multipoint distribution services (LMDS), satellite communication [2] and parallel combinatory spread spectrum communication technology [3].

The current theoretical research on the jamming of MQAM signals mainly includes two aspects. (1) Ignore the influence of the external environment and internal signal interference, perform jamming analysis on pulse amplitude modulation (PAM) signals, and generalize the analysis results to the MQAM signals. Azizoglu investigated the convexity properties of error probability in the detection of the binary-valued scalar signals corrupted by additive noise, and the error probability of the maximum-likelihood receiver is a convex function of the signal power when the noise has a unimodal distribution [4]. In [5], a self-screening jammer is considered for the evaluation of the performance of 4-level PAM (PAM4). It is observed that PAM4 performs much better than conventional radar signals in the presence of a jammer signal, thereby indicating its potential as an effective countermeasure in hostile signal environments. Zhang proposed a method to divide the MQAM channel into several parallel binary-input channels with a constant noise power and provided the design in detail for the MPAM/MQAM. The proposed scheme has good performance in polarization code applications [6]. (2) Assume that the jammed signal is Gaussian and then perform the best jamming analysis under the hypothesis. Sun analyzed the optimal jamming against a QAM signal, and a general formula was deduced for the bit error rate (BER) of an MQAM signal under a two-dimensional digital modulation jamming over an additive white Gaussian noise (AWGN) channel [7] Kashyap considered a zero-sum mutual information game on multiple-input multiple-output (MIMO) Gaussian Rayleigh-fading channels and proved that the knowledge of the channel input is useless to the jammer [8]. Purwar described a simple and efficient way to simulate GPS signals using MATLAB with a focus on investigating GPS signal jamming and devising an anti-jamming technique to counter different jamming scenarios besides AWGN [9]. However, the above studies are not so useful as external noise and internal signal interference cannot be ignored in practical wireless environments, and it is also impractical to assume that the jammed signal has a Gaussian property. Therefore, the analysis results of the above methods are not applicable in practical jamming tasks.

In practical jamming tasks, the coherence characteristics between signals are often used to jam target signals by constructing similar signals [10]. However, this method has no strict theoretical basis and cannot guarantee that it is the optimal jamming method, and too large signal power waste resources. In addition, the jamming signal is constructed according to known modulation schemes, such as binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), and 16 quadrature amplitude modulation (16QAM). In some special circumstances, if the target signal constellation is distorted [11], the true optimal jamming parameters cannot be obtained with existing methods. Therefore, the core problem of the jamming task is as follows: for a power-limited jammer, how to choose the lowest jamming power,

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[†]The authors are with Electronic Countermeasure Institute, National University of Defense Technology, No. 460, Huang Shan Road, Shu Shan District, Hefei, Anhui, China.
a) E-mail: zhuansunss@sina.com
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and the optimal jamming scheme to achieve the expected jamming effect.

Aiming at the above problems, this paper proposes an optimal jamming method for the MQAM signal based on orthogonal decomposition (OD). The method decomposes the MQAM into two PAM signals for analysis and constructs signals from the in-phase dimension (I-phase) and orthogonal dimension (Q-phase). The jamming performance is analyzed by combining the symbol error rate (SER) of the two PAM signals. Then, the particle swarm optimization algorithm (PSO) is used to solve the optimization problem, and finally, the jamming of the MQAM signal is completed. Compared with existing jamming methods, the proposed method has a comparable performance and can achieve better jamming effects under constellation distortion conditions. In general, the purpose of this paper is to show that the unconventional jamming scheme proposed in this paper always has the best jamming performance when directed against MQAM in different environment scenarios. The contribution of this paper is to overcome the shortage of existing methods that have few jamming schemes and low jamming effects in jamming tasks. With the proposed unconventional jamming scheme, the jammer in [12] can make use of the characteristics of trial and error of reinforcement learning (RL) to select and use the best jamming scheme.

2. Orthogonal Decomposition

For communicators who use the PAM modulation scheme, the transmitter generates waveforms of different magnitudes based on the encoded information and the carrier frequency and then transmits the generated signals via the antenna. The received signal becomes a low-pass signal after coherent demodulation, and the low-pass equivalent of the signal [13] has the following form:

$$s(t) = \sum_{m=-\infty}^{\infty} \sqrt{P_T} s_m g(t - mT) \tag{1}$$

where P_T denotes the power of the transmitted signal at the receiver, $g(t)$ represents the real pulse waveform, T stands for symbol period, and s_m represents the transmitted modulation symbol, with a discrete uniform distribution $f_S(s)$, i.e., all possible constellation points are equally likely and are transmitted with the same probability. Without the loss of generality, the average energy of $g(t)$ and modulated symbols $E\left(|s_m|^2\right)$ are normalized to unity.

After the jamming is performed to the communication signal, the low-pass equivalent of the jamming signal at the receiver is:

$$j(t) = \sum_{m=-\infty}^{\infty} \sqrt{P_J} j_m g(t - mT) \tag{2}$$

where P_J denotes the power of the jamming signal at the receiver and j_m represents the modulated jamming signal with a discrete uniform distribution $f_J(s)$. The jammer can determine the values of P_T and P_J by the positioning technique and the path transmission loss formula [14], and the jammer can analyze the jamming performance only when the above conditions are met. If the above conditions are not satisfied, then the jammer can only abandon the optimization algorithm and choose the RL method to learn the best jamming scheme.

Assuming that the receiver and the transmitter are completely synchronized and that there is a jamming signal in the transmission channel, after filtering, coherent demodulation, sampling, etc., the received signal waiting for the decision has the following form:

$$r_k = r(t = kT) = \sqrt{P_T} s_k + \sqrt{P_J} j_k + n_k, k = 1, 2, \cdots \tag{3}$$

where n_k denotes the noise signal with distribution $f_N(n)$ and assumes that the samples of the communication signal s_k, jamming signal j_k, and noise signal n_k are statistically independent. In other words, we ignored the influence of the antenna gains, channel coefficients, multiplicative noise, amplitude limitation, notch and other factors in the wireless communication. We will relax this assumption in Sect. 4.5. The symbol error rate of the signal is calculated with Eq. (4).

$$\zeta = 1 - \sum_{m=0}^{M-1} \pi_m \int_{\Gamma_m} \mathrm{E}\left\{ f_N\left(r - \sqrt{P_T} s_k - \sqrt{P_J} j_k\right)\right\} dr \tag{4}$$

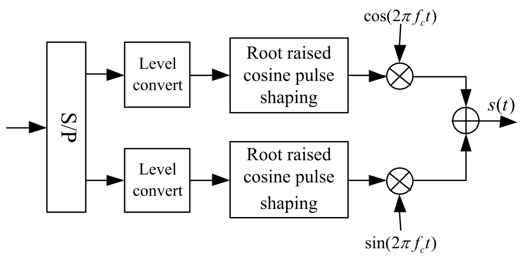
where π_m indicates the probability that symbol s_m is sent and Γ_m means the corresponding decision area.

For an MQAM signal with $M = 2^k$ signal points, which is equivalent to a PAM signal on two orthogonal carriers, the I-phase of the PAM signal has $X = 2^{k_1}$ signal points and the Q-phase has $Y = 2^{k_2}$ signal points, where $k_1 + k_2 = k$ and $X * Y = M$. For common MQAM modulation schemes such as QPSK, 16QAM, 64QAM, and 256QAM, the I-phase and Q-phase have the same number of signal points, i.e., $X = Y$. For 8QAM, 32QAM, 128QAM and other modulation schemes, the I-phase and Q-phase have different numbers of signal points, i.e., $X \neq Y$. Because the two signal components are orthogonal in phase that can be completely separated in the demodulator, the symbol error rates $\zeta^{(1)}$ and $\zeta^{(2)}$ of the two signals can be calculated by Eq. (4), and jointly determine the symbol error rate ζ of the MQAM signal. Superscripts (1) and (2) indicate that the marked parameters belong to the I-phase and Q-phase, respectively.

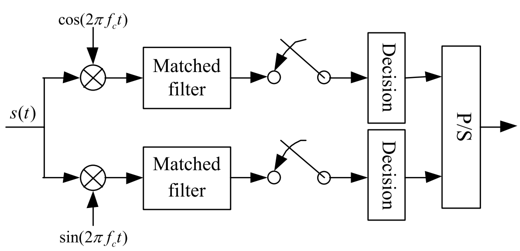
$$\zeta = 1 - \left(1 - \zeta^{(1)}\right)\left(1 - \zeta^{(2)}\right) \tag{5}$$

Figure 1 shows a block diagram of the modulating and demodulating process of the MQAM signals. The generation and recovery processes of the MQAM signal are performed independently by the I-phase and Q-phase, where f_c is the carrier frequency. The jammer performs jamming to the above two phases separately, which is beneficial for the reasonable distribution of the jamming power, thereby achieving more excellent jamming effects.

For the jammer, the value of the jamming power after demodulation is $P_J \in [P_{J(\min)}, P_{J(\max)}]$, $P_{J(\min)}$ and $P_{J(\max)}$ are the minimum and maximum jamming power, respectively. To achieve the expected symbol error rate ζ_E, it is necessary to determine the power of the jamming signal and



(a) Modulation process of the MQAM signal



(b) Demodulation process of the MQAM signal

Fig. 1 Modulation and demodulation process of the MQAM signal.

plan a reasonable allocation of power between the I-phase and Q-phase. On the one hand, the jamming effect should meet the jamming demand ζ_E; on the other hand, the jamming power should be as low as possible to avoid interference with our communications. The objective function of the jammer is shown in Eq. (6).

$$\begin{cases} minimize: & P_J^{(1)}, P_J^{(2)} \\ subject\ to: & \zeta \geq \zeta_E \\ & P_J = P_J^{(1)} + P_J^{(2)}, P_J \in [P_{J(\min)}, P_{J(\max)}] \end{cases} \tag{6}$$

where $P_J^{(1)}$ and $P_J^{(2)}$ are the components of jamming power in I-phase and Q-phase, respectively. By solving Eq. (6), the PSO algorithm [14] can be used to optimize the optimal jamming parameters. The PSO algorithm was proposed by Eberhart in 1995 because of its simple formula, lack of gradient information, lack of parameters to adjust, and ease of programming, It has been widely used in many fields, such as nonlinear programming, vehicle path problems, constrained layout optimization, advertising resource optimization, multi-objective optimization, automatic target detection, real-time path planning of robots and other problems. Figure 2 shows the flow chart for the PSO algorithm, and the particle updating method is shown in Eq. (7) and Eq. (8).

$$V_i = wV_{i-1} + C_1 rand(Pbest - pl) + C_2 rand(Gbest - pl) \tag{7}$$

$$pl = pvl + V_i \tag{8}$$

where V_i is the current velocity, V_{i-1} is the previous velocity, w is the inertia weight, C_1 and C_2 are the learning factors, *pl* is the present location of the particle, *pvl* is the previous position of the particle, and *rand* is the random number between (0, 1).

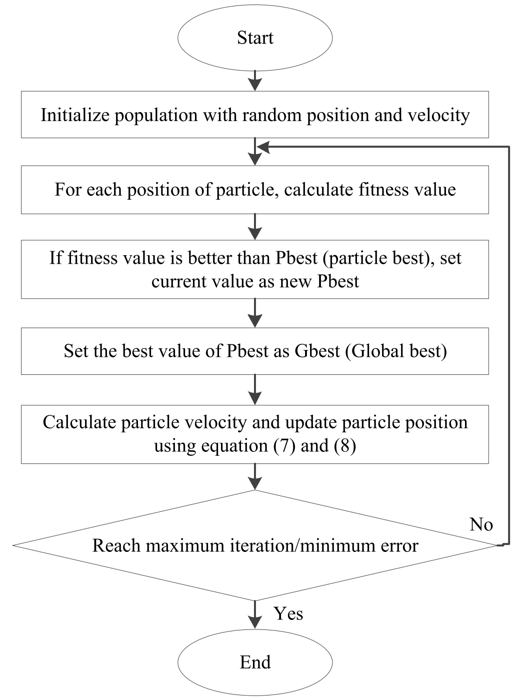


Fig. 2 Flow chart for the standard PSO algorithm.

The parameter w employed in Eq. (7) is used to balance the global detection ability and local search ability of the PSO algorithm. With a proper w value, the PSO algorithm can find the global optimal solution.

The OD method considers the communication signal as a composite signal composed of the I-phase signal and Q-phase signal. The modulation schemes of the two signals are in the form of the PAM and may have respective power and signal points. When analyzing the signal, the two signals after decomposition are analyzed independently, but the analysis results of the two signals jointly determine the characteristics of the synthesized signal. The jamming method based on the OD generates signals from the I-phase and Q-phase, which constitute a jamming signal. The two phase signals are separated by coherent demodulation at the receiver and jam against the I-phase and Q-phase of the target signal. According to Eq. (5), the symbol error rate caused by the jamming signal can be calculated.

The advantage of using the OD method lies in its ability to construct different jamming schemes with various power allocations. For example, for the conventional QPSK scheme, its I-phase and Q-phase have the same power, and the two phases are orthogonal to each other and have the same amplitude levels. When the ratio of $P_J^{(1)} : P_J^{(2)} = 5 : 1$ and the amplitude levels of the two phases are 4 and 2, the modulation scheme of the composite signal is the conventional 8QAM, and the Euclidean distance between neighboring signal points is equal. However, for the jammer who adopts the proposed OD algorithm, it is not intended to divide the power uniformly or integer times in the I-phase and Q-phase. If the ratio of the I-phase power to the Q-phase power belongs to other non-integer values, then an uncon-

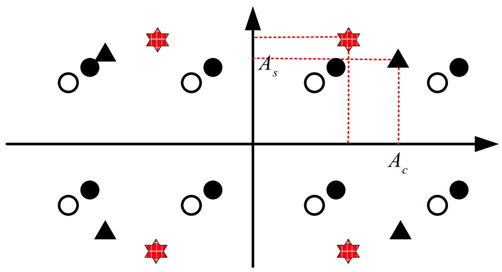


Fig. 3 Jamming with constellation distortion signals.

ventional modulation signal will be synthesized at this time, as shown by the black triangle in Fig. 3.

Taking the communication signal using the 8QAM as an example, the ideal constellation (shown by a white circle) is distorted (shown by a black circle) due to noise, continuous wave interference, carrier suppression, compression gain, etc. In view of this effect, the optimal jamming signal constellation (shown by the hexagonal star) without noise also needs a corresponding change (shown by the triangle) to achieve the optimal jamming. The new jamming signal constellation is apparent, whose amplitudes of the points are no longer equal or in integer multiples but, are closely related to the distorted constellation, and there are various possible relationships. When constructing a jamming scheme with such a special constellation, only the OD method can be used to obtain the values of the optimal jamming power of I-phase and Q-phase. The OD method is no longer limited to the selection of a known jamming scheme, but from the fundamental factors, namely, the jamming power of the I-phase and Q-phase, the problem of finding the optimal jamming scheme is converted to the distribution of jamming power in the I-phase and Q phase.

3. Optimal Jamming in Different Environments

Due to the difference between jamming environments, the communication signals in the different states are jammed, and the optimal jamming methods used are also quite different. The following is an analysis of the optimal jamming method for the jammer in an AWGN environment, an asynchronous state and a constellation distortion environment.

3.1 Optimal Jamming in AWGN Environment

In a practical wireless channel, most of the noise jamming can be decomposed into many independent noises, and a type of noise has a Gaussian distribution that is widely present in wireless communication channels. For ease of analysis, this section assumes that the demodulated noise term is AWGN with mean zero and variance $\delta_n^2 = N_0/2$, and the number of signal points for the I-phase and Q-phase of the MQAM signal are X and Y. After the calculation, the symbol error rate of the X-ary PAM signal [16] is:

$$\zeta^{(1)} = \frac{(X-1)}{4X}\left\{Q\left(\sqrt{\frac{P_T^{(1)}}{N_0}} + \sqrt{\frac{P_J^{(1)}}{N_0}}\right) + Q\left(\sqrt{\frac{P_T^{(1)}}{N_0}} - \sqrt{\frac{P_J^{(1)}}{N_0}}\right)\right\} \tag{9}$$

The symbol error rate of the Y-ary PAM signal in the Q-phase is:

$$\zeta^{(2)} = \frac{(Y-1)}{4Y}\left\{Q\left(\sqrt{\frac{P_T^{(2)}}{N_0}} + \sqrt{\frac{P_J^{(2)}}{N_0}}\right) + Q\left(\sqrt{\frac{P_T^{(2)}}{N_0}} - \sqrt{\frac{P_J^{(2)}}{N_0}}\right)\right\} \tag{10}$$

The objective function of the jammer is shown in Eq. (11).

$$\begin{cases} \mathit{minimize}: & P_J^{(1)}, P_J^{(2)} \\ \mathit{subject\ to}: & \zeta^{(1)} + \zeta^{(2)} - \zeta^{(1)} * \zeta^{(2)} \geq \zeta_E \\ & P_J = P_J^{(1)} + P_J^{(2)}, P_J \in [P_{J(\min)}, P_{J(\max)}] \end{cases} \tag{11}$$

3.2 Optimal Jamming in the Asynchronous State

In the jamming process, due to the influence of the transmission delay, noise jamming and other factors, the jamming signal and the communication signal will be asynchronous [17], which mainly includes phase asynchronous and time asynchronous behaviors. When the phase is not synchronized, Eq. (3) has the following form.

$$\begin{aligned} r_k &= r(t = kT) = \sqrt{P_T}s_k + \sqrt{P_J}j_k e^{i\theta_k} + n_k \\ k &= 1, 2, \cdots, \theta_k \in [0, 2\pi) \end{aligned} \tag{12}$$

where $\theta_k \in [0, 2\pi)$, and its expected value in Eq. (12) is $E\left(e^{i\theta_k}\right) = \int_0^{2\pi} \theta_k \cdot e^{i\theta_k} d\theta_k = 2/\pi$, which represents the influence of the phase asynchronous effects on the jamming power and will lower the impact of jamming at the victim receiver.

When the time is not synchronized, Eq. (3) changes to:

$$\begin{aligned} r_k &= \sqrt{P_S}s_k + \sqrt{P_J}j_k g(t - mT - \tau)] + n_k \\ k &= 1, 2, \cdots, \quad \tau \in [0, T) \end{aligned} \tag{13}$$

where τ denotes the time offset and $E\left[g(t - mT - \tau)\right] = 1/2$.

In other words, influenced by the asynchronous phenomenon between the jamming signal and communication signal, the effective power of the jamming signal will be attenuated, and the value of the attenuation factor γ is shown in Eq. (14).

$$\gamma = \begin{cases} 2/\pi, & \text{phase asynchronous} \\ 1/2, & \textit{time}\ \text{asynchronous} \end{cases} \tag{14}$$

At this time, Eq. (9)–Eq. (10) can be written in the form of Eq. (15)–Eq. (16).

$$\zeta^{(1)} = \frac{(X-1)}{4X}\left\{Q\left(\sqrt{\frac{P_T^{(1)}}{N_0}} + \sqrt{\frac{P_J^{(1)} * \gamma}{N_0}}\right) + Q\left(\sqrt{\frac{P_T^{(1)}}{N_0}} - \sqrt{\frac{P_J^{(1)} * \gamma}{N_0}}\right)\right\} \tag{15}$$

$$\zeta^{(2)} = \frac{(Y-1)}{4Y}\left\{Q\left(\sqrt{\frac{P_T^{(2)}}{N_0}} + \sqrt{\frac{P_J^{(2)} * \gamma}{N_0}}\right) + Q\left(\sqrt{\frac{P_T^{(2)}}{N_0}} - \sqrt{\frac{P_J^{(2)} * \gamma}{N_0}}\right)\right\} \tag{16}$$

The objective function of the jammer is shown in Eq. (17)–Eq. (18).

$$\begin{cases} \textit{minimize}: & P_J^{(1)}, P_J^{(2)} \\ \textit{subject to}: & \zeta^{(1)} + \zeta^{(2)} - \zeta^{(1)} * \zeta^{(2)} \geq \zeta_E \\ & P_J = P_J^{(1)} + P_J^{(2)}, P_J \in [P_{J(\min)}, P_{J(\max)}], \theta_k \in [0, 2\pi) \end{cases} \tag{17}$$

$$\begin{cases} \textit{minimize}: & P_J^{(1)}, P_J^{(2)} \\ \textit{subject to}: & \zeta^{(1)} + \zeta^{(2)} - \zeta^{(1)} * \zeta^{(2)} \geq \zeta_E \\ & P_J = P_J^{(1)} + P_J^{(2)}, P_J \in [P_{J(\min)}, P_{J(\max)}], \tau \in [0, T) \end{cases} \tag{18}$$

3.3 Optimal Jamming in a Constellation Distortion Environment

Taking the imbalances between the I-phase and Q-phase as an example [18], it is also assumed that the noise term is AWGN with a mean of zero and variance $\delta_n^2 = N_0/2$, and the phase between the jamming signal and the communication signal is completely matched, the constellation of the communication signal is offset $\delta^{(1)}$ to the right, and offset $\delta^{(2)}$ in the upward direction, according to Eq. (3):

$$\begin{aligned} r_k = r(t = kT) = \sqrt{P_T}s_k + \sqrt{P_J}j_k + \delta + n_k \\ k = 1, 2, \cdots, \quad \delta = \left[\delta^{(1)}, \delta^{(2)}\right] \end{aligned} \tag{19}$$

At this time, the symbol error rate of the I-phase and Q-phase is calculated as:

$$\zeta^{(1)} = \frac{(X-1)}{4X}\left\{Q\left(\sqrt{\frac{P_T^{(1)}}{N_0}} \pm \sqrt{\frac{P_J^{(1)}}{N_0}} \pm \frac{\delta^{(1)}}{N_0}\right)\right\} \tag{20}$$

$$\zeta^{(2)} = \frac{(Y-1)}{4Y}\left\{Q\left(\sqrt{\frac{P_T^{(2)}}{N_0}} \pm \sqrt{\frac{P_J^{(2)}}{N_0}} \pm \frac{\delta^{(2)}}{N_0}\right)\right\} \tag{21}$$

The objective function of the jammer is shown in Eq. (22).

$$\begin{cases} \textit{minimize}: & P_J^{(1)}, P_J^{(2)} \\ \textit{subject to}: & \zeta^{(1)} + \zeta^{(2)} - \zeta^{(1)} * \zeta^{(2)} \geq \zeta_E \\ & P_J = P_J^{(1)} + P_J^{(2)}, P_J \in [P_{J(\min)}, P_{J(\max)}], \delta = \left[\delta^{(1)}, \delta^{(2)}\right] \end{cases} \tag{22}$$

4. Simulations

Taking the communicators who adopt MQAM as an example [1]–[3], we assume that $P_T = 100$ W, the noise power $N_0/2 = 1$ W [13], $P_J \in [50, 300]$ W and $\zeta_E = 0.38$. To verify the jamming performance of the OD method, this method is compared with the AWGN jamming, 16QAM jamming, BPSK jamming and jamming bandit learning (JB learning) algorithms [12]. In the PSO algorithm, we set $C_1 = 2$, $C_2 = 2$, and employ a linear strategy for decreasing the inertia weight w [19]. In addition, the particle population is set to 20, and the number of iterations is set to 30.

4.1 Optimization Parameters

In the jamming tasks, the jammer expects to achieve the desired jamming effect ζ_E, and at the same time expects the jamming power to be as low as possible. Therefore, in Eq. (11), Eq. (17), Eq. (18) and Eq. (22), the objective of optimization is $P_J^{(1)}$ and $P_J^{(2)}$, and the constraint conditions are $\zeta \geq \zeta_E$ and $P_J \in [P_{J(\min)}, P_{J(\max)}]$. If the optimization parameters change to $-\zeta$ and the restriction conditions are $\zeta \geq \zeta_E$ and $P_{J(\min)} \leq P_J = P_J^{(1)} + P_J^{(2)} \leq P_{J(\max)}$, the comparison of the two optimization parameters is given in Table 1, where the unit of power is watts.

It can be seen that with a given ζ_E value, the two objective functions mentioned above are optimized, and both results meet the expected jamming effect, where $\{15.681, 34.319\}$ represents the jamming power $P_J = 50$ W, the I-phase jamming power $P_J^{(1)} = 15.681$ W, and the Q-phase jamming power $P_J^{(2)} = 34.319$ W. However, for the latter three objective functions, no matter what the value of ζ_E is, the jammer will minimize the value of $-\zeta$ by increasing the jamming power. Although the expected SER is satisfied, the requirement of power minimization is not satisfied. Hence, we employed $P_J^{(1)}$ and $P_J^{(2)}$ as the optimization parameters.

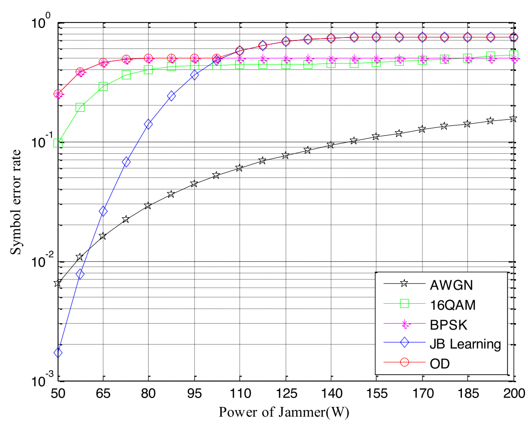
4.2 Jamming Method in the AWGN Environment

JB is a jamming strategy learning algorithm based on RL. This algorithm assumes that when the jammer chooses the jamming power and the jamming scheme to generate the jamming signal, it can only choose randomly from the BPSK, QPSK, and AWGN, then learns the optimal jamming scheme by trial and error. Because the jammer can only choose from the above three schemes, after many interactions, the optimal jamming scheme can only be one of the three, which is QPSK. When using TCP/IP as the communication protocol, the receiver should send acknowledge/no acknowledge (ACK/NACK) frames to the transmitter as a response, and sometimes the frames are not encrypted. If a jammer counts the number of ACK/NACK frames, then the packet error rate (PER) can be easily calculated, and can be used to estimate the SER with $SER = 1-(1-PER)^{1/H}$, where H represents the bit numbers in the frame check sequence. Therefore, according to the feedback from the receiver, the optimal jamming scheme is learned.

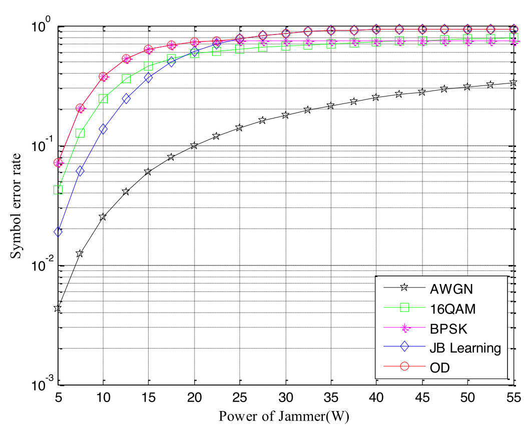
When the noise belongs to AWGN with a zero mean and 1 variance, the communicators adopt QPSK and 16QAM for communication. To achieve the expected SER, the optimal jamming parameters are calculated according to Eq. (11). The results show that the optimal jamming power

Table 1 Comparison of the different optimization parameters

Objective functions	AWGN	phase asynchronous	time asynchronous	constellation distortion
$\min(P_J^{(1)}, P_J^{(2)})\,, st.\, \zeta \geq \zeta_E = 0.25, P_J \in [P_{J(\min)}, P_{J(\max)}]$	{50.001, 0}	{78.541, 0}	{100.001, 0}	{15.681, 34.319}
$\min(P_J^{(1)}, P_J^{(2)})\,, st.\, \zeta \geq \zeta_E = 0.35, P_J \in [P_{J(\min)}, P_{J(\max)}]$	{58.771, 0}	{86.993, 0}	{110.764, 0}	{33.108, 22.469}
$\min(P_J^{(1)}, P_J^{(2)})\,, st.\, \zeta \geq \zeta_E = 0.45, P_J \in [P_{J(\min)}, P_{J(\max)}]$	{63.637, 0}	{99.961, 0}	{127.273, 0}	{88.327, 0}
$\min(-\zeta)\,, st.\, \zeta \geq \zeta_E = 0.25, P_J \in [P_{J(\min)}, P_{J(\max)}]$	{80.065, 80.065}	{125.912, 125.912}	{150, 150}	{110.421, 138.623}
$\min(-\zeta)\,, st.\, \zeta \geq \zeta_E = 0.35, P_J \in [P_{J(\min)}, P_{J(\max)}]$	{80.065, 80.065}	{125.912, 125.912}	{150, 150}	{110.421, 138.623}
$\min(-\zeta)\,, st.\, \zeta \geq \zeta_E = 0.45, P_J \in [P_{J(\min)}, P_{J(\max)}]$	{80.065, 80.065}	{125.912, 125.912}	{150, 150}	{110.421, 138.623}



(a) Jamming against the QPSK signal in the AWGN environment



(b) Jamming against the 16QAM signal in the AWGN environment

Fig. 4 Jamming against the QPSK and 16QAM signals in the AWGN environment.

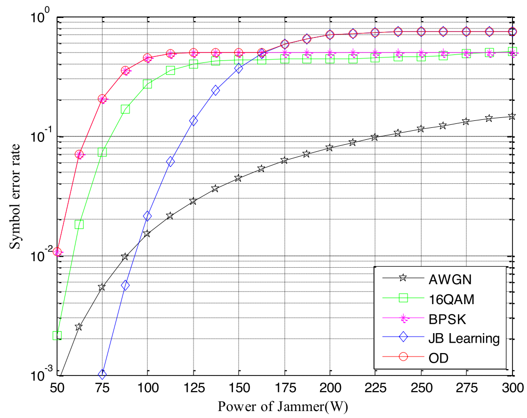
for the QPSK signal is 57.314 W, and the jamming scheme is BPSK. The optimal jamming power for the 16QAM signal is 10.075 W, and the jamming scheme is BPSK. Figure 4 shows the performance of jamming against QPSK and 16QAM signals in the AWGN environment.

Figure 4(a) shows that when the jamming power is small, the BPSK signal has the optimal jamming effect. When the jamming power is large, the JB learning algorithm learns that QPSK has the optimal jamming effect. Comparing the SER curves of the different jamming methods, it can be found that the OD algorithm always has the optimal jamming effect regardless of the jamming power; that is, the optimal jamming scheme obtained by OD is consistent with the method adopted under practical conditions. From Fig. 4(b), a conclusion similar to Fig. 4(a) can be drawn, i.e., when the jamming power is small, the BPSK signal has the optimal jamming effect, and when the jamming power is large, QPSK has the optimal jamming effect. The above results show that the jamming signal similar to the communication signal does not always have the optimal jamming effect. Comparing Fig. 4(a) with Fig. 4(b), it can be found that the optimal jamming scheme for 16QAM is QPSK when the jamming power is large, but the optimal jamming scheme for the QPSK signal is not 16QAM, indicating that the jamming relationship between different modulation schemes is not reciprocal.

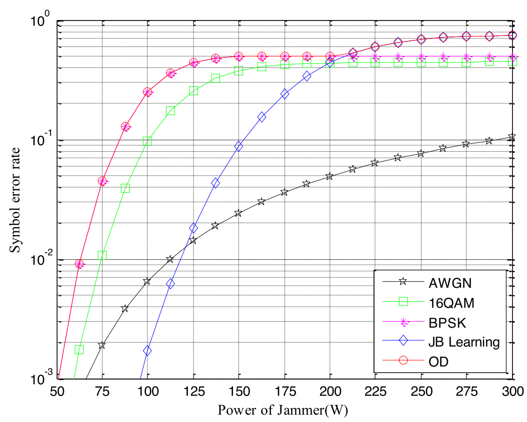
4.3 Jamming Method in the Asynchronous State

Due to the non-synchronization between the jamming signal and the communication signal, the effective jamming power will have certain attenuation. Therefore, in the simulation process, the value range of the jamming power is set to [50, 300] W, and the demodulated noise parameters are consistent with Sect. 4.1. Figure 5 shows the jamming performance of different jamming methods against the QPSK signal in an asynchronous state.

It can be seen from Fig. 5 that, whether it is a phase asynchronous or a time asynchronous state, BPSK has the optimal jamming effect when the jamming power is low, and when the jamming power is high, the JB learning algorithm also learns that the QPSK signal has the optimal jamming effect. In Fig. 5(a), the optimal jamming power is 90.055 W, and the jamming scheme is BPSK to achieve the expected jamming effect. In Fig. 5(b), the optimal jamming power is 114.636 W, and the jamming effect is also achieved when the jamming scheme is BPSK. However, regardless of the value of the jamming power, the OD method always has the optimal jamming effect. Comparing Fig. 5(a) with Fig. 5(b), it can be found that the influence of time synchronization on the jamming performance is more serious, and the SER value is lower under the same jamming power conditions.



(a) Jamming against QPSK in a phase asynchronous state



(b) Jamming against QPSK in a time asynchronous state

Fig. 5 Jamming against the QPSK signal in the asynchronous state.

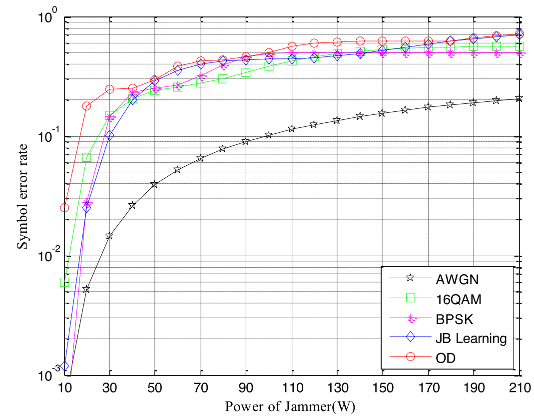


Fig. 6 Jamming against the QPSK signal in a constellation distortion environment.

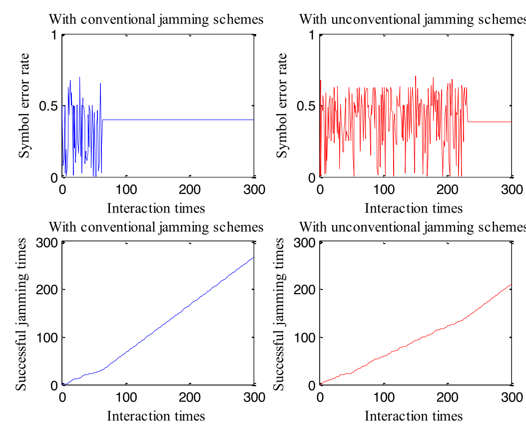


Fig. 7 The process of JB learning with conventional and unconventional jamming schemes.

4.4 Jamming Method in the Constellation Distortion Environment

In this section, the imbalances between the I-phase and the Q-phase of the communication signal are taken as an example. The experimental conditions remain unchanged. The jamming target is still a QPSK signal, and the constellation offset $\delta = [\delta^{(1)}, \delta^{(2)}] = [\sqrt{6}, 3\sqrt{2}]$ is assumed. Figure 6 shows the effect of jamming against the QPSK signal in a constellation distortion environment.

To achieve the expected $\zeta_E = 0.38$, the PSO algorithm is used to obtain the optimization result, that is, the jamming power $P_J = 59.879$ W, the I-phase jamming power $P_J^{(1)} = 36.186$ W, and the Q-phase jamming power $P_J^{(2)} = 23.693$ W. Comparing the power components of the I-phase and Q-phase, it can be known that the two are not equal in value. The jamming signal constructed at this time is not a QPSK signal. In other words, the optimal jamming signal is different from the conventional modulation scheme when the constellation of the communication signal is distorted. In addition, comparing the jamming effect of various methods under different jamming powers, the OD method always has the best jamming effect.

4.5 Learning the Best Jamming Scheme by Trial and Error

In practical jamming tasks, many factors such as antenna gains, channel coefficients, multiplicative noise, amplitude limitation and notch are unknown and cannot be ignored. Although unconventional jamming schemes have better performance, they cannot be obtained by optimization, but only by trial and error. In this section, we apply the proposed new jamming schemes to [12] and compare the process of JB learning with conventional and unconventional jamming schemes. In the simulation, we assume that $P_{J(\min)} = 10$ W and $P_{J(\max)} = 210$ W, and the interval $[10, 210]$ W is evenly divided into 21 levels. To construct the unconventional jamming schemes, we divide each level mentioned above into 11 parts, each representing the component of the level in the I-phase; therefore, there are $21 \times 11 = 231$ jamming strategies, and 231 interaction times are needed to find the best strategy. In [12], conventional jamming schemes include AWGN, BPSK, and QPSK; therefore, there are $21 \times 3 = 63$ jamming strategies. Figure 7 shows the interaction process.

With conventional jamming schemes, the JB learning requires 63 interaction times to find the best jamming strategy, that is, $P_J = 70\,\mathrm{W}$, and the best jamming scheme is QPSK. With unconventional jamming schemes, the JB learning requires 231 interaction times to find the best jamming strategy, that is, $P_J = 60\,\mathrm{W}$, the I-phase jamming power $P_J^{(1)} = 36\,\mathrm{W}$, and the Q-phase jamming power $P_J^{(2)} = 24\,\mathrm{W}$. That is to say, the JB learning algorithm using the unconventional jamming scheme requires less jamming power on the premise that the expected jamming effect is satisfied. Because the latter requires more interaction times, the number of successful jamming times is less than the former in 300 interactions. Moreover, how to reduce the number of interactions required in the learning process has become the focus of our next research project.

5. Conclusion

In this paper, an optimal jamming method for MQAM signals based on orthogonal decomposition is proposed. The OD method is used to divide the MQAM signal into two independent PAM signals for analysis. Additionally, the jamming signals are constructed from the I-phase and Q-phase to ensure that the jamming power is properly distributed between the two jamming signals, thereby improving the utilization of the jamming power and achieving better jamming effects with the same power. The simulation results show that when the jammer ideally knows the received power at the receiver, the OD method is consistent with the jamming effect of the existing methods in the AWGN environment and asynchronous state. In the case of the distortion of the communication signal constellation, the OD method achieves better jamming effects than the existing jamming methods. Moreover, the constructed unconventional jamming scheme can be employed in reinforcement learning methods that learn the best jamming scheme by interacting with the environment without accurately knowing the parameters of the environment and communication.

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Shaoshuai Zhuansun received the B.S. degree in communication engineering from Lanzhou Jiao Tong University, Lanzhou, China in 2012 and the M.S. degree in communication & information systems from the Electronic Engineering Institute, Hefei, China in 2015. He is currently pursuing the Ph.D. degree with the Department of Communications, National University of Defense Technology, Hefei, China. His research interests include cognitive jamming and reinforcement learning.

Jun-an Yang received the B.S. degree in radio technology from Southeast University, Nanjing, China in 1986 and the M.S. degree in communication & information system from Electronic Engineering Institute, Hefei, China in 1991. He received the Ph.D. degree in signal & information processing from the University of Science and Technology of China (USTC), Hefei, China in 2003. He is currently a professor in the Department of Communications at National University of Defense Technology, Hefei, China. His research interests include signal processing and intelligence computing.

Cong Tang received his B.S. degree and M.S. degree in optical engineering from Hefei Electronic Engineering Institute in 2012 and 2015, respectively. He is currently pursuing his Ph.D. degree at the National University of Defense Technology, Hefei, China. His current interests include deep learning, computer vision, and pattern recognition.