Optimization Method for Multiple Phases Sectionalized Modulation Jamming Against Linear Frequency Modulation Radar Based on a Genetic Algorithm

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ABSTRACT Multiple phases sectionalized modulation (MPSM) jamming is a kind of blanket jamming method against linear frequency modulation (LFM) radar, which can produce range-controllable noise-like jamming effect by dividing the signal into multiple subsections in the time domain and modulating different phases on each subsection. However, the partial relationship between the jamming effect and jamming parameters is complicated, which decrease the controllability of MPSM jamming effect. By transforming the problem of the controllability of MPSM jamming effect into the problem of the optimization of MPSM jamming effect, an optimization algorithm based on genetic algorithm (GA) is proposed to solve the problem in this paper. In the optimization based on GA, first, the objective function is constructed according to the jamming evaluation, the parameters are coded, the population is initialized, and the fitness value of the initial population is calculated. Then, the selection operation, crossover operation and mutation operation are performed, the next population is generated and its fitness value is calculated. Finally, judge if reach the termination, continue or output the optimization result and its corresponding parameters. The optimization method proposed in this paper can not only effectively increase the controllability of MPSM jamming effect, but also optimize the jamming effect. The simulation results show that the optimization method is feasible and has strong stability.

INDEX TERMS Linear frequency modulation (LFM) radar, multiple phases sectionalized modulation (MPSM) jamming, range-controllable blanket jamming, genetic algorithm (GA), jamming effect optimization.

I. INTRODUCTION

Linear frequency modulation (LFM) signals and pulse compression technique are widely used in modern radar for ranging and imaging [1], [2]. To protect the key targets from being detected by the radar reconnaissance, many jamming methods have been developed.

According to the jamming effect, jamming can be classified into deception jamming and blanket jamming [3]–[11].

There are many kinds of deception jamming, such as shift-frequency jamming [12], [13], intermittent sampling jamming [14]–[16], false moving target jamming [17], and convolution modulation jamming [18], [19]. Deception jamming can confuse the enemies and consume the radar resources. However, deception jamming generally cannot blanket the real targets, and always need high accuracy [20]–[22]. Blanket jamming can blanket the real targets with noise-like jamming effects, such as radio frequency noise jamming, noise amplitude modulation jamming and noise frequency modulation jamming [23]. The jamming range
of traditional jamming methods is always large, and the jamming power is always high, which is usually unnecessary for protecting the real targets.

Multiple phases sectionalized modulation (MPSM) jamming is a kind of partial coherent jamming method, which can produce noise-like jamming effect in a relatively controllable jamming range [24]–[27]. MPSM jamming can also obtain the process gain from pulse compression, which decreases the jamming power. However, the partial relationship between the jamming effects and jamming parameters of MPSM jamming is difficult to analyze, which decreases the controllability of MPSM jamming and limits the application. To solve the problem, the problem of jamming effect control can be transformed into the problem of jamming effect optimization, and an optimization algorithm based on genetic algorithm (GA) [28]–[30] is proposed in this paper.

First, the principle of MPSM jamming is introduced and analyzed. Then, the principle and steps of the GA-based optimization method is introduced and analyzed. Finally, the simulation is performed to verify the algorithm.

II. MPSM JAMMING PRINCIPLE

A. JAMMING SIGNAL MODEL

Multiple phases sectionalized modulation (MPSM) is the modulation that divides the signal into several subsections in the time domain, and modulates different phases on each subsection, which is shown as below.

In Fig 1, $x(t)$ denotes the original signal, whose pulse width is $T$, the signal envelope is rectangular, and $J(t)$ denotes the MPSM jamming signal, which is expressed as follows:

$$J(t) = x(t) \cdot p(t) \tag{1}$$

where, $p(t)$ denotes the multiple phases sectionalized modulation signal, which is as below:

$$p(t) = \sum_{i=1}^{p} [\varepsilon(t - a_i) - \varepsilon(t - a_{i+1})] \cdot \exp(j\phi_i) \tag{2}$$

where $p$ denotes the number of subsections, $\varepsilon(t)$ denotes the step function, $a_i$ denotes the starting point of the $i$th subsection, $a_{i+1}$ denotes the ending point of the $i$th subsection, and $-T/2 \leq a_i < a_{i+1} \leq T/2$. $\phi_i$ denotes the modulation phase, and $\phi_i \in [0, 2\pi]$. 

B. PULSE COMPRESSION OF MPSM JAMMING

Assume $x(t)$ is LFM signal, and $x(t)$ is expressed as below:

$$x(t) = \text{rect}(t/T) \cdot \exp\left(j\pi K t^2\right) \tag{3}$$

where, $\text{rect}(t/T)$ denotes the rectangle function and $K$ denotes the frequency modulation rate. The pulse compression result of MPSM jamming can be expressed as below:

$$S(t) = \sum_{i=1}^{p} \left\{ \text{rect}(t/T) \cdot \exp\left[j\pi K t^2\right] \cdot \left[\varepsilon(t - a_i) - \varepsilon(t - a_{i+1})\right] \cdot \exp(j\phi_i) \right\} \otimes \text{rect}(t/T) \cdot \exp\left(-j\pi K t^2\right) \tag{4}$$

where, $\otimes$ denotes the convolution operation. After calculation, $S(t)$ can be expressed as in (5), shown at the bottom of the next page, where, $\sin c(t)$ denotes the sin$c$ function, and $\sin c(t) = \sin(\pi t)/\pi t$. Equation (5) is complicated and needs simplification. Equation (5) can simplify as below by variable substitution:

$$S(t) = \sum_{i=1}^{p} \left\{ \exp(j\phi_i) \cdot \exp\left(-j\pi K t^2\right) \cdot [A_i(t) + B_i(t) + C_i(t)] \right\} \tag{6}$$

where,

$$A_i(t) = \text{rect}\left[\frac{t - (a_i + a_{i+1} + T)/2}{a_{i+1} - a_i}\right] \cdot \left(t + \frac{T}{2} - a_i\right) \cdot \sin c\left[K t \left(t + \frac{T}{2} - a_i\right)\right] \cdot \exp\left[j\pi K t \left(t + \frac{T}{2} + a_i\right)\right] \tag{7}$$

$$B_i(t) = \text{rect}\left[\frac{t - (a_i + a_{i+1} + T)/2}{a_{i+1} - a_i}\right] \cdot \left(a_{i+1} - a_i\right) \cdot \sin c\left[K t (a_{i+1} - a_i)\right] \cdot \exp\left[j\pi K t (a_i + a_{i+1})\right] \tag{8}$$

$$C_i(t) = \text{rect}\left[\frac{t - (a_i + a_{i+1} + T)/2}{a_{i+1} - a_i}\right] \cdot \left(a_{i+1} - a_i\right) \cdot \sin c\left[K t (a_{i+1} - t + \frac{T}{2})\right] \cdot \exp\left[j\pi K t (t - \frac{T}{2} + a_{i+1})\right] \tag{9}$$

The value ranges of $A_i(t)$ and $C_i(t)$ are far smaller than that of $B_i(t)$. And the amplitude of $A_i(t)$ and $C_i(t)$ in the corresponding value ranges is also far smaller than that of $B_i(t)$. Therefore, $S(t)$ can be simplified as below:

$$S(t) \approx \sum_{i=1}^{p} \left\{ \exp(j\phi_i) \cdot \exp\left(-j\pi K t^2\right) \cdot B_i(t) \right\} \tag{10}$$
According to (11), the jamming parameters include the sublobe widths, phases, different amplitude coefficients, and different main lobe widths.

III. ANALYSIS OF JAMMING PARAMETERS

According to (11), the jamming parameters include the subsection situation \( a_i \), the number of subsections \( p \), and the modulation phase \( \phi_i \).

A. SUBSECTION SITUATION

The subsection width is the time width of the \( i \)th subsection, which is as below:

\[
\Delta a_i = a_{i+1} - a_i, \quad i = 1, 2, \ldots, p
\]  

(12)

1) UNIFORM SUBSECTION

The uniform subsection means that all subsection widths \( \Delta a_i \) are equal, where \( \Delta a_i = T/p \). When MPSM jamming is under the uniform subsection situation, equation (11) can be expressed as below:

\[
S(t) = \frac{T}{p} \cdot \sin c \left[ Kt \cdot \frac{T}{p} \right] \cdot \sum_{i=1}^{p} \left\{ \exp (j\phi_i) \right. \\
\left. \cdot \exp \left( -j\pi Kt^2 \right) \cdot \exp \left[ j\pi Kt \left( a_i + a_{i+1} \right) \right] \right\}
\]  

(13)

According to (13), under the uniform subsection situation, each \( \sin c \) function in \( S(t) \) obtains the same main lobe width and amplitude coefficient, which means that \( S(t) \) obtains a fixed main lobe width and amplitude coefficient.

2) RANDOM SUBSECTION

The random subsection means that all subsection widths \( \Delta a_i \) are unequal. When MPSM jamming is under the random subsection situation, equation (11) can be expressed as below:

\[
S(t) = \sum_{i=1}^{p} \left\{ \Delta a_i \cdot \sin c \left[ Kt \cdot \Delta a_i \right] \cdot \exp (j\phi_i) \\
\cdot \exp \left( -j\pi Kt^2 \right) \cdot \exp \left[ j\pi Kt \left( a_i + a_{i+1} \right) \right] \right\}
\]  

(14)

According to (14), under the random subsection situation, the \( \sin c \) function in \( S(t) \) obtains different main lobe width and amplitude coefficient, which means that \( S(t) \) obtains no fixed main lobe width nor amplitude coefficient.

B. NUMBER OF SUBSECTIONS

1) UNIFORM SUBSECTION

Under the uniform subsection situation, the amplitude coefficient of each \( \sin c \) function is \( T/p \), and the main lobe width of each \( \sin c \) function is \( 2p/B \), which are all determined by the number of subsections \( p \). Because of the same main lobe width and amplitude coefficient of each \( \sin c \) function, the main lobe width and amplitude coefficient of \( S(t) \) can be expressed as below:

\[
\beta_s = 2p/B
\]  

(15)

\[
\alpha_p = T/p
\]  

(16)

Equation (15) and (16) indicate that the main lobe width and amplitude coefficient of \( S(t) \) are controllable by the number of subsections \( p \) under the uniform subsection situation, which means that the jamming range of MPSM jamming is also controllable.

2) RANDOM SUBSECTION

Under the random subsection situation, the main lobe width and amplitude coefficient of \( S(t) \) is unfixed because of the different main lobe width and amplitude coefficient of each \( \sin c \) function.

The main lobe width and amplitude coefficient of \( S(t) \) is calculated by the values corresponding to all subsections, which means that the main lobe width and amplitude coefficient is between the values corresponding to the largest subsection and the values corresponding to the smallest subsection. To apply the MPSM jamming under the random subsection more effectively, define the average subsection width \( \bar{\Delta} a_i \) as below.

\[
\bar{\Delta} a_i = T/p
\]  

(17)

So the average main lobe width and amplitude coefficient of \( S(t) \) can be calculated as follows:

\[
\bar{\beta}_s = 2/(K \cdot \bar{\Delta} a_i) = 2p/B
\]  

(18)

\[
\bar{\alpha}_p = T/p
\]  

(19)

According to (18) and (19), the average main lobe width and amplitude coefficient under the random subsection is
equal to that under the uniform subsection situation. Although the average main lobe width and amplitude coefficient under the random subsection may not completely accurate, it increases the controllability of the jamming range and jamming amplitude under the random subsection.

According to the analysis above, the jamming range of MPSM jamming is proportional to the number of subsections, and the amplitude coefficient of MPSM jamming is usually negatively correlated to the number of subsections, which means that the jamming range and jamming amplitude of MPSM jamming is controllable.

C. MODULATION PHASE SITUATION

1) UNIFORM PHASE

The uniform phase means that the modulation phase difference between $\phi_1$ and $\phi_{i+1}$ is fixed. Under the uniform phase situation, $p(t)$ can be expressed equivalently as the sum of multiple intermittent sampling signals with the same modulation phase and different time delays under the uniform subsection, which is shown as below:

In Fig 2, $p_d(t)$ denotes the $d$th intermittent sampling signal with the same modulation phase and different time delays, where $d = 1, 2, \ldots, m$, $m$ denotes the number of intermittent sampling signals. $p(t)$ can be expressed as follow:

$$p(t) = \sum_{d=1}^{m} p_d(t)$$  \hspace{1cm} (20)

According to Fig 2, $p_d(t)$ can be expressed as follows:

$$p_d(t) = \text{rect}(t/\tau) \otimes \sum_{n=-\infty}^{\infty} \delta(t - nT_s - t_d)$$

$$\cdot \sum_{i=1}^{p} [\epsilon(t - a_i) - \epsilon(t - a_{i+1})] \cdot \exp[j(\phi_0 + d \cdot \Delta\phi)]$$  \hspace{1cm} (21)

where, $\tau$ denotes the intermittent sampling width, $\tau = T/(p \cdot m)$, and $t_d$ denotes the time delay of each intermittent sampling signal. $\phi_0$ denotes the initial modulation phase, $\Delta\phi$ denotes the modulation phase difference.

When $m$ is large, $\Delta\phi$ can be considered as the result caused by frequency shift. Therefore, equation (21) can be expressed as follows:

$$p_d(t) = \text{rect}(t/\tau) \otimes \sum_{n=-\infty}^{\infty} \delta(t - nT_s - t_d)$$

$$\cdot \sum_{i=1}^{p} [\epsilon(t - a_i) - \epsilon(t - a_{i+1})] \cdot \exp(j\phi_0)$$

$$\cdot \exp(j2\pi f_d t)$$  \hspace{1cm} (22)

where, $f_d$ denotes the equivalent frequency shift as below:

$$f_d = \frac{1}{2\pi} \cdot \frac{\Delta\phi}{T/p}$$  \hspace{1cm} (23)

According to the time-frequency coupling characteristics of LFM signal, under uniform phase situation and uniform subsection situation, MPSM jamming can be expressed as a kind of intermittent sampling repeater jamming with frequency shift, which will produce a series of false targets with equal intervals and different amplitudes.

When the subsection situation is random, the randomness will cause a mismatch in the jamming effect, which will produce noise-like jamming effect additionally.

2) RANDOM PHASE

The random phase means that the phase difference $\Delta\phi$ is not fixed. $S(t)$ can simplify as below:

$$S(t) = \sum_{i=1}^{p} A(t) \cdot \exp[j\phi_i(t)]$$  \hspace{1cm} (24)

where, $A(t) = \Delta a_i \cdot \sin(cKt \cdot \Delta a_i)$, $\exp[j\phi_i(t)] = \exp(-j\pi Kt^2) \cdot \exp(j\phi_i) \cdot \exp[j\pi Kt(a_i + a_{i+1})]$. $\phi_i(t)$ is random due to random phase situation. Under the uniform subsection situation, $S(t)$ can be expressed as follows:

$$S(t) = A(t) \cdot \sum_{i=1}^{p} \exp[j\phi_i(t)]$$  \hspace{1cm} (25)
The randomness of $\phi_i(t)$ makes the jamming effect to be noise-like. When under the random subsection, the randomness of $A(t)$ will increase the randomness of the jamming effects, which means that the jamming effect of MPSM is more like noise.

According to the analysis above, modulation phase situation mainly affects the jamming form within the main lobe width. When the modulation phase is uniform, the jamming effect is similar to a series of false targets with equal intervals and different amplitudes. When the modulation phase is random, the jamming effect is more similar to noise.

### IV. TYPICAL MPSM JAMMING WITH DIFFERENT PARAMETERS

The jamming parameter includes the number of subsections $p$, the subsection situation $a_i$ and the modulation phase situation $\phi_i$. The relationship between the number of subsections and jamming effect is controllable, which mainly determines the jamming range and jamming amplitude. The relationship between the subsection situation and modulation phase situation and jamming effect is controllable when the subsection situation and modulation phase situation are uniform, and is un-controllable when they are random. Therefore, according to the subsection situation and modulation phase situation, MPSM jamming can be divided into 4 kinds of typical jamming methods, including MPSM jamming with uniform subsection and uniform phase, MPSM jamming with uniform subsection and random phase, MPSM jamming with random subsection and uniform phase, and MPSM jamming with random subsection and random phase.

#### A. UNIFORM SUBSECTION AND UNIFORM PHASE

The MPSM jamming with uniform subsection and uniform phase, whose controllability of jamming effect is high, produces a series of false targets with equal intervals but different amplitudes according to the analysis. However, the blanket jamming effect of MPSM jamming with uniform subsection and uniform phase situation is weak because of the regularity and interval of the jamming effect.

#### B. UNIFORM SUBSECTION AND RANDOM PHASE

The MPSM jamming with uniform subsection and random phase produces noise-like jamming effect within the obvious main lobe, whose controllability of jamming effect is low due to the random modulation phase.

#### C. RANDOM SUBSECTION AND UNIFORM PHASE

The MPSM jamming with random subsection and uniform phase produces noise-like jamming effect around a jamming peak, whose position is similar to that of MPSM jamming with uniform subsection and uniform phase. However, its controllability of jamming effect is low due to the random subsection.

#### D. RANDOM SUBSECTION AND RANDOM PHASE

The MPSM jamming with random subsection and random phase produces noise-like jamming effect without obvious main lobe, whose controllability of jamming effect is the lowest due to the random subsection and random modulation phase.

### E. COMPARISON OF TYPICAL MPSM JAMMING

From the perspective of degree of freedom, the degree of freedom of MPSM jamming with uniform subsection and uniform phase is low. The degree of freedom of MPSM jamming with uniform subsection and random phase the degree of freedom of MPSM jamming with random subsection and uniform phase is high. The degree of freedom of MPSM jamming with random subsection and random phase is the highest. However, the higher the degree of freedom, the lower the controllability. In addition, the higher the degree of freedom is, the more noise-like jamming effect, and the better blanket jamming effect.

### V. OPTIMIZATION METHOD BASED ON A GENETIC ALGORITHM

#### A. PROBLEM ANALYSIS

According to the analysis, MPSM jamming can divide into 4 kinds of typical jamming methods. MPSM jamming with uniform subsection and uniform phase is highly controllable. The other three kinds of typical jamming methods are less controllable due to the random subsection and random phase. To increase the controllability of the other three kinds of typical jamming methods, one way is to go through all the jamming parameters and their corresponding jamming effect. However, it is basically impossible due to the huge computation, especially when the number of subsections is large. In another way, we can transform the problem of controllability of MPSM jamming effect into the problem of optimization of MPSM jamming effect, which means that the specified jamming effect can be obtained by optimization algorithm according to the specified objective function.

In this way, an optimization method based on genetic algorithm (GA) is proposed. GA is a random search algorithm that has the ability of global search and strong robustness. By transforming the problem of controllability into the problem of optimization, the controllability of MPSM jamming effect can be solved by GA.

For MPSM jamming with uniform subsection and random phase, the phase situation needs optimization. For MPSM
jamming with random subsection and uniform phase, the subsection situation needs optimization. For MPSM jamming with random subsection and random phase, the phase situation and subsection situation need optimization.

B. OBJECTIVE FUNCTION
To obtain the specified jamming effect, the objective function of GA is important. According to the blanket-jamming effect of MPSM jamming, the mean value, variance value, entropy value and equivalent number of looks (ENL) value are chosen to evaluate the jamming effect and construct the objective functions.

The mean value of MPSM jamming means the average jamming value within the main lobe width. When the jamming power and jamming range are fixed, the larger the mean value is, the better the blanket-jamming effect. Therefore, the objective function of the mean value is the maximum mean value, which is as below:

\[ f_1 = \max \mu \]  

(26)

where, \( \max \) denotes the maximum operation, \( \mu \) denotes the mean value within the main lobe width of MPSM jamming.

The variance value of MPSM jamming means the deviation degree within the main lobe width. The smaller the variance value is, the better the blanket-jamming effect. The objective function of variance value is the minimum variance value, which is as below:

\[ f_2 = \min D \]  

(27)

where \( \min \) denotes the minimum operation, \( D \) denotes the variance value within the main lobe of MPSM jamming.

Entropy value of MPSM jamming denotes the measure of the disorder or randomness of energy. The larger the entropy value is, the better the blanket-jamming effect. The objective function of entropy value is the maximum entropy value, which is as below:

\[ f_3 = \max S \]  

(28)

where \( S \) denotes the entropy value of MPSM jamming.

ENL denotes the measure of jamming contrast. The larger ENL is, the better blanket-jamming effect. The objective function of ENL value is the maximum value, which is as below:

\[ f_4 = \max ENL = \max \left( \frac{\mu}{\sigma} \right) \]  

(29)

where \( \sigma \) denotes the standard deviation of MPSM jamming within the main lobe width.

C. STEPS OF THE GENETIC ALGORITHM
The flow chart of the GA is shown as below.

1) CODE AND DECODE
GA has multiple code methods, which include binary code, Gray code, real number code, and symbol code. Gray code is similar to binary code, but can effectively avoid Hamming cliffs, and improve the local search ability. Therefore, the Gray code is chosen in the paper.

The length of the Gray code is the same as that of the binary code, and both are positive correlated to the accuracy of the solution. For example, the code length for the parameter is \( l \), the parameter range is \([\theta_{\text{min}}, \theta_{\text{max}}]\), and the accuracy is \((\theta_{\text{max}} - \theta_{\text{min}})/2^l\).

Code is the process that turn the real number into the gray code. For example, the modulation phase sequence, which is called chromosome, is \(110101010101010000100111110101010011110, \) 0.27π, whose number of subsections is 4. Assume that the code length is 10, the gray code of each modulation phase sequence is 11010101010101000000100111110101010011110, so the gray code of modulation phase sequence, which is called chromosome, is \(110101010101010000100111110101010011110\).

Or, the subsection width sequence is 0.25T, 0.17T, 0.36T, and 0.31T, whose number of subsections is 4. Assume that the code length is 10, the gray code of each subsection width is 0110000000, 0001010101, 0111001001, 0110100011, so the gray code of subsection width sequence is 011000000010101011110101100110011.

Decode is the inverse process of code, which turn the gray code into the real number.

2) POPULATION INITIALIZATION
Before the optimization operation, the population of parameter sequence needs to initialize. The population consists of many individuals. The population initializes randomly to contain more population information. Studies have shown that the larger the population size, the more population information it contains, and the more likely the GA will converge to a global optimal solution. However, a large size population will consume huge storage space and computation. Therefore, to balance the convergence and computation speed, a proper population size needs to be set. In this paper, the population size \( M \) is set to be 100.

3) FITNESS CALCULATION
Fitness is the measurement of the superiority of the individual in the population. Fitness value is the result calculated according to the different objective functions. The higher the fitness value, the closer to the optimal solution, and the greater the probability of inheritance to the next generation.

4) JUDGEMENT
If reach the maximum generation, the result outputs, and the iteration stops. If not reach the maximum generation, the selection, crossover, and mutation operations perform to generate the next population.

5) SELECT OPERATION
The main optimization operation of the GA includes the select operation, crossover operation and mutation operation. The first step is the select operation, which selects the individuals from the former population to the new population.
In this paper, stochastic universal sampling is chosen for selection operation. The generation gap is the parameter for the degree of individual overlap between the former population and new population. A high generation gap helps maintain the characteristic of the population and avoids premature convergence, but prevent external information. Therefore, the generation gap is set to 0.9 in this paper.

The selection probability for the $i$th individual can be expressed as below:

$$p_i = \frac{F_i}{\sum_{i=1}^{M} F_i}, \quad i = 1, 2, \ldots, M \quad (30)$$

where $M$ denotes the population size, $F_i$ denotes the fitness value of the $i$th individual. Equation (30) indicates that the higher the fitness value, the greater the probability of being selected. The selection operation ensures that the optimal individuals according to the different objective functions can be selected to the new population.

6) CROSSOVER OPERATION

The second step of the optimization operation is the crossover operation, which exchanges the genes between the two individuals. The crossover operation is the main operation for generating new individuals.

In this paper, single-point crossover operation is chosen for the lowest probability of destroying the excellent characteristics of the individuals and reducing fitness. The single-point crossover diagram is shown follows:

$$A : \cdots 1011 \cdots 010 \cdots \cdots \text{One-point} \quad A' : \cdots 1011:101 \cdots \quad (31)$$

$$B : \cdots 0110 \cdots 101 \cdots \cdots \text{Crossover} \quad B' : \cdots 0110:010 \cdots \quad (32)$$

A higher crossover rate can speed up the convergence speed of the GA, but it also increases the probability of GA premature convergence. Therefore, the crossover probability is set to 0.7 in this paper.

7) MUTATION OPERATION

The third step of the optimization operation is the mutation operation, which mutates the gene in all individuals randomly. The mutation operation is an indispensable operation for generating new individuals.

Single-point mutation is chosen in this paper. For individuals represented by the Gray code, the gene mutation operation change 0 to 1 after mutation, and change 1 to 0 after mutation. The single mutation diagram is shown below:

$$A : \cdots 10101 \cdots \quad \text{Simple} \quad \rightarrow \quad A' : \cdots 10001 \cdots$$

A higher mutation rate maintains the diversity of the population and avoids premature convergence of the GA. However, a higher mutation rate also increases the destruction rate of good individuals. Therefore, the mutation probability is set to be 0.002 in this paper.

The crossover and mutation operation both help generate the new individuals, which may be a better one or a worse one.

VI. SIMULATION

A. PARAMETER SETTINGS

The parameter settings of the signal are shown in TABLE 2.

| Parameter | Value | Unit |
|-----------|-------|------|
| Speed of light $c$ | 300000 | km/s |
| Bandwidth $B$ | 100 | MHz |
| Pulse width $T$ | 10 | μs |
| Frequency modulation rate $K$ | 10 | MHz/μs |
| Sampling frequency $f_s$ | 200 | MHz |

The parameter settings of the GA parameters are shown in TABLE 3.

| Parameter | Value |
|-----------|-------|
| Population size $M$ | 100 |
| Code length $l$ | 10 |
| Max generation $G$ | 1000 |
| Generation gap $g$ | 0.9 |
| Probability of crossover $P_c$ | 0.7 |
| Probability of mutation $P_m$ | 0.002 |

B. SIMULATION OF MPSM JAMMING EFFECT

1) UNIFORM SUBSECTION AND UNIFORM PHASE

This section simulates MPSM jamming with uniform subsection and uniform phase under different number of subsections. The number of subsections is set to 50, 100, and 200, the uniform phase difference is $1/3\pi$, and the jamming to signal ratio (JSR) is 0 dB. The simulation results are shown in Fig 4.

In Fig 4, MPSM jamming with uniform subsection and uniform phase is a series of false target strings with equal intervals and different amplitudes. As the number of subsections increases, the distance between the main false target and the real target increases, and the interval between the false targets increases. When the number of subsections is 50, the width $\Delta a_i$ of each subsection is 0.2 μs, and the equivalent intermittent sampling frequency $f_s$ is calculated as 5 MHz. The theoretical value of the false target interval is 0.5 μs, and the simulation result of the false target interval in the figure is 0.5 μs, which is consistent with the theoretical analysis. When the number of subsections is 100 and 200, the simulation results are also consistent with the theoretical analysis.

This section also simulates MPSM jamming with a uniform subsection and uniform phase under different phase differences. The phase difference is set to $1/6\pi$, $1/3\pi$, and $2/3\pi$, the number of subsection is 100, and JSR is 0 dB. The simulation results are shown in Fig 5.
In Fig 5, as the phase difference increases, the distance between the main false target and the real target increases. Due to the fixed number of subsections, the false target interval remains the same. When the phase difference is $1/6\pi$, the equivalent frequency shift $f_d$ is 0.83 MHz according to the analysis before. The theoretical offset of the main false target is 0.083 $\mu$s, and the simulation result of the false target offset in the figure is 0.083 $\mu$s, which is consistent with the theoretical analysis. When the phase differences are $1/3\pi$ and $2/3\pi$, the corresponding offsets are 0.167 $\mu$s and 0.333 $\mu$s, which are consistent with the simulation results in the figures.

2) UNIFORM SUBSECTION AND RANDOM PHASE
This section simulates the MPSM jamming with uniform subsection and random phase under different numbers of subsections. The number of subsections is set to 50, 100, and 200, the modulation phase is random, and JSR is 7.5 dB. The simulation results are shown in Fig 6.

In Fig 6, MPSM jamming with uniform subsection and random phase can concentrate the main jamming power in an obvious range, which has a relatively clear limit, and produces a noise-like jamming effect within the range. As the number of subsections increases, the jamming range increases, but the jamming amplitude decreases. When the number of subsections is 50, the range of MPSM jamming is 1 $\mu$s according to the analysis before. In Fig 6.(a), the jamming range is 1 $\mu$s, which is consistent with the theoretical analysis. When the number of subsections is 100 and 200, the corresponding ranges are 2 $\mu$s and 4 $\mu$s, which are consistent with the theoretical analysis.

3) RANDOM SUBSECTION AND UNIFORM PHASE
This section simulates the MPSM jamming with random subsection and uniform phase under different numbers of subsections.
subsections. The number of subsections is set to 50, 100, and 200, the uniform phase difference is 1/3\pi, and the JSR is 4.5 dB. The simulation results are shown in Fig 7.

In Fig 7, MPSM jamming with a random subsection and uniform phase produces a mixed jamming effect of false target and noise-like jamming. As the number of subsections increases, the distance between the false target and the real target increases, and the amplitude of the false target decreases. When the number of subsections is 50, the offset of the false target is approximately 0.083 \mu s according to the analysis before. The offset of the false target in Fig 7. (a) is approximately the same as the theoretical analysis. When the number of subsections is 100 and 200, the corresponding offsets are 0.167 \mu s and 0.33 \mu s, and the simulation results are 0.167 \mu s and 0.383 \mu s, which are approximately the same.

This section also simulates MPSM jamming with random subsection and uniform phase under different phase differences. The phase difference is set to 1/6\pi, 1/3\pi, 2/3\pi, the number of subsection is 100, and JSR is 0 dB. The simulation results are shown in Fig 8.

In Fig 8, as the phase difference increases, the distance between the false target and the real target increases, which is similar to MPSM jamming with a uniform subsection and uniform phase. When the phase difference is 1/6\pi, the corresponding offset is 0.083 \mu s, and the simulation result is 0.075 \mu s, which is approximately the same. When the phase difference is 1/3\pi, 2/3\pi, the corresponding offsets are
FIGURE 9. MPSM jamming under different numbers of subsections. (a) The number of subsections is 50; (b) the number of subsections is 100; (c) the number of subsections is 200.

FIGURE 10. Optimized results of MPSM jamming with a uniform subsection and random phase. (a) The result without optimization; (b) the optimized result of the maximum mean value; (c) the optimized result of the minimum variance value; (d) the optimized result of the maximum ENL value; (e) the optimized result of the maximum entropy value.

0.167 $\mu$s and 0.33 $\mu$s, and the simulation results in the figures are 0.167 $\mu$s and 0.29 $\mu$s, which are approximately the same.

4) RANDOM SUBSECTION AND RANDOM PHASE
This section simulates MPSM jamming with random subsection and random phase under different numbers of subsections. The number of subsections is set to 50, 100, and 200, and JSR is 7.5 dB. The simulation results are shown in Fig 9.

In Fig 9, MPSM jamming with random subsection and random phase produces a local noise-like jamming effect. As the number of subsections increases, the jamming range of MPSM jamming increases and the jamming amplitude decreases, but the jamming range is not obvious.

C. SIMULATION OF OPTIMIZED MPSM JAMMING BASED ON GA
According to the analysis and simulation results, MPSM jamming with uniform subsection and random phase, MPSM jamming with random subsection and a uniform phase and MPSM jamming with a random subsection and random phase needs to be optimized by GA due to the randomness of the subsection situation and phase situation. MPSM jamming with a uniform subsection and uniform phase is highly controllable, which does not need to be optimized by a GA.

1) UNIFORM SUBSECTION AND RANDOM PHASE
This section simulates optimized MPSM jamming with uniform subsection and random phase based on GA. The number of subsections is 50, and each subsection width is $T/50$. The JSR is 5 dB. The simulation results are shown in Fig 10.
According to Fig 10 and TABLE 3, compared with the results of the unoptimized or other objective functions, the corresponding results are the optimal results according to the different objective functions.

According to Fig 11, when the jamming power is fixed, the target detection probability under unoptimized MPSM jamming is higher than that under optimized MPSM jamming, which means that the optimized MPSM jamming can not only reach the optimization objective, but also obtain a better blanket jamming effect. The target detection probabilities under optimized MPSM jamming are different according to the different objective functions, and the target detection probability of optimized entropy is slightly lower than those of different objective functions when the jamming power is fixed, which means the optimized entropy is more effective than those of different objective functions.

2) RANDOM SUBSECTION AND UNIFORM PHASE

This section simulates optimized MPSM jamming with a random subsection and uniform phase based on GA. The number of subsections is 50, and the modulation phase difference of adjacent subsection is $2\pi / 3$. The JSR is 5 dB. The simulation results are shown in Fig 12.

According to Fig 12 and TABLE 4, compared with the results of the unoptimized or other objective functions, the corresponding results are the optimal results according to the different objective functions.

| Mean   | Variance | ENL   | Entropy |
|--------|----------|-------|---------|
| (a)    | 4.218    | 10.458| 1.304   | 3.584   |
| (b)    | 4.663    | 6.489 | 1.838   | 3.719   |
| (c)    | 4.577    | 5.856 | 1.892   | 3.758   |
| (d)    | 4.621    | 5.864 | 1.908   | 3.747   |
| (e)    | 4.296    | 8.565 | 1.468   | 3.795   |

1 Bold italics represent the optimal value.

According to Fig 13, when the jamming power is fixed, the target detection probability under unoptimized MPSM jamming is slightly higher than that with optimization, which
means that the optimized MPSM jamming can not only reach the optimization objective, but also obtain a better blanket jamming effect. The target detection probabilities under optimized MPSM jamming are different according to the different objective functions, and the target detection probability of optimized entropy is slightly lower than those of different objective functions when the jamming power is fixed, which means the optimized entropy is more effective than those of different objective functions.

3) RANDOM SUBSECTION AND RANDOM PHASE
This section simulates optimized MPSM jamming with a random subsection and random phase based on a GA.

According to Fig 15, when the jamming power is fixed, the target detection probability under optimized MPSM jamming is higher than that with optimization, which means that the optimized MPSM jamming can not only reach the optimization objective, but also obtain a better blanket jamming effect. The target detection probabilities under optimized MPSM jamming are different according to the different objective functions, and the target detection probability of optimized entropy is slightly lower than those of different objective functions when the jamming power is fixed, which means the optimized entropy is more effective than those of different objective functions.

TABLE 5. Optimized results of MPSM jamming with a random subsection and uniform phase.

| Objective | Mean  | Variance | ENL   | Entropy |
|-----------|-------|----------|-------|---------|
| (a)       | 4.098 | 9.658    | 1.319 | 3.872   |
| (b)       | 4.735 | 5.576    | 2.005 | 3.822   |
| (c)       | 4.683 | 5.076    | 2.079 | 3.950   |
| (d)       | 4.730 | 5.153    | **2.084** | 3.867   |
| (e)       | 4.267 | 8.338    | 1.478 | **3.972**   |

1 Bold italics represent the optimal value.

FIGURE 14. Optimized results of MPSM jamming with a random subsection and random phase. (a) The result without optimization; (b) the optimized result of the maximum mean value; (c) the optimized result of the minimum variance value; (d) the optimized result of the maximum ENL value; (e) the optimized result of the maximum entropy value.
| TABLE 6. Optimized results of MPSM jamming with random subsection and random phase. |
|-----------------|----------------|--------|----------------|
|                | Mean     | Variance | ENL    | Entropy   |
| (a)            | 4.065    | 10.947   | 1.228  | 3.699     |
| (b)            | **4.815**| 4.798    | 2.198  | 3.841     |
| (c)            | 4.670    | **3.906**| 2.362  | 3.961     |
| (d)            | 4.699    | 3.911    | **2.576**| 3.939     |
| (e)            | 4.461    | 6.017    | 1.819  | **4.037** |

1. Bold italics represent the optimal value.

FIGURE 15. CA-CFAR results of unoptimized and optimized MPSM jamming with a random subsection situation and a random phase situation.

The results indicate that the optimization method for the MPSM jamming effect based on GA is feasible and can obtain the optimal results according to the different objective functions, which solves the problem of controllability in another way. According to the simulation results, MPSM jamming of optimized entropy obtains better blanket jamming effect than those of other objective functions.

4) COMPARISON OF TYPICAL MPSM JAMMING
The simulation results indicate that the blanket-jamming effect of MPSM jamming with random subsection and random phase is better than those with uniform subsection and random phase as well as with random subsection and random phase, which is consistent with the theoretical analysis, indicating that the higher the degree of freedom, the better blanket-jamming effect.

D. COMPARISON OF DIFFERENT GENETIC ALGORITHM PARAMETERS
This section simulates the convergence performance and computation time of optimized MPSM jamming. The number of subsections is 50, the number of individuals is 100, the number of generations is 1000, the code length is 10, the selection probability is 0.9, the crossover probability is 0.7, and the mutation probability is 0.002.

According to Fig 16, the results can converge to the optimal results within a certain generation. The convergence performances of different MPSM jamming are slightly different.

According to TABLE 7, the optimized MPSM jamming can be obtained within an acceptable computation time, and the computational time of optimized MPSM jamming with uniform subsection random phase is longer than that of random subsection uniform phase, and is shorter than that of random subsection random phase. The computation times of different objective functions are also different.

| TABLE 7. Computation time of optimized MPSM jamming with different parameters. |
|-----------------|----------------|--------|----------------|
|                | Mean     | Variance | ENL    | Entropy |
| (a)            | 18.58s   | 19.75s   | 21.07s | 41.96s   |
| (b)            | 17.11s   | 18.29s   | 19.31s | 40.66s   |
| (c)            | 19.39s   | 20.74s   | 21.47s | 42.83s   |

1. (a) Uniform subsection and uniform phase MPSM jamming; (b) random subsection and uniform phase MPSM jamming; (c) random subsection and random phase MPSM jamming.

This section also simulates the convergence performance and computation time of optimized MPSM jamming under uniform subsection and random phase, whose objective function is the minimum variance.

FIGURE 16. Convergence performance of optimized MPSM jamming with different objective functions. (a) Uniform subsection and random phase MPSM jamming; (b) random subsection and uniform phase MPSM jamming; (c) random subsection and random phase MPSM jamming.
According to Fig 17, considering the computational time in TABLE 8, when the number of individuals is 100, the code length is 10, the selection probability is 0.9, the crossover probability is 0.7, and the mutation probability is 0.002, the convergence performance of the objective function of the minimum variance is the best.
TABLE 8. Computation time of optimized MPSM jamming under a uniform subsection and random phase of optimized variance with different optimization parameters.

| Number of Individuals | 50    | 100   | 200   |
|-----------------------|-------|-------|-------|
| Code Length           | 18.82s| 19.82s| 22.19s|
| Selection Probability | 0.85  | 0.9   | 0.95  |
| Crossover Probability | 18.88s| 19.89s| 20.84s|
| Mutation Probability  | 0.001 | 0.002 | 0.004 |
| Probability           | 19.76s| 19.88s| 19.86s|

E. MONTE CARLO SIMULATIONS OF OPTIMIZED MPSM JAMMING BASED ON A GA

Fifty times of Monte Carlo simulations of optimized MPSM jamming based on GA are performed for each kind of MPSM jamming and each kind of objective function respectively. The number of subsections is 50, JSR is 5 dB, and the phase difference is $2\pi/3$ for MPSM jamming with a random subsection and uniform phase.

Situation 2 denotes MPSM jamming with a uniform subsection and random phase, situation 3 denotes MPSM jamming with a random subsection and uniform phase, and situation 4 denotes MPSM jamming with random subsection and random phase. The results are shown in Fig 18.

Fig 18. (a) indicates that the mean values of the optimized MPSM jamming are larger than those of unoptimized and the results of optimized 50 Monte Carlo simulations are more stable than those of unoptimized jamming, which means that the optimization algorithm based on GA is effective and stable. Fig 18. (a) also indicates that the mean values of optimized MPSM jamming with random subsection and random phase are larger than those of MPSM jamming with a uniform subsection and random phase as well as MPSM jamming with a random subsection and uniform phase, which is consistent with the theoretical analysis. The same conclusions can also be obtained from Fig 18. (b)-(d).

The results indicate that the optimization method for MPSM jamming based on GA has strong stability. Comparing the three kinds of MPSM jamming, optimized MPSM jamming with a uniform subsection and uniform phase has the best blanket jamming effect according to the results.

VII. CONCLUSION

Although the principle of MPSM jamming is simple, it can produce many types of blanket jamming effects according to different modulation parameters, including false targets jamming effect and range-controllable noise-like jamming effects. MPSM jamming, as a kind of coherent jamming method, can obtain the process gain from pulse compression, which effectively reduces the power requirement. However, when the subsection situation and phase situation are random, the controllability of the MPSM jamming effect is seriously reduced, which affects the application of MPSM jamming.

The problem of jamming effect control can be transformed into the problem of jamming effect optimization, and an optimization method for the MPSM jamming effect based on GA is proposed in this paper. By optimizing the subsection situation and phase situation, the problem of controllability is solved by the proposed method, and an optimized jamming effect can also be obtained. The theoretical analysis and simulation results show the feasibility and stability of the proposed method.

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