

Design of Low-Interception Short-Range Detection Signal for Co-Address MIMO-OCDM

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Abstract— The rapid development of electronic reconnaissance system has seriously threatened the survivability of fuse. To improve the survivability of fuse, a co-address Multiple Input Multiple Output-Orthogonal Chirp Division Multiplexing (MIMO-OCDM) signal is designed, and a signal processing method of two-phase parametric accumulation is adopted to improve the signal-to-noise ratio of the echo signal. Firstly, the transmission power of a single signal is evenly distributed to each sub-chirp signal of the OCDM signal, and the sub-chirp signals are transmitted by the co-address MIMO radar to reduce the signal transmission power. Subsequently, the first coherent accumulation is carried out on multiple sub-chirp signals received by a single antenna, and the second coherent accumulation is performed on the echo signals received by multiple antennas to significantly enhance the signal-to-noise ratio of the echo signals. The simulation results show that, compared with the traditional single signal, under the condition of ensuring that the echo signal-to-noise ratio is not lost, the co-address MIMO-OCDM signal can significantly reduce the transmission power of the signal, thereby resulting in a significant decrease in the interception distance of the electronic reconnaissance system and enabling the fuse to have excellent low interception performance.

Keyword— Low Probability of Intercept, Signal Design, MIMO Radar, OCDM Signal, Signal Processing

I. INTRODUCTION

IN the modern complex and ever-changing electronic countermeasure environment, the rapid development of electronic reconnaissance system has made the signal emitted by fuse easily intercepted by enemy reconnaissance equipment, thus exposing fuse to threats such as interference and destruction [1]-[3]. Enhancing the ability of fuse to counter enemy electronic reconnaissance equipment can, to a certain extent, improve the survival and defense capabilities of fuse. However, the high-power signal emitted by traditional fuse are easily intercepted by the enemy's electronic reconnaissance system, causing the position of the fuse to be exposed prematurely and subject to enemy interference and destruction [4], [5]. Therefore, the Low Probability of Intercept of the fuse system has become a core

indicator of the survivability and combat capability of fuse.

The interception of radar signal by electronic reconnaissance system is usually divided into four sequential stages, namely signal detection, signal parameter measurement, signal sorting, and signal recognition. Electronic reconnaissance system will apply corresponding processing and analysis techniques to the signals of each stage. The study of the low interception characteristics of radar should, in principle, start from the interception process of the counter-electronic reconnaissance system [6], [7]. Corresponding counter-techniques should be adopted for each interception stage to ensure that the radar has excellent low interception characteristics. Signal detection, as the first stage of the electronic reconnaissance system's interception of radar signals, plays an irreplaceable role. If the electronic reconnaissance system fails to complete the signal detection, the subsequent processes cannot proceed. Therefore, this paper aims to design low-interception short-range detection signals from the perspective of anti-detection.

The traditional low-interception radar signal design mainly includes waveform design and modulation technology, signal parameter rapid variation, combination and coding technology [8], [9]. Waveform design and modulation technology are at the core of LPI radar signal design. By adopting complex signal forms such as phase coding, frequency modulation, and noise modulation techniques to design wide-bandwidth and wide-product signals, the energy of the radar signal can be dispersed over a wider frequency band, reducing its power spectral density per unit frequency band [10]. This makes it difficult to be effectively detected and identified by the enemy's electronic reconnaissance system. However, due to the small size of the fuse, the time-bandwidth and wide-product of the signal cannot be too large, so the degree of reducing the power spectral density is limited. Moreover, as the sensitivity of the electronic reconnaissance system increases, the low interception performance of signals with large time-bandwidth and wide-product also gets worse and worse [11], [12]. Signal parameter variability mainly includes pulse repetition interval variability, carrier frequency variability, pulse width variability, etc [13], [14]. The regularity of radar pulse

sequences is an important basis for the enemy's electronic reconnaissance system to sort and identify. Signal parameter variability can increase signal uncertainty and disrupt the enemy's signal sorting and identification. However, with the rapid development of artificial intelligence technologies such as deep learning and reinforcement learning, Relying solely on increasing the uncertainty of the signal to achieve the low interception characteristics of the signal is severely challenged; Combined signal and coding techniques combine the use of multiple signals of different modulation types or utilize special coding techniques to complement the advantages and disadvantages of various signals and form signals with more superior comprehensive performance. However, the design of complex signals requires high-performance signal generation and processing hardware, which increases the complexity and cost of the system and is not suitable for fuse system [15], [16].

In conclusion, all the above-mentioned methods can achieve the design of low-interception short-range detection signals, but they all have certain limitations. Therefore, this paper designs low-interception short-range detection signals from the perspective of anti-detection, combining signal design and fuse hardware design. The transmission power of a single signal is evenly distributed to each sub-chirp signal of the OCDM signal to reduce the signal transmission power, and each sub-chirp signal is transmitted by a separate antenna. At the Signal receiving end, the same number of antennas are used to receive the echo signal. The multiple sub-chirp signals received by a single antenna and the echo signals received by multiple antennas are respectively accumulated in a coherent manner. Under the condition of low transmission power, the Signal-to-Noise Ratio (SNR) of the echo signal can be ensured to be within the available range. The designed co-address MIMO-OCDM signal can significantly reduce the transmission power, has good anti-detection performance, and has certain engineering application value.

II. PRINCIPLE OF LOW-INTERCEPTION SHORT-RANGE DETECTION SIGNAL

The definition of the interception factor is the ratio of the maximum interception distance of the electronic reconnaissance receiver to the maximum detection distance of the radar [17]. Assuming the transmission power of the radar signal is P_t , the gain of the radar transmitting antenna is G_t , the scattering cross-sectional area of the target is σ , and the gain of the radar receiving antenna is G_r . Due to the short detection distance of the fuse, Therefore, the atmospheric attenuation can be ignored, and the expression of the maximum detection range of the radar can be derived as[18]

$$R_r = \left[\frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 S_{r\min} L_r} \right]^{1/4} \quad (1)$$

In equation (1), λ is the signal wavelength, L_r is the loss of the radar system and $S_{r\min}$ represents the sensitivity of the radar receiver.

The radar signal processing gain is M [19], so equation (1) can be rewritten as

$$R_r = \left[\frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 S_{r\min} L_r} \cdot M \right]^{1/4} \quad (2)$$

Under normal circumstances, electronic reconnaissance receivers do not have signal processing gain. By the same token, the expression for the maximum interception distance of an electronic reconnaissance receiver can be derived as

$$R_i = \left[\frac{P_t G_{ti} G_i \lambda^2}{(4\pi)^2 S_{i\min} L_i} \right]^{1/2} \quad (3)$$

In equation (3), G_{ti} represents the transmission gain of the radar antenna in the interception direction. Considering the main lobe interception, it can generally be assumed that $G_{ti} = G_t$ and G_i are the receiving antenna gains of the electronic reconnaissance receiver, $S_{i\min}$ is the sensitivity of the electronic reconnaissance receiver, and L_i is the loss of the electronic reconnaissance system.

From equations (2) and (3), the expression of the interception factor can be derived as

$$\alpha = \frac{R_i}{R_r} = \left[\frac{P_t}{4\pi} \cdot \frac{\lambda^2}{\sigma} \cdot \frac{G_{ti}^2 G_i^2}{G_t G_r} \cdot \frac{S_{r\min}}{S_{i\min}^2} \cdot \frac{L_r}{L_i^2} \cdot \frac{1}{M} \right]^{1/4} \quad (4)$$

From the definition of the interception factor, it can be known that to make the radar have low interception performance, the interception factor α needs to be less than 1. For the fuse, its detection distance is usually within the range of several meters to tens of meters. According to the definition of the interception factor α , if the fuse is required to have low interception characteristics, this requires that the interception distance of the electronic reconnaissance receiver be only tens of meters or even a few meters. During combat, intercepting the fuse signal at such a distance dimension is meaningless. Therefore, there are certain limitations in using traditional interception factor α to evaluate the low interception performance of the fuse.

In summary, the concepts of the working performance of the fuse and the working performance of the electronic reconnaissance system are proposed. When the maximum detection distance of the fuse is equal to the expected value, it can be considered that the working performance (PE_r) of the fuse is 100%. When the maximum detection distance is less than the expected value, it is regarded as the working performance being less than 100%. When the maximum detection distance is greater than the expected value, it is regarded as the working performance being greater than 100%. When the maximum interception distance of the electronic reconnaissance system is equal to the expected value, it can be considered that the working performance (PE_i) of the electronic reconnaissance system is 100%. When the maximum interception distance is greater than the expected value, it is regarded as the working performance being greater than 100%. The calculation method of and is as shown in Equation (5).

$$PE_r = \frac{R_r}{R_{ro}} \times 100\% \quad (5)$$

$$PE_i = \frac{R_i}{R_{io}} \times 100\%$$

In equation (5), R_{ro} and R_{io} are the expected values of the maximum detection distance of the fuse and the maximum interception distance of the electronic reconnaissance system, respectively.

Based on the interception factor, a new definition of the low interception characteristic of the fuse is proposed. That is, under the condition that the working performance of the fuse is greater than or equal to 100%, the ratio of the working performance of the electronic reconnaissance system to that of the fuse is used to measure the low interception characteristic of the fuse signal. This Ratio is named the Reconnaissance Detection Performance Ratio (RDPR). If RDPR is less than 1, it can be considered that the fuse has the characteristic of low interception, and RDPR can be expressed as

$$RDPR = \frac{PE_i}{PE_r} \quad (PE_r \geq 100\%) \quad (6)$$

III. OCDM SIGNAL MODEL BASED ON CO-ADDRESS MIMO RADAR

A. OCDM Signal Model

According to the Fresnel transform, the chirp basis signal form in the OCDM signal is defined as

$$\psi_0(t) = e^{j\frac{\pi}{4}} e^{-j\pi\frac{N}{T^2}t^2}, \quad 0 \leq t < T \quad (7)$$

According to equation (7), N sub-chirp signals can be extended. The signal set composed of N sub-chirp signals is the complete OCDM signal [20], where the expression of the KTH sub-chirp signal is

$$\psi_k(t) = e^{j\frac{\pi}{4}} e^{-j\pi\frac{N}{T^2}(t-k\frac{T}{N})^2}, \quad 0 \leq t < T \quad (8)$$

In equation (8), $k = 0, 1, \dots, N-1$.

Figure 1 is the waveform diagram of the OCDM signal containing three subcarriers.

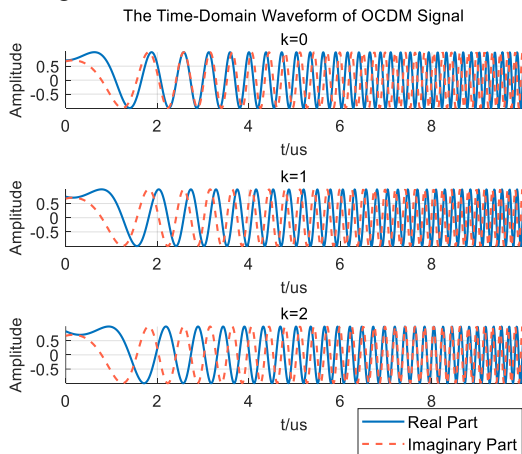


Fig. 1. The time-domain waveform of OCDM signal

From equation (8), it can be known that each sub-chirp signal in the OCDM signal set is a phase shift change of the

base signal, and it can be proved through equation (9) that the sub-chirp signals are pately orthogonal to each other and will not interfere with each other during spatial transmission.

$$\begin{aligned} & \frac{1}{T} \int_0^T \psi_m(t) \psi_n^*(t) dt \\ &= \frac{1}{T} \int_0^T e^{j\frac{\pi}{4}} e^{-j\pi\frac{N}{T^2}(t-m\frac{T}{N})^2} \cdot e^{-j\frac{\pi}{4}} e^{j\pi\frac{N}{T^2}(t-n\frac{T}{N})^2} dt \\ &= \frac{1}{T} \int_0^T e^{-j\pi\frac{N}{T^2}(t-m\frac{T}{N})^2} \cdot e^{j\pi\frac{N}{T^2}(t-n\frac{T}{N})^2} dt \\ &= \frac{1}{T} e^{-j\pi\frac{m^2-n^2}{N}} \int_0^T e^{j2\pi\frac{(m-n)t}{T}} dt \\ &= \delta(m-n) \end{aligned} \quad (9)$$

B. Co-address MIMO-OCDM Signal Model

From the analysis in Section 1.1, it can be known that to make the short-range detection signal have a low interception characteristic, it is necessary to reasonably design a large time-bandwidth wide-product signal to obtain a higher signal processing gain, and then transmit the signal at a lower transmission power to reduce the interception distance of the electronic reconnaissance receiver. However, a lower transmission power will inevitably cause a significant reduction in the signal-to-noise ratio of the echo signal. For the echo signal of co-address MIMO radar, except for the signal phase difference introduced by different antenna positions, all the target parameters are the same. However, the volume of the fuse is small. Due to the compact arrangement of the antennas, the signal phase difference introduced by different antenna positions can be ignored. Therefore, it can be considered that all the target parameters of the echo signal of the fuse co-address MIMO radar are the same[21], [22].

Under this premise, each sub-chirp signal in the OCDM signal set is transmitted separately by a single antenna, thereby evenly distributing the transmission power to each sub-chirp signal, thereby reducing the transmission power of the co-address MIMO radar. At the receiving end, the same number of antennas are used to receive the OCDM sub-chirp signals. When processing radar echoes, for the signals received by a single antenna, since each OCDM sub-chirp signal contains the same target parameters, by performing matched filtering processing and parametric accumulation on each OCDM sub-chirp signal, it can be ensured that the signal-to-noise ratio of the signal will not drop significantly. Meanwhile, as it is received by multiple antennas, For the signals received by each antenna, the corresponding accumulation can be carried out again, which can further improve the signal-to-noise ratio of the signal to a certain extent. The implementation flowchart of this scheme is shown in Figure 2.

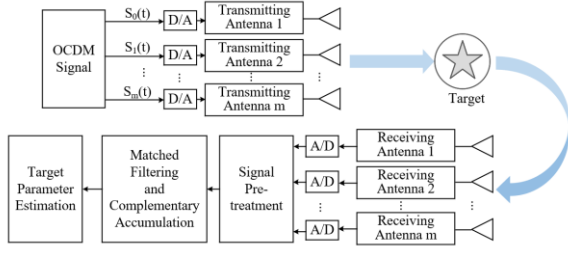


Fig. 2. The time-domain waveform of OCDM signal

IV. SIMULATION ANALYSIS OF CO-ADDRESS MIMO-OCDM SIGNAL

A. Simulation Parameters

The fuse echo receiving system and the electronic reconnaissance receiver were modeled, and the simulation parameter settings are shown in Table I.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Fuse receive and transmit antenna gain $G_t = G_r$	16dB
Main lobe interception gain G_{ti}	16dB
Gain of the receiving antenna of the reconnaissance receiver G_i	4dB
Target scattering cross-sectional area σ	0.55m ²
The sensitivity of the fuse receiving system S_{rmin}	-85dB
Sensitivity of reconnaissance receiver S_{imin}	-65dB
Fuse system loss L_r	4dB
Reconnaissance receiver system loss L_i	5dB
LFM signal transmission power	16mW
OCDM sub-signal transmission power	2mW
The number of OCDM sub-signals N	8
OCDM sub-signal bandwidth	100MHz
Signal transmission carrier frequency	5GHz
The expected value of the maximum detection distance of the fuse	30m
The expected value of the maximum interception distance of the reconnaissance receiver	3000m

B. Low Interception Performance Analysis

a. Co-address MIMO-OCDM Signal Detection Performance

The simulation is carried out according to the parameters in Section 3.1. The bandwidth of each sub-chirp signal of the OCDM signal is 100 MHz, the time width is 10μs, the transmission power of each sub-chirp signal of the OCDM signal is 2mW, the target distance is 30m, and 0.5 mW of Gaussian white noise is added.

Because there will be losses in the accumulation of mutual reference [23], [24]. Therefore, the received signals of the 8 antennas are further subjected to parallel coherent accumulation to significantly improve the signal-to-noise ratio of the echo signal, and then the signal detection is carried out. The echo signal is accumulated twice. The variation of the accumulated signal-to-noise ratio is shown in Figure 3. To visually demonstrate the improvement of the signal-to-noise ratio, without considering the accumulation in the time dimension, a single Linear Frequency Modulation (LFM) signal is added for comparison. The transmission power of the LFM signal is 16 mW.

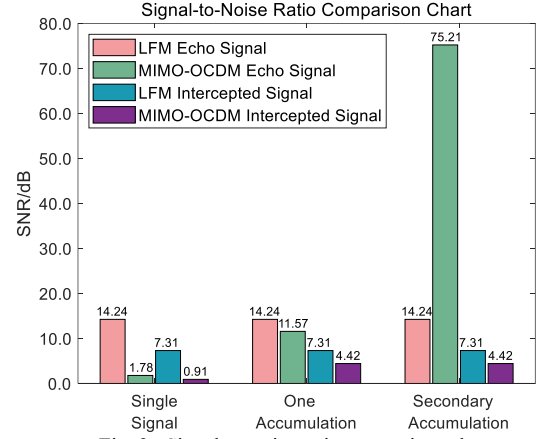


Fig. 3. Signal-to-noise ratio comparison chart

From the analysis of Figure 3, it can be seen that for LFM signal, due to the use of single-transmitting and single-receiving antenna, the echo signal cannot be accumulated in parallel, and the signal-to-noise ratio remains unchanged. At the fuse receiving end, for the OCDM sub-chirp signal, after power distribution, the echo signal-to-noise ratio of the sub-chirp signal is reduced to 1/8 of that of the LFM echo signal. However, when receiving the echo signal, one antenna can receive multiple sub-chirp signals and can perform the first coherent accumulation. The signal-to-noise ratio was raised to 11.57 dB, but failed to reach the 14.24dB of the LFM echo signal. This was due to certain losses in the coherent accumulation. After the second parallel accumulation of the signals received by the 8 antennas, the signal-to-noise ratio of the echo signal was increased to 75.21dB. The detection results of the target are shown in Figure 4.

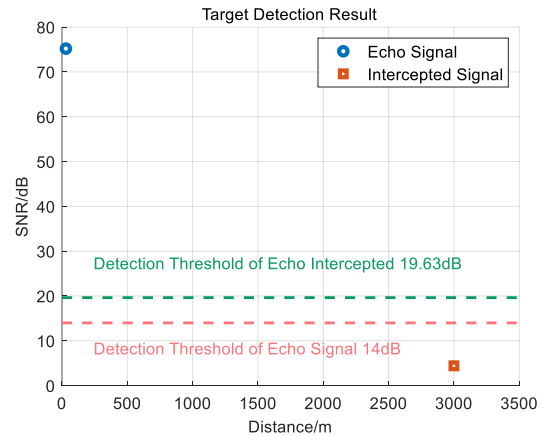


Fig. 4. Target detection result

As can be seen from Figure 4, the signal-to-noise ratio of the echo signal exceeds the detection threshold of the radar

receiver, indicating that the short-range radar has successfully detected the target at 30m. The working performance of the short-range radar is 100%, and it has not been intercepted by the reconnaissance receiver at 3000m. The co-address MIMO-OCDM signal can successfully complete the detection task.

b. Low Interception Performance of Co-address MIMO-OCDM Signal

The LFM signal and the co-address MIMO-OCDM signal were respectively selected for simulation. The transmission power of the LFM signal was 16mW, and the other parameters were consistent with those of the OCDM sub-chirp signal. The maximum detection distance of the two signals and the maximum interception distance of the electronic reconnaissance receiver are shown in Figure 5.

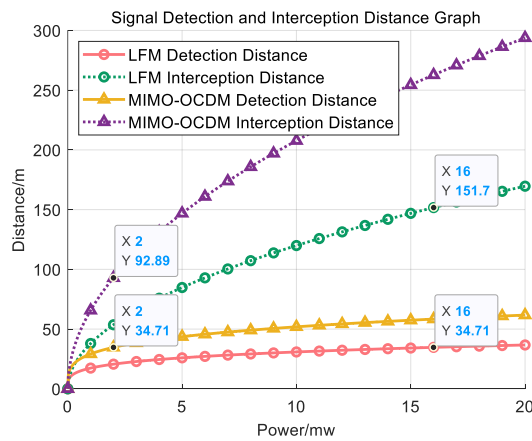


Fig. 5. Target detection result

It can be seen from Figure 5 that if the transmission power of the LFM signal is 16mW, the maximum detection distance of the radar is 34.71m, and at this time, the maximum interception distance of the electronic reconnaissance receiver is 151.7m. The transmission power of 16mW is evenly distributed to 8 OCDM sub-chirp signals. The transmission power of each sub-chirp signal is 2mw. At this time, the maximum detection distance of the co-address MIMO-OCDM signal is 34.71m, and the maximum interception distance of the electronic reconnaissance receiver is 92.89m. Both signals can complete the detection task. However, the low interception performance of the two signals is different. The comparison of low interception performance is shown in Table II.

TABLE II
LOW INTERCEPTION PERFORMANCE OF LFM AND CO-ADDRESS MIMO-OCDM SIGNAL

Signal Type	The Value of RDPR
LFM	0.04
Co-address MIMO-OCDM	0.03

By comparing the maximum detection distance and the maximum interception distance of the two signals, it can be known that after the power of the LFM signal is evenly distributed to each OCDM sub-signal, the maximum detection distance remains unchanged, but the maximum interception distance of the electronic reconnaissance receiver decreases by 58.81m. At this time, the RDPR value of the LFM signal is 0.04. The RDPR value of the co-address MIMO-OCDM signal is 0.03. Compared with the LFM

signal, after the power is evenly distributed to the sub-signals of OCDM, the RDPR value is reduced by 25%. The adoption of the co-address MIMO-OCDM signal makes the RDPR value smaller, which enables the fuse to have better low interception performance.

V. CONCLUSION

Starting from the definition of the interception factor, this paper deduces the design principle of the low-interception signal of short-range radar, and designs the co-address MIMO-OCDM signal to reduce the transmission power of the signal. The maximum interception distance of the electronic reconnaissance receiver decreases as the transmission power of the signal decreases, and the transmission power of a single signal is evenly distributed to each sub-chirp signal of the OCDM signal. And multiple transmitting antennas of the co-address MIMO radar are used to respectively transmit each sub-chirp signal, thereby reducing the signal transmission power and thus minimizing the maximum interception distance of the electronic reconnaissance receiver. At the signal receiving end, since reducing the signal transmission power will inevitably lead to a decrease in the echo signal-to-noise ratio, multiple receiving antennas of co-address MIMO radar are used to receive the echo signal. A single antenna can receive multiple sub-chirp signals, and the first coherent accumulation of multiple sub-chirp signals can be carried out to improve the signal-to-noise ratio of the echo signal. However, the coherent accumulation is difficult to achieve 100% efficiency. Considering the second coherent accumulation of the echo signals received by multiple antennas to significantly improve the signal-to-noise ratio of the echo signals. The simulation results show that, compared with the traditional single signal, under the condition that the echo signal-to-noise ratio is not lost, the co-address MIMO-OCDM signal can significantly reduce the transmission power of the signal. After evenly distributing the power of the LFM signal to each co-address MIMO-OCDM sub-chirp signal, the maximum interception distance of the electronic reconnaissance receiver has decreased by 58.81 meters, and the working factor has decreased by 25%. The designed co-address MIMO-OCDM signal has good low interception performance and certain engineering application value.

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