Study of Jamming Technology to Frequency Division Multiplexing Linear Frequency Modulation MIMO Radars

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Abstract—**The orthogonal frequency division multiplexing linear frequency modulation (OFDM-LFM) MIMO radar, as a typical MIMO radar has been studied comparatively well. It is necessary to study its countermeasure method. For this purpose, a jamming method is proposed in this paper. Which can degrade the radar performance by transmitting multi-signal synchronously. First, the parameters of OFDM-LFM radar are analyzed and the multi-jamming-signals are generated at the same time. Compared with the traditional methods, the approach requires less jamming power. Furthermore, the bigger amount of subarrays the less jamming power is required. The simulation experiments show that the method is effective to counter MIMO radar with a small jamming power.**

Keywords-OFDM-LFM; MIMO radar; active jamming; multi-signal; synchronal jamming

I. INTRODUCTION

At present, the multi-input multi-output (MIMO) radar technique has become a focus of research in radar area. Different from a standard phased-array radar, a MIMO radar system transmits multiple probing signals. Which may be correlated or uncorrelated with each other via its antennas. The MIMO radar contains multiple transmitters and receivers. Which are distributed in space. In general, the MIMO radar can be considered to a multistatic radar. The separate nomenclature in [1] sets MIMO radar apart from the multistatic radar. While it has a close relation with MIMO communications.

The traditional array radar works with high gain and narrow beams to obtain a high signal-to-noise ratio (SNR) [2]. However, the orthogonal signals MIMO radar transmits orthogonal signals with wide and low gain beams [3, 4]. It receives the orthogonal echoes in different narrow beams. Which are formed by the digital beam forming (*DBF*) technique. The orthogonal echoes are received with the whole antenna. They are separated by matching filters. Which can overlap the scope by low gain transmitting beams [5, 6].

The OFDM-LFM is a typical kind of orthogonal signal in MIMO radar. Which can suppress jamming [7, 8]. Otherwise, the pulses transmitted from the OFDM-LFM MIMO radar are difficult to be analyzed in a reconnaissance receiver. Both the above two factors make it difficulty to counter OFDM-LFM MIMO radar. At present, only a few jamming methods to the MIMO radar are proposed. [9, 10] considered the power allotment for the jammer which counters MIMO radar. [11-13] studied some methods to counter radar net. This paper presents an approach to jam the OFDM-LFM MIMO radar effectively. Firstly, this paper analyzes OFDM-LFM MIMO radar signal forms and it's working principle. Next, the research adopts methods of the center frequency guide and signal separation etc. for reconnaissance and signal processing. Finally, this paper adopts much synchronous creation and compounding many signals for shooting. It's intention is to deal with the MIMO radar. It has many orthogonal signals. This paper illuminates a method feasible to jam OFDM-LFM MIMO radars in theories. It analyzes and verifies the usefulness of the method by simulation.

II. THE WORKING PRINCIPLE OF OFDM-LFM MIMO RADAR

The functional block diagram of an orthogonal signal MIMO Radar is shown in the Fig.1. It can be seen that there exists M subarrays to transmit the orthogonal signals $s_1(t)$, $s_2(t)$,..., $s_M(t)$ respectively. These transmitted orthogonal signals cannot form a high gain and narrow beam in the space. Which form low gain and wide beams.

The orthogonal echoes are separated from each other by matching filters. Then, the high gain and narrow beams can be formed through the *DBF* technique. As shown in Fig.1, the formed beams overlay the scope of transmitting wave beam [5]. The *DBF* processing can be considered to be an integration of two types of beams equivalently. The first one is receiving array, which forms a beam to receive target signals. The second one is transmitting array, which forms *M* transmitting beams. The receiving beam is formed before matching filter processing and it is not related to the orthogonal signal forms.

The transmitting array with L units is divided into M subarrays. Each subarray transmits the mutually orthogonal linear frequency modulation (LFM) signal with a wide transmitting beam. Assume that the radar works in narrow band and there are L units in the transmitting array. Which is divided into M subarrays in the MIMO mode and each subarray has L_1 $(L = ML_1)$ units, then the receiving signal can be expressed as follows (Supposing that each transmitting unit has equal power in phase arrays) [12,13]:

$$p_{mimo}(t)=\sum_{m=1}^{M}\sqrt{\alpha_t P_t / M}\, s_m(t-\tau/2)\,. \quad (1)$$

Where α_t is the transmitting loss factor, P_t is the total transmitting power， τ is the delay time of transmitting signal from the radar to the target.

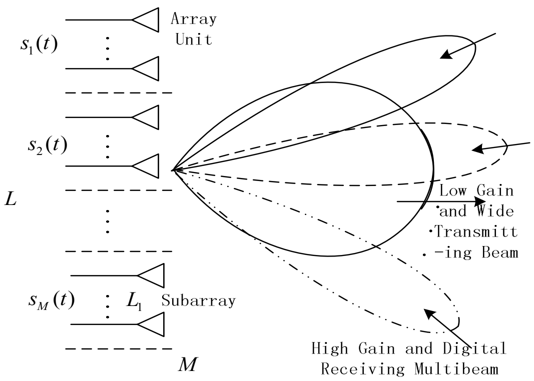

Figure 1. Principle sketch map of orthogonal signal MIMO radar

In order to form the orthogonal condition, they should have the transmitting frequency intervals f_Δ between the adjacent subarrays. It must be integral multiple of 1/Tp (Tp is the pulse width). Then the total bandwidth of signals can be written as:

$$B_\Sigma = B_s + (M-1) f_\Delta\,. \quad (2)$$

where B_s is the bandwidth of a single signal. For the traditional phase array radar, its receiver bandwidth is only B_s , which is smaller than MIMO radar.

III. MIMO RADAR COUNTERMEASURE TECHNOLOGY

A. MIMO radar signal reconnaissance

The working parameters of MIMO radar can be measured with the reconnaissance receiver, such as center frequency and waveforms of the M transmitting signals. Next, the direction of arrival (DOA) of the MIMO radar is estimated in high precision based on intercepted signals [14].

The M signals from the MIMO radar is received with an flat, spiral and equal-bandwidth antenna and a wideband frequency measuring receiver at the same time. Then, all the center frequencies of signals are obtained by the frequency spectrum analysis or other methods. According to these center frequencies the receive channels are controlled as a standard. It can realized by the local oscillator and intermediate frequency (IF) circuits which have narrow-band bandwidths. Signals are mixed in narrow-band channels and processed in IF. Then the inter pulse parameters can be acquired including the center frequencies and modulation types, as shown in Fig.2. The radar signal power received by reconnaissance receiver can be written as:

$$P_{r.r} = \frac{P_t G_t(\theta_j) G_r \lambda^2 \gamma_j}{(4\pi)^2 R_j^2}\,. \quad (3)$$

Where P_t is the total power of all the MIMO radar signals, $G_t(\theta_j)$ is the antennae transmitting gain of the MIMO radar signals in the direction relative to the jammer's direction, R_j is the distance between the jammer and the radar, γ_j is the polarization loss of the reconnaissance jamming signal, G_r is the antenna receiving gain of the reconnaissance receiver, λ is the working wavelength of the MIMO radar, θ_j is the direction of the jammer.

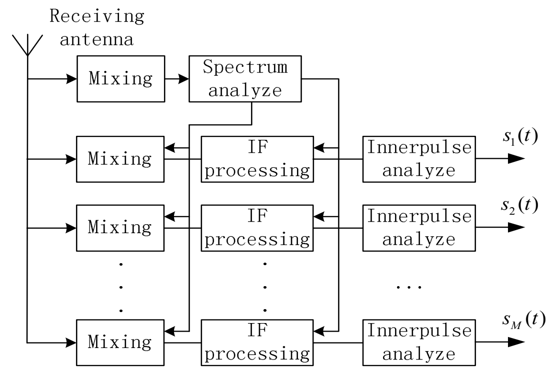

Figure 2. The reconnaissance receiver principle of MIMO Radar

The total power is divided into M signals power equally, so the power of every signal is $P_{r.r}/M$.

$G_t(\theta)$ is the signals receiving gains of MIMO radar receiving antennae. Which will be deduced by the underneath formulae. The normalized array factor of a phased array can be represented as:

$$E_a(\theta)=\frac{\sin\left[N\pi\left(d/\lambda\right)(\sin\theta-\sin\theta_0)\right]}{N\sin\left[\pi\left(d/\lambda\right)(\sin\theta-\sin\theta_0)\right]}\,. \quad (4)$$

Where θ is the angle from the normal line of antenna plane, *N* is the antenna number of the antenna array, *d* is the distance between two the adjacent antennae, θ_0 is the direction of the antenna beam center points.

The maximum value of the antenna gains is $G_0 = N\pi\cos\theta_0$ [15].

The antenna gain at different directions could be expressed as follows:

$$G(\theta) = G_0 \left|E_a(\theta)\right|^2 . \tag{5}$$

If $d = \lambda / 2$, the antenna beam center will point to the zero position, and $\cos\theta_0 = 1$. Then the antenna beam transmitting gain is obtained as:

$$G_t(\theta) = L_1 \pi \left[\frac{\sin\left(\frac{\pi}{2} L_1 \sin\theta\right)}{L_1 \sin\left(\frac{\pi}{2} \sin\theta\right)} \right]^2 . \tag{6}$$

The receiving gain of antenna beam with different beam center directions can be written as:

$$G_m(\theta) = L\pi \cos\theta_m \left\{ \frac{\sin\left[\frac{\pi}{2} L(\sin\theta - \sin\theta_m)\right]}{L \sin\left[\frac{\pi}{2} (\sin\theta - \sin\theta_m)\right]} \right\}^2 . \tag{7}$$

Where $m = 1, 2, \cdots, M$.

B. Synchronous Multi-signal jamming to OFDM-LFM MIMO radar

For active jamming, the jamming power, jamming type, and signal style should be taken into account. In this paper, random jamming pulses are transmitted in a high pulse repetition frequency (PRF). The jamming signals have the same pulse modulation parameters as the radar signals, such as the pulse width, center frequency, and frequency modulation slope and so on. The Jamming pulses have high and random PRF. Moreover, all the M jamming signals should be transmitted at the same time. To ensure that the M jamming signals are generated at the same time and have same pulse width, the control circuit must be unified and synchronized. After MIMO radar receives and disposes the jamming signal, the echo signal characteristic will be similar to the original signal. Through the way, a lot of false pulses are generated.

The JSR of MIMO radar is larger than the given suppression ratio K_j. This signal style will bring out high processing gain which is equal to the original signal in the MIMO radar. The final signals can pass the matched filters.

High precision digital frequency storage is used to intercept all signals. Which are received by different reconnaissance channels. The signals can synchronize by using the same synchronized jamming control circuit to implement time-delay, power amplification. Then all the outputs are sent to the transmitting antennae. As shown in Fig.3, the antenna aims at the direction of the MIMO radar.

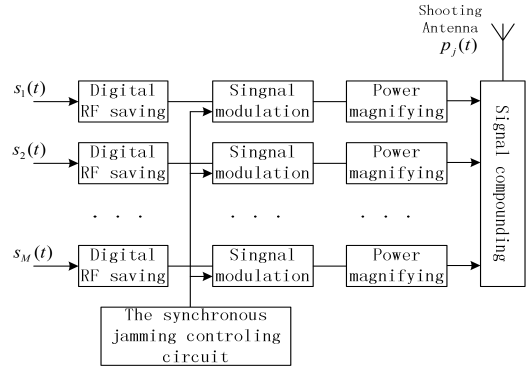

Figure 3. The production principle of jamming signal to MIMO Radar

The receiving power of the MIMO radar from the reflected signal of target can be represented as:

$$P_{rs} = \frac{P_t G_t(\theta_{tgt}) G_m(\theta_{tgt}) \sigma \lambda^2}{(4\pi)^3 R_t^4} . \tag{8}$$

Where θ_{tgt} denotes the direction of target, σ is the reflection cross area of target, R_t is the distance between the target and the radar.

The receiving power of the MIMO radar from the jammer can be written as:

$$P_{rj} = \frac{P_j G_j G_m(\theta_j) \lambda^2 \gamma_j}{(4\pi)^2 R_j^2} . \tag{9}$$

Where $P_j G_j$ is the effective jamming power.

Every jamming signal jams one signal of MIMO radar. Because the MIMO radar receives electromagnetic wave in M narrow beams, it could receive only one target echo. Different echoes have different frequency and thus they cannot accumulate with each other. However, the exact direction of the receiving beam which aims at the target is unknown. Thus, all jamming signals have to mixed together. If the receiving beam of the *m*th signal is aimed at the target, the jamming power to the *m*th signal can be written as:

$$\frac{P_{rjm}}{P_{rsm}} = \frac{P_{jm} G_j M}{P_t G_t(\theta_{tgt})} \frac{4\pi\gamma_j}{\sigma} \frac{R_t^4}{R_j^2} \frac{G_m(\theta_j)}{G_m(\theta_{tgt})} \geq K_j . \tag{10}$$

In the above equation, P_{jm} is the necessary jamming power for the *m*th radar signal, whose value is:

$$P_{jm} = \frac{P_t G_t\left(\theta_{tgt}\right) G_m\left(\theta_{tgt}\right) \sigma K_j R_j^2}{4\pi M \gamma_j G_j G_m\left(\theta_j\right) R_t^4} . \tag{11}$$

The total jamming power is M multiples of the mth radar signal and it can be expressed as:

$$P_j = MP_{jm} . \tag{12}$$

IV. THE SIMULATION ANALYSIS

Assume that the total power of the MIMO radar antenna is: $P_t = 50kw$, the distance between radar and target is: $R_t = 62km$, the distance between radar and jammer is: $R_j = 75km$, the gain of jamming antenna is: 20dB, the RCS value of the protected target is: $\sigma = 5m^2$, the suppression coefficient is: $K_j = 4.5$.

(1)The influence caused by different numbers of subarray

Assume that the total number of MIMO radar antenna units is L, and $L = 1024$. The relationship between the number of subarray and the required total jamming power is shown as Fig.4. We can see that the jamming power of MIMO radar is less than that of phased array (When the number of subarray is 1, the MIMO radar becomes a phase array radar). When the number of subarray increases, the jamming power will be easier. The required jamming power is inversely proportional to the square of the number of subarray.

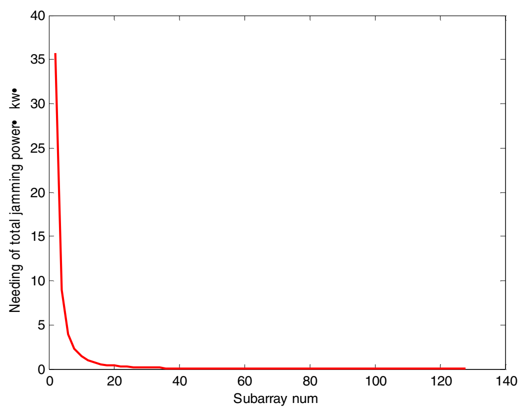

Figure 4. the relationship between the number of submatrix and the required total jamming power

(2)The receiving power of the reconnaissance receiver

The MIMO radar is similar to the phased array system. The transmitting gain at the direction of target will change as the DOA of target changes. So the required jamming power changes, which ignores the different gains of different receiving beams. The required jamming power to target of different direction is shown as Fig.5. If all the centers of signal transmitting beams are aimed at zero position, as $\theta = 0$, $\theta_0 = 0$, $L = 64$, $M = 8$. The transmitting gain becomes less as the angle deviating from the zero position is larger. Then the signal power received by the jammer will get to be less too.

(3)The influence of the jamming in different receiving beams of MIMO radar

The receiving beam is high directional. Its gain changes with different directions. This change is discrete. At the same time, the gains of transmitting beam are different. So the required jamming power in different receiving beams is different. Assume that the fixed direction of target is: $\theta_{tgt} = 5°$,and $L = 64$, $M = 8$, jammer is located separately in the receiving beam center denoted by number from 1 to 8, as shown in Fig.6. The first and eighth beams are aimed at -35 and 35 degrees, respectively. The interval between the neighboring beams is 10 degrees.

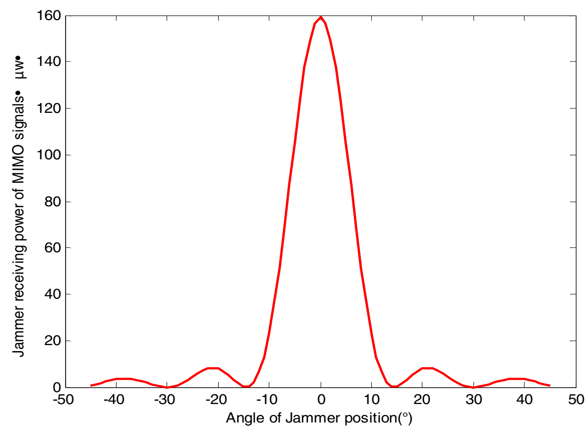

Figure 5. the relationship between the direction of jammer and receiving jamming power

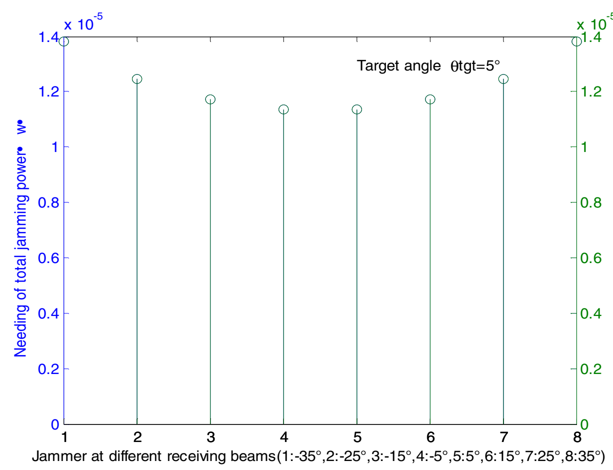

Figure 6. the relationship between the receiving beam which the jammer locates

(4)The influence of jamming in different directions

Assume that the total units of array is 64, and $M = 8$, $\theta_{tgt} = 5°$, $R_j = R_t = 62km$. The receiving and transmitting gains of MIMO radar to targets are decided by both receiving beams and transmitting beams. The required jamming power is changed by the target directions, as shown in Fig.7. Two situations are considered: one is that jammer and target are located in the same position (Self-defensive jamming); the other is that the jammer is in different directions, while target is fixed in the direction $\theta_{tgt} = 5°$. The value near the zero position is the biggest, and it becomes less when the degree is away from the zero position. The required power of the supporting jamming is larger than the self-defensive jamming. The required power of supporting jamming is larger or less in different directions, as shown in Fig 7.

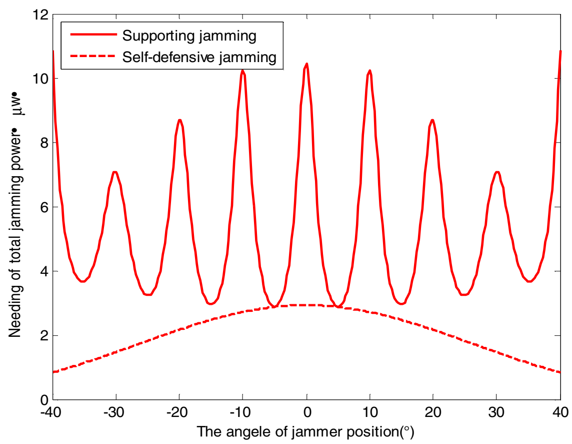

Figure 7. the relationship between the direction of target and the required power of the jammer

V. SUMMARY

Compared with the traditional phased array radar, the MIMO radar has important technical advantages, such as larger dynamic range, better performance of weak target detecting, and better ability of target recognition. On the other hand, the required jamming power for the MIMO radar is less than the phased array radar. Thus the MIMO radar will be jammed more easily, if the number of subarrays increases. However, the number of subarrays increases with the increasing number of orthogonal signals. The jammer becomes difficult to detect the signals and produces jamming signals. Then it requires us to improve its performance. Against this background, a method is proposed to jam OFDM-LFM MIMO radar, and a new idea is provided in this paper.

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