Simulations of the OFDM signal from distinguishing the aircraft from the chaff jamming

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Abstract: This study discusses the capability of the orthogonal frequency division multiplexing (OFDM) radar recognition on the aircraft in the chaff jamming, in contrast to the linear frequency modulation (LFM) signal form. The process result of the LFM signal form induces a fake target in the recognition on the aircraft in the chaff jamming, because the range and the Doppler are coupled. The process result of the OFDM signal form can separate the real target and the chaffs clearly, because the range and the Doppler are uncoupled from the signal form. The OFDM signal form is a novel and efficient way to solve the chaff jamming.

1 Introduction

The chaff jamming is one of the most wide passive jamming in the world, since the Second World War. The chaff jamming is used for the oppressive jamming and the deception jamming. When used for oppressive jamming, the chaffs occupy a larger space area to make radars hard to detect the targets, usually for covering the behind warplanes breaking the defence [1]. When used for deception jamming, the chaffs are dropped by warplanes or warships to form the fake targets to disturb the radar to scan and track on the real target [2].

Here, we introduce the orthogonal frequency division multiplexing (OFDM) radar to recognise the real target in the chaff jamming. The OFDM concept was originally proposed as a digital modulation technique in communication fields and later on introduced into radar community by Jankiraman [3]. Since then, a large amount of work has been done, such as target detection and tracking [4, 5], synthetic aperture radar (SAR) imaging [6, 7], and so on. For now, there exists some representative OFDM radar systems, such as HYCAM [8], the system for radar and tracking [4, 5], synthetic aperture radar (SAR) imaging [6, 7], and so on. Recently, the OFDM signal form was developed to estimate the radial range and the radial velocity of the target in one single pulse [10, 11], in contrast to that the linear frequency modulation (LFM) signal form is not able to distinguish the radial range and the radial velocity of the target in one single pulse.

In this paper, we adopt the OFDM signal form based on [10, 11] to recognise the aircraft in the chaff jamming, using the difference of the radial ranges and the radial velocities between the aircraft and the chaffs.

2 OFDM signal form

The basic OFDM signal form is shown in Fig. 1, \( f_0 \) denotes the carrier wave, \( \Delta f \) denotes the subcarrier spacing, \( T_p \) denotes the pulse width, \( T_r \) denotes the pulse repetition interval, \( M \) denotes the pulse number, \( N \) denotes the subcarrier number, \( B = N \Delta f \) denotes the total bandwidth. Then, a single pulse is represented as:

\[
s(t) = \sum_{n=0}^{\frac{N-1}{2}} \text{rect}(t, T_p) \exp[2\pi j f_0 + n\Delta f] r(t)
\]

where

\[
\text{rect}(t, T_p) = \begin{cases} 
1 & 0 \leq t \leq T_p \\
0 & \text{Otherwise} 
\end{cases}
\]

and \( T_p \Delta f = Z \), where \( Z \) is a positive integer.

Considering \( L \) targets, \( R_{i0} \) and \( v_i \) (\( i = 1, 2, \ldots, L \)) are the \( i \)th initial radial range and radial velocity. The received signal is written as:

\[
s(t) = \sum_{i=1}^{L} \sum_{n=0}^{\frac{N-1}{2}} \rho_i \text{rect}(t - \tau_{i0}, T_p) \exp[2\pi j (f_0 + \Delta f) (t - \tau_{i0})]
\]

where \( \rho_i \) denotes the complex scattering coefficient corresponding to the \( i \)th target and \( \tau_{i0} = 2(R_{i0} + v_i t)/c \) is the round-trip delay, \( c \) is the light velocity in vacuum. After demodulation to each channel, the e.g. (3) is written as:

\[
s(t) = \sum_{i=1}^{L} \sum_{n=0}^{\frac{N-1}{2}} \rho_i \text{rect}(t - \tau_{i0}, T_p) \exp[-2\pi j f_0 + n\Delta f] r_{i0}
\]

The sampling rate \( f_s \) is set to be \( B \) and the sampling time \( T_s \) is set as \( KT_s = T_p \). Then, the received signal can be derived as a two-dimensional matrix:

\[
s(t) = \sum_{i=1}^{L} \rho_i \text{rect}(t - \tau_{i0}, T_p) \exp[-2\pi j f_0 \frac{2R_{i0}}{c}] X
\]

\[
X = \begin{bmatrix}
x_{0,0} & x_{0,1} & \cdots & x_{0,K-1} \\
x_{1,0} & x_{1,1} & \cdots & x_{1,K-1} \\
\vdots & \vdots & \ddots & \vdots \\
x_{N-1,0} & x_{N-1,1} & \cdots & x_{N-1,K-1}
\end{bmatrix}
\]
where \( x_{n,k} = \exp(-j4\pi n\Delta f R(t)/c)\exp(-j4\pi (\nu + n\Delta f) kT_p/c) \), \( n = 0, 1, \ldots, N-1 \), \( k = 0, 1, \ldots, K-1 \). If \( B < f_0 \), then \( x_{n,k} \) can be expressed as \( x_{n,k} = \exp(-j4\pi n\Delta f R(t)/c)\exp(-j2\pi kT_p/c) \), where \( f_d = 2f_0/c \) denotes the Doppler frequency, which means the range and the Doppler information are independent. After applying a two-dimensional discrete Fourier transform (2D-DFT) on \( s(t) \), we can derive the range-Doppler image of the targets in a single pulse.

In this OFDM signal form, the radial range resolution is defined as \( c/2B \), the maximum radial range without eclipsing is \( c/2\Delta f \), the Doppler resolution is \( 1/T_p \), and the unambiguous Doppler frequency is \( 1/T_p \).

3 Power spectrum of the chaffs

The power spectrum of the chaffs is set as a Gaussian distribution [12]:

\[
S(f) = S_0 \exp \left( -\frac{(f - f_\nu)^2}{2\sigma^2} \right)
\]

(7)

where \( S_0 \) is the average power, \( f_\nu \) is the average Doppler frequency of the chaffs related to the wind velocity, and \( \sigma = 2\sigma_d/\lambda \) denotes the standard deviation of the power spectrum. \( \sigma_d \) is the standard deviation of the chaffs radial velocity, and \( \lambda \) is the wavelength of the radar signal. \( \sigma_d \) can be evaluated as \( \sigma_d = 0.4 \text{ m/s} \times 1.2 \text{ m/s} \) [12].

When the chaffs are used for the oppression jamming, the chaffs are preset on the route of the aircraft, and the diffusion of the chaffs can be treated as homogeneously distributed. The radial range distribution of the chaffs is set to be a constant in a small distance. When the chaffs are used for the deception jamming, the distance between the chaffs and the aircraft is very small at the moment of the aircraft dropping the chaffs.

4 Simulation

The OFDM radar parameters are set as the carrier frequency \( f_0 = 10 \text{ GHz} \), the number of subcarriers \( N = 10 \), the subcarrier \( \Delta f = 1 \text{ MHz} \), the total bandwidth \( B = NA\Delta f \approx 10 \text{ MHz} \), the pulse width \( T_p = 1 \text{ ms} \), the sampling time \( T_s = 5 \mu s \), \( K = 200 \). According to the above settings, \( B < f_0 \), the range and the Doppler information can be treated as uncoupled, and the maximum velocity of the aircraft is usually below 2 Ma (680 m/s), which means the Doppler frequency \( f_d \) is below 46 kHz, and the energy loss of the subcarrier can be tolerated for \( f_d < \Delta f \). According to the above settings, the radial range resolution is 15 m, the maximum radial range without eclipsing is 150 m, the Doppler resolution is 1 kHz, which means the radial velocity resolution is 15 m/s, and the unambiguous Doppler frequency is 200 kHz, which means the unambiguous radial velocity is 3 km/s.

The LFM signal form is adopted as a contrast and the parameters of the LFM signal form are set as the carrier frequency \( f_0 = 10 \text{ GHz} \), the bandwidth \( B = 10 \text{ MHz} \), the pulse width \( T_p = 1 \text{ ms} \).

The total scattering amplitude of the chaffs can be considered as 5 to 10 times as the scattering amplitude of the aircraft [13]. In this simulation, the standard deviation of the chaffs radial velocity is set to be \( \sigma_d = 30 \text{ Hz} \), the wind velocity is set to be 10 m/s, and the average Doppler frequency of the chaffs can be set as \( f_\nu = 300 \text{ Hz} \).

Concerning the deception jamming situation, the radial velocity of the aircraft is set to be 450 m/s, the radial range is 3 km, and the total scattering amplitude of the chaffs is set to be 10 times as the scattering amplitude of the aircraft. The power spectrum of the chaffs, the pulse compression of the LFM signal form result with no noise, and the OFDM signal form result with no noise are displayed in Figs. 2–4, respectively.

It can be seen in Fig. 3, that the pulse compression of the LFM signal form induces a fake target in the radial range recognition. It is because that, when the aircraft drops the chaffs, the distance between the chaffs and the aircraft is very close and the radial range of them can be treated as the same, but the velocity of them are different, which induce the coupling of the range and the Doppler. The fake distance between the fake target and the real target is defined as \( \Delta f_{\text{chaff}}T_p/c' = 2B \times f_{\text{chaff}}T_p/c' = 2B \), because the radial velocity of the aircraft is further larger than the radial velocity of the chaffs.

In Fig. 4, the OFDM signal form can derive the radial range and the radial velocity of the target at the same time. Even though the chaffs locate at the same place of the target, but the difference of the radial velocities between the chaffs and the target can be used to recognise the target. It can be seen that the target and the chaffs are separated clearly in Fig. 4.

Concerning the oppressive jamming situation, the chaffs are set as a corridor with the radial range of 150 m. The other parameters are set as the same as the deception jamming situation. The pulse compression of the LFM signal form result with no noise and the OFDM signal form result with no noise are displayed in Figs. 5 and 6.

It can be seen in Fig. 5, that the chaff jamming signals form a passage of the fake target signals in the LFM signal form result. If the chaff corridor is much longer than 150 m radial range, the real target may be covered up. However in Fig. 6, the chaff jamming signals are concentrated at the passage with the velocity near 0 m/s, which is clearly separated from the real target.
5 Conclusions

The capability of the OFDM radar recognition on the aircraft in the chaff jamming is simulated. In principle, the OFDM radar signal can locate the target accurately in the radial range and the radial velocity, but it proposes higher requirements on the signal generator, the signal amplifier, and the signal process in the backend of the receiver. The most obvious shortcoming of the OFDM radar signal is the lower energy using efficiency in the radial velocity evaluation. However, it is still a novel and efficient way to solve the chaff jamming.

6 References

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Fig. 6 OFDM signal form result among the real target and the chaff jamming with no noise