C&I Jamming Technology Based on Frequency Diverse Array Antenna

Hui Wang and Zhenwei Li and Lu Zhang and Xiaowei Wang and Tao Su

Information & Telecommunication Branch, State Grid Anhui Electric Power Co., Ltd, Hefei 2030041, Anhui, China
Email: wang_hui@std.uestc.edu.cn

Abstract. Chopping and Interleaving (C&I) interference can produce better jamming effect on pulse compression radar. Based on this, a novel radar jamming approach to utilize frequency diverse array (FDA) antenna is proposed in this paper. Compared with the traditional phased array antennas, there is a small frequency increment (Δf) between each element of the FDA antenna, which provides promising prospect to develop new radar jamming techniques. The jamming approach proposed in this paper can quickly produce more false targets. Moreover, the number of false targets is manipulated by the elements and frequency offset of FDA antenna, which indicates that many false targets can be easy to control. The simulation results provide strong support for the effect of the proposed approach.

Keywords. Chopping and interleaving (C&I); frequency diverse array (FDA); frequency increment; more false targets; controlled.

1. Introduction
Judging from the wars that have occurred in the world in recent years, modern wars are all high-tech wars, and their prominent feature is electronic warfare [1]. It is self-evident that electronic warfare is at the core in modern warfare. To some extent, electronic warfare has become the decisive factor in determining the victory and defeat of modern warfare. The radar plays an important role in modern warfare. Therefore, radar jamming technology has become an important subject and direction for scholars at home and abroad [2].

In 2006, the concept of frequency diversity array (FDA) radar was firstly proposed by Antonik and Wicks [3]. Compared with the traditional phased array antennas, there is a small frequency offset (Δf), as compared to the carrier frequency between each element of the FDA [4]. FDA provides a potential to contrive deceptive jamming methods against pulse compression radar, which plays an important role in radar deceptive jamming [5].

M. J. Sparrow et al. Proposed in 2006 that chopping and interleaving (C&I) interference is a novel type of multiple false target jamming [6, 7]. The development of this interference benefits from the rapid development of Digital Radio Frequency Memory (DRFM) technology. Digital Radio Frequency Memory (DRFM) is the main component of an active radar jammer in modern electronic countermeasure systems [8]. It is used to accurately copy the received radar signal and then forward it to the radar system to generate false targets. The paper [6] provides a detailed analysis of the principle and characteristics of the basic style of C&I interference, namely intermittent sampling and forwarding interference, and the two interferences are essentially the same. C&I interference has the dual functions of suppression and deception, which can hide real targets among multiple false targets, and which has a outstanding jamming effect on radars that emit linear frequency modulated (LFM) signals.
C&I interference technology has attracted great attention from researchers studying radar interference at home and abroad since it was proposed. Scott D. et al. conducted an in-depth study of the frequency spectrum of C&I interference signals and proposed an effective method for identifying interference signals [7]. Greco of Italy analyzed the effect of phase quantization and delay quantification on the signal spectrum under different circumstances and the effect of quantitative delay on the signal spectrum, and derived its interference model [8]. Although the paper [9] analyzes and simulates the principle of C&I interference, it is slightly inadequate compared to the interference proposed in this paper. Because C&I interference is highly correlated with radar signal, and its interference power is reduced after radar processing, and obtains excellent deception effect. Therefore, this paper presents a C&I interference method based on FDA antenna.

Our proposed deceptive interference method based on the FDA antenna, which takes full advantage of the unique properties of FDA, and its advantages are as follow. Firstly, it can quickly produce many false targets. Secondly, the number of false targets can be controlled by the frequency offset or determined by the elements [9]. This article is arranged as follows. Section II introduces the FDA signal model and analyzes its beam characteristics [10]. Then, the principles of C&I interference. Section III simulates the C&I interference effect. Section IV concludes this paper.

2. FDA Signal Model and Principle of C&I Jamming

2.1. FDA Signal Model

For simplicity without losing generality, we presume that a uniform linear array antenna contains $M$ elements with spacing $d$ [5], and its signal model is shown in figure 1. Suppose that the carrier frequency of the first element is $f_0$. The carrier frequency of the second element is $f_0 + \Delta f$. $\Delta f$ is a small frequency increment or frequency offset [11]. Then, the expression of the transmitted signal of the $k$ th element can be written as:

$$s_k(t) = \exp(-j2\pi f_k t)$$

where, the carrier frequency of the $k$ th element is $f_k = f_0 + (k - 1)\Delta f$, $k = 0, 1, \cdots, M - 1$, with $f_0$ being the carrier frequency. Assuming there is a point target that is at range $R_0$ and azimuth $\theta$, according to the electromagnetic field theory, the beam intensity pattern of the FDA antenna at the far-field point target is written as [12] shown in equation (2).

![Figure 1. FDA signal model.](image)
\[ E(t, R_0, \theta) = \sum_{k=0}^{M-1} \frac{1}{R_k} \exp \left[ -j2\pi f_c \left( t - \frac{R_k}{c} \right) \right] \]
\[ = \exp \left( j\phi_0 \right) \sum_{k=0}^{M-1} \frac{1}{R_k} \exp \left[ -j2\pi \left( k\Delta f t - k \frac{\Delta f R_0}{c} - k \frac{d \sin \theta}{\lambda_0} - k^2 \frac{\Delta f d \sin \theta}{c} \right) \right] \]

where \( \phi_0 = -2\pi (f_c t - R_0 / \lambda_0) = -2\pi f_c (t - R_0 / c) \), \( R_k = R_0 + k d \sin \theta, \lambda_0 = c / f_0 \). Since \( (M - 1)\Delta f < f_0, k^2 \Delta f d \sin \theta / c < \pi / 12 \) the influence can be ignored, so equations (2) can be approximately written as shown in equation (3).

\[ E(t, R_0, \theta) \approx \frac{ \exp \left[ j \left( f_c + \pi (M - 1) \frac{d \sin \theta}{\lambda_0} \right) \right] \sin \left[ \pi M \left( \frac{\Delta f t}{c} - \frac{d \sin \theta}{\lambda_0} \right) \right] }{ \frac{1}{R_0} \sin \left[ \pi \left( \frac{\Delta f t}{c} - \frac{d \sin \theta}{\lambda_0} \right) \right] } \]

where \( f_c = -2\pi f_c (t - R_0 / c), f_c = \frac{1}{M} \sum_{k=0}^{M-1} f_k = f_0 + \frac{M - 1}{2} \Delta f \).

Assume that the FDA element \( M = 8 \), carrier frequency \( f_0 = 15\text{GHz} \), frequency offset \( \Delta f = 10\text{KHz} \), time \( t = 0\text{ms} \), element spacing \( d = \lambda_0 / 2 \). The position of the point target is located at \((24, 30\text{km})\). Then, Matlab simulation result of the transmitting antenna beam pattern of the FDA is shown in figure 2.

![FDA Beampattern](image)

**Figure 2.** FDA Beampattern: (a) Top view of beam; (b) 3D beam.

### 2.2. Principle of C&J Jamming

C&I interference is a kind of range false target jamming for chirp radar, unlike other interference, which is a copy of the received radar signal in each segment. C&I interference process is as follows. Firstly, use the jammer to intercept the radar transmitted signal and store it in DRFM. Then, the intercepted radar signal is sampled with an equally spaced rectangular pulse sequence, this process is the Chopping stage. Finally, the sampled radar signal is copied into the adjacent gap until the gap is filled, this process is called the Interleaving phase. The specific generation process is shown in figure 3.
Assuming the radar signal is $s(t)$, C&I interference signal can be expressed as:

$$s_{CI} = \sum_{k=0}^{n-1} p(t - kT / mn)$$

where $m$ is the number of rectangular pulse trains (fragment number), $n$ is the number of filled time slots per segment (interleaving number). $T$ stands for radar signal pulse width.

$$p(t) = s(t) \left[ rect \left( \frac{t - \tau_a}{\tau_a} \right) * \sum_{i=0}^{\frac{m-1}{2}} \delta \left( t - iT_a \right) \right]$$

where $\tau_a$ is the pulse width of the rectangular pulse train is (fragment time width, $\tau_a = T / mn$). $T_a$ is the fundamental period of the rectangular pulse train ($T_a = n\tau_a$).

According to the above mathematical model, we can see that essentially every part of C&I interference is a copy of the received radar signal, so the interference signal and the radar signal must contain the same chirp rate, and which is matched with the matched filter of the radar transmitted signal. Therefore, C&I interference can generate a large number of false targets at the receiving end of the radar to achieve the effect of confusing true targets.

The implementation of FDA-based C&I interference is to replace the phased array antenna with an FDA antenna.

### 3. Simulation Analysis

In section, we suppose that the parameters of the jammer can be obtained by the reconnaissance device. Typical simulation parameters are shown in following table 1.

| parameter              | Numerical value |
|------------------------|-----------------|
| Carrier frequency      | 10GHz           |
| Bandwidth              | 50MHz           |
| Pulse width            | 30us            |
| Fragment time width    | 1.5us           |
| Chopping Number        | 5               |
| Interleaving Number    | 4               |
| True target range      | 6km             |
First of all, we unpack the effect of C&I interference based on phased-array. Figure 4a is a time-frequency analysis diagram of the radar transmitting signal received by the jammer, which shows that the radar is transmitting a chirp signal. The time-frequency analysis results of C&I interference based on phased array are shown in figure 4b. It can be found that the C&I interference signal is divided into five large blocks and each block consists of four small blocks, which is consistent with the previous simulation parameter settings. The C&I interference effect based on phased array is shown in figure 5. Figures 4b and 5 verify that the C&I interference is correct and effective.

![Figure 4. Time-frequency analysis.](image1)

![Figure 5. C&I jamming result based on phased-array.](image2)

Next, we simulate the effect of C&I interference based on FDA. Presume the simulation parameters: $\Delta f = 300\text{kHz}$, $M = 4$. The time-frequency analysis of C&I interference based on the FDA antenna is shown in figure 6a. Comparing figures 5 and 6b, we can find that FDA-based C&I interference can get more false targets. Comparing figures 6b and 6c, we can show that the quantity of false targets increases with the number of FDA elements. Figure 6d is the C&I interference effect of frequency offset ($\Delta f = 10\text{kHz}$). From figures 6d and 5, we can know that when the frequency deviation is relatively small, the C&I interference based on FDA antenna and the C&I interference based on phased array are basically the same.
6

\section*{Acknowledgments}
The work was supported by National Natural Science Foundation of China (Grant 61671122).

\section*{References}
[1] Butt F A and Jalil M 2013 An overview of electronic warfare in radar systems The International Conference on Technological Advances in Electrical, Electronics and Computer Engineering (TAECE) (Konya) pp 213-217.
[2] Zohuri B 2020 Electronic countermeasure and electronic counter-countermeasure Radar Energy Warfare and the Challenges of Stealth Technology (Springer, Cham) pp 111-145.
[3] Antonik P, Wicks M C, Griffiths H D, et al. 2006 Multi-mission multimode waveform diversity Proceedings of the IEEE Radar Conference pp 580-582.
[4] Wang H, Zhan S, Wang W, Guan H and Ding H 2018 Homogeneously distributed multiple false targets jamming using frequency diverse array 2018 International Conference on Radar (RADAR) (Brisbane, QLD) pp 1-6.
[5] Mao W, Wang H, Zhang S and Liu X 2019A novel deceptive jamming method via frequency diverse array IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium (Yokohama, Japan) pp 2369-2372.

\section*{4. Conclusion}
C&I interference using on FDA antenna can generate more false targets, and the number of false targets is manipulated by the elements and frequency offset of FDA antenna. Increasing the number of FDA antenna elements or increasing the frequency offset will increase the number of false point targets. Simulation results demonstrate that the proposed method can produce effective jamming effects on chirp system radar.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{C&I jamming result based on FDA antenna.}
\end{figure}
[6] Zhou C, Shi F Q and Liu Q H 2016 Research on parameters estimation and suppression for C&I jamming *International Conference on Radar* pp 1-4.

[7] Sparrow M J and Cakilo J 2006 ECM techniques to counter pulse compression radar *US7081846 B1*.

[8] Zhang X, et al. 2019 Joint polarisation and frequency diversity for deceptive jamming suppression in MIMO radar *IET Radar, Sonar Navigation* pp 1-4.

[9] Huang L, et al. 2019 Multi-targets deception jamming for ISAR with frequency diverse array *IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium*.

[10] Wang Y and Zhu S 2020 Main-beam range deceptive jamming suppression with simulated annealing FDA-MIMO radar *IEEE Sensors Journal* 20 (16) 9056-9070.

[11] Li Z, et al. 2019 A robust STAP approach for airborne FDA radar with multiple possible prior information constraints *Multidimensional Systems & Signal Processing* 1-4.

[12] Sammartino P F, Baker C J and Griffiths H D 2013 Frequency diverse MIMO techniques for radar *IEEE Transactions on Aerospace and Electronic Systems* 49 (1) 201-222.