A Novel Jamming Method against LFM Radar Using Pseudo-random code Phase Modulation

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***Abstract*—Linear frequency modulation (LFM) waveform is widely used in modern tracking radars and missile seekers for high resolution. In this paper, a blanket jamming method for countering LFM radar is proposed based on pseudo-random code phase modulation. Utilizing the structure of digital radio frequency memory (DRFM), we impose phase modulation onto the intercepted radar signal and retransmit it to the victim radar. The characteristics of pseudo-random code are analyzed in detail and then the jamming signal model is presented. Theoretical analyses and simulation results show that by flexible adjusting the parameters of pseudo-random code, different blanket jamming effects can be obtained. Comparing with the conventional noise jamming, the method is capable of obtaining considerable processing gain and taking full use of the jamming power. The proposed method provides an idea for the coherent jamming signal design.**

***Index Terms*—Blanket jamming, pseudo-random code, phase modulation, CFAR detection, LFM radar.**

I. INTRODUCTION

LFM pulse compression radar owns a large time bandwidth product, which makes the LFM radar getting a finer range resolution as well as a large working distance. Therefore, it has been widely adopted in modern radar systems to improve the detection distance and range resolution [1-3]. High resolution radars, such as synthetic aperture radar (SAR) or inverse synthetic aperture radar (ISAR), make the target identification and recognition by utilizing the high-resolution characteristics of LFM signal. After matched-filter processing or pulse Doppler processing to the echo, radar receiver can obtain big processing gain [4]. The convolution noise jamming is easily identified because it is not coherent with the radar signal. So, it is a demanding research field to find an effective jamming method for countering LFM radar.

The jamming methods of LFM radar has been studied in past research. The jamming method mainly consists of blanket jamming and deceptive jamming. Both of them have better jamming effects in different situations. Also they can consume radar resources and significantly deteriorate the detection performance of a radar [5, 6]. However, conventional RF noise requires greater jamming power while countering LFM radars. Noise jamming method transmits noise or noise-like signal to suppress the target echo and prevents the radar detecting the real target. It does not need much radar signal information and is easy to implementation. But because the jamming signal is not coherent with the radar signal, it needs more energy to achieve better jamming effect. According to the characteristics of linear frequency modulation radar signal processing, a new response jamming technique named convolution jamming, is proposed in [7]. The intercepted radar signal is made convolution with a video signal and then retransmitted to the victim radar. This jamming method can obtain multiple false targets deceptive jamming or blanket jamming effect when using different video signal. At the same time, the needed jamming power is relatively small. However, this jamming method requires that the jamming signal bandwidth is equal to the radar signal bandwidth to achieve better jamming effect, which is very difficult to implement in practical applications. Based on DRFM structure, interrupted sampling repeater jamming, interrupted sampling periodic repeater jamming and frequency shift jamming are studied in detail [8-10]. When the radar using frequency agility or other signal processing technology, these false targets can easily be identification by radar and thus losing the interference effect.

In order to solve the above problems and take full advantage of the jamming power, a novel blanket jamming method is proposed in this paper based on pseudo-random code phase modulation. The intercepted radar signal is modulated according to the pseudo-random sequence and retransmitted to the victim radar. Then the blanket jamming effect can be obtained. The minimal jamming-to-signal ratio (JSR) is analyzed based on the CFAR detection algorithm for the pulse compression result. The design of the key parameters is given and the jamming effect is analyzed

The remainder of the paper is organized as follows. Section II introduces the characteristics of pseudo-random code in time domain and frequency domain and reveals the theory for the generation of jamming signal. The jamming signal model is presented in section III and the properties are analyzed in detail. The simulation results and discussions are given in section IV. Finally, some conclusions are given in the final part.

II. CHARACTERISTICS OF PSEUDO-RANDOM CODE

Pseudo-random code is one of the forms of phase-coded pulse signals [11]. The so-called phase coded pulse signal is composed of many sub-pulses and the width of each sub-pulse is equal while the phase is determined by a coding sequence. Depending on the different coding phase, the phase coded signal can be divided into two-phase coded signal and multi-

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phase coded signal. The phase value of the two-phase coded signal is 0 or π, and the phase of the multi-phase coded signal has multiple phase values. The two-phase coded signal can be expressed as

$$x(t)=a(t)\exp\lfloor \mathrm{j}\varphi(t)\rfloor\exp(\mathrm{j}2\pi f_0 t) \tag{1}$$

where $a(t)$ is the amplitude modulation function, $\varphi(t)$ the phase modulation function (0 or π), and f_0 is the signal carrier frequency. The complex envelope function of the two-phase coded signal is

$$\begin{aligned} p(t)&=a(t)\exp\lfloor j\varphi(t)\rfloor \\ &=\mathrm{rect}\left(\frac{t-n\tau_0}{\tau_0}\right)\otimes\sum_{n=-\infty}^{+\infty}c_n\delta(t-n\tau_0) \end{aligned} \tag{2}$$

where c_n is the n th encoded value and is 1 or -1. $\otimes$ represents the convolution operation. $\mathrm{rect}(t/\tau_0)$ yields 1 when $|t/\tau_0|<0.5$, otherwise is 0. For the two-phase coded pulse signal, the coding value of the each sub-pulse is random.

In the research of two-phase code, the common frequently-used sequences are Barker code, L sequence code and M sequence code. The order autocorrelation function of the Barker code has the ideal characteristics, but only 7 Barker code sequences are found at present and the longest sequence is 13 bits, so it is restricted in the actual applications. L sequence code and M sequence code have similar pseudo-random properties, but only 13 L sequences exist within the length of 100 bits, so the length and number of L sequences are limited. M sequence code is widely adopted in the radar systems because the generation principle is simple and the length is not restricted. The M-sequence is a linear sequence that can be generated by the following shift register network, as is shown in Fig. 1

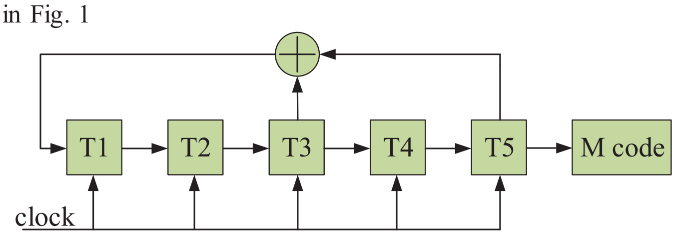


Fig. 1. The generation block diagram of M code

The M codes can be generated by using shift registers with feedback. The length of the code is related to the number of shift registers. By using n shift registers, codes of length $P=2^n-1$ can be formed. The M codes are easy to be generated by using FPGA digital logic circuit. The addition of binary codes can be implemented by using "XOR" operation in FPGA. The numbers T1 to T5 denote the 5 taps on the shift registers. The initial values of T1 to T5 can be all '1's or the combination of '1's and '0's, but not all '0's which will result in all '0's output. The registers would be clocked at the rata of $1/T_c$, where T_c is the code width.

According to Eq. (2) and Fig. (1), the M sequence can be written as

$$m(t)=\sum_{l=-\infty}^{+\infty}\sum_{i=1}^{P}rect\left[\left(t-\frac{T_c}{2}-iT_c-lPT_c\right)\Big/T_c\right]c_n \tag{3}$$

where P is the code number, PT_c is the M code period,. So in one M code period, the normalized autocorrelation function of M sequence can be written as

$$\begin{aligned} R(\tau)&=\frac{1}{PT_c}\sum_{i=0}^{P-1}m(iT_c)\cdot m(iT_c+\tau) \\ &=\begin{cases} 1-\left(1+\dfrac{1}{P}\right)\dfrac{\tau}{T_c} & 0\le\tau<T_c \\ -\dfrac{1}{P} & T_c\le\tau\le(P-1)T_c \\ \left(1+\dfrac{1}{P}\right)\dfrac{\tau}{T_c}-P & (P-1)T_c<\tau\le PT_c \end{cases} \end{aligned} \tag{4}$$

From Eq. (4), we can see that the autocorrelation function is cyclic with periodic time PT_c, and the maximal value is 1, while the minimal value is $-1/P$. According to the signal processing theory, the signal power spectrum and autocorrelation function are Fourier transform pairs. So the signal spectrum can be obtained as

$$P(f)=a_0\delta(f)+a_n\sum_{\substack{n=-\infty\\ n\neq 0}}^{+\infty}\delta(f-nf_0) \tag{5}$$

where $f_0=1/PT_c$, a_0 and a_n are amplitude coefficients and can be derived from Eq. (4) and Eq. (5)

$$a_0=\frac{1}{PT_c}\int_0^{PT_c}R(\tau)d\tau=-\frac{1}{P^2} \tag{6}$$

$$a_n=\frac{1}{PT_c}\int_0^{PT_c}R(\tau)\cos(2\pi f_0\tau)d\tau=\frac{P+1}{P^2}\cdot\left|\frac{\sin(\pi fT_c)}{\pi fT_c}\right|^2 \tag{7}$$

When the phase factor is ignored, we can get the expression of power spectrum presented as Eq. (8)

$$P(f)=\frac{1}{P^2}\delta(f)+\frac{P+1}{P^2}\cdot\left|\frac{\sin(\pi fT_c)}{\pi fT_c}\right|^2\sum_{\substack{n=-\infty\\ n\neq 0}}^{+\infty}\delta(f-nf_0) \tag{8}$$

An illustration of Eq. (4) and Eq. (8) is shown in Fig. 2 and Fig. 3

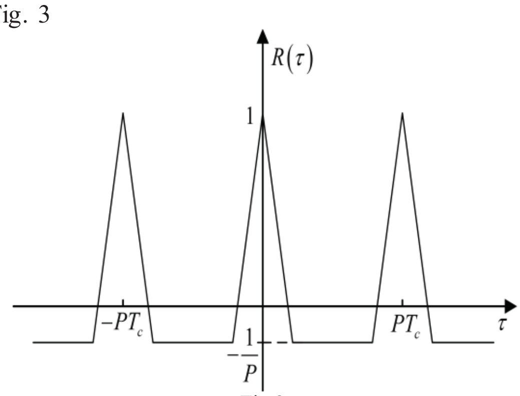


Fig 2.

Fig. 2. The normalized autocorrelation function of M sequence

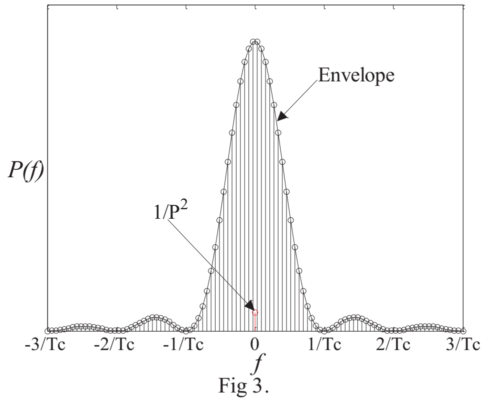


Fig. 3. The power spectrum of M sequence

As we can see from Fig. 2 and Fig. 3 that when P is large enough, the autocorrelation function has acuity peak that approaches to δ function and the amplitude of power spectrum line approaches to zero. The power spectrum is discrete line spectrum with the envelope $\left|\sin(\pi f T_c)/\pi f T_c\right|^2$ due to the periodic property of autocorrelation function. The power spectrum bandwidth has a close relationship with T_c instead of the periodic time PT_c.

III. JAMMING SIGNAL MODEL

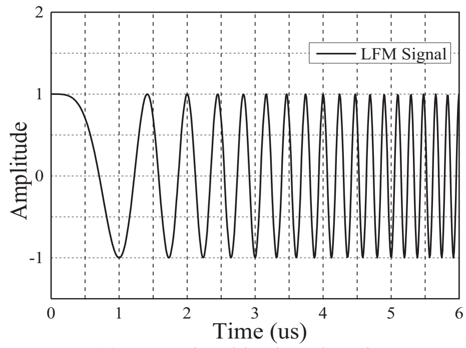
The radar transmits the LFM signal and can be presented as

$$s(t) = \mathrm{rect}\left(\frac{t}{T_p}\right)\exp\left(\mathrm{j}2\pi\left(f_c t + \frac{1}{2}kt^2\right)\right) \tag{9}$$

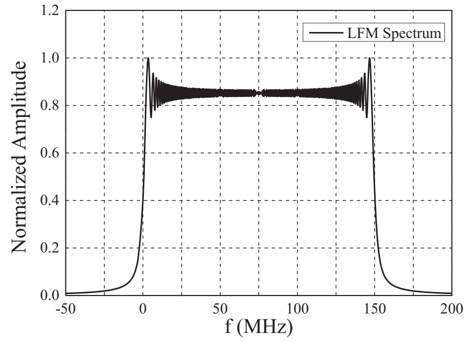
where f_c is the signal carrier frequency, T_p is the pulse width, and k is the chirp ratio. So the signal bandwidth is $B = T_p k$. Next, we impose the phase modulation onto the LFM signal according to the pseudo-random code. The jamming signal can be written as

$$\begin{aligned} s_j(t) &= m(t)\cdot s(t) \\ &= rect\left(\frac{t}{T_p}\right)\exp\left[\mathrm{j}2\pi\left(f_c t + \frac{1}{2}kt^2\right)\right] \\ &\quad \cdot rect\left(\frac{t}{T_c}\right) * \left[\sum_{i=1}^{P} c_i \delta\left(t - iT_c\right)\right] \end{aligned} \tag{10}$$

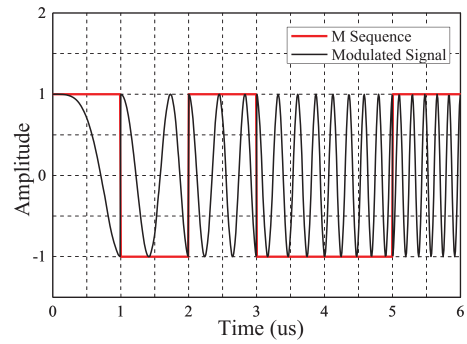
From Eq. (10) we can see that after the phase modulation on the LFM signal, the phase uncontinus points occur at the times of T_c. Fig. 4(a-d) demonstrate the signal waveform and spectrum of LFM singnal and jamming signal. As we can see, Fig. 4 (b) shows the phase jump contrast to Fig. 4 (a) due to the impact of modulation in time domain. While in frequency domain, the modulated signal spectrum is not as smooth as the origin signal in bandwidth compared with LFM spectrum in Fig. 4 (c). The LFM pulse is divided into N equal short pulses, and each pulse is allocated a phase value, 0 or π. When the adjacent short pulses have the same phase value, the signal phase is continuous and otherwise discontinuous. However, each short pulse is still a LFM signal with the B/N in bandwidth. It results in a gap between the phase discontinuous adjacent short pulses as shown in Fig. 4 (d). The modulated LFM spectrum can be considered as the superposition of the short pulses spectrum. Thus, the level out of bandwidth is also lifted.



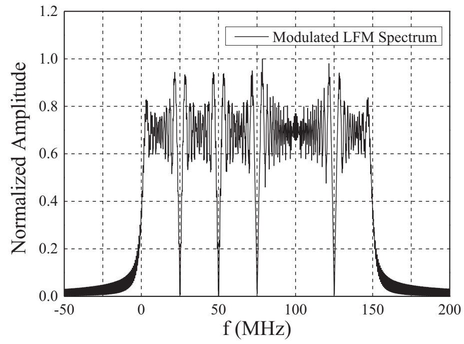
(a) LFM signal in time domain



(b) LFM signal spectrum



(c) Jamming signal in time domain

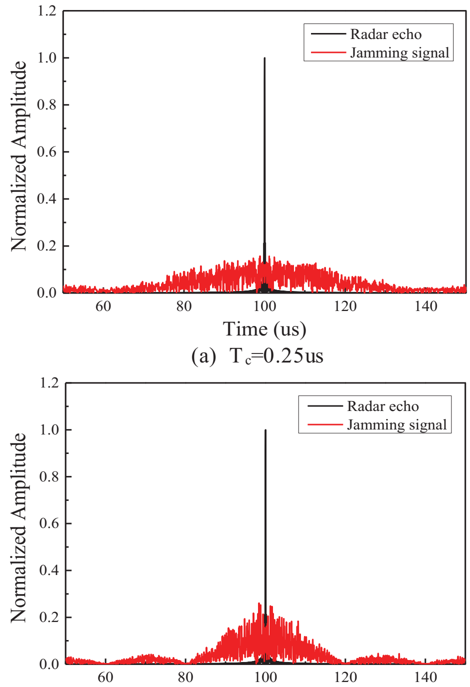


(d) Jamming signal spectrum

Fig. 4. The waveform and spectrum of LFM signal and jamming signal

IV. SIMULATION AND DISCUSSIONS

The intercepted LFM signal is retransmitted back to radar after modulation. The jamming signal and target echo will arrive at the radar receiver simultaneously when neglecting the modulation time delay. As is shown in Fig. 5, the pulse compression results are presented with different code widths. The LFM signal with duration 100 us, bandwidth 10 MHz is adopted in simulations. From Fig. 5, it can be seen that a larger code width leads to a narrower pulse compression width for jamming signal. The short T_c produce a wide covering span but the amplitude is small. When T_c becomes large, the covering span decreases but the amplitude becomes large. That is, the jamming power is relatively concentrated. However, we must note that the code width is neither too large nor too small for the covering span and the utilization of jamming power. So we should take the jamming power and covering distance into consideration when selecting the code width.

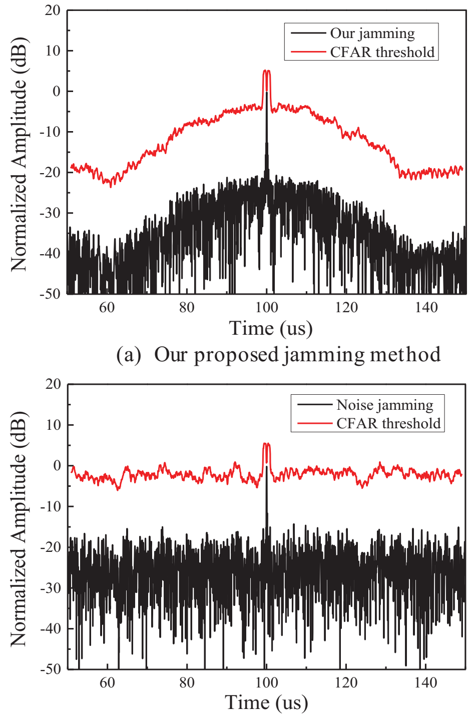


(a) T_c=0.25us

(b) T_c=0.5us

Fig. 5. The pulse results of jamming signal with different code width

In order to illustrate that our proposed jamming method can save jamming power, next we use CFAR detector to analyze the jamming effect for different jamming signal. Take CA-CFAR detector for example, the alarm rate is set 10^{-6}, protection cell number is 8 and average cell number is 64. The minimal needed jamming power is analyzed when the real target can't be detected. Fig. 6 presents the CFAR detection results of different jamming signal. In Fig. 6(a), the code width is 0.25 us and P=511. It just needs a jamming-to-signal ratio (JSR) of 0.9 dB to cover the real target. However, Fig. 6(b) is the CFAR detection result of white noise jamming signal. Because this white noise signal is non-coherent with the reference signal of matched filter, it needs more jamming power to decrease the signal-to-noise ratio (SNR) in radar receiver. To overlap the real target, it needs a JSR 15.4 dB, which is much larger than our jamming signal.



(a) Our proposed jamming method

(b) Noise jamming

Fig. 6. The results of different jamming signal with CFAR detection

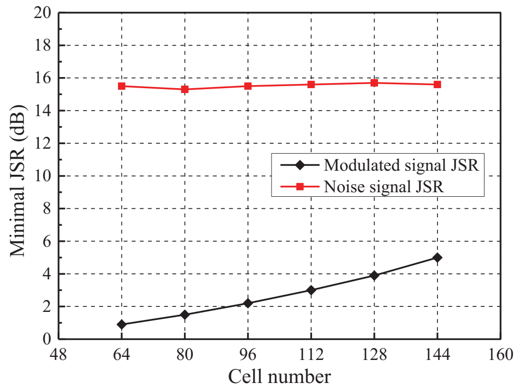


Fig. 7. The minimal JSR of different average cells

Considering that CFAR detector uses multiple average cells to derive the threshold. Now we analyze the influence of average cells number to JSR. The parameters are the same as that used in above simulation except that the average cells number is changed. We select 64, 80, 96, 112, 128, and 144 as the average cells number respectively. The minimal needed JSRs are obtained through simulations for different jamming signals. Fig. 7 demonstrates the minimal needed JSRs with different average cells number. From Fig. 7, we can see that the minimal JSRs of noise jamming signal are not sensitive to the average cells number. These values maintain about 15.5 dB. The minimal JSR of our jamming becomes large with the average cells number increasing. This is determined by the property of the M code power spectrum. The power of our jamming concentrates around the target position. When the average cells number increases, the power of average cells which are far away from the target becomes small. So the threshold decreases synchronously and it needs larger JSR to cover the real target. However, the JSRs of our jamming are still much lower than that of white noise jamming. Therefore, our jamming can make full use of the jamming power.

V. CONCLUSION

In this paper, a novel blanket jamming method is proposed based on pseudo-random code phase modulation which can lower the jamming power. The characteristic of pseudo-random code is analyzed in detail. Then, the jamming signal model is deduced step by step. Simulation results show that the target echo is suppressed by the jamming signal and the radar cannot detect the real target properly. Comparing to conventional noise jamming, this proposed method can take full advantage of jamming signal power. Both the theoretical analysis and simulation results measurements demonstrate the validation of this jamming idea. This research presents a new idea for coherent jamming signal design.

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