Study on the Influence of Intermittent Phase Modulation on the Spectrum Shift Characteristics of Radar Signals

Tengfei Ai, Yonghe Su, Mingxin Kou
China Satellite Maritime Tracking and Control Department, Jiangyin, 214431, China

Abstract. Intermittent sampling and forwarding interference is a new type of radar interference. It captures and transmits intercepted signals to enemy radars to form multiple false targets. The essence is an amplitude modulation. The phase modulation technique alternates the phase of the electromagnetic wave by adjusting the instantaneous phase of the electromagnetic wave. Phase modulation technology is currently widely used in the field of communication and radar signal design, such as binary phase shift keying and phase encoding signals. In this paper, the spectral shift characteristics of intermittent phase modulation on radar signals are studied, and the influence of modulation parameters on the moving results is analyzed. Finally, the simulation results verify the effectiveness of the method.

1. Introduction
Signal modulation technology is widely used in the field of electronic information by changing the electromagnetic characteristics of electromagnetic waves. It mainly includes amplitude modulation, phase modulation, polar modulation, beam pointing, and integrated modulation. As one of the phase modulations, phase modulation is a modulation method in which the carrier phase deviation from the reference signal varies proportionally with the modulation signal. The phase modulation technique was originally applied in the field of communications, including binary phase shift keying, whose code values vary from 0 to 1. Phase modulation in digital communication is a kind of nonlinear modulation, which is a finite number of discrete values that characterize phase changes. Phase modulation technology can increase the reliability of signal transmission. In the field of radar waveform design, with the development of new system radar, large-time wide bandwidth product pulse signals have been vigorously developed, and phase-encoded signals have received extensive attention due to their good distance and speed resolution.

In the field of radar signal processing, more research is currently on amplitude modulation and frequency modulation. In 2006, the team of Wang Xuesong of National University of Defense Technology proposed an intermittent sampling and forwarding interference method, which can intercept and transmit the intercepted signal to the enemy radar, which can realize the effect of spectrum shifting of the radar signal, and can form the distance after being processed by the radar receiver. Too many false targets. However, due to the limitation of the signal modulation mode, the zero-order peak of the spectrum of the intermittent amplitude modulation signal still exists, and the real target equivalent to the original position after the radar signal processing is not blanked. In this paper, the spectral shift characteristics of intermittent phase modulation for radar signals are studied. Firstly, the spectral characteristics of intermittent phase modulated signals are theoretically analyzed.
Then the spectrum shifting effect of intermittent phase modulated signals on single-frequency signals and chirp signals is studied. Finally, the simulation results verify the effectiveness of the method.

2. Intermittent phase modulation signal model
The intermittent phase modulation signal can be regarded as a bipolar rectangular pulse train. As shown in FIG. 1, the amplitude coefficient of the modulation signal is switched back and forth between +1 and -1. The switching period is $T$, the modulation frequency is $f_s=1/T$, and $\tau/T$ is the modulation duty ratio. Therefore, the intermittent phase modulation signal can be expressed as:

$$p(t) = A_0 + \sum_{n=1}^{+\infty} 2A_n \sin(2\pi nf_s t)$$

(1)

Where $A_0=2\pi T-1$, $a_n=(1/n\pi)(1-\cos(2n\pi\tau/T))$. In particular, when $\tau/T=0.5$, $A_0=0$.

![Figure 1. Intermittent phase modulation signal time domain diagram](image)

The spectrum of the modulated signal can be expressed as:

$$P(f) = A_0\delta(f) + \sum_{n=-\infty}^{+\infty} \frac{\sin(n\pi / 2)}{n\pi / 2} \delta(f - nf_s)$$

(2)

It can be seen from equation (2) that the spectrum of the modulation function is composed of a number of discrete sin functions whose energy is dispersed to a frequency centered at the carrier frequency and separated by a modulation frequency $f_s$. Intermittent phase modulation therefore allows the energy of the incident wave to be spread over several discrete frequency points. When $f=0$, the signal spectrum output is:

$$P(0) = \frac{2\tau}{T} - 1$$

(3)

When $\tau/T=0.5$, a zero point appears at the center of the original carrier frequency. When $\tau/T\neq0.5$, the peak position of the carrier frequency appears.
Figure 2. Intermittent modulation signal spectrum characteristics

Assume that the intermittent phase modulation waveform $f_s=50\text{MHz}$, $\tau/T=0.5$, Figure 2(a) shows the spectrum of the signal. It can be seen from the figure that the frequency domain signal is discretely distributed and multiple discrete sidebands appear at the modulation frequency. The odd-numbered position of $f_s$, the center frequency point $P(0)=0$. Fig. 2(b) shows a spectrogram with a modulation waveform $f_s=100\text{ MHz}$ and $\tau/T=0.4$. A plurality of discrete sidebands appear at integer multiples of the modulation frequency $f_s$, and a zero-order peak appears.

3. Effect of the spectrum shift

The chirp signal is often used as a radar signal in modern radar systems. In this paper, the linear frequency modulation signal is taken as an example. The center frequency is $f_0$, the pulse width is $T_p$, the frequency modulation slope is $K_r$, and the bandwidth is $B$. Then the transmitted signal is:

$$s(t) = \text{rect}\left(\frac{t}{T_p}\right) \exp\left[j2\pi\left(f_0t + \frac{1}{2}K_r t^2\right)\right]$$  \hspace{1cm} (4)

In equation (4), $\text{rect}(\cdot)$ represents a rectangular pulse. When $\left|t/T_p\right| < 0.5$, its value is 1, otherwise it is 0. Its spectrum is:

$$S(f) = \frac{1}{\sqrt{B}} e^{j2\pi f_0} e^{-j\pi f^2/2K_r} e^{j\pi f^2/4}, \quad -\frac{B}{2} < f < \frac{B}{2}$$  \hspace{1cm} (5)

After the radar transmit signal is intermittently phase modulated, its echo can be expressed as:

$$r(t) = s(t), p(t)$$  \hspace{1cm} (6)

Therefore, the spectrum of the echo signal is $R(f) = S(f) * P(f)$, where $*$ represents the convolution operation. It can be seen from the analysis in Chapter 2 that when the modulated signal is a bipolar periodic rectangular pulse, according to the nature of the Fourier transform, the spectrum of the echo signal is:
\[ R(f) = A_0 S(f) + \sum_{n=-\infty}^{n=\infty} \sin\left(\frac{n\pi}{2}\right) \frac{S(f - nf_0)}{n\pi/2} \]  

After the LFM signal is intermittently phase-modulated, the spectrum of the incident signal and the echo signal is as shown in FIG. Set the carrier frequency center frequency \( f_0 = 10 \) GHz, pulse width \( T_p = 10 \) μs, signal bandwidth \( B = 50 \) MHz, and the modulation signal is a periodic rectangular square wave with a duty ratio \( \tau/T = 0.5 \), assuming that the modulation signal frequency is 100 MHz and 10 MHz. According to Fig. 3(a), when \( B < f_m \), the spectrum of the echo signal is outside the bandwidth of the radar receiver, forming several discrete sidebands; when \( B > f_m \), the spectrum of the echo signal is at the receiver bandwidth. Internally, the spectrum of the entire echo signal is completely blurred due to spectral aliasing caused by frequency shifting.

![Spectrum comparison](image)

(a) \( f_s = 100 \) MHz, \( \tau/T = 0.5 \)  
(b) \( f_s = 10 \) MHz, \( \tau/T = 0.5 \)

**Figure 3.** Incident signal and reflected signal spectrum

4. Conclusion

This paper proposes a method for spectrum shifting of radar signals based on phase modulation. The method realizes intermittent modulation of the radar signal by using a periodic bipolar rectangular wave, thereby further controlling the spectral characteristics of the reflected signal. At the same time, the spectral shifting effect of the reflected signal is controlled by the modulation parameters. Simulation results verify the effectiveness of the proposed method.

References

[1] M. A. Richards. Fundamentals of Radar Signal Processing [M]. McGraw-Hill, New York, 2005: 67-80.

[2] Xu Qing, Xu Jilin, Zhou Xianmin, Huang Xiangxi. Analysis of Linear Frequency Modulation-Two Phase Coding Radar Signals[J]. System Engineering and Electronics, 2000, 22(12): 7-9.

[3] Xu Letao. Research on target feature control of imaging radar based on intermittent modulation [D]. Changsha: National University of Defense Technology, 2016.

[4] Zhang Ran. Characteristics of phase modulation surface and its radar effect [D]. Changsha: National University of Defense Technology, 2016.

[5] Wang X S, Liu J C, et al. Mathematic principles of interrupted-sampling repeater jamming [J]. Science in China, Series F: Information Sciences, 2007, 50(1): 113-123.

[6] D. Feng, L. Xu, X. Wang, and X. Pan, “Jamming Wideband Radar Using Interrupted-Sampling Repeater,” IEEE Trans. Aerosp. Electron. Syst., vol. 53, no.3, pp. 1341–1354, Jun, 2017.