Research on Non-uniform Interrupted Sampling Repeater Jamming for Phase Coded Radar

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Abstract. Because of using correlation processing technology, it is difficult for traditional jamming patterns to achieve the desired jamming effect on phase coded radar. At present, the forward deception jamming of phase coded radar is mainly realized by uniform interrupted sampling repeater jamming (UISRJ). In order to solve the problem that the UISRJ can only produce a single and delayed false target, a kind of non-uniform interrupted sampling repeater jamming (NUISRJ) is proposed. The non-uniform sampling pulse train is generated through pseudo random sequence, and then sampled and forwarded to generate jamming signal, which is processed by radar pulse compression to form dense false targets. Combining the theoretical analysis and simulation results, it can be seen that the NUISRJ has the dual effects of suppressing jamming and spoofing jamming, and the distribution of false target string is more random, including the leading and lagging false target. The amplitude and coverage area of false targets group can be controlled by adjusting sampling pulse width and forwarding times to effectively implement jamming.

1. Introduction

With the rapid progress of modern radar detection technology, phase coded radar [1] is widely used because it can not only ensure the detection range of radar but also obtain high range resolution. The interference that does not match phase coded signal cannot gain corresponding gain during the pulse compression processing, so it has strong anti-interference performance. Therefore, effective jamming of phase coded radar becomes an important research direction in the field of radar countermeasures.

In recent years, the digital radio frequency memory (DRFM) [2] has become a common way of modern radar to counter coherent interference because it can sample, quantify, encode, store and delay the transmission of the received signal. There are many researches on jamming for linear frequency modulation (LFM) pulse compression radar at home and abroad. Multiple jamming modes of LFM signals have been studied in [3]-[6], which can produce sound spoofing or suppressing jamming effects. However, the interference of phase coded signal is seldom studied. The simulation analysis of UISRJ of phase coded radar in [7] shows that only single and delayed false target can be generated. Lai et al. [8] firstly propose a dense dummy target jamming method based on random symbol modulation, but the dummy target density is not controllable. As mentioned in [9]-[10], interrupted sampling predictive repeater jamming can form the leading false target. However, the effectiveness of
this jamming method is based on the accurate interception of radar signal and the successful prediction of the complete coding sequence, so it is difficult to implement.

Therefore, the sampling method of intermittent sampling is changed in this paper. The interference
is generated by NUISRJ, and the side lobe output will be deteriorated after pulse compression treatment. Multiple false targets will be generated through the elevation of side lobe amplitude, which can effectively implement interference.

2. Phase coded signal characteristics
The phase modulation function of LFM is continuous, while the phase coded signal is completely different and its phase modulation function is discrete. Phase coded signals are usually modulated by binary pseudo random sequences for high frequency and wide pulse. When the code value is only 0 and 1, it is the binary phase-coded signal which is easy to realize, and the commonly used mainly includes Barker code, m-sequence and so on.

The general binary phase-coded signal can be expressed as:

\[ s(t) = a(t)e^{j\phi(t)}e^{j2\pi fr(t)} (0 \leq t \leq T) \]  

Where \( a(t)e^{j\phi(t)} \) is the signal complex envelope function, \( e^{j2\pi fr(t)} \) denotes the phase coding value, 1 or -1. \( e^{j2\pi fr(t)} \) is the carrier frequency signal, when \( T \) denotes the signal time length. If the envelope of the binary phase-coded signal is rectangular, the complex envelope can be written as:

\[ u(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} c_k v(t - k\tau) \]  

Where \( v(t) \) is defined as the complex envelope of the signal sub-impulse function. \( \tau \) and \( N \) are the time widths and numbers of signal sub-impulse respectively when \( c_k = e^{j\phi(k)} = +1, -1 \). Using the properties of function \( \delta \), Equation (2) can be rewritten as:

\[ u(t) = v(t) * \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} c_k \delta(t - k\tau) = u_1(t) * u_2(t) \]  

Which satisfies \( u_1(t) = 1/\sqrt{\tau} \) and \( u_2(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} c_k \delta(t - k\tau) \). The fuzzy function of the binary phase-coded signal is its time-frequency compound autocorrelation function; it can be obtained:

\[ \chi(\tau_d, \xi_d) = \int_{-\infty}^{+\infty} u(t)u^*(t + \tau_d)e^{j2\pi d(t)\xi_d} dt \]

\[ = \chi_1(\tau_d, \xi_d) \star \chi_2(\tau_d, \xi_d) \]

\[ = \sum_{m=-N}^{N-1} \chi_1(\tau_d - m\tau, \xi_d) \chi_2(m\tau, \xi_d) \]  

Where \( \chi_1(\tau_d, \xi_d) \) and \( \chi_2(\tau_d, \xi_d) \) are the fuzzy functions of sub-pulse signals \( u_1(t) \) and \( u_2(t) \) respectively. If \( \tau_d \) determined, \( m \) is the uniquely certain integer. If \( \tau_d \) is greater than or equal to 0, then \( m = \lfloor \tau_d / \tau \rfloor \), otherwise \( m = \lceil \tau_d / \tau \rceil \).

According to the definition of fuzzy function, it can be expressed as:

\[ \chi_1(\tau_d - m\tau, \xi_d) = e^{j2\pi j(\tau_d - m\tau)} \sin c(\xi_d (\tau_d - m\tau)) \frac{\tau - |\tau_d - m\tau|}{\tau} (|\tau_d - m\tau| \leq \tau) \]  

\[ \chi_2(m\tau, \xi_d) = \frac{1}{N} \sum_{k=0}^{N-1} c_k e^{j2\pi jkm\tau} (0 \leq m \leq N - 1) \]
According to the symmetry of the fuzzy function, the above equation also applies when\(- (N - 1) \leq m \leq 0\). By substituting equations (5) and (6) into (4), the corresponding fuzzy function of the binary phase-coded signal can be calculated.

3. Analysis of interrupted sampling repeater jamming

3.1 The principle of UISRJ

The principle of UISRJ based on DRFM is shown in Figure 1. Radar signals are sampled and forwarded, and the above actions are repeated until the last radar signal ends.

Interrupted sampling of radar signal is equivalent to multiplying a rectangular envelope pulse train on the base of the original radar signal. If \( N \) is sampling times, \( T_b \) represents the sampling pulse width and forwarding time, and satisfies sampling pulse period \( T_s \geq 2T_s \). The sampled pulse signal is denoted as \( p(t) \), and its expression by Fourier transform is

\[
p(t) = \text{rect} \left( \frac{t}{T_b} \right) * \sum_{n=-\infty}^{+\infty} \delta(t - nT_s) = \sum_{n=-\infty}^{+\infty} a_n e^{j2\pi nf_s t}
\]

Where satisfies \( a_n = T_b f_s \sin c(nf_s T_b) \), and \( T_b / T_s \) denotes the duty cycle. When the jammer receives radar signal \( u(t) \), its matching filter satisfies \( h(t) = u^*(t_0 - t) \). Without loss of generality, \( t_0 \) can be 0, then \( h(t) = u^*(-t) \). If the signal after sampling is \( s(t) \) and the pulse pressure is

\[
y(t) = s(t) * h(t) = p(t)u(t) * h(t) = \sum_{n=-\infty}^{+\infty} a_n u(t)e^{j2\pi nf_s t} * h(t) = \sum_{n=-\infty}^{+\infty} a_n u(t) * u^*(-t)e^{j2\pi nf_s t}
\]

If \( \xi_d = nf_s \), according to fuzzy function definition, then

\[
y(t) = \sum_{n=-\infty}^{+\infty} a_n \chi(\tau_d, -\xi_d) = \sum_{n=-\infty}^{+\infty} a_n \chi(\tau_d, -nf_s)
\]

From equations (9), it can be seen that \( y(t) \) is equivalent to the superposition of pulse pressure results of transmitted signals after countless times of different Doppler frequency shifts, so the UISRJ is the result of joint action of signals of different frequency shifts. However, the phase coded signal is sensitive to Doppler shifts, and except for the zero-order component, the weighting coefficient of other orders is far less than 1, so it can also be written as:

\[
y(t) \approx a_0 \chi(\tau_d, 0) = \frac{T_b}{T_s} \chi(\tau_d, 0)
\]
The generated false target amplitude is $T_n/T_s$ of the true target and is related to the duty cycle. Because there is a delay between the forwarded interference and the sampled signal, the false target generated by the UISRJ is single and lags behind the true target.

3.2 The principle of NUISRJ
The UISRJ results in a delay between the jamming signal and the sampled signal, so the false target with lag will be formed after the pulse compression. Therefore, we consider the NUISRJ of phase coded radar signal, whose essence is to disturb the received signal element, so that the generated jamming signal element is mismatched with the radar matching filter. In the case, the side lobe output of the jamming signal will be deteriorated after pulse compression processing, and multiple false targets are formed before and after the real target by the elevation of the side lobe amplitude. We can also use the pseudo random sequence for the selection of non-uniform sampling pulse train (NUSPT).

Pseudo random sequence is a deterministic sequence with properties similar to random sequence and its correlation function is close to white noise. The most common binary pseudo random sequence is the m-sequence, which is a code sequence of period $2^n - 1$ generated by the n-order shift register of the linear feedback. It has the following three features:

1. The number of zeros and ones in the sequence is roughly equal.
2. The proportion of consecutive 0 and 1 subsequences in the sequence is determined.
3. The sequence has good autocorrelation.

The random sampling pulse width and relatively more sampling times can be guaranteed by using the continuous sub-sequence of pseudo random sequence as each sampling pulse width. It is regular and easy to produce. Supposing $T_m$ is the symbol width, the number of symbols of successive sub-sequence is $N_n$, and $\tau_n = T_m \cdot N_n$ denotes the pulse width of each sample, then the pulse train of non-uniform intermittent sampling is shown in Figure 2.

\[
\begin{align*}
\text{m-Sequence:} & \quad 000000 \quad 1111111 \quad 0 \quad 1 \quad 0 \quad 1 \quad 0 \quad 0 \quad 1 \quad 1 \\
N_n : & \quad 6 \quad 1 \quad 1 \quad 1 \quad 2 \\
\text{NUSPT :} & \quad \begin{array}{ccccccc}
\hline
\hline
\end{array}
\end{align*}
\]

Figure 2. The generation of non-uniform intermittent sampling.

4. Analysis of simulation results
To further demonstrate the jamming characteristics presented in the former analysis, some simulations are carried out to verify its effectiveness and correctness. Different jamming styles will produce different jamming effects on false targets. The following is the analysis of simulation results and comparison of two different ways of sampling repeater jamming. The main parameters are given in Table 1.

| Parameters                  | Value                  |
|-----------------------------|------------------------|
| Encoding type               | m-sequence             |
| Series                      | 7                      |
| Feedback coefficient        | [1000001]              |
| symbol width                | $0.5 \mu s$            |
| signal length               | $63.5 \mu s$           |

Table 1. The simulation parameters.
4.1 Analysis of UISRJ

When the duty cycle is determined, the jamming effect can be changed by changing the sampling pulse width. In order to facilitate analysis, the sampling method is integral sampling and integral forwarding, and different parameter combinations of sampling period and sampling pulse width are:

(a) $T_b = 2\mu s, T_i = 4\mu s$  
(b) $T_b = 4\mu s, T_i = 8\mu s$  
(c) $T_b = 8\mu s, T_i = 16\mu s$.

![Figure 3. Influence of sampling pulse width on UISRJ.](image1)

![Figure 4. A larger view of local detail of Figure 3.](image2)

The simulation results are shown in Figure 3 which shows the experimental results of UISRJ with different sampling pulse widths. Figure 4 is a detailed enlarged image. It can be seen that the forwarding interference of uniform intermittent sampling can only form a false target with lag, and when the sampling duty ratio remains constant, the amplitude of the false target is basically unchanged, and the wider the sampling pulse width, the longer the lag time of the false target.

When the sampling pulse width is determined, the jamming effect can be changed by changing the duty cycle. For the sake of analysis, the sampling method is sampling and forwarding, and different parameter combinations of sampling period and sampling pulse width are:

(a) $T_b = 2\mu s, T_i = 8\mu s$  
(b) $T_b = 4\mu s, T_i = 12\mu s$  
(c) $T_b = 8\mu s, T_i = 16\mu s$.

![Figure 5. Influence of the duty cycles on UISRJ.](image3)

![Figure 6. A larger view of local detail of Figure 5.](image4)

The simulation results are shown in Figure 5 which shows the experimental results of UISRJ with different duty cycles. Figure 6 is a detailed enlarged image. It can be seen that the forwarding interference of uniform intermittent sampling can only form a false target with lag, and when the sampling pulse width remains constant, the delay of the false target is consistent, and the amplitude of
the false target formed by the direct forwarding of intermittent sampling is related to the sampling duty ratio, and the larger the sampling duty ratio is, the larger the amplitude of the false target is.

Therefore, the amplitude of the false target is proportional to the duty cycle of the sampled signal, and the lag time of the false target is proportional to the sampling pulse width, and only one false target is formed in UISRJ.

4.2 Analysis of NUISRJ

In the case of NUISRJ, m sequence, series 7 and feedback coefficient [1000001] are adopted to interfere phase coded signals, and the interference effect is shown in Figure 7. When the forwarding gain is 16dB, the interference effect is observed again as shown in Figure 8.

![Figure 7](image1.png)  ![Figure 8](image2.png)

Figure 7. The rendering of NUISRJ for the symbol width $T_b = 1\mu s$.

Figure 8. The jamming effect when the forwarding gain is 16dB.

Combined with Figure 7 and Figure 8, it can be seen that the number of false targets generated by NUISRJ increases significantly, with both leading and lagging false targets, and the distribution of false targets is random. Although the amplitude is reduced, the false targets can suppress the real target by appropriate compensation of forwarding gain, which has the dual effects of suppressing jamming and spoofing jamming.

When the symbol width of the sampled pulse train changes, the jamming effect also changes.

![Figure 9](image3.png)  ![Figure 10](image4.png)

Figure 9. When the symbol width of sampling pulse string $T_b = 2\mu s$, the jamming effect of NUISRJ.

Figure 10. When the symbol width of sampling pulse string $T_b = 4\mu s$, the jamming effect of NUISRJ.
By comparing Figure 7, 9 and 10, it can be seen that with the increase of the width of the sampling code element, the false target group gradually moves to the right, and when it reaches a certain extent, it presents the interference effect of UISRJ. This is because the increase of symbol width leads to the decrease of sampling times. After non-uniform sampling of the received message number element, the mutual correlation of the original symbol element is still maintained. In the case, the output of the pulse compression of the interference signal is similar to the UISRJ.

Therefore, a better jamming effect can be achieved by selecting appropriate forwarding gain and sampling symbol width.

5. Conclusion
In this paper, the characteristics of interference signals generated by different sampling methods are studied by analyzing the sampling methods of interrupted sampling repeater jamming. In order to solve the shortcomings of single and lag false target in UISRJ, the NUISRJ based on pseudo random sequence is proposed, which has the following advantages:

1. The NUISRJ can generate the leading and lagging false targets with more random distribution and wide suppression range.

2. The amplitude and coverage area of false targets group can be controlled by adjusting sampling pulse width and forwarding times to effectively implement jamming.

Combining the theoretical analysis and simulation results, it can be seen that the NUISRJ can generate false targets before and after the real targets by deteriorating the side lobe output after pulse compression, and the positions of false targets are more dispersed. Meanwhile, it can adapt to the interference requirements under different conditions by controlling the width of symbols and appropriate forwarding gain. Compared with UISRJ, it has stronger jamming effect on phase coded radar. However, the generated false target has a low amplitude, which is the next problem to be solved in the future.

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