The Design of Broadband Multi-target Folding Jammer Based on a Periodic Non-uniform LFM Local Oscillator

Qi Zhang¹, Jun Zhu¹, Bin Tang¹, Huan Yang²

1. School of Electronic Engineering (EE), University of Electronic Science and Technology of China, (UESTC), Chengdu, China
2. Institute of Electronic Engineering, China Academy of Engineering Physics, Mianyang, China
E-mail: 809768504@qq.com

Abstract. This paper proposes a novel broadband multi-target folding jammer based on a periodic non-uniform linear frequency modulation (LFM) local oscillator (LO). It can achieve broadband receiving and transmitting with a small count of equipment. This paper also proposes a de-chirp function (DF) which is used to estimate the Nyquist zone index of the received signals and a new multi-beamforming method. The estimation value can be used to guide the transmitting frequency of the jamming signals and the new multi-beamforming method can be used to achieve the accurate multi-target jamming. The scale experiments show that the proposed folding jammer is feasible to achieve in practice and the method of DF works better than the cubic phase function (CPF) for guiding the frequency of jamming signals. The multi-beamforming simulation shows that the designated areas are covered by the relevant jamming.

1. Introduction
Owing to the limits of the conventional jammer [1-3] on the instantaneous receiving and transmitting bandwidth, jamming the broadband signals in real time needs a combination of multi-stage LO and frequency sweep mode [4]. This will make the jammer complicated. In order to reduce the complexity and cost of the jammer, this paper proposes a novel broadband folding jammer which can be used to jam the broadband signals with a small amount of equipment.

Increasing the receiving and transmitting bandwidth is difficult for existing technology [5]. A feasible technology which is proposed in recent years for broadband receiving and transmitting is based on compressed sensing technology [6]. Fudge et al. [7] proposed a simplified structure for the compressed sensing system. But the related research of Fudge is limited to the wavelet analysis [8] for the processing of receiving signals. The performance of this system needs to be improved. The folding transmitting structure has not been discussed before.

Inspired by the DF method of LFM signal [9], this paper proposes a novel periodic non-uniform LFM LO which is different from the LO in [7]. Based on this design, the paper proposes a Nyquist zone index estimation algorithm which has better performance than the CPF [10]. The estimation value can be used to guide the jamming signals accurately on the appointed frequency. This paper also proposes an available structure of the transmitting LO which is different from the receiving LO for the jammer.

At last, the paper proposes a new multi-beamforming method for transmitting of jamming signals. This method lead into the parameter of distance dimension [11-12]. Therefore, the jamming signals can cover the areas which have the fixed distance and direction.
In summary, we propose a novel broadband multi-target folding jammer with a small count of equipment in this paper. We demonstrate the complete structure of the folding jammer and analyze the signal processing flow in Section 2. Next, we propose a robust Nyquist zone index estimation algorithm based on the LFM LO and a new multi-beamforming method in Section 3. In Section 4, we conduct scale experiments to demonstrate that the folding jammer is feasible to achieve and the proposed estimation algorithm has better performance than the CPF under this structure, then the multi-beamforming simulation proves that the designated areas are covered by the relevant jamming signals. In Section 5, we conclude this paper.

2. System structure

2.1. The structure of the folding jammer

The receiving structure of the folding jammer is shown in Fig.1. The input signal is received in the broadband filter $BPF$. After filtering the out-of-band noise, the complex signal $x(t)$ is obtained. $x(t)$ is then mixed with the periodic non-uniform LFM LO $p(t)$ to obtain the signal $r(t)$. The $p(t)$ is generated by the digital-to-analog converter (DAC) and the direct digital synthesizer (DDS) in digital signal processor (DSP). $r(t)$ passes through the complex low-pass filter $LPF$ and then the signal $s(t)$ is obtained. $s(t)$ is then sampled by the analog-to-digital converter (ADC) to obtain the baseband digital signal $s(n)$.

The transmitting structure of the folding jammer is shown in Fig.2. The jamming signal $s(t)$ is mixed with the periodic non-uniform LO $p'(t)$ to obtain the signal $x'(t)$. The $p'(t)$ is also generated by the DAC and the DDS in DSP. $x'(t)$ then passes through the filter banks to obtain the output signal of jammer.

2.2. Signal processing in the folding jammer

In the receiving part of the jammer, the signal model received can be expressed as follows

$$x(t) = \exp[j(2\pi f_0 t + \phi_0)] + v(t)$$  \hspace{1cm} (1)

where $f_0$ and $\phi_0$ are carrier frequency and initial phase of the signal. $v(t)$ is the zero-mean white Gaussian noise whose variance is $\sigma_v^2$ and it is independent of the signal.
The periodic non-uniform LFM LO can be simplified as

$$p(t) = \sum_{m=0}^{M-1} \sum_{h=0}^{\frac{M}{2}} \mu(t-hT) \exp \left[ j \left( 2\pi f_i t / 2 + 2\pi m(f_i + \theta(t)) \right) \right]$$

(2)

where $\theta(t) = f_{LFM}(t-hT) + 0.5K_0(t-hT)^2$ is a periodic instantaneous phase modulation, $h = 0, 1, \cdots$. $f_{LFM}$, $K_0$ and $T$ are the initial frequency, chirp rate and repetition period of the LFM LO. $f_i$ is the carrier frequency of the LO, $m$ represents the Nyquist zone, $M$ is the number of the Nyquist zone, the $\mu(t)$ can be expressed as

$$\mu(t) = \begin{cases} 1, & 0 \leq t < T, \\ 0, & \text{otherwise} \end{cases}$$

(3)

After the deducing and arrangement, the receiving signal of DSP $s(n)$ can be expressed as

$$s(n) = \sum_{k} \mu(t-hN_T) \cdot$$

$$\exp \left[ j \left( 2\pi f_i nT - 2\pi m \cdot f_{LFM} (n-hN_T) T_i \right) \right] \cdot$$

$$\exp \left[ j \phi_0 - m \cdot \pi K_0 (nT_h - hN_T)^2 \right] + v'(n)$$

(4)

where $f_{LFM} = f_i - f_c / 2 - m \cdot f_c$, $N_T$ is the number of sampling points for in time $T$, $T_i = 1 / f_i$. $v'(n)$ is also the zero-mean white Gaussian noise. $m_r \in \{0, 1, \cdots, M-1\}$ is the index of the Nyquist zone.

In the transmitting part of the jammer, we assume the jamming signal model as

$$s'(t) = \exp \left[ j \left( 2\pi f_c t + \phi \right) \right] + n(t)$$

(5)

where $f_c$ and $\phi$ are carrier frequency and initial phase of the jamming signal. $n(t)$ is the zero-mean white Gaussian noise whose variance is $\sigma^2$ and it is independent of the signal.

The transmitting LO can be simplified as

$$p'(t) = \sum_{m=0}^{M-1} \exp \left[ jm(2\pi f_c t) \right]$$

(6)

After the jamming signal is mixed with the transmitting LO, the mixing signal $x'(t)$ can be expressed as

$$x'(t) = \exp \left[ j \left( (2\pi f_c \pm 2\pi f_c m) t + \phi \right) \right] + n'(t)$$

(7)

In (7), $n'(t)$ is also the zero-mean white Gaussian noise. Finally $x'(t)$ passes through the filter banks to obtain the output jamming signal on the appointed frequency based on the value of $m_r$.

3. Algorithm Analysis

3.1. Nyquist zone index estimation based on the DF

The method defines the DF as follows

$$DF(d, K) = \frac{1}{N_T - d} \sum_{n=d}^{N_T-1} s(n) s'(n-d) \exp\left( jK n T_i \right)$$

(8)

where $d$ is the time delay. The DF will produces the auto term of the signal. When $K = 2\pi m K_0 d T_i (m = 0, 1, \cdots, M-1)$, the auto term can be denoted as
In (9), \( f'_0 = f'_0 - m_H f_H \) and we have

\[
DF(d,2\pi m_K d_T) = \left. \frac{1}{N_T - d} \exp\left[j\left(2\pi f'_0 d_T + m_H \pi K_0 (d_T)^2\right)\right] \sum_{m=d}^{N_T-1} \exp j2\pi (m-m_H) K_0 d n T^2 \right]
\]

In (9), \( f'_0 = f'_0 - m_H f_H \) and we have

\[
DF(d,2\pi m_K d_T) \bigg|_{m=m_H} = \exp\left[j\left(2\pi f'_0 d_T + m_H \pi K_0 (d_T)^2\right)\right]
\]

\[
DF(d,2\pi m_K d_T) \bigg|_{m=m_H} = 0
\]

When \( m = m_H \), \( DF(d,2\pi m_K d_T) \) is a non-zero value. When \( m \neq m_H \), \( DF(d,2\pi m_K d_T) \) is zero. Therefore, \( \hat{m}_H \) can be obtained when the value of \( DF(d,2\pi m_K d_T) \) comes to non-zero value by scanning the value of \( m \). \( \hat{m}_H \) is the estimation value of \( m \).

After obtaining the estimation value of \( m_H \), we can choose the output of the corresponding filter in the filter banks. The filter banks is described in Fig.3.

\[
\text{Amplitude}
\]

\[
0 \quad \frac{f_s}{2} \quad \frac{3f_s}{2} \quad (m_H - 1/2)f_s
\]

\[ f \]

Figure 3. The structure of the filter banks.

3.2. Multi-beamforming algorithm

For the conventional beamforming algorithm, array transmitting signal model can be expressed as

\[
S(f_0) = \begin{bmatrix} S_1(f_0), S_2(f_0), \cdots, S_N(f_0) \end{bmatrix}
\]

In (12), \( \{S_i(f_0)\}_{i=1}^{N} \) is the transmitting signal for each array element. \( f_0 \) is the transmitting frequency of signal. \( N \) is the number of array element.

In this paper, the array transmitting signal model has been modified with a frequency offset. It can be denoted as

\[
\begin{bmatrix}
S_1(f_0) & S_1(f_0 + f_T) & \cdots & S_1(f_0 + (M_z - 1)f_T) \\
S_2(f_0 + f_T) & S_2(f_0 + 2f_T) & \cdots & S_2(f_0 + (M_z - 1)f_T) \\
\vdots & \vdots & \ddots & \vdots \\
S_N(f_0 + (M_z - 1)f_T) & S_N(f_0 + (M_z - 1)2f_T) & \cdots & S_N(f_0 + (M_z - 1)(M_z - 1)f_T) \\
\end{bmatrix}_{N \times N}
\]

where \( M_z \) is the number of the frequency offset, \( f_T \) is the frequency offset, \( f_0 \gg f_T \). Each column represents the transmitting signal of each array element. Then the arrived signals of far field from one array element can be expressed as
\[ P_r = \sum_{n=0}^{N} \sum_{m=1}^{M} w_n \left( \exp \left( -j2\pi \left( f_n + (m-1)f_r \right)(t-t_0) \right) \right) / R \]
\[ - \frac{1}{R} \exp \left( -j2\pi f_n (t-t_0) \right) \]
\[ \cdot \sum_{n=0}^{N} \sum_{m=1}^{M} w_n \exp \left( -j2\pi \left( (m-1)f_r \right)(t-t_0) \right) \]
\[ = F(t)w_d^T \mathbf{A}_d \]  

In (14), \( F(t) = \frac{1}{R} \exp \left( -j2\pi f_o \left( t-t_0 \right) \right) \), \( t_0 = R/c \), \( c \) is the light speed, \( R \) is the distance. \( w_d \) is the weight vector for distance dimension, \( w_d = [w_{d_1}, w_{d_2}, \cdots, w_{d_M}]^T \), \( \mathbf{A}_d \) is the steering vector for direction dimension. \( \mathbf{A}_d \) can be expressed as

\[ \mathbf{A}_d = \begin{bmatrix} 1, \exp \left( -j2\pi \left( f_r \left( t-t_0 \right) \right) \right), \cdots, \\ \exp \left( -j2\pi \left( (m-1)f_r \left( t-t_0 \right) \right) \right) \end{bmatrix}^T \]

The arrived signals of far field from all array elements can be expressed as

\[ P = \frac{1}{R_y} \sum_{n=0}^{N} \sum_{m=1}^{M} w_n w_n \left( \exp \left( -j2\pi \left( f_n + (m-1)f_r \right)(t-t_0) \right) \right) / R_y \]
\[ \cdot \frac{1}{R_y} \exp \left( -j2\pi f_n (t-t_0) \right) \]
\[ \cdot \sum_{n=0}^{N} \sum_{m=1}^{M} F_y(t) w_n \exp \left( -j2\pi \left( (m-1)f_r \left( t-t_0 \right) \right) \right) \]
\[ \cdot \exp \left( j2\pi f_o \left( n-1 \right) d \sin \theta / c \right) \exp \left( j2\pi \left( m_0 f_d \sin \theta / c \right) \right) \]  

In (16), \( F_y(t) = \frac{1}{R_y} \exp \left( -j2\pi f_o \left( t-t_0 \right) \right) \), \( t_y = \frac{R_y}{c} \), \( R_y = R + nd \sin \theta \). We can see that the energy of beam is associated with the distance parameter and direction parameter. The conventional beam is only associated with the direction parameter.

![Figure 4](image-url)  
**Figure 4.** The folding jammer laboratory scale experiment.

### 4. Simulation Analysis

We construct a laboratory scale experiment as shown in Fig.4 to verify our analyses. The field-programmable gate array (FPGA) (XC7VX485TFFG1761) generates the receiving and transmitting LO signals. The signal generator generates the analog input signals. The non-uniform receiving LO signal and the analog input signal are mixed and filtered in the mixer-filter and its output is sampled by a uniform sampling ADC (AD9643). The model of DSP is the TI TS201. The model of
DAC is DAC0800. Considering the FPGA processing capability, the receiving and transmitting LO carrier frequency are 31.25MHz. The sampling frequency of the ADC/DAC are 70MHz. The parameters of the input analog signals are shown in Table 1.

In Table 1, MP represents the mono-pulse signal, PRI is the pulse repetition interval and PW is the pulse width. These two parameters are arbitrarily variable. The Signal1 is a narrowband signal and The Signal2 is a wideband signal.

| Signal Parameter | Signal 1 | Signal 2 |
|------------------|----------|----------|
| Modulation type  | MP       | LFM      |
| Carrier frequency| 41.25MHz | 66.5MHz  |
| Signal bandwidth | 0MHz     | 6MHz     |
| PRI              | 8μs      | 10μs     |
| PW               | 4μs      | 5μs      |

4.1. The results of the folded receiving signals

Fig. 5 and Fig. 6 show the time-frequency distribution of the signals which are sampled by ADC. As is shown in Fig. 5, the frequency of Signal 1 has been folded to the 10MHz. As is shown in Fig. 6, the initial frequency of the LFM pulse signal has been folded to the 4MHz. These results satisfy the folding theory which is described above. Therefore, the design of the receiving part is achieved in practice.

Figure 5. The time-frequency distribution of Signal 1.

Figure 6. The time-frequency distribution of Signal 2.
4.2. Comparative experiment between DF and CPF
We set the SNR of the input signals as \(-10 - 15\, \text{dB}\). 500 times hardware tests are used for each SNR value in DSP. Then we export the each test result.

Fig. 7. The correct ratio of Nyquist zone index estimation. The correct ratio represents the correct values in these 500 times tests. The proposed DF method works better than the CPF method when SNR<-3dB. When SNR> -8dB, the correct ratio of Nyquist zone index estimation using the DF can reach 100%. So the CPF method is more sensitive to noise than the DF method. The performance of the proposed method is better in test.

4.3. The results of the jamming signals
After obtaining the estimation value of the Nyquist zone index, we can transmit the jamming signal to the corresponding zone by folding transmitting. We set the jamming signal as the broadband noise jamming signal whose bandwidth is 10MHz. In this paper, we use the ADC whose sampling frequency is 150MHz to sample the transmitting signal of the folding jammer again. Then we can use the sampling data to analyze the jamming signals.

As is shown in Fig.8 and Fig.9, the jamming signals are folded to the appointed frequency accurately. The results prove that the design of transmitting part is also achieved in practice.
4.4. The results of the beamforming method

In this correspondence, we consider an 31-element uniform linear array operating at a carrier frequency $f_0 = 10$ GHz with a fixed inter-element spacing $d = c_0/(2f_0)$. Each element transmits the signal in a linearly increased carrier frequencies, where the frequency step is $f_r = 3$ kHz. In the simulation we use the following parameters: $T_r = 1/(10f_r)$ seconds, $t_s = 3/(10f_r)$ seconds, $R = r_s = 20$ km, $\theta = 30^\circ$, $\epsilon = 0.5$, and $U - L = 0.05$. These parameters are described in complete detail in [13].

As is shown in Fig.10, the main lobe of beam is formed at the fixed distance and direction. The energy of beam is very weak at the other areas. Therefore, the concerned area is covered by jamming, but the others is not. This can improve the accuracy of the jamming, and develop the stealth of the jammer. If we transmit multi-jamming, the each beam for multi-jamming could be added in digital domain, and then transmitted together. So multi-beam is the superposition of single beam.

5. Conclusion

The broadband folding jammer presented in this paper not only can achieve the receiving of broadband signals with a small amount of equipment, but also can efficiently obtain Nyquist zone index of broadband signals to guide the jamming signals. The proposed DF method works better than the
classical method based on the design of LFM LO. The scale experiments prove that the proposed folding jammer is feasible to achieve. The transmitting beamforming method uses the distance parameter firstly. The simulation shows that the areas which has the fixed direction and distance are covered by the energy of jamming, and the jamming energy on the other areas are so weak. Therefore, the broadband folding jammer has many advantages, it can has broader applications in the higher frequency jamming, ultra-broadband jamming and multi-target jamming field.

6. Acknowledgment
This work is supported by National Natural Science Foundation of China (61571088).

7. References
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