Blind Detection and Parameter Estimation of Single Frequency-Hopping Signal in Complex Electromagnetic Environment

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Abstract—*according to the non-stationary property of frequency-hopping signal, this paper presents a new blind detection and parameter estimation algorithm, which is based on Short-Time Fourier Transform, for single frequency-hopping signal in complex electromagnetic environment. The frequency-hopping signal can be recognized by the same dwell duration of the signal component on different frequencies, which the interference signal and the noise can be effectively removed to achieve the purpose of blind detection. Then, the hopping frequency and frequency-hopping cycle can be accurately estimated with Fast Fourier Transform. Theory analysis and simulation show that the algorithm can improve the performance of detection and parameter estimation in complex electromagnetic environment.*

Keywords—crequency-hopping signal; Short-Time Fourier Transform; blind detection; parameter estimation;

I. INTRODUCTION

Frequency hopping (FH) communication [4] is a kind of spread spectrum communication [3]. Due to the advantages such as the strong anti-interference ability, good secrecy and convenience for networking, frequency hopping (FH) communication has been widely used in civil and military communication. For radio reconnaissance, the research on signal detection and parameter estimation of FH signal is very important.

Among the traditional signal processing methods, it is generally assumed that the received signal is globally stable and the spectrum of the signal is time-invariant. Based on the hypothesis, the signal is analyzed in time domain or frequency domain individually. But FH signal is a kind of typical non-stationary signal and the spectrum changes over time, so the traditional signal processing method is not suitable for the analysis of FH signal. While the time-frequency analysis methods can analyze signals both in time and frequency domain, which is the most important method in analyzing and processing FH signal. The time-frequency analysis method is generally divided into two categories [5]: one is the Wigner-Ville distribution (WVD) and its derivative algorithm; the other is the linear time-frequency transform algorithm, including wavelet transform algorithm and Short-Time Fourier Transform (STFT) algorithm, etc. WVD algorithm has high time-frequency resolution, but the serious cross-term interference limits the application. WVD derived algorithms, such as Smoothing Pesudo-Wigner-Ville Distribution (SPWVD) [6], can effectively suppress the cross-term interference, but the cost of such algorithm is time-frequency resolution and the complexity of calculation. The advantage of wavelet transform is its variable time-frequency resolution, but it is too sensitive to noise and must be provided with a priori knowledge. Although STFT doesn't perform well in time-frequency resolution, it can work without a priori knowledge and calculation is not complicated, which is easy to implement in engineering. Under the condition of blind detection, considering computation complexity and the convenience in engineering implementation, STFT is chosen as the tool to analyze and process FH signal. In the literature about blind detection of FH signal, the algorithm of the paper [1] can deal with the complex electromagnetic environment, but it doesn't perform well in parameter estimation; In paper [2], the parameter of FH signal can be estimated more accurately, but it is assumed that the received signal doesn't include interference, which is not suitable for complex electromagnetic environment. Therefore, the algorithm in this paper aims to get a higher accuracy in estimating the parameters of FH signal, which is in the complex electromagnetic environment.

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II. SIGNAL MODEL IN COMPLEX ELECTROMAGNETIC ENVIRONMENT

A. Frequency-Hopping Signal

Frequency hopping communication refers to that the carrier frequency of the signal changes quickly over time under the control of a certain pseudo-random code. So the frequency hopping communication system can be understood as multi-frequency shift keying (MFSK) system, which the carrier frequency changes according to some rules. The mathematical model [7] of FH signal is defined as (1).

$$\begin{aligned} s(t) = &\sum_k rect(t - kT_H - \alpha T_H)\cdot \\ &\exp[j2\pi f_k(t - kT_H - \alpha T_H)], 0 < t \le T \end{aligned} \tag{1}$$

T is the detection time, $rect$ is the rectangular window which the time length is T_H . f_k is the hopping frequency, T_H is frequency-hopping cycle, αT_H is the timing deviation.

According to the definition, the parameters of FH signal mainly include the hopping frequency and the frequency-hopping cycle. FH signal has an important feature that the dwell duration at different frequencies is same, which is the basis of blind detection and parameter estimation of FH signal. The frequency-hopping pattern of single FH signal is shown in Figure 1:

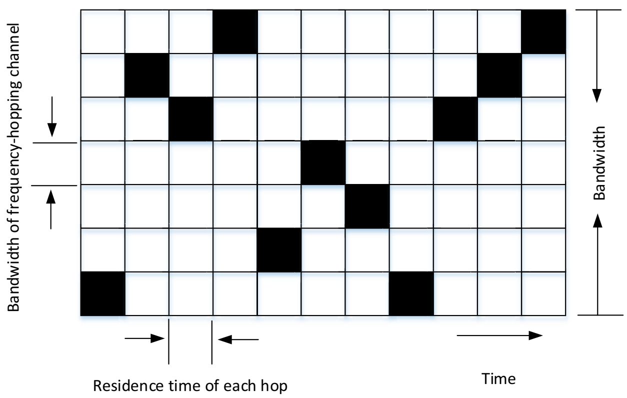


Fig.1. The frequency-hopping pattern of single frequency-hopping signal

Figure 1 is an example of frequency-hopping pattern, in which there is only one hopping frequency at each time; the frequency-hopping pattern of multiple FH signals is similar to Figure 1, but there may be multiple FH signals at each time. It is necessary to separate different signals by using blind source separation algorithm, which is not in the research scope of this paper. This paper focuses on the algorithm for single FH signal.

B. *Frequency-Hopping Signal Model in Complex Electromagnetic Environment*

The electromagnetic environment [1] refers to the collection of all electromagnetic phenomena in certain areas. The complexity of electromagnetic environment means that various types of signals overlap each other in the interesting frequency domain, resulting that it is difficult to work normally for the electronic device. Due to jamming on the battlefield, the electromagnetic environment may be very terrible, which make detection become very difficult.

Establish a mathematical model of FH signal in complex electromagnetic environment as follows:

$$z(t) = s(t) + J(t) + n(t) \tag{2}$$

$s(t)$ is FH signal, $J(t)$ is the interference signal, $n(t)$ is the noise, $z(t)$ is the mixed signal received by antenna. Due to the complexity of the actual electromagnetic environment, the received signal contains the noise, the interference signal and the FH signal which is to be detected. In order to ensure the detection effect of FH signal, it is necessary to remove or decrease the noise and interference signal.

III. BLIND DETECTION AND PARAMETER ESTIMATION OF FREQUENCY-HOPPING SIGNAL BASED ON STFT

A. *Short-Time Fourier Transform (STFT)*

Assume the signal is $s(t)$, and its STFT is:

$$STFT_s(t,f) = \int_{-\infty}^{\infty} s(t)\gamma^*(t-\tau)e^{-j2\pi f\tau}d\tau \tag{3}$$

$\gamma^*(t-\tau)$ is window function limited in time domain, * denotes complex conjugate. Let $s(t)$ multiply by $\gamma^*(t-\tau)$ at $t=\tau$, then get the spectral information of time t through the Fourier Transform. Therefore, $STFT_s(t,f)$ is a kind of two-dimension function on time domain and frequency domain. It is easy to get the time-frequency spectrum of the received signal through STFT, which is the first step of blind detection and parameter estimation for FH signal.

The higher the time resolution and the frequency resolution are, the better the effect of signal analysis. But according to the principle of uncertainty [1], it is impossible to improve the time resolution and frequency resolution at the same time. If the window function is shorter in time domain, the time resolution will be improved, but the frequency resolution will get worse; and vice versa. In order to achieve better analysis effect, when setting the length of window function, it is necessary to consider the time resolution and frequency resolution simultaneously.

B. *Algorithm Steps*

After receiving the signal, we can use the algorithm to detect whether the received signal includes the FH signal, and estimate the parameters if it does. The steps are as follows:

Step 1: Analyze the received signal data with STFT to get the time-frequency spectrum.

Step 2: Set a normalized threshold to remove the noise.

Step 3: Check the continuous frequencies along the frequency axis of the time-frequency spectrum, and combine these frequencies into one frequency whose amplitude is the largest among them.

Step 4: Set a frequency difference Δf and compare the frequencies, whose difference of each other is smaller than Δf, along the frequency axis. Then change the frequency, whose amplitude is smaller, into the other frequency, whose amplitude is larger.

Step 5: Set an error Δn and count the occurrence number of each frequency, then divide the frequencies, whose difference of total occurrence number of each other is smaller than Δn, into the same frequency set. If there is frequency set which includes the largest number of frequencies and the number is more than 4, go to next step; otherwise, end the algorithm.

Step 6: According to the frequency set of the last step, remove the interference signal to get the time-frequency spectrum, which only contains FH signal.

Step 7: Along the frequency axis of the time-frequency spectrum, add the amplitude of all time on the same frequency together to get the frequency-spectrum, in which the horizontal coordinate of the wave crest is the hopping frequency.

Step 8: Along the time axis of the time-frequency spectrum, add the amplitude of all frequencies on the same time together, then use FFT to get the frequency spectrum, in which the horizontal coordinate of the highest wave crest is the reciprocal of frequency-hopping cycle.

C. Algorithm Analysis

According to the algorithm steps, it is clear that the core of the algorithm is to take advantage of the feature of FH signal, which the dwell duration on different frequencies is same. It divides the frequency of the same dwell duration into the same frequency set. Then it is assumed that the set, which contains the largest number of frequencies, is the hopping frequency set. Therefore, it requires that there are at least 4 different frequencies in each detection result; otherwise the result is not reliable.

Assume that the number of received signal data are N , the sampling rate is f_s , $hopspeed$ is the hopping rate, which is the reciprocal of frequency-hopping cycle. It is clear that the data number of the dwell duration is $f_s / hopspeed$. The algorithm requires that every detection result contains at least 4 different frequencies, so there is the following formula:

$$\frac{fs}{hopspeed} \cdot 4 \leq N \tag{4}$$

Thus

$$hopspeed \geq \frac{4fs}{N} \tag{5}$$

(5) shows the lower bound of $hopspeed$, which is determined by f_s and the number of total data points N . It means that $hopspeed$ of the received FH signal should be larger than the lower bound, otherwise it can't be estimated. The larger f_s is, the larger the detected frequency range is, but the lower bound of $hopspeed$ gets larger, which means the scope of application is narrower; the bigger N is, the smaller the lower bound becomes, which means the scope of application is broader, but it requires stronger hardware computing power, resulting that the cost for engineering implementation increases.

IV. SIMULATION

A. Simulation Conditions

In view of the complexity of the actual electromagnetic environment, add the noise and interference into the received signal in order to make the simulation more similar with the real environment. The simulation conditions are shown in table 1:

TABLE1 Simulation conditions

Sampling rate: f_s=5MHz
Total number of sampling points: N=5*1024(1024 is the data length of dwell duration)
Frequency-hopping cycle: 0.2048ms
Frequency-hopping interval: ΔF=0.2MHz
Frequency-hopping pattern: f_k={0.3,0.1,0.5,0.9,0.7,1.1}MHz
The interference signal includes a burst signal whose frequency is 1.5MHz, and two fixed frequency signals, which the frequency is 1.7MHz and 2.1MHz respectively.
SNR: 5dB

B. Simulation Results

According to the conditions in Table 1, set the window length of STFT, which is $N/4$, and simulate in MATLAB. The results are as follows:

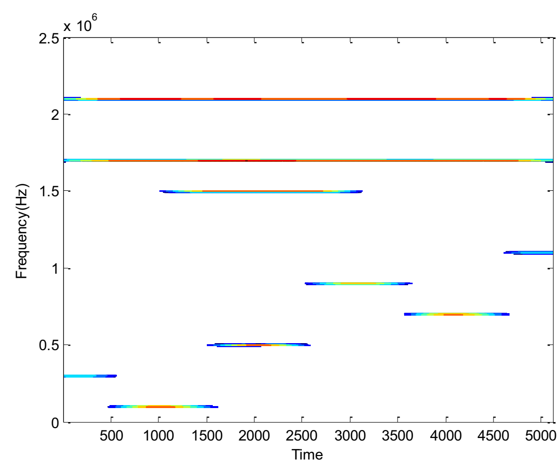


Fig.2. The time-frequency spectrum of the received signal

The time-frequency spectrum of the received signal is shown in Figure 2.The horizontal axis is time, the vertical axis is the frequency and the part of color represents the signals of different frequencies. In Figure 2, it is clear that the part below is FH signal and the part up is the interference signal.

Figure 3 is the time-frequency spectrum of FH signal after step 6, and it is the basis of parameter estimation. After step 7, the frequency spectrum of FH signal is shown as Figure 4, and the hopping frequency is the horizontal coordinate of each peak.

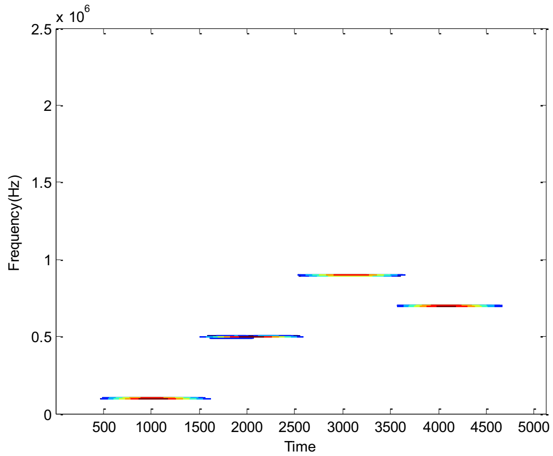


Fig.3. The time-frequency spectrum after removing the interference signal the noise

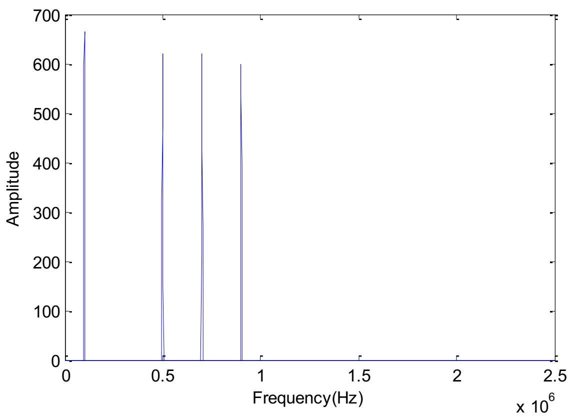
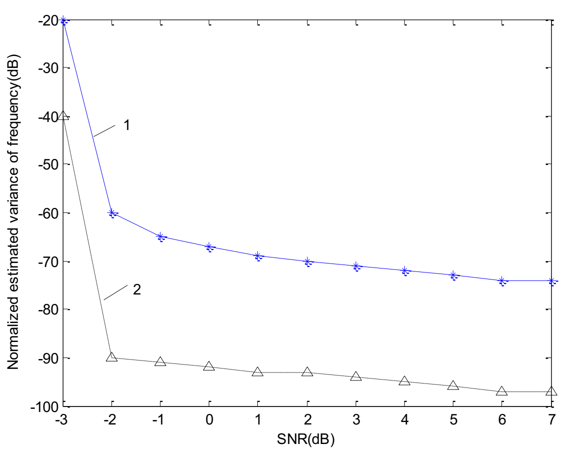


Fig.4. The frequency pectrum of frequency-hopping signal



1-the algorithm of the paper[1]; 2-the algorithm of this paper
Fig.5. Comparison of the normalized estimated variance of the hopping frequency

In order to analyze the performance of hopping frequency estimation, define the normalized variance of frequency estimation as follows:

$$\xi = \frac{1}{M}\sum_{j=1}^{M}\left(\frac{f_j}{F_j}-1\right)^2 \quad (6)$$

f_j is the hopping frequency which is estimated, F_j is the true hopping frequency, M is the number of different hopping frequencies. Simulate 100 times with different SNR and then take the average value to get the curve of normalized estimated variance about the hopping frequency, as shown in Figure 5.

Figure 6 shows the frequency spectrum about the hopping rate after step 8.The frequency hopping cycle is the reciprocal of the hopping rate, which is the horizontal coordinate corresponding to the maximum peak. It is clear that the frequency hopping cycle is 1/4883 s, about 0.204792 ms.

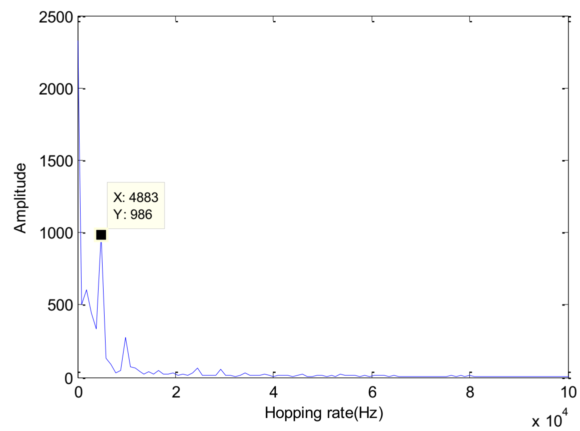


Fig.6. The frequency spectrum of the hopping rate

C. *Simulation Results Analysis*

In Figure 5, it is clear that the estimation error of the hopping frequency in this paper is less than that in paper [1]; compared with that the relative estimation error of the frequency-hopping cycle is about 0.0005 in paper [1], the estimation value is 0.204792ms in this paper, almost exactly same with the true value 0.2048ms, whose relative error is less than 0.00004. Compared with paper [2], the algorithm in this paper can deal with electromagnetic environment. In summary, the simulation results show that the algorithm, which can be applied in electromagnetic environment, has better parameter estimation performance of FH signal, especially the estimation about the frequency-hopping cycle, whose relative error is reduced by an order of magnitude.

V. CONCLUSION

According to the non-stationary property of frequency-hopping signal, this paper presents a new blind detection and parameter estimation algorithm, which is based on STFT, for single frequency-hopping signal in complex electromagnetic environment. Simulation results show that FH signal, in complex electromagnetic environment, can be detected effectively without a prior knowledge. That is a very important property, which can make the algorithm have more extensive application scope. And the algorithm performs well in parameter estimation, especially the estimation of the frequency-hopping cycle, whose relative error is reduced by an order of magnitude.

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