Application of the wavelet rearrangement algorithm in the detection of noncooperative frequency hopping signals

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Abstract—**How to get good time-frequency distribution of the noncooperative frequency hopping (FH) signals is crucial to detect and trace the FH signals. In the paper, the noncooperative FH signal model is given firstly, then the principles and properties of the noncooperative FH signal detection based on the rearrangement algorithm of the Morlet wavelet scale spectrum are discussed in detail, and finally through the computer simulation analysis, it's proved that the rearrangement algorithm not only has ideal anti-interference effect, but also improves the time-frequency aggregation performance of the FH signals aiming to implement the blind estimation of the FH signal parameters accurately.**

Keywords-wavelet; time-frequency distribution; rearrangement of the scale spectrum; noncooperative FH

I. INTRODUCTION

The FH communication is widely used in the military and commercial areas because of its inherent security features. To get the time-frequency distribution of the unknown FH signals with noise inside by the means of time-frequency analysis is one of the most important researches in the modern military communication countermeasure because it's the major premise to estimate the parameters of frequency hopping speed, frequency hopping map, etc, so as to intercept the enemy communications or produce the best interference signal to disrupt their normal communications.

In the FH signal process, it's not enough to analyze the signal only based on the frequency domain analysis. The time-frequency analysis based on the combination of time domain analysis and frequency domain analysis is an efficient way to analyze the FH signal as it can get the time-frequency distribution to describe the joint time-frequency characteristics of the signal. The rearrangement algorithm of the time-frequency distribution not only can get better performance of the time-frequency aggregation, but also reduce the cross interference further more. In the paper, the rearrangement algorithm based on the time-frequency transformation of the Morlet wavelet is adopted to process the noncooperative FH signal. The simulation results prove that the wavelet rearrangement algorithm can be well applied in the FH signal detection and parameter estimation because of its good performance.

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II. NONCOOPERATIVE FH SIGNAL MODEL

The FH signals can be seen as multiple frequency-shift keying (MFSK) signals whose carrier frequency changes regularly because its carrier frequency controlled by the pseudo-noise (PN) code hops continuously and randomly. The direct digital frequency synthesizer (DDS) controlled by the PN code outputs the frequency changing in accordance with the state of the PN code and then the radio frequency signal is produced. The frequency output from the DDS is $f_i, f_i \in \{f_1, f_2, \cdots, f_N\}$, which means f_i is one element of the frequency set $\{f_1, f_2, \cdots, f_N\}$ during the time $(i-1)T_h \le t \le i \cdot T_h$, where T_h is duration time of one hopping. Suppose the transmitting signal is.

$$s_i(t) = m(t)\mathrm{e}^{\mathrm{j}(2\pi f_i t + \varphi_i)} \tag{1}$$

In the above equation, $m(t)$ is the data information to be transmitted, φ_i is pseudo phase, and the receiving signal in the receiver is

$$y(t) = s_i(t) + n(t) \tag{2}$$

$n(t)$ is additive white Gauss noise in above equation.

Please notice that the analytic expression of the signal is preferred to the real expression during calculation when cross interference suppression is considered, not only because in some time-frequency analysis there is more cross interference in the real signal analysis than that in the analytic signal analysis, but also the data information is not lost or false when removing the negative frequency component. So if the data signal is real signal, the Hilbert transformation may be used to transform the real signal to analytic signal before time-frequency analysis.

III. PRINCIPLES AND PROPERTIES OF THE SCALE SPECTRUM REARRANGEMENT OF THE MORLET WAVELET

In 1966, Cohen found that many kinds of time-frequency distribution are transformed from Wigner-Ville distribution and can be expressed in uniform. The uniform expression is called Cohen class time-frequency distribution[1], in which there is a large class of distribution which is considered Wigner-Ville distribution after two dimensional (2D) filtering.

It can be proved that if and only if the time-frequency distribution $P(t,f)$ is deduced from Wigner-Ville distribution using the time-frequency convolution, the $P(t,f)$ belongs to Cohen class distribution and is called energy-type Cohen class distribution marked as C_E and expressed as following:

$$\begin{aligned} & P(t,f) \in C_E \Leftrightarrow P(t,f) \\ & = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \Phi(t-t', f-f')W_x(t',f')\mathrm{d}t'\mathrm{d}f' \\ & = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \Phi(t', f')W_x(t-t',f-f')\mathrm{d}t'\mathrm{d}f' \end{aligned} \tag{3}$$

Rearranging the time-frequency distribution can improve the performance of the time-frequency aggregation. The rearrangement algorithm deduction begins from (3), which indicates that the time-frequency distribution value at any point (t,f) equals to the sum of all the product factor $\Phi(t',f')W(t-t',f-f')$ which is considered as the weighting Wigner-Ville distribution at the point $(t-t',f-f')$ which is adjacent to the point (t,f). So the time-frequency distribution $P(t,f)$ is the average value of signal energy in the adjacent region with the kernel function $\Phi(t',f')$ and the center point (t,f). The average calculation reduces the cross interference, but it also diffuses the signal energy. The Fig.1 is the principle of the rearrangement algorithm.

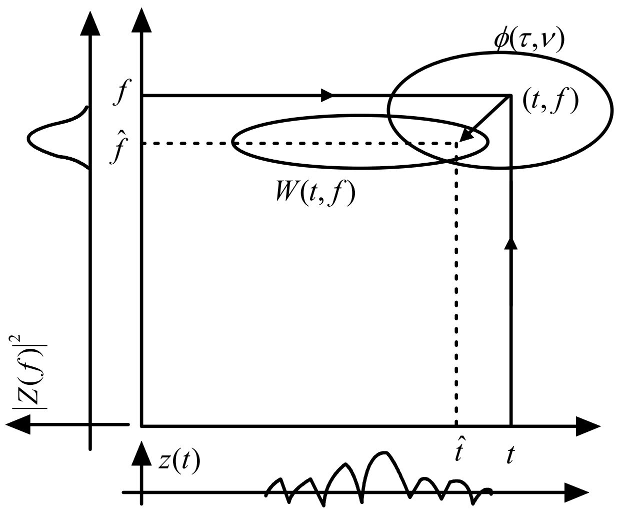

Figure 1. The principle of the rearrangement algorithm

In the Fig.1, the new coordinate value of $\hat{t}$ and $\hat{f}$ are defined as

$$\begin{aligned} & \hat{t}(t,f) \\ & = t - \frac{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} t'\Phi(t',f')W_x(t-t',f-f')\mathrm{d}t'\mathrm{d}f'}{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \Phi(t',f')W_x(t-t',f-f')\mathrm{d}t'\mathrm{d}f'} \\ & \hat{f}(t,f) \\ & = f - \frac{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} f'\Phi(t',f')W_x(t-t',f-f')\mathrm{d}t'\mathrm{d}f'}{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \Phi(t',f')W_x(t-t',f-f')\mathrm{d}t'\mathrm{d}f'} \end{aligned} \tag{4}$$

The equation (4) is called rearrangement operator, in which the new coordinate $(\hat{t},\hat{f})$ is the function of the original time-frequency coordinate (t,f).

In the Fig.1, it indicates that even if there is no energy at the point (t,f) while there is nonzero distribution value at the adjacent region of the point, the time-frequency distribution value $P(t,f)$ after weighting in (3) doesn't equal to zero. To avoid this, the equation (3) has to be modified as follows:

$$\begin{aligned} & P_M(t',f') \\ & = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} P(t,f)\delta\left[t'-\hat{t}(t,f)\right]\delta\left[f'-\hat{f}(t,f)\right]\mathrm{d}t\mathrm{d}f \end{aligned} \tag{5}$$

The above equation indicates that the modified time-frequency distribution value $P_M(t',f')$ is the sum of the original Cohen class distribution values at the point. But the aim of rearrangement is to rearrange the signal energy distribution in the time-frequency plane to improve the signal component aggregation. So when the distribution value at the point is zero, the rearrangement operator is nonsense. In addition, if the kernel function value is real, the value of the rearrangement operator is also real because the Wigner-Ville distribution value in (4) is real.

Please notice that $P(t,f)$ is dual linear time-frequency distribution while $P_M(t',f')$ is not, but $P_M(t',f')$ has the same characteristics as $P(t,f)$ [2]. It should be pointed out that there is contradiction between the cross interference suppression and the signal maintenance because reducing the cross interference at the same time has side effect that the signal is diffused. In the time-frequency domain where there is no signal component, the interference can be suppressed totally, but where there is signal component, there is always cross interference.

As a special case of the Affine class time-frequency distribution, the scale spectrum is defined using the square value of the wavelet transformation modulus as follows:

$$SC_x(t,a;\psi) = |T_x(t,a;\psi)|^2 \tag{6}$$

$SC_x(t,a;\psi)$ is the signal energy distribution in the time-scale plane, which is related to $\mathrm{d}t\mathrm{d}a/a^2$ and has characteristics of time and scale shift invariance. In the paper, the FH signal is analyzed based on the scale spectrum of the Morlet wavelet, and the Morlet wavelet transformation is as follows:

$$
\begin{aligned}
&T_x(t,a;\psi)\\
&=\frac{1}{\sqrt{a\sqrt{\pi}}}\int_{-\infty}^{+\infty} x(s)\psi^*\left(\frac{s-t}{a}\right)\mathrm{d}s \qquad (7)\\
&=\frac{1}{\sqrt{a\sqrt{\pi}}}\int_{-\infty}^{+\infty} x(t)e^{\mathrm{j}\omega_0\left(\frac{t-s}{a}\right)}e^{-\frac{1}{2}\left(\frac{t-s}{a}\right)^2}\mathrm{d}s
\end{aligned}
$$

In the above equation, $x(s)$ is the input signal. $\psi^*(\frac{s-t}{a})$ is the conjugate of the $\psi(s)$ after stretching and shifting, in which a is scale factor (or stretch factor) and t is shift factor.

The rearrangement algorithm is to move the time-frequency distribution value at any point (t,f) in the scale spectrum to another point $(\hat{t},\hat{f})$ which is the center of signal energy around the point (t,f). The rearrangement algorithm of the scale spectrum based on the Morlet wavelet transformation is expressed in [3] as follows:

$$
\begin{aligned}
&SC_x^{(r)}(t',a';\psi)\\
&=\iint_{-\infty}^{+\infty} a'^2\, SC_x(t,a;\psi)\delta(t'-\hat{t}(x;t,a))\delta(a'-\hat{a}(x;t,a))\mathrm{d}t\frac{\mathrm{d}a}{a^2} \qquad (8)
\end{aligned}
$$

and the rearrangement operator is

$$
\begin{aligned}
&\hat{t}(x;t,a)=t-\mathcal{R}\left\{a\frac{T_x(t,a;\tau_\psi)T_x^*(t,a;\psi)}{|T_x(t,a;\psi)|^2}\right\}\\
&\hat{f}(x;t,a)=\frac{f_0}{\hat{a}(x;t,a)}=\frac{f_0}{a}+\mathcal{I}\left\{\frac{T_x(t,a;D_\psi)T_x^*(t,a;\psi)}{2\pi a|T_x(t,a;\psi)|^2}\right\} \qquad (9)\\
&\tau_\psi(t)=t\times\psi(t), D_\psi(t)=\frac{\mathrm{d}\psi}{\mathrm{d}t}(t)
\end{aligned}
$$

The modified distribution is no more dual linear distribution, but still has characteristics such as time and scale shift invariance, energy conservation and nonnegativeness.

IV. SIMULATION ANALYSIS AND PARAMETER ESTIMATION

For convenient simulation, suppose the analytic FH signal is expressed as following:

$$
s(n)=\begin{cases}
\exp(2\pi f_1T_sn+\theta_1) & 0\le n\le 255\\
\exp(2\pi f_2T_sn+\theta_2) & 256\le n\le 511\\
\exp(2\pi f_3T_sn+\theta_3) & 512\le n\le 767\\
\exp(2\pi f_4T_sn+\theta_4) & 768\le n\le 1023
\end{cases} \qquad (10)
$$

The frequency interval $\Delta f=5kHz$, the signal to noise ratio $S/N=0\mathrm{dB}$, and the parameters in (10) are:

$$
\begin{aligned}
&f_1=10.21MHz\\
&f_2=f_1+\Delta f\\
&f_3=f_2+\Delta f\\
&f_4=f_3+\Delta f \qquad (11)\\
&\theta_1=\theta_2=\theta_3=\theta_4=0\\
&f_s=1/T_s=250\mathrm{kHz}
\end{aligned}
$$

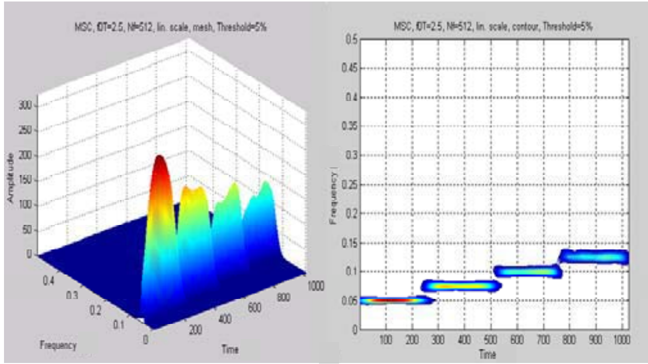

Figure 2. The time-frequency map of the Morlet wavelet (S/N=0dB)

The Fig. 2 shows the three dimensional (3D) map and the contour map of the Morlet scale chart (MSC). And there are two conclusions got from the Fig. 2: ① Except signal distribution, there are little cross interference and noise, which indicates that the wavelet transformation can suppress the cross interference and noise to some extent; ② In the contour map of the time-frequency distribution, the bandwidth in the high frequency band is wider than that in the low frequency band, that is to say the frequency resolution of the wavelet transformation in high frequency band is lower.

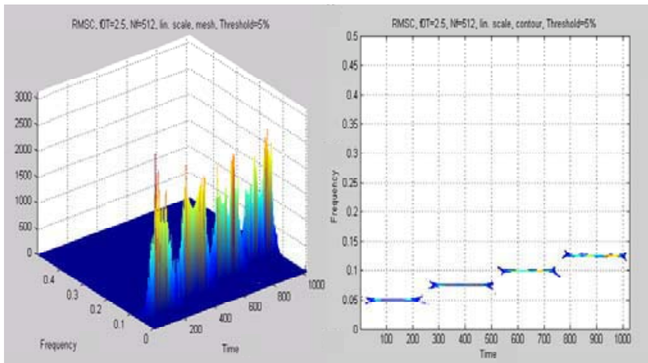

Figure 3. The time-frequency distribution of the Morlet wavelet after rearrangement (S/N=0dB)

The Fig. 3 shows the 3D map and the contour map of the rearrangement of the Morlet scale chart (RMSC). There are two conclusions got after comparing the Fig. 2 and Fig. 3: ① The time-frequency aggregation performance are improved after comparing the magnitude values in the two 3D maps in Fig. 2 and Fin. 3. Improving the decision threshold can suppress the interference, so the time-frequency distribution after rearrangement has stronger ability than that before to suppress the cross interference and noise; ② Comparing the two contour maps in the two figures, it is concluded that the frequency aggregation performance in the high frequency band after rearrangement is better than that before as the signal in the time-frequency plane is well localized after rearranging the FH signal energy. That is to say the frequency resolution after rearrangement is higher than that before.

The FH signal parameters can be estimated using the time-frequency distribution in the condition that the signal is unknown. The Fig. 3 indicates that there is a peak value at the time center of one frequency hopping. So the FH period can be got after calculating the maximum value of the time-frequency distribution along the frequency axis at every moment. As the maximum values on the time axis show big steps after the distribution rearrangement, the maximum values should be smoothing filtered before analysis for convenience.

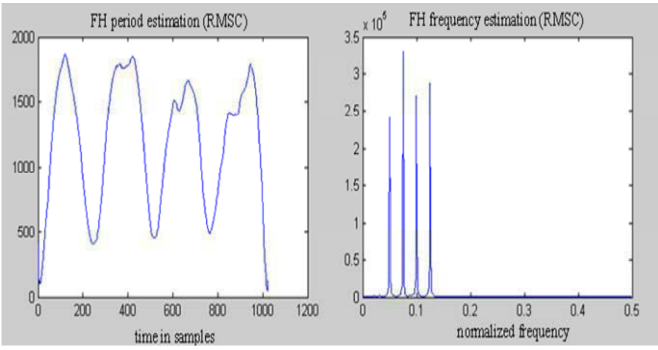

Figure 4. The FH period and frequency estimation using RMSC (S/N=0dB)

The Fig. 4 indicates that the FH period chart estimated through RMSC algorithm has obvious periodic oscillating characteristic, and the oscillating period is the frequency hopping period. So the FH speed is the FH period reciprocal or equals to the frequency corresponding to the peak value of the oscillating signal spectrum after the FFT transformation. Based on the FH period, the FH frequency points corresponding to the peak values along the frequency axis shown in the Fig. 4 can be got after accumulating the time-frequency distribution value along the time axis during every FH period. In addition, the estimation precision of the FH parameters is related to the length of the signal samples observed. The longer the observation time and the more the signal samples, the higher the estimation precision, but at the same time it needs long time to complete the calculation[4].

V. THE END

The aim of the rearrangement algorithm which modifies the time-frequency distribution is to improve the precision of the signal component localization by rearranging the signal energy in the time-frequency plane. As the rearrangement algorithm maintains characteristics such as time-frequency shifting invariance, energy conservation, etc[5], it improves the signal localization ability in the time and frequency domain. The Morlet wavelet rearrangement algorithm can be applied promisingly in the fast noncooperative FH signal detection as it obviously improves the readability of the signal time-frequency expression, recognizes the FH signal and estimates the FH signal parameter effectively.

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