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An Improved Cyclic Feature Spectrum Detection Algorithm in CR Systems

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Abstract

Accurate detection performance of spectrum sensing will obviously affect the communication quality of licensed users and secondly users. Robust spectrum sensing algorithm can reduce interfere to primary users. This paper presents a new OFDM cyclic spectrum sensing scheme which based on overlay parts sub-carriers to original OFDM signals. In this paper, the parts sub-carriers come from original OFDM cyclic feature signals. Simulation and numerical results show that new method has a high success rate of sensing and a shorten detection time. Moreover, computational complexity is almost no change. Algorithm improved detection performance obviously and enhanced the effectiveness of anti-noise uncertainty and improved the robustness of detecting weak signal. Algorithm meets the spectrum sensing technology requirements of low SNR environment.

Keywords: *Cognitive radio; spectrum sensing; OFDM signals cyclic feature; cyclic spectrum*

1. Introduction

Nowadays wireless systems are based on fixed spectrum allocations, allocated fixed spectral bandwidth to licensed user at any time. The allocated spectrum is idle most of the time, which resulting waste of resources and spectrum utilization decreased. As the rapid development of wireless communication technology, available spectrum is fewer. Cognitive radio can make full use of idle spectrum resources and will not interfere with authorized users. Dynamic spectrum access techniques promise greater spectral-usage efficiency. Cognitive radio technology can solve the problem of low spectrum utilization. Spectrum sensing as one of the key technologies should be provided with a capacity of rapid detecting channels is idle or occupied in harsh environment.

Accurate detection performance of spectrum sensing will obviously affect the communication quality of licensed users and secondly users. Robust spectrum sensing algorithm can reduce interfere to primary users. Especially sensing technology in low SNR environment becomes a hot research topic in the international. Domestic and foreign scholars have done a lot of work in spectrum sensing algorithm. e.g., matched filter detection method [1-5], energy detection method [1-6], cyclic feature spectrum detection method [1-8], etc. In spectrum sensing, research shows that these methods has its advantages, however, cyclic feature spectrum detection method is best in the anti-noise uncertainties.

In this paper, cyclic feature of OFDM signals has been analyzed. Paper derived Detection probability and false alarm probability expressions. In order to improve detection efficiency, should be periodically repeated sensing. Duplicate detection cycle must be less than or equal to the period of authorized users access signal. And spectrum sensing method should try to make the detection time and false alarm probability as low as possible [9]. While ensuring high detection probability to shorten the detection time, which can reduce interference to licensed users and improve real-time spectrum sensing.

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2. Mathematics Foundations of Cyclostationary Signals

Many of the communications signals in use today may be modeled as cyclostationary signals due to the presence of one or more underlying periodicities which arise as a result of the coupling of stationary message signals with periodic sinusoidal carriers, pulse trains or repeating codes [10].

A signal $x(t)$ is cyclostationary if its autocorrelation function is periodic in time t for each lag time τ

$$R_{xx}(t,\tau) = E\left\{x(t)x^*(t+\tau)\right\} \tag{1}$$

The formula (1) can be represented as Fourier series

$$R_{xx}(t,\tau) = \sum_{\alpha} R_{xx}^{\alpha}(\tau)e^{j2\pi\alpha t} \tag{2}$$

Here the Fourier coefficients $R_{xx}^{\alpha}(\tau)$ are referred to cyclic autocorrelation function and parameter α are called cyclic frequency. So as the definition of cyclic autocorrelation function (CAF) and spectral correlation density (SCD) [11]

$$R_{xx^{(*)}}^{\alpha}(\tau) = \lim_{T\to\infty}\frac{1}{T}\int_{-T/2}^{T/2} R_{xx^{(*)}}(t,\tau)e^{-j2\pi\alpha t}dt \tag{3}$$

$$S_{xx^{(*)}}^{\alpha}(f) = \int_{-\infty}^{\infty} R_{xx^{(*)}}^{\alpha}(\tau)e^{-j2\pi\alpha\tau}d\tau \tag{4}$$

Let's denote the superscript $(*)$ as an optional of complex conjugate. So $R_{xx}^{\alpha}(\tau)$ and $R_{xx^*}^{\alpha}(\tau)$ are respectively called cyclic autocorrelation function and conjugate cyclic autocorrelation function, $S_{xx}^{\alpha}(f)$ and $S_{xx^*}^{\alpha}(f)$ are called cyclic spectrum and conjugate cyclic spectrum. In order to reducing the computation complexity, the cyclic spectral correlation density can also be represented as [11]

$$S_{xx,T}^{\alpha}(t,f) = \frac{1}{T}X_T(t,f+\alpha/2)X_T^*(t,f-\alpha/2) \tag{5}$$

In expression (5), $X_T(t,\upsilon) = \int_{t-T/2}^{t+T/2} x(u)e^{-j2\pi\upsilon u}du$, $T = 1/\Delta f$ with center frequency υ, bandwidth Δf , and duration T .

3. OFDM Signals Cyclic Feature

The base-band OFDM signal can be expressed as a composite of N_c statistically independent sub-carrier signals

$$s(t) = \sum_{n=-\infty}^{\infty}\sum_{i=0}^{N_c-1} d_{n,i}e^{j2\pi i\Delta f(t-nT_s)}g_R(t-nT) \tag{6}$$

In (6), information symbols $d_{n,i}$ is an independent and identically distributed (i.i.d.) symbol sequence, N_c is the number of sub-carriers and $g_R(t)$ is a square pulse of duration T , T_s is the source symbol duration and T_g is the cyclic prefix length, Baseband OFDM signal duration is $T = T_s + T_g$, $\Delta f = 1/T_s$ is the carrier separation.

The cyclic autocorrelation function can be expressed as

$$R_{ss}(t,\tau) = \sigma_d^2\sum_{-\infty}^{\infty}\sum_{i=0}^{N_c-1} e^{j2\pi i\Delta f\tau}g_R(t-nT)g_R^*(t-nT+\tau) \tag{7}$$

Here $\sigma_d^2 = E\left\{d_{n,i}d_{n,i}^*\right\}$, further simplification

$$R_{ss}\left(t,\tau\right)=\sigma_d^2\frac{\sin\left(\pi N_c\Delta f\tau\right)}{\sin\left(\pi\Delta f\tau\right)}\sum_{n=-\infty}^{\infty}g_R\left(t-nT\right)g_R^*\left(t-nT+\tau\right) \tag{8}$$

From (8), $R_{ss}\left(t,\tau\right)$ period function, therefore, OFDM signals showing cyclostationary, cyclic-frequency is $\alpha=k/T=kf, k=0,\pm1,\pm2,...$, so the cyclic autocorrelation function can be expressed as [10][12]

$$R_{ss}^{\alpha}\left(\tau\right)=\begin{cases}\sigma_d^2\dfrac{\sin\left(\pi N_c\Delta f\tau\right)\sin\left[\pi kf\left(T-|\tau|\right)\right]}{\sin\left(\pi\Delta f\tau\right)}, \alpha=k/T=kf,|\tau|<T\\ 0 \qquad , otherwise\end{cases} \tag{9}$$

Because $g_R(t)$ is a square pulse, the Fourier transform of $g_R(t)$ is $G_R\left(\theta\right)=\sin\left(\pi\theta T\right)/\left(\pi\theta\right)$, then time varying autocorrelation function is

$$R_{ss}\left(t,\tau\right)=\sigma_d^2\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}G_R\left(\theta\right)G_R^*\left(\phi\right)e^{j2\pi\left(\theta-\phi\right)t}e^{-j2\pi\phi t}\cdot\sum_{n=-\infty}^{\infty}\sum_{i=0}^{N_{c-1}}e^{j2\pi i\Delta f\tau}d\theta d\phi \tag{10}$$

According Poisson summation formula

$$\sum_{n=-\infty}^{+\infty}e^{-j2\pi nTf}=\frac{1}{T}\sum_{n=-\infty}^{+\infty}\delta\left(f-\frac{n}{T}\right) \tag{11}$$

Further simplification of (10), cyclic autocorrelation function can be simplified

$$R_{ss}^{\alpha=kf}\left(\tau\right)=\frac{\sigma_d^2}{T}\int_{-\infty}^{\infty}G_R\left(\theta\right)G_R^*\left(\theta-\frac{k}{T}\right)\cdot\sum_{i=0}^{N_{c-1}}e^{-j2\pi i\Delta f\tau}e^{-j2\pi\left(\theta-\frac{k}{T}\right)t}d\theta \tag{12}$$

Taking the Fourier transform of the cyclic autocorrelation function we can get the cyclic spectrum density function

$$S_{ss}^{\alpha}\left(f\right)=\begin{cases}\dfrac{\sigma_d^2}{T}\displaystyle\sum_{i=0}^{N_c-1}G_R\left(f-i\Delta f+\frac{N_c}{2}\Delta f\right)\\ \times G_R^*\left(f-\dfrac{k}{T}-i\Delta f+\dfrac{N_c-1}{2}\Delta f\right),\alpha=\dfrac{k}{T}\\ 0 \qquad , otherwise\end{cases} \tag{13}$$

Here is cyclic spectral correlation density function simulation diagram. Simulation parameters are set as follows. Number of sub-carrier $N_c=4$,cyclic prefix length $T_g=T_s/4$. Fig.1 is the cyclic spectrum of OFDM signals, and Fig.2 is the cyclic spectrum of OFDM with noise. From the contour figure of Fig.2, not illustrate of cyclic spectrum, because of noise is random and wreak the cyclic feature of OFDM. An improved method will be discussed.

4. Improved OFDM Signals Cyclic Feature

In order to improved the detection performance of cyclic feature, in the derivation of OFDM cyclic spectrum, selecting some sub-carrier of original OFDM signal, and superimposed together to calculate the cyclic spectral. Therefore, the improved OFDM signals can be expressed

$$s'\left(t\right)=\sum_{-\infty}^{\infty}\left(\sum_{i=0}^{N_c-1}d_{n,i}e^{j2\pi i\Delta f\left(t-nT\right)}+\sum_{l=q}^{q+m}d_{n,l}e^{j2\pi l\Delta f\left(t-nT\right)}\right)g_R\left(t-nT\right) \tag{14}$$

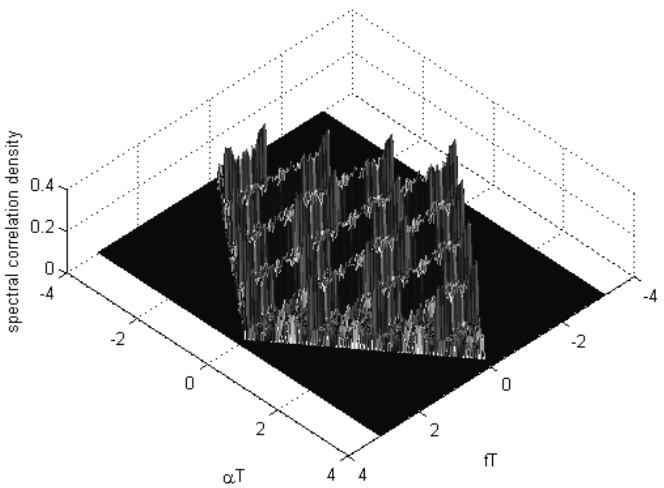

Figure 1. Cyclic Spectral of OFDM Signals

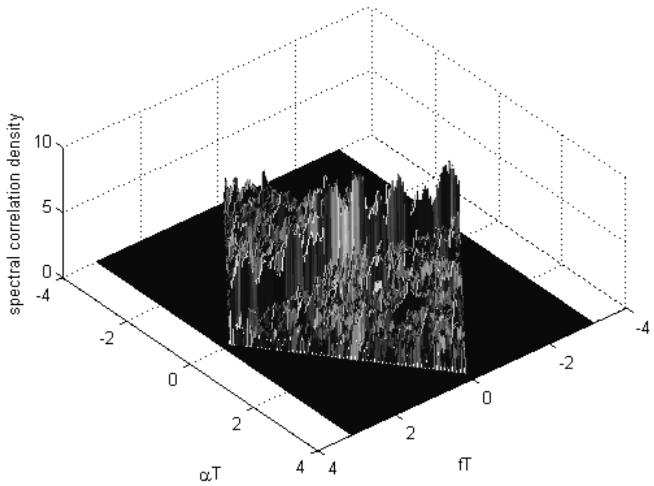

Figure 2. Cyclic Spectral OFDM Signals with Noise

In (14), $0 \le q \le N_c - m$, l is the initial position of selected sub-carriers, m is the number of selected sub-carrier. Thence, the cyclic autocorrelation function of improved OFDM signals can be derived

$$R'^{\alpha=kf}_{ss}(\tau) = \frac{\sigma_d^2}{T}\int_{-\infty}^{\infty} G_R(\theta) G_R^*\left(\theta - \frac{k}{T}\right) \cdot \left(\sum_{i=0}^{N_c-1} e^{-j2\pi i\Delta f\tau} + \sum_{l=q}^{q+m} e^{-j2\pi l\Delta f\tau} e^{j2\pi\frac{m}{2}\Delta f\tau}\right) e^{-j2\pi\left(\theta-\frac{k}{T}\right)t} d\theta \tag{15}$$

Where, $\sigma_d^2 = E\left\{d_{n,i} d_{n,i}^*\right\}$, taking Fourier transform of the cyclic autocorrelation function we can get the cyclic spectrum density function

$$S'^{\alpha}_{ss}(f)=\begin{cases}\frac{\sigma_d^2}{T}\sum_{i=0}^{N_c-1}G_R\left(f-i\Delta f+\frac{N_c}{2}\Delta f\right)\cdot G_R^*\left(f-\frac{k}{T}-i\Delta f+\frac{N_c-1}{2}\Delta f\right) \\ +\frac{\sigma_d^2}{T}\sum_{l=q}^{q+m}G_R\left(f-l\Delta f+\frac{m+1}{2}\Delta f\right)\cdot G_R^*\left(f-\frac{k}{T}-l\Delta f+\frac{m}{2}\Delta f\right) & ,\alpha=\frac{k}{T} \\ 0 & ,\text{otherwise}\end{cases} \tag{16}$$

$$S'^{\alpha}_{ss}(f)=\begin{cases}S^{\alpha}_{ss}(f)+\Delta S^{\alpha}_{ss}(f) & ,\alpha=\frac{k}{T} \\ 0 & ,\text{otherwise}\end{cases} \tag{17}$$

Comparing (13) with (16), and (16) significantly add one part than (13), such as $S'^{\alpha}_{ss}(f)=S^{\alpha}_{ss}(f)+\Delta S^{\alpha}_{ss}(f)$, so $S'^{\alpha}_{ss}(f)> S^{\alpha}_{ss}(f)$. Here $\Delta S^{\alpha}_{ss}(f)$ is the cyclic spectrum of selected OFDM signal, and showing the same cyclic spectrum with original signals. Therefore, improved method enhance the spectrum characteristics of cyclic frequency, improved the robustness of ant-noise interference.

The following figures are the simulation result of improved OFDM signals. Here, sub-carrier number $N_c=4$, cyclic prefix duration $T_g=T_s/4$, selected OFDM signal is the first two sub-carriers and $m=2$. Moreover, the selected sub-carriers overlay to the last two sub-carrier of original signal with sequence. Fig.3 is the spectrum of OFDM, and Fig.4 is the spectrum of OFDM with noise. It is obviously that, Fig.4 enhanced the anti-noise result. From the complexity of algorithm, not increase the computational complexity because of the selected sub-carriers is linear with original OFDM signals.

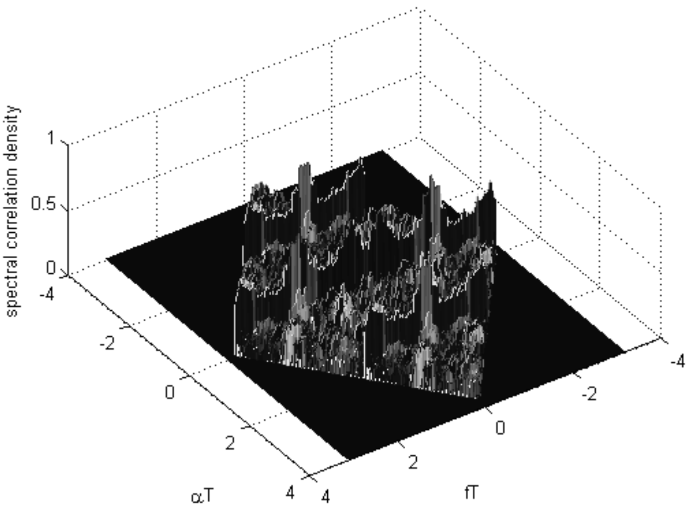

Figure 3. Cyclic Spectral of Improved OFDM Signal

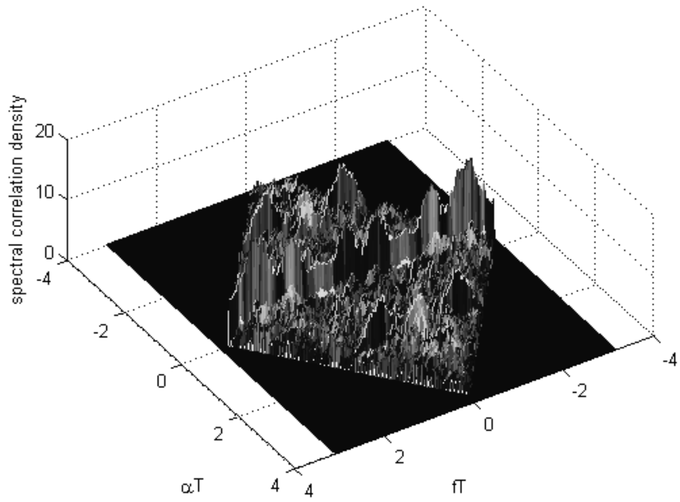

Figure 4. Cyclic Spectral of Improved OFDM Signal with Noise

5. Detection Performance Analysis

Defining detection probability P_D and false alarm probability P_{FA} [13]

$$\begin{cases} P_D = \Pr\left(\text{cyclic spectrum } S_{ss}^{\alpha}(f)\text{ has been detected} \middle| \text{cyclic spectrum } S_{ss}^{\alpha}(f)\text{ existence}\right) \\ P_{FA} = \Pr\left(\text{cyclic spectrum } S_{ss}^{\alpha}(f)\text{ has been detected} \middle| \text{cyclic spectrum } S_{ss}^{\alpha}(f)\text{ inexistence}\right) \end{cases} \quad (18)$$

According to the central limit theory, received signals from primary users can be considered complex Gaussian process in the cognitive radio node. Simultaneously, the received signals have been interfered by Gaussian white noise with zero mean.

The spectrum located zero cyclic frequency can be detected by energy detector, in other words, energy detector main detecting energy spectrum of existence on non-cyclic frequency. However, in the process of cyclic feature detection, in addition to detecting the spectral existence problem at zero cyclic frequency, but also to detecting the spectral whether or not existing at cyclic frequency. As we all know, noise does not exist cyclic spectral. So, energy detection method for detecting signals mixed noise. In the cyclic feature detection process, mainly detecting signals at cyclic frequency which does not existing noise. This section mainly discussed the cyclic-feature detection method.

At the zero cyclic frequency, cyclic feature detection scheme is similar with energy detection scheme. Proposed a binary hypothesis testing problem as following [13-15]:

$$\begin{cases} D\left(Y_{H_0}\right)\Big| f_0 \sim N\left(\sigma^2, 2\sigma^4 / N\right) \\ D\left(Y_{H_1}\right)\Big| f_0 \sim N\left(\mathrm{P}+\sigma^2, 2\left(\mathrm{P}+\sigma^2\right)^2 / N\right) \end{cases} \quad (19)$$

Where $D\left(Y_{H_0}\right)| f_0$ represents decision variable of zero cyclic frequency and no noise, $D\left(Y_{H_1}\right)| f_0$ denotes decision variable of zero cyclic frequency and have noise. $\sim N(\cdot)$ indicates a variable of Gaussian distribution. P represents signals average power, σ^2 is signals variance. According to the definition of signal detection and estimation [13], signal detection probability and false alarm probability can be derived as

$$\begin{cases} P_D = Q\left(\dfrac{\gamma - \left(\mathrm{P} + \sigma^2\right)}{\sqrt{2/N}\left(\mathrm{P} + \sigma^2\right)} \right) \\ P_{FA} = \Pr\left(D\left(Y_{H_0}\right) | f_0 > \gamma \right) = Q\left(\dfrac{\gamma - \sigma^2}{\sqrt{2/N}\sigma^2} \right) \end{cases} \tag{20}$$

In (20), γ represents decision threshold, $Q(\cdot)$ is the standard Gaussian complementary cumulative distribution function (CDF), N denotes signal sampling number. Simplification public variable γ and derived next expression

$$N = 2\left[Q^{-1}\left(P_{FA}\right) - Q^{-1}\left(P_D\right)\left(1 + SNR\right) \right]^2 SNR^{-2} \tag{21}$$

Where $Q^{-1}(\cdot)$ represent the inverse transformation of standard Gaussian complementary cumulative distribution function, SNR is the ratio of signal power with noise power. From (21) can show that if noise power σ^2 perfectly known, communication signal can be detected even though SNR is small enough, as long as N is large enough. Fig.5 is numerical result of (21)

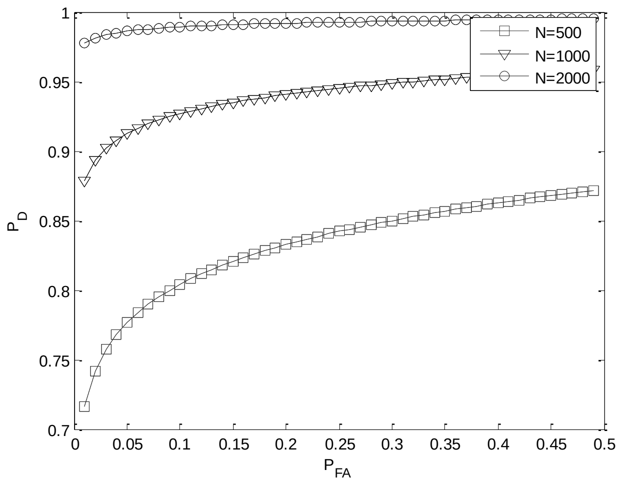

Figure 5. ROC Curves of P_{FA} and P_D

In Figure 5, $SNR = 0.1$, expressed in dB as $\mathrm{snr} = 10\lg(SNR) = -10\left(\mathrm{dB}\right)$, $P_{FA} \in \left(0, 0.5\right)$. As N increases, detection performance improved significantly. When signal sampling number $N = 2000$, false alarm probability $P_{FA} = 0.1$, detection probability approaching 98%.

Previous section discussed the spectral detection problem at zero cyclic frequency only, which is the same with energy detection. Next part will discuss the spectral detection at cyclic frequency. Model as following

$$\begin{cases} D\left(Y_{H_0}\right)\Big| f_0 \sim N\left(\sigma^2, 2\sigma^4 / N\right) \\ D\left(Y_{H_1}\right)\Big| f_0 \sim N\left(\mathrm{P} + \sigma^2, 2\left(\mathrm{P} + \sigma^2\right)^2 / N\right) \\ D\left(Y_{H_1}\right)\Big| f_i \sim N\left(\mathrm{P}, 2\mathrm{P}^2 / N\right) \end{cases} \tag{22}$$

In (22), $D\left(Y_{H_1}\right)\big| f_i, i = 1, 2, 3, \cdots$ represents decision variable of the i th cyclic frequency and where noise spectral is nonexistence, in other words, noise does not exist cyclic spectrum. Therefore, only signal spectrum can be detected at i th cyclic frequency. Signal detection probability and false alarm probability can be derived as

$$\begin{cases} P_D = Q\left(\dfrac{\gamma - \mathrm{P}}{\sqrt{2/N}\mathrm{P}}\right) \\ P_{FA} = \Pr\left(D\left(Y_{H_0}\right) \mid f_0 > \gamma\right) = Q\left(\dfrac{\gamma - \sigma^2}{\sqrt{2/N}\sigma^2}\right) \end{cases} \tag{23}$$

Similarly, simplification public variable γ and derived next expression

$$N = 2\left[Q^{-1}\left(P_{FA}\right) - Q^{-1}\left(P_D\right)SNR\right]^2\left(SNR-1\right)^{-2} \tag{24}$$

In the case of same value of the three variables and respectively SNR 、 P_{FA} and P_D. Compared (21) with (24), if SNR valued relatively small, such as $1 \pm SNR \approx 1$, so SNR^{-2} □ $\left(SNR-1\right)^{-2}$. In the two expressions, SNR and $\left(1+SNR\right)$ almost no obvious change to formula result according to $Q^{-1}\left(P_D\right)$ mathematics characteristics. Therefore, result of (24) is much smaller than (21). Improved algorithm shorten detection time in the case of ensure detection performance.

Figure 6 is the numerical ROC results of cyclic feature detection and parameters value as previous section. E.g., $SNR = 0.1$, expressed in dB as $\mathrm{snr} = 10\lg(SNR) = -10\left(\mathrm{dB}\right)$, $P_{FA} \in \left(0, 0.5\right)$. Compare Fig.6 and Fig.5, in the case of same detection performance. If $P_{FA} = 0.1$, then $P_D \approx 0.98$, so $N \approx 20$. Therefore, detection time is reduced by about two orders of magnitude. It shows that cyclic spectrum detection algorithm significantly better than energy detection scheme.

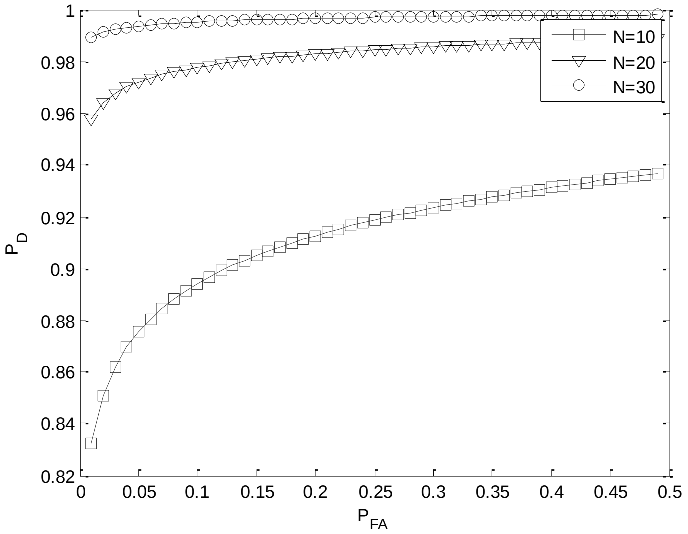

Figure 6. ROC Curves of P_{FA} and P_D

Figure 7 is numerical ROC results of improved cyclic feature detection and the same value of signal sampling number. $SNR = 0.01$, expressed in dB as $\mathrm{snr} = 10\lg(SNR) = -20\left(\mathrm{dB}\right)$. If $N = 30$ and $P_{FA} = 0.1$, then $P_D \approx 1$. As the decreasing of signal sampling number, detection performance deteriorated significantly. However, detection performance is still very good. Comparing Figure 7 with Figure 6, when signal sampling number unchanged. In the case of SNR low an order of magnitude, e.g., 0.01 is lower than 0.1 an order of magnitude. Detection performance of improved Algorithm is still better than Figure 6. Algorithm improves the robustness of weak signal detection.

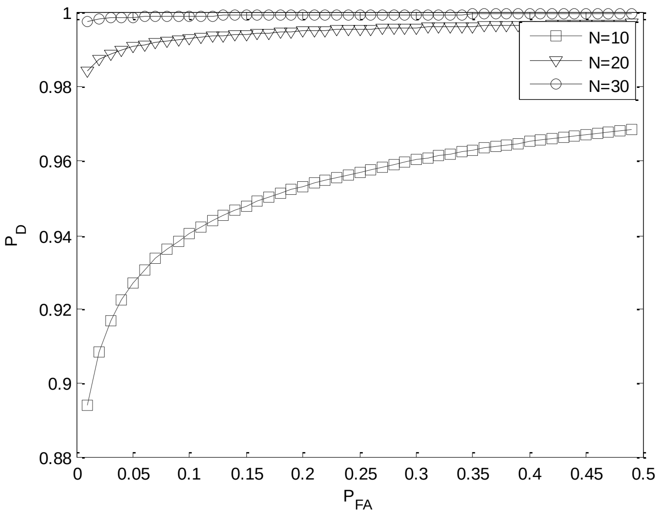

Figure 7. ROC Curves of P_{FA} and P_D

In this section, focus on discussing the detection performance of cyclic feature spectrum detection. From numerical result can be drawn following conclusions. Firstly, the cyclic feature detection algorithm of zero cyclic frequency has been discussed. When signal noise ratio $SNR = 0.1$, signal sampling number $N = 2000$ and false alarm probability $P_{FA} = 0.1$, then detection probability approaching 98% . Secondly, paper discussed cyclic feature detection algorithm of non-zero cyclic frequency. Parameters value as first condition, signal sampling number $N = 30$ and much smaller than $N = 2000$, however, detection performance $P_D \approx 1$ and cyclic spectrum detection algorithm significantly better than energy detection scheme. Thirdly, improved cyclic feature spectrum detection scheme has been studied and numerical simulated. Consistent with the conclusion of section four that improved the robustness of ant-noise interference.

In summary, when overlay parts sub-carriers on OFDM signals, simultaneously keeping power of transmitting consistent, however, sacrifice a little computational complexity. Improved algorithm can enhance detection performance obviously and has a good robustness of ant-noise interference. Novel method improved the robustness of detecting weak signals.

6. Conclusions

In this paper, a novel cyclic feature spectrum detection scheme has been proposed. In the detection processing, overlay parts sub-carriers on OFDM signals and superimposed signals come from original cyclic feature OFDM signals. This algorithm has a high success rate of detecting and a shorten detection time, at the same time, computational complexity is almost no change. Simulation results show that detection performance has been improved even if SNR lower an order of magnitude than original algorithm, prerequisite is to keep detection time consistent. From theory analysis results, cyclic spectral contour figures and detection performance curves analyze results can be drawn conclusion that novel algorithm improved detection performance and enhanced the effectiveness of anti-noise uncertainty and improved the robustness of detecting weak signal. Algorithms meet the spectrum detection technology requirements of low SNR environment.

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