Analysis of the Classical Spectrum Sensing Algorithm Based on Transmitter

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Abstract. Spectrum sensing technology is implemented in cognitive radio spectrum, the basis of switching, spectrum management and spectrum sharing is the precondition of effective, reliable, wireless communication, the spectrum sensing algorithm based on sending and have energy detection, matched filtering test and cyclic stationary test three classical algorithms, detailed description of the classical algorithm, and through the simulation to compare the performance of three algorithms, put forward the suitable application scenario, provide some reference for researchers of the algorithm.

Keywords: Double threshold · Energy detection · Performance analysis

1 Introduction

Spectrum sensing technology is the basis for realizing spectrum switching, spectrum management and spectrum sharing in cognitive radio communication, and the prerequisite for effective and reliable wireless communication. Therefore, it is of great significance to carry out research on this aspect for the application and development of cognitive radio technology. The main task of the spectrum sensing process is to detect the spectrum hole through monitoring the use of spectrum resources, so as to provide the basis for cognitive users in the cognitive wireless network to be waiting for access to the idle frequency band, timely and accurate spectrum sensing information, and effectively avoid interference to the authorized users. On the premise of not affecting the communication of authorized users, cognitive users also realize the communication of information through the frequency band, so as to realize the sharing of spectrum resources. The perceived quality of the visible spectrum determines whether the spectrum resources can be utilized efficiently and directly determines the overall performance of the wireless communication network. Usually, in the study of spectrum perception, the key research issues include the design of the perception algorithm, which can realize the fast and efficient detection of spectrum information through algorithm research and improvement. The multi-user cooperative spectrum sensing strategy is studied so as to effectively solve the hidden terminal problem, make efficient use of multi-user data information, and realize spectrum detection more reliably. A series of issues such as how to make tradeoffs between perceptual time selection and spectral transmission efficiency are studied.

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2 Classic Algorithms

According to the essence of spectrum perception, the spectrum perception problem can be transformed into the signal processing problem, so as to build the detection model. Spectrum perception completes the process of cognitive users to judge whether there is an authorized user signal in the frequency band that they are interested in from the received signals. At present, it is representative of Energy Detector (ED), matching Filter Detector (MFD), cycle-stationary Feature Detector (CFD), and so on [1].

In the cognitive radio network, the perception algorithm based on transmitter is mainly centered on the transmitter. The cognitive users in the network detect the authorized user signal information, and decide whether the frequency band is available or not according to the existence or not. The detection model is as follows:

$$y(t) = \begin{cases} n(t), & H_0 \\ hx(t) + n(t), & H_1 \end{cases} \tag{1}$$

Among them,

$y(t)$—Cognitive users receive signal information;
$x(t)$—Primary User information;
$n(t)$—Additive white gaussian noise;
h—Channel amplitude gain;
H_0—Only under noise conditions;
H_1—There are Primary User conditions.

2.1 Energy Detection

Energy detection is a relatively simple signal detection method, and its detection principle is shown in Fig. 1. The essence of energy detection is to realize the purpose of spectrum detection by measuring the energy of a signal on the frequency band and setting specific energy threshold value. If the frequency band is reached or exceeded, it is considered that the frequency band has been occupied. In the energy detection, the input signal is filtered through the front filter, and then after the transformation through A/D, the modulus and square of the input signal can be obtained. Alternatively, the time domain information can be converted to the frequency domain, that is, the received signal is filtered by the front filter, followed by the n-point FFT transformation, and then the modulus square of the frequency domain signal is obtained to obtain its energy value. Energy detection is the energy accumulation in a certain frequency band, that is, through the sum of N samples, the detection statistics are obtained. Then judgment is made through the judgment unit. If it is lower than the specific threshold value, the signal does not exist but only noise. If the detection statistic is higher than the set judgment threshold, the judgment signal exists [2].

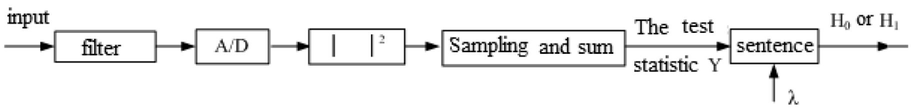

Fig. 1. Energy detection principle

In the above energy detection method, the judgment statistic Y can be expressed as

$$Y = \begin{cases} \chi^2_{2TW}, & H_0 \\ \chi^2_{2TW}(2\gamma), & H_1 \end{cases} \tag{2}$$

$\chi^2_{2TW}(2\gamma)$—The judgment statistics is subject to 2γ non-central chi-square distribution of 2TW;
χ^2_{2TW}—The central chi-square distribution of the statistic Y obeying degree of freedom is 2TW;
TW—Time and bandwidth product;
γ—SNR.

The method of energy detection is simple and easy to implement, and the theoretical technology has been very mature. At present, it is widely studied and discussed in signal detection, and various improved algorithms of energy detection have been derived. However, in the case of low signal-to-noise ratio (SNR), the authorized user's signal is very weak, which is usually submerged in noise. In addition to the impact of noise variance uncertainty, the performance of the energy detection algorithm is very poor [3]; Moreover, according to the basic model of energy perception, energy detection can only distinguish the existence of authorized users, and information such as the form of transmitting signals and the type of authorized users cannot be obtained.

2.2 Matched Filter

When the cognitive user knows the prior information of the authorized user signal, the input signal and the transmitting signal are multiplied by the multiplier, and the sampling judgment is used to obtain the test statistics, and then the judgment is compared with the specific threshold. In essence, the matched filter detection method is a coherent detection algorithm, which is the optimal linear filter with the maximum output signal-to-noise ratio and the maximum signal-to-noise ratio of the received signal [4]. Matching filtering detection is a common method in signal detection [5], and its block diagram is shown in Fig. 2.

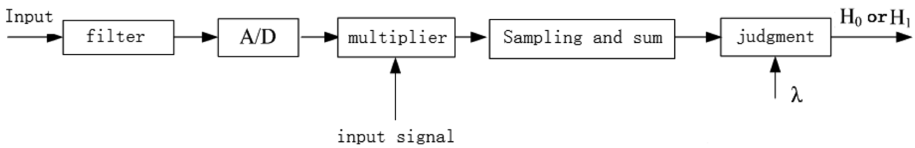

Fig. 2. The principle of matched filtering detection

If the input signal of the matched filter is

$$r(t) = s(t) + n(t) \tag{3}$$

Among them, $s(t)$ is PU, $n(t)$ is additive white Gaussian noise. Let's say that $s(t)$ and $n(t)$ are independent. After the input signal is prefiltered, A/D transformation is performed, and then the statistic Y is detected by multiplying the original transmitting signal and the received signal sampling:

$$Y = \sum_{n=0}^{N-1} r(n)s(n) \tag{4}$$

$r(n)$—$r(t)$ The received signal sequence obtained after sampling N points;
$s(n)$—$s(t)$ The sequence of transmitting signals obtained after sampling N points;
N—Sampling spot number.

Test statistics achieve the judgment by comparing with the set threshold value λ. When the threshold value λ is greater than, the judgment is "1", indicating the existence of the authorized user; otherwise, the judgment is "0", indicating that the authorized user does not exist.

The matching filtering detection algorithm adopts the coherent detection technology, which can achieve the advantages of relatively less time required for higher processing gain, and it can be known through theoretical derivation that the algorithm can maximize the output SNR [6]. But needs to know that originated in the process of implementation of correlation detection signal of a priori information, a priori information is accurate or not directly decides the matched filtering performance of detection algorithm, and the matched filtering detection algorithm implementation process is very high to the requirement of phase synchronization, synchronization technology must be used when using even equalization to meet the requirements, the process complexity is high, not easy to achieve.

2.3 Cycle-Stationary Feature Detection

In radio communications, the transmission of a signal is usually modulated. If the signal of the authorized user is modulated, the corresponding information will be pulse sequence, carrier, repetitive extension and cyclic prefix. This characteristic makes the modulated signal inherently periodic [43]. The so-called cyclic stability characteristic refers to the authorized user signal after modulation. Its mean value and autocorrelation function are both periodic. We can apply this characteristic by analyzing the spectral correlation function. The most important characteristic of the spectral correlation function is that the energy of the modulated signal can be separated from the energy of the noise signal. It is because the modulated signal correspondingly has inherent periodicity and spectral correlation, while the noise signal, because it is a broadband and static signal, has no intrinsic correlation. In this case, its periodic moment or periodic cumulative quantity or periodic cycle spectral value is zero. According to this characteristic, it can decide whether the authorized user information exists [7].

The cyclic stationary signal feature detection can overcome the shortcoming of energy detection and is little affected by the signal signal-to-noise ratio. The mutual interference between signals can also be eliminated through the circular stationary signal processing [8]. If the mean value $A_x(t) = E[x(t)]$ of a random process is a periodic function, we call it a first order cyclic stationary process. The mean value of a cyclic stationary process can be expressed as:

$$A_x(t) = \sum_{n=-\infty}^{\infty} A_x^{\alpha} e^{j2\pi\alpha t} \tag{5}$$

Among them, $\alpha = m/T_0$, T_0 is the period of the mean, A_x is the Fourier series coefficients and its calculation formula:

$$A_x(t) = \frac{1}{T_0} \int_{-T_0/2}^{T_0/2} A_x(t) e^{j2\pi\alpha t} dt \tag{6}$$

If $x(t)$ is a non-stationary complex exponential signal whose mean is zero, and its mean Fourier series expansion does not satisfy Eq. (5). If the correlation function $R_x(t,\tau)$ is a periodic signal, then x(t) is a second-order stationary process [9]. The correlation function of the random process is shown in formula (7).

$$R_x(t,\tau) = E\{x(t)x * (t-\tau)\} \tag{7}$$

Let me write it in terms of the average of time:

$$R_x(t,\tau) = \lim_{N\to\infty} \frac{1}{2N+1} \sum_{n=-N}^{N} x(t+nT_0)x * (t+nT_0-\tau)\} \tag{8}$$

Where N is the number of data. The periodic correlation functions $R_x(t,\tau)$ are continued to be carried out for Fourier series expansion, as shown in formula (9).

$$R_x(t,\tau) = \sum_{n=-N}^{N} R_x^{\alpha}(\tau) e^{j2\pi\alpha t} \tag{9}$$

Among $\alpha = m/T_0$, T_0 is the relevant cycle. The Fourier coefficients of the Fourier series is

$$R_x^{\alpha}(\tau) = \frac{1}{T_0} \int_{-T_0/2}^{T_0/2} R_x(t,\tau) e^{-j2\pi\alpha t} dt \tag{10}$$

So:

$$R_x^{\alpha}(\tau) = \lim_{T_0 \to \infty} \frac{1}{T_0} \int_{-T_0/2}^{T_0/2} x(t)x*(t-\tau)e^{-j2\pi\alpha t}dt = <x(t+\frac{\tau}{2})x*(t-\frac{\tau}{2})e^{-j2\pi\alpha t}>_t \quad (11)$$

The Fourier coefficient in the corresponding Fourier series expansion represents the cyclic autocorrelation intensity of the loop frequency α, which is a function of phi, or the cyclic autocorrelation function for short. The autocorrelation function of the signal achieves coherent accumulation at different cyclic frequencies, and achieves or is nearly identical in phase, thus causing the cyclic spectrum of the input signal to appear spectral peak at some cyclic frequencies [9]. Fourier transform is applied to the cyclic autocorrelation function, so

$$S_x^{\alpha}(f) = \int_{-\infty}^{\infty} R_x^{\alpha}(\tau)e^{-j2\pi f\tau}d\tau \quad (12)$$

$S_x^{\alpha}(f)$ is the cyclic spectral density function. According to the above analysis, for stationary noise, it can be completely suppressed through cyclic spectrum, and for all kinds of non-stationary noise, as long as the periodic frequency of the signal and the periodic frequency of noise are different, it can be separated in the circular spectrum plane.

Rewrite Eq. (11) as follows:

$$R_x^{\alpha}(\tau) = <x(t+\frac{\tau}{2})e^{-j2\pi\alpha(t+\tau/2)}x*(t-\frac{\tau}{2})e^{-j2\pi\alpha(t-\tau/2)}>_t \quad (13)$$

$$\begin{cases} u(t) = x(t)e^{-j2\pi\alpha t} \\ v(t) = x(t)e^{j2\pi\alpha t} \end{cases} \quad (14)$$

The Fourier transform of the above formula is given

$$\begin{cases} U(f) = X(f+\alpha/2) \\ V(f) = X(f-\alpha/2) \end{cases} \quad (15)$$

Then, $R_x^{\alpha}(\tau) = R_{uv}(\tau) = <u(t+\frac{\tau}{2})v*(t-\frac{\tau}{2})>_t$, $u(t)$ is related to $v*(t)$. From a frequency domain perspective, the Fourier transform of $R_x^{\alpha}(\tau)$ can be expressed as the correlation of the spectrum of the signal up and down by the translation of the common component of $\alpha/2$ [12]. Therefore, the cyclic power spectral density function is also called spectral correlation function. However, the general noise signal does not have this cyclic stationary characteristic, so it is easy to distinguish the interference from the signal by using this difference, and extract the cyclic stationary signal information. The detection of cyclic stationary feature is based on this principle.

The spectrum sensing method based on cyclic spectral correlation detection USES the periodicity of the signal's autocorrelation function to detect the idle spectrum. Although it has the advantage of being able to distinguish between authorized user signals and interference signals, and is less affected by the uncertainty of noise variance, in some complex conditions, it can not distinguish between signals and noises through the periodicity of second-order statistics of cycle spectrum. In this context, high-order cycle statistics have been extensively studied. This is due to the strict cyclic stationarity of higher-order cyclic statistics, complete separation of stationary and circular stationary signals, effective suppression of any noise, and better receiver operating characteristic curve (ROC) [51]. Therefore, the theory of asymptotic optimization is used to construct the hypothesis testing model and test statistics of higher-order cyclic statistics [13], and the use of the higher-order cyclic statistical characteristics of authorized user signals to carry out spectrum perception is a hot research topic in recent years.

3 The Simulation Analysis

Energy detection, matched filtering detection and cyclic stationary feature detection are three classic non-cooperative sensing technologies based on receiver detection. Below is the additive gaussian white noise environment, $SNR = -15$ dB, the algorithm performances are simulated. Figure 3 shows the ROC performance simulation curves of these three classic perception technologies.

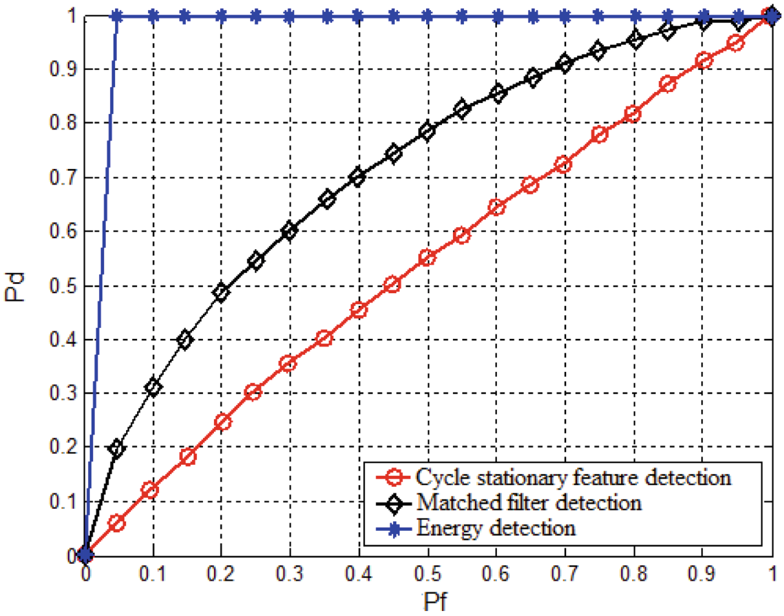

Fig. 3. SNR = 15 dB three classic ROC performance comparison of test method

It can be found from the figure that, for performance, the matched filter detection is obviously better than the energy detection and cyclic stationary detection methods, but in the process of implementation, because the matched filter detection requires to know a large amount of prior information of authorized users, which greatly limits its practical application in the cognitive radio system. In the simulation, an ideal energy detection model with assumed noise power is adopted. In this case, the energy detection performance is superior to the ordinary cyclic stationary detection.

4 Conclusion

The energy detection method is a nonuniform detection which simplifies the matching filter. The most remarkable feature of it is simple structure, easy to implement, good practicability, and energy detection does not need prior information of detection signal, so it has better universality. However, in the case of low signal-to-noise ratio (SNR), the detection time needs to be increased to improve the detection performance. In other words, the number of samples should be increased, but the complexity is also increased. Furthermore, the threshold value of energy detection is easily subject to noise fluctuation and cannot be determined accurately. For example, it will be difficult to set the threshold under the weak channel, and the detection performance is greatly affected by noise variance uncertainty. Moreover, the energy detector is not suitable for detection under broadband signal conditions, and more sophisticated signal processing methods should be developed for these signals. The ideal way to detect any signal is to match the filter, as its output SNR is maximized. However, for the matched filter to work effectively requires correct demodulation of the authorized user signal, which means that cognitive radio requires prior information of the authorized user signal at the physical and MAC levels. As described in the detection method, the signal is assumed to be known and a matching filter is constructed from the signal. But the inflexible part is that demodulation requires timing and carrier synchronization or even channel balancing to be consistent with the authorized user. If the prior information obtained is not accurate enough, the accuracy of the result of the matched filter detection will be greatly affected. The main advantage of a matched filter is that it takes very little time to achieve a high processing gain. However, one of its biggest drawbacks is the prior information needed to authorize users. Most of the modulating signals have the characteristics of stable circulation, so the cyclic power spectrum characteristic detection has the identifiability, and can extract the signal from the noise background. Considering that energy detection is susceptible to noise variance uncertainty, compared with energy detection, the detection performance of cyclic stationary feature is superior to energy detection in the case of low signal-to-noise ratio. This shows the anti-noise property of cycle stationary feature detection. But at the same time, the computational complexity is higher and the detection time is longer.

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