A Spectral Correlation Based Detection Method for Spectrum Sensing in Cognitive Radio

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ABSTRACT

Cognitive radio, which is designed to dynamically adapt its transmission to the environments, is believed to be one of the fundamental techniques for future spectrum utilization. As the first step of cognitive radio, spectrum sensing is treated as the most important technique, through which cognition is well explained. In this paper, we propose a spectral correlation based detection method for spectrum sensing. An unlicensed secondary user system operating in TV broadcast bands is taken as an example. Based on the cyclostationarity of communication signals, spectral correlation function is used to minimize the effect of random noise and interference. Energy measurement and peak detection based criteria are proposed. Simulation results show that the proposed detection method outperforms the energy detection and is more suitable for spectrum sensing in cognitive radios.

Key Words : cognitive radio, spectrum sensing, cyclostationary, spectral correlation, spectral coherence function

Ⅰ. Introduction

Nowadays, as the technology developed, our limited spectral resources have been used sufficiently, especially the frequency below 3GHz. But not all of them are used efficiently. Actual measurements show that most of the allocated spectrum is vastly underutilized at any specific location and time[1]. This point of view is also supported by the studies of the FCC's (Federal Communication Commission) Spectrum Policy Task Force who reported vast temporal and geographic variations in the usage of allocated spectrum with utilization ranging from 15% to 85%[2]. Under this circumstances, spectrum deregulation is a necessary step in the future for increasing spectrum efficiency. Cognitive radio is proposed as a candidate solution to scavenge the idle spectrum[3]. It is an intelligent wireless communication system that is aware of its surrounding environment, and dynamically adapt its operating parameters in real-time to realize highly reliable communications whenever and wherever needed with efficient utilization of the radio spectrum[4]. Although the concept of cognitive radio seems to be an optimum solution, two problems are still unpredictable which cause the uncertainty of regulators. First, can practical cognitive system even operate without causing excessive interference to legacy users? Second, can useful wireless systems operate under these constraints? Well-designed spectrum sensing method gives a reliable solution to these questions. Spectrum sensing is a procedure to learn the spectrum environments and find the available bands for secondary user.

In this paper, we present a spectrum sensing method with which the transmissions of secondary user are guaranteed while the interference to the

※ 본 연구는 한국과학재단 국가지정연구실사업(M10600000019406)의 일환으로 수행되었습니다.
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논문번호 : KICS2006-05-218, 접수일자 : 2006년 5월 19일, 최종논문접수일자 : 2006년 7월 1일

primary user is minimized. After a brief review of cognitive radio and spectrum sensing, a description of our model is shown in the second part. The fundamental knowledge used in this paper which is called cyclostationary theory is reviewed in part three. Based on the spectral correlation property of cyclostationary signal, our proposed method is detailed in part four. Two detection criteria are also discussed and analyzed for the proposed method. In order to verify the performance of the proposed method, conventional energy detection method is studied and simulated. Some simulation results are shown and analysed in part five. After that, some conclusions are drawn to finish the state of this paper.

Ⅱ. Detection Model for Spectrum Sensing

TV broadcast bands is considered as some of the most promising bands for unlicensed devices. The FCC has already released a Notice Of Proposed Rule Making exploring the operation of unlicensed devices on spatially / temporally "unused" television broadcast bands[5]. Currently, another kind of unlicensed devices which are Part 74 devices have already allowed to operate in these TV broadcast bands.

The term primary user in this paper denotes the user who operates in the TV broadcast bands. These primary users are TV users (Analog TV and Digital TV (DTV)) and Part 74 device users. As we all known, the transition from analog TV to DTV will be finished within a few years; therefore, we only consider DTV to represent TV users. Meanwhile, Wireless Microphone (WMP) is used to stand for Part 74 devices. As defined by FCC, the WMP users can use any kind of modulations with bandwidth equals 200 kHz. Considering that most of the WMP users use the amplitude and frequency based modulation techniques, AM and 4-FSK modulated signals are used. Here we show the spectrum of the primary user signals which will be discussed in this paper.

Spectrum sensing which relies on the detection

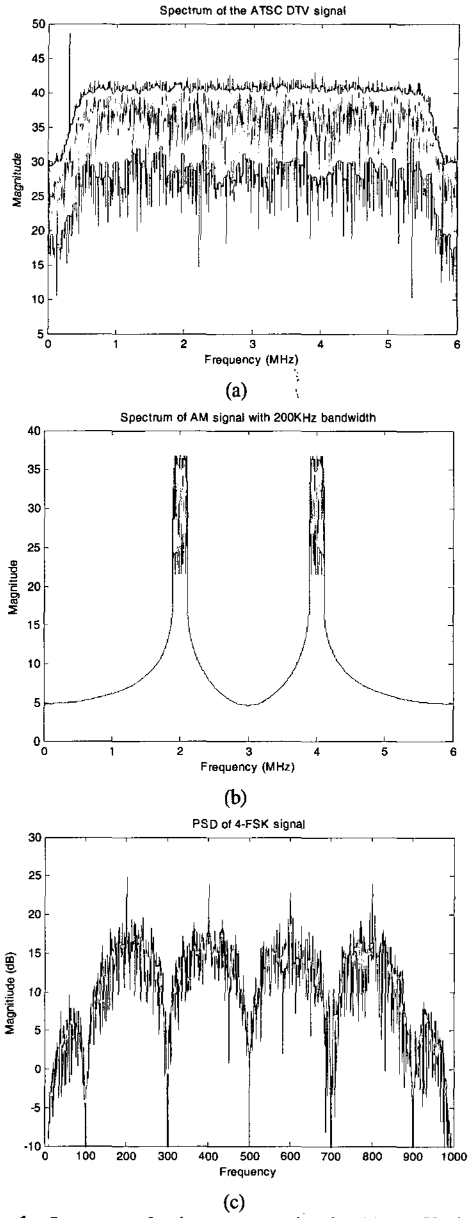


Fig 1. Spectrum of primary users signals: (a). DTV signal (b). AM signal (c). 4-FSK signal

technique is a procedure to search the empty frequency bands for secondary users. As there is no designated frequency bands for secondary users, the detection procedure is essential for the success of cognitive radios.

Technically, spectrum sensing is a simple binary hypotheses detection test[6]. This two-hypotheses test is modeled as:

(1) H0: only noise in the received signals:

$$r(t) = n(t) \quad (1)$$

(2) H1 : noise plus message signals in the received signals:

$$r(t) = s(t) + n(t) \quad (2)$$

here r(t), n(t) and s(t) are defined as the received signals, noise and transmitted message signals, respectively.

Ⅲ. Conventional Method for Spectrum Sensing

Energy detection is one of the conventional methods for spectrum sensing. The classical energy detection was first proposed by Urkowitz in 1967[7]. The detection procedure is shown in figure 2. This energy detector consists of a noise pre-filter, a square law device and an integrator.

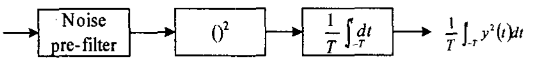


Fig 2. Block diagram of energy detection method

The noise pre-filter is used to keep the detected signal in the frequency band we desired which is the same as the TV band. During the detection interval, the energy of the received signal is measured by the energy detector which will be used to deicide whether this frequency band is empty. As the noise power increases, the energy of received signal also increases, therefore, the decision of spectrum sensing is interfered.

Ⅳ. Proposed Method for Spectrum Sensing

4.1 Cyclostationarity of Communication Signals

Generally, the signal of interest is modeled as a stationary random process. However, in most of the communication systems, the signal of interest can be treated as a cyclostationary random process instead. In appendix A, we review some basic knowledges of cyclostationary random process and define the spectral correlation function (SCF) as shown in (A-1). The spectral correlation of the primary signals are shown in figure 3.

As explained in section Ⅲ, cyclostationarity of signal shows us another way for signal detection.

Another motivation of implementing spectral correlation for signal detection lies on its robustness to random noise and interference as shown in figure 4. Spectral correlation of noise is significant

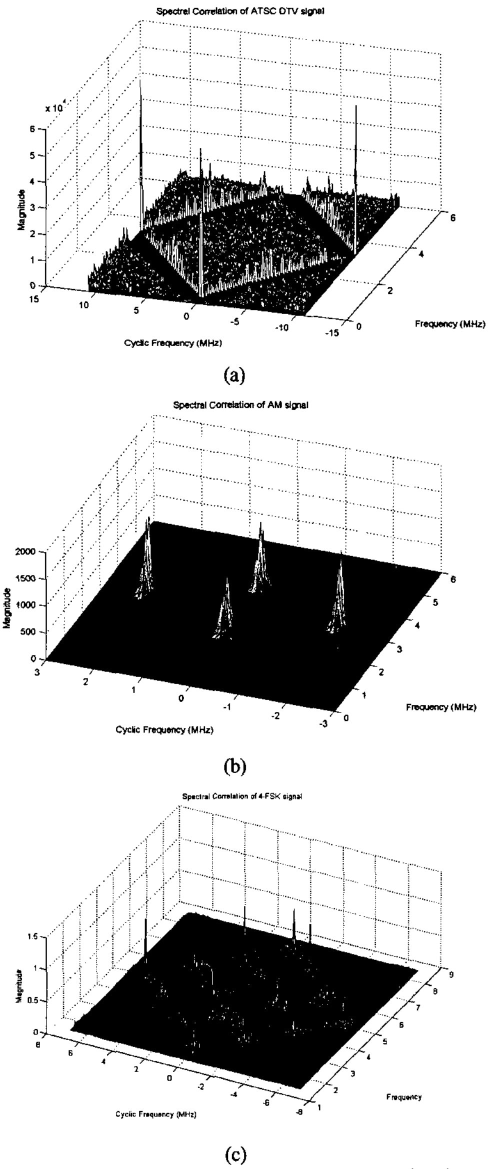


Fig 3. Spectral correlation of primary users signals. (a) AM signal (b) DTV signal (c) 4-FSK signal

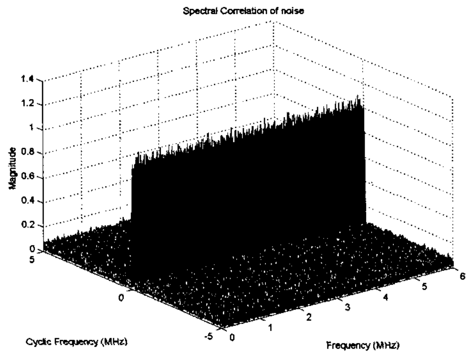


Fig 4. Spectral correlation of noise

large when cycle frequency equals to zero comparing to that of other values. This noise wall effect could be seen clearly at the zero cyclic frequency.

4.2 Proposed SCF Based Detection Method

In this paper, we propose an SCF based detection method under the innovation of cyclostationary theory. This proposed method is used to detect the primary signal in TV broadcast bands. The possible modulation types of WMP signal could be known by survey all the products of potential manufactures.

The block diagram of proposed method is shown in figure 5. The possible cycle frequencies of the received signal are known in the receiver. When spectrum sensing begins, the detector checks all the possibile cycle frequencies one cycle

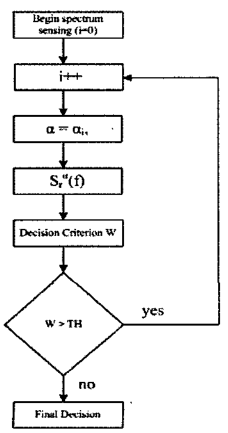


Fig 5. Detection Procedure of Proposed Method

by another.

After select the cycle frequency, the SCF is calculated based on the procedure shown in figure 5. A certain criterion (W) is calculated and is used to compare with a predefined threshold (TH). Then the decision about whether the cycle frequency belongs to the received signal can be made based on the comparison. After checking all possible cycle frequencies, a list of unique frequencies is compared to the theoretical values of different modulated signal to decide the modulation type of the received signal.

In the decision stage, we propose two criteria which are suitable in a single cycle frequency. First criterion is based on energy measurement in a individual cycle frequency, and is a statistic method. Second one is based on the peak characteristic of primary signals and is a deterministic method.

4.2.1 Energy measurement based criterion

After calculating SCF of the received signal in a individual cycle frequency αi, the energy in the frequency interval F is measured. This process is expressed in the following equation:

$$W=\sum_{i=1}^{F} S_r^2(f) \tag{3}$$

As the noise and interference level changes, the measured energy is a variable. Meanwhile, the spectral coherent function is defined as shown in (4) with two normalized factors[8]:

$$C_r^{\alpha_i}(f)=\frac{S_r^{\alpha_i}(f)}{\sqrt{S_r(f+\alpha_i/2)S_r(f-\alpha_i/2)}} \tag{4}$$

The square of this function is shown in (5). It is generally defined as the magnitude squared coherence function[9].

$$C_r^{\alpha_i^2}(f)=\frac{S_r^{\alpha_i^2}(f)}{S_r(f+\alpha_i/2)S_r(f-\alpha_i/2)} \tag{5}$$

Under hypotheses H0, the received signal are only noise, therefore the two terms in denominator can be treated as two independent Gaussian random process, and the probability distribution for $C_r^{\alpha^2}(f)$ is derived in[10]:

$$\Pr\{C< TH\}=1-(1-TH)^{N-1} \quad \text{for } 0 \le TH \le 1,\ N \ge 2 \tag{6}$$

Therefore, the corresponding false alarm probability for the proposed detection method is:

$$\Pr\{C< TH|H_0\}=1-(1-TH)^{N-1} \quad \text{for } 0 \le TH \le 1,\ N \ge 2 \tag{7}$$

Now, we can set our threshold for a desired false alarm probability independent of the input signal.

4.2.2 Peak detection based criterion

Another decision criterion is based on the peak characteristics of primary signals' SCF. As shown in figure 3, each primary user signal exhibits various peaks in its unique cycle frequencies. By checking the positions and numbers of these peaks in each possible cycle frequency, the unique frequencies of received signal can be determined. Take 4-FSK signal as an example, after checking all possible cycle frequencies, peaks are detected only on three of them as shown in figure 3(c). Then, the corresponding information is compared to the database, due to the unique cycle frequencies of different modulated signals, the detection decision can be made correctly. Considering the effect of random noise and interference, a threshold should be set in order to recognize the real peaks.

This is a deterministic criterion. Therefore, no statistic property could be gained like that of the previous used criterion. An advantage of this deterministic criterion is the extremely low false alarm probability and a outstanding performance in low SNR. As this is a strict criterion, the robustness to channel effect is low.

V. Simulation Results and Analysis

To verify the performance of proposed method, simulations are made under AWGN (Additive White Gaussian Noise). The spectral correlation based method is denoted by proposed method. Method 1 uses the energy measurement based criterion while method 2 uses the peak detection based criterion.

The ROC (Receiver Operating Characteristic) is considered as the main performance evaluation parameter for statistic detection method. ROC curves of energy detection and proposed method 1 are shown in figure 6 and 7, respectively.

As SNR increases, the detection performance gets better for both methods. However, in the low SNR which means noise power is much larger than signal power, the advantages of proposed method 1 is obviously. With 10% false alarm

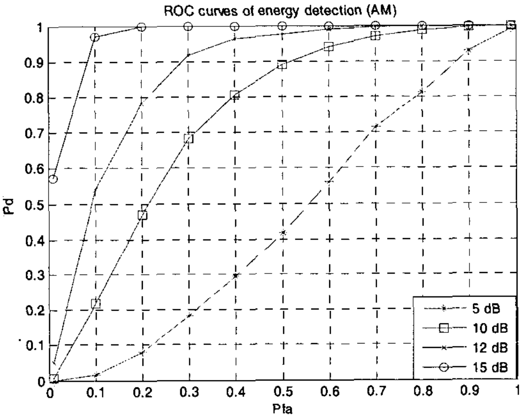


Fig 6. ROC Curves of energy detection of AM signal with different SNR levels.

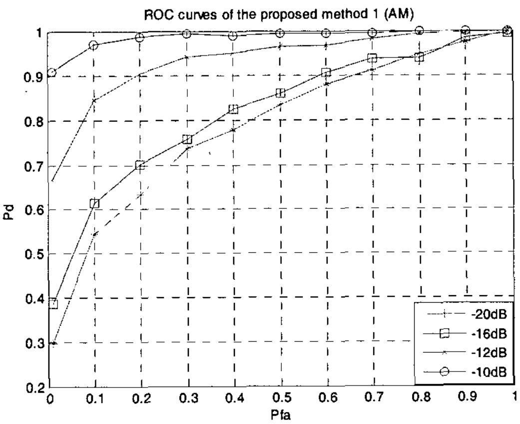
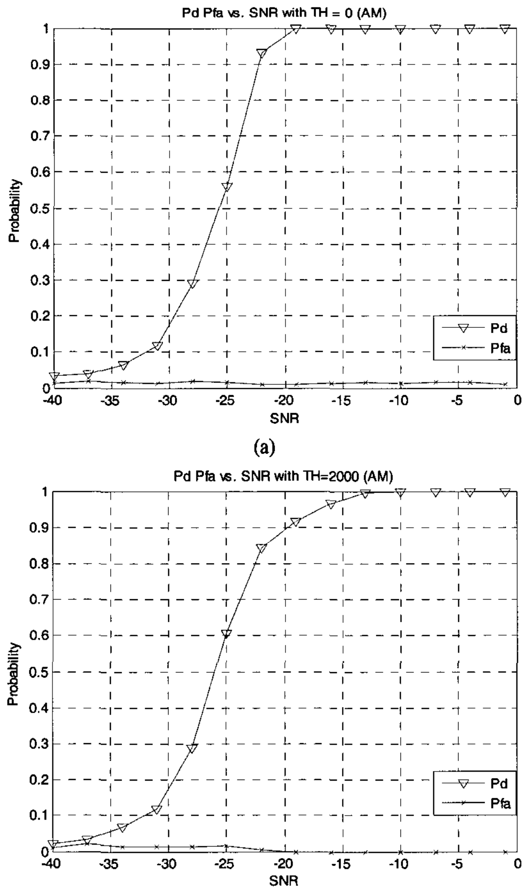


Fig 7. ROC Curves of proposed method1 of AM signal with different SNR levels.

probability and over 90% detection probability, gain of the proposed method 1 is more than 25dB.

In figure 8, the performances of proposed method 2 is shown. As it is based on a deterministic criterion, the detection and false alarm probabilities are shown as a function of SNR. Because the detection criterion of method 2 is mainly based on peak location, the false alarm probability is extremely low. By comparing the curves in figure 8, the threshold is only used to reduce the false alarm probability as the SNR level increases.

In figure 9 the detection probability of these three methods are shown. False alarm probability of statistic methods is set to 1%, because of the



(a)

(b)

Fig 8. Pd vs. SNR Curves of proposed method 2 of AM signal: (a). without threshold (b). with threshold

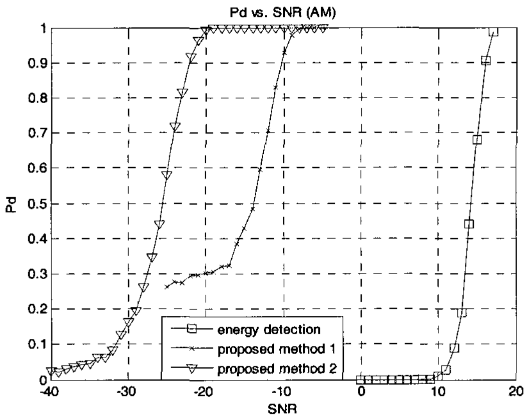


Fig 9. Pd vs. SNR Curves of AM signal with Pfa=0.01.

low false alarm probability of proposed method 2. As we predicted, both proposed methods outperform the conventional energy detection method for spectrum sensing.

Ⅵ. Conclusions

In this paper, spectral correlation based detection method is proposed for spectrum sensing in cognitive radio. As an example, a cognitive radio based secondary user system is assumed to operate in the TV broadcast bands. Spectrum sensing in these bands are carried out based on the proposed method. We proposed two detection criteria for detection. Both of them are analysed. The conventional energy detection method is studied as a comparison. Simulation results show that the proposed method outperforms the conventional energy detection method even in low SNR and it is believed to be more suitable for spectrum sensing in cognitive radio.

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Appendix A

A process, for instance X(t), is said to be cyclostationary in the wide sense if its mean and autocorrelation are periodic with some period, say T[11]:

$$m_X(t+T)=m_X(t) \qquad \text{(A-1)}$$

$$R_X\left(t+T+\frac{\tau}{2},t+T-\frac{\tau}{2}\right)=R_X\left(t+\frac{\tau}{2},t-\frac{\tau}{2}\right) \qquad \text{(A-2)}$$

$R_x(t+\tau/2,t-\tau/2)$, which is a function of two independent variables, t and τ, is periodic in t with period T for each value of τ.

The SCF which is also known as the cyclic spectral density function could be measured by the normalized correlation between two spectral components of x(t) at frequencies $(f+\alpha/2)$ and $(f-\alpha/2)$ over an interval of length Δt.

$$S^{\alpha}_{xT}(f)_{\Delta t}=\frac{1}{\Delta t}\int_{\Delta t/2}^{-\Delta t/2}\frac{1}{\sqrt{T}}X_T\left(t,f+\frac{\alpha}{2}\right)\cdot\frac{1}{\sqrt{T}}X_T^*\left(t,f-\frac{\alpha}{2}\right)dt \qquad \text{(A-3)}$$

In (A-3) the spectral of x(t) over the time interval [t-T/2,t+T/2] is defined by:

$$X_T(t,v)=\int_{-T/2}^{+T/2}x(u)e^{-j2\pi vu}du \qquad \text{(A-4)}$$

The ideal measurement of the SCF for the received signal x(t) is given by:

$$S^{\alpha}_{x}(f)=\lim_{T\to\infty}\operatorname{Lim}_{\Delta t\to\infty}S^{\alpha}_{xT}(f)_{\Delta t} \qquad \text{(A-5)}$$

In order to generate the SCF, the procedure in figure A-1 can be used.

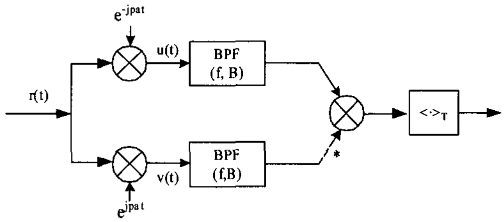

Fig A-1. Block diagram to generate spectral correlation function

The spectral correlation characteristic of the cyclostationary signals provides us a richer domain signal detection method. Different modulated signals have their unique cycle frequencies. Their unique cycle frequencies are obviously. We can accomplish the detection task by searching the unique cyclic frequency of different modulated signals. Also, information such as the carrier frequency, chip rate could be calculated according to the unique cyclic frequency.

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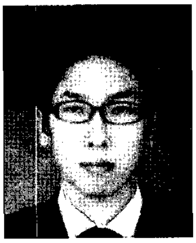

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