Performance Evaluation for the Two-Stage Cooperative Spectrum Sensing Scheme in Cognitive Radio

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Abstract: - In order to obtain more precise spectrum sensing performance in cognitive radio networks, a two-stage spectrum sensing approach is investigated. More specifically, a coarse spectrum sensing based on energy detection is introduced in the first stage. When the sensing decision is idle channel by coarse sensing, a fine spectrum sensing based on first order cyclostationary feature detection is exploited in the second stage. Moreover, the problem formulation and discussion of two-stage spectrum sensing is presented. Optimization algorithm is to maximize the throughput under the probability of error sensing constraint. Numerical results show that the sensing performance is improved significantly as opposed to conventional one stage spectrum sensing.

Key-Words: - cognitive radio; two-stage spectrum sensing; performance evaluation; energy detection; first order cyclostationary feature detection

1 Introduction

Due to the conflicts between spectrum congestion and spectrum under-utilization, cognitive radio (CR) has been recently considered as an efficient approach to improve the spectrum utilization via opportunistic spectrum sharing [1][2]. However, in order to avoid the interference to the primary user (PU), secondary user (SU) is considered to have the lower priority to the spectrum. Therefore, SU needs to sense the availability of spectrum before accessing the channel. Currently, spectrum sensing techniques mainly focus on primary transmitter detection and usually can be classified as matched filter, cyclostationary feature detection and energy detection. However, sensing techniques mentioned above have their own limitation in fact. More specifically, matched filter technique needs the prior information of PU; Cyclostationary feature detection technique has the higher complexity; Even though the energy detection is widely used currently, it has the weak performance in low signal-to-noise ratio environment.

To meet time and sensitivity requirement, a two-stage spectrum sensing (TSS) scheme is introduced which consists of coarse and fine sensing in IEEE 802.22 WRAN [3][4][5]. Henceforth, various two-stage spectrum sensing strategies have been investigated in many different contexts. Authors in [6] focus on different decision thresholds for two-stage sensing. Yue et.al in [7] takes first order cyclostationary feature sensing as fine sensing, the proposed approach is applied into the shading environment. Besides, two-stage sensing is also studied in the application of cooperative sensing in [8], the investigated approach is composed of hard information combing and soft information combing, but the only considered sensing technique is energy detection.

Recent years, there are still many scholars to study the two-stage spectrum sensing. A novel two stage spectrum sensing was proposed in [9], which is based on energy detection as coarse sensing first stage and combination of maximum-minimum eigen value based detection technique (CMME) as fine sensing second stage . Authors in [10] present the performance evaluation of seven spectrum sensing techniques including four single-stage spectrum sensing and three two-stage spectrum sensing for cognitive radio systems. Authors in [11] propose two novel schemes of two-stage spectrum sensing for cognitive radio under environment as noise power uncertainty. A new cooperative spectrum sensing (CSS) scheme with two-stage reporting is proposed in [12] so as to improve the throughput of SUs through reducing the reporting overhead. In the proposed scheme, the reporting process of the SUs is divided into two stages (a dedicated reporting stage and a contention-based reporting stage). A two-stage wideband spectrum sensing scheme is considered in [13] to proceed spectrum sensing with low time consumption and high performance to tackle this predicament. In this scheme, a novel multitaper spectrum sensing (MSS) method is proposed to mitigate the poor performance of energy detection (ED) in the low signal-to-noise ratio (SNR) region.

The main contributions of this paper are described as follows. First, two-stage sensing scheme is investigated. We focus on the precise of sensing performance in order to avoid the interference to the greatest extent. In special, first-order cyclostationary detection is taken for fine sensing due to lower complexity. Second, the problem formulation of two-stage sensing is presented. We are interested in maximizing the throughput under the probability of error sensing constraint. Last, using computer simulations, it is shown that optimizing problem of presented scheme significantly decreases the probability of error sensing.

The rest of this paper is organized as follows. System model of two-stage sensing is described in Section 2. Section 3 analyzes the sensing performance of energy detection and one-order cyclostationary feature detection which are performed for coarse and fine sensing, respectively. Two-stage spectrum sensing scheme is investigated and the problem formulation is discussed in Section 4. Performance evaluation of proposed approach is given in Section 5, and finally, conclusions are drawn in Section 6.

2 System model

The detection problem for spectrum sensing in cognitive radio networks can be formulated as a binary hypothesis. Therefore, the goal of spectrum sensing is to decide between the following two hypotheses,

$$\begin{cases} H_0 : x(t) = n(t) & 0 < t \le T \\ H_1 : x(t) = hs(t) + n(t) & 0 < t \le T \end{cases} \quad (1)$$

where T denotes the observed time. $x(t)$ is the received signal by SU, s(t) is the transmitted signal of the PU and h is the amplitude gain of the channel. $n(t)$ is a Gaussian random variable with zero mean and variance δ^2 in the Additive White Gaussian Noise (AWGN). H_0 denotes primary user is absent, H_1 denotes primary user is in operation.

Currently, the spectrum sensing usually is one stage sensing. We assume that the entire spectrum band is composed of an M-set of channels with equal-size bandwidth. The two-stage spectrum sensing scheme is shown in Fig.1. We assume that channels are to be sensed serially.

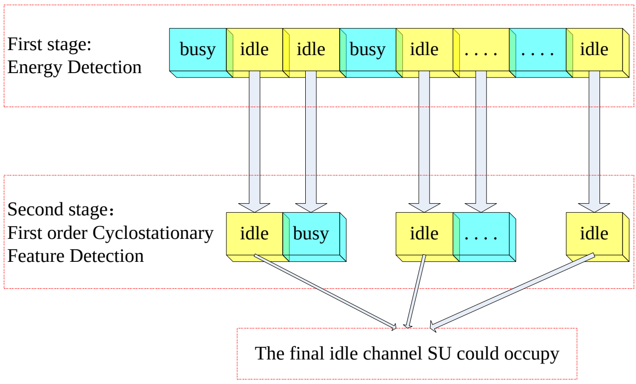

Fig.1 Two-Stage Spectrum Sensing Scheme

In Fig.1, yellow channel is taken as idle channel (unoccupied by PU) and blue channel means busy channel (occupied by PU). Considering PU's low power in fading environment, it is hard to detect after the first sensing based on energy detection. Therefore, in order to avoid the interference to PUs, we carry out the second stage sensing on idle channels after first stage sensing. In special, the fine sensing is performed by first order cyclostationary feature detection. After second stage sensing, final idle channels can be occupied by SUs.

3 Two-stage spectrum sensing

In this section, we first review the energy detection scheme for the coarse spectrum sensing. Then, the first order cyclostationary feature detection is discussed for the fine spectrum sensing. The probability of detection and the probability of false alarm of the coarse and fine spectrum sensing are given, respectively.

3.1 Energy Detection Technique

In cognitive radio networks, spectrum sensing is a key technique to improve the spectral efficiency. Therefore, there are amount of literatures for spectrum sensing nowadays. In particular, the work on detection of PU has generally exploited the energy detector for low computational complexity. Hence, we also carry out the energy detection for the coarse sensing in the two-stage sensing scheme. In the following, we will analyze the performance of energy detection technique.

Based on the binary hypothesis in (1) for the cognitive radio networks, the test statistic for the energy detector Y is given by

$$Y = \frac{1}{N}\sum_{t=1}^{N}\left|x(t)\right|^2 \tag{2}$$

where N is the sample point.

When N is larger enough, the output of energy detector Y follows the distribution as follows:

$$Y - \begin{cases} x_{2TW}^2 & H_0 \\ x_{2TW}^2(2\gamma) & H_1 \end{cases} \tag{3}$$

where χ_{2TW}^2 and $\chi_{2TW}^2(2\gamma)$ represent central and conditionally non-central chi-square distribution with *2TW* degrees of freedom, respectively. 2γ is a non-centrality parameter for the latter distribution. γ represents instantaneous signal to noise ratio (SNR) and for simplicity we assume that time-bandwidth product, *TW*, is an integer number which is denoted by *m*.

An approximate expression for the probability of detection P_{d_ED} and the probability of false alarm P_{f_ED} over AWGN in the energy detection can be given, respectively [14].

$$P_{d\_ED} = P(Y > \lambda \left| H_1\right.) = Q_m(\sqrt{2\gamma}, \sqrt{\lambda}) \tag{4}$$

$$P_{f\_ED} = P(Y > \lambda \left| H_0\right.) = \frac{\Gamma(m, \lambda/2)}{\Gamma(m)} \tag{5}$$

Where $\Gamma(a,x)$ is incomplete gamma function given by $\Gamma(a,x) = \int_x^\infty t^{a-1}e^{-t}dt$, $\Gamma(a)$ is the complete gamma function. $Q_m(a,b)$ is the generalized Marcum Q-function given by $Q_m(a,x) = \frac{1}{a^{m-1}}\int_x^\infty t^m e^{-\frac{t^2+a^2}{2}} I_{m-1}(at)dt$, $I_{m-1}(\cdot)$ being the modified Bessel function of the first kind and order *m*-1, and λ stands for decision threshold.

3.2 First Order Cyclostationary Feature Technique

According to most modulated signals are characterized as cyclostationarity since their mean and autocorrelation exhibit periodicity. Common analysis of cyclostationarity signal is based on autocorrelation function, however, we exploit the mean characteristics of the PU's signals to improve the efficiency of the channel sensing in time domain [7].

Therefore, we will analyze the sensing performance of first order cyclostationary feature detection over AWGN channels. We consider a deterministic complex sine signal *s(t)*, and it may be expressed as

$$s(t) = ae^{j(2\pi f_0 t + \theta)} \tag{6}$$

After the transmission of *s(t)* through an AWGN channel, *x(t)*=*s(t)*+*n(t)* denotes the received signal. The mean function of *x(t)* can be written as received signal,

$$M_x(t) = E\{x(t)\} = s(t) \tag{7}$$

For a particular threshold λ , the cumulative density functions (CDF) of the envelope of *M(t)* under different hypotheses over AWGN channel are given by (8), respectively.

$$\begin{cases} F(\lambda) = 1 - \exp\left(-\frac{\lambda^2}{2\delta_A^2}\right) & , \mathrm{H}_0 \\ F(\lambda) = 1 - \mathrm{Q}_1\left(\frac{\sqrt{2\gamma}}{\delta}, \frac{\lambda}{\delta_A}\right) & , H_1 \end{cases} \tag{8}$$

Where δ^2 denotes variance and $\delta_A^2 = \frac{\delta^2}{2N+1}$.

Under H_0, the probability of false alarm P_{f_CFD} can be evaluated as:

$$P_{f\_CFD} = P(M_x(t) > \lambda \left| H_0\right.) = e^{-\frac{\lambda^2}{2\delta_A^2}} \tag{9}$$

Similarly under H_1, the probability of detection P_{d_CFD} can be obtained as:

$$P_{d\_CFD} = P(M_x(t) > \lambda \left| H_1\right.) = Q_1\left(\frac{\sqrt{2\gamma}}{\delta}, \frac{\lambda}{\delta_A}\right) \tag{10}$$

4 Performance evaluation of two-stage sensing scheme

In this section, we focus on the performance analysis of two-stage sensing scheme. Specifically, in order to protect PU from the interference and effectively utilized the spectrum, we investigate the probability of error sensing and the throughput for proposed approach.

According to the system model of proposed scheme mentioned above, the overall probability of false alarm and detection for the proposed two-stage sensing scheme are given by

$$P_{f\_TSS} = P_{f\_ED} + (1 - P_{f\_ED})P_{f\_CFD} \tag{11}$$

$$P_{d\_TSS} = P_{d\_ED} + (1 - P_{d\_ED}) P_{d\_CFD} \quad (12)$$

4.1 The Throughput Analysis

In cognitive radio networks, throughput is an important factor. It depends on accuracy of spectrum sensing and transmission time. Inaccurate spectrum sensing will reduce the throughput due to the interference. On the other hand, the more sensing time, the less transmission time, and the lower throughput.

Therefore, in order to compare the capable of utilizing spectrum between two-stage sensing scheme with conventional sensing approach, we need to investigate the performance of throughput.

Throughput of two-stage sensing scheme R_{TSS} consists of two parts: secondary user's throughput and primary user's throughput. It can be computed as follows [15]

$$R_{TSS} = \left(1 - \frac{T_s}{T_p}\right) \cdot (1 - P_{f\_TSS}) P(H_0) C_0 + \left(1 - \frac{T_s}{T_p}\right) (1 - P_{d\_TSS}) P(H_1) C_1 \quad (13)$$

where the first term corresponds to the secondary user throughput, the second term corresponds to the primary user throughput, T_p is frame duration, T_s is spectrum sensing time. $P(H_0)$ is the probability for primary user being absent and $P(H_1)$ is the probability for primary user being present. C_0 and C_1 are secondary user's channel capacity under the hypothesis H_0 and H_1, respectively.

With the assumption of white Gaussian signal, the secondary channel capacity can be written as follows

$$\begin{cases} C_0 = \log(1 + SNR) \\ C_1 = \log(1 + SINR) \end{cases} \quad (14)$$

For the hypothesis H_1, primary user's signal suffer from the interference of secondary user's signal, therefore the SINR instead of SNR is used in the lower part of (14).

Substitution of (4) and (5) to (13), the throughput of energy detection R_{ED} can be written as follows,

$$R_{ED} = \left(1 - \frac{T_{s1}}{T_p}\right) \cdot \left[(1 - P_{f\_ED}) P(H_0) C_0 + (1 - P_{d\_ED}) P(H_1) C_1 \right] \quad (15)$$

Substitution of (9) and (10) to (13), the throughput of first order cyclostationary feature detection R_{CFD} can be written as follows

$$R_{CFD} = \left(1 - \frac{T_{s2}}{T_p}\right) \cdot \left[(1 - P_{f\_CFD}) P(H_0) C_0 + (1 - P_{d\_CFD}) P(H_1) C_1 \right] \quad (16)$$

where T_{s1} and T_{s2} denote the sensing time of energy detection and first order cyclostationary feature detection, respectively.

4.2 Problem Optimization based on Probability of Error Sensing constraints

The overall probability of error sensing P_{error} is composed of the probability of miss detection P_{md} and the probability of false alarm P_f by each hypothesis probability. Therefore, P_e can be calculated by

$$P_{error} = P(H_1) P_{md} + P(H_0) P_f = P(H_1)(1 - P_d) + P(H_0) P_f \quad (17)$$

For the proposed scheme, the optimized aim is to maximize the throughput of CRNs subject to the probability of error sensing, the goal is to find the optimal sensing time. Therefore, the problem formulation is given by

$$\begin{aligned} &\max_{T_s} \ R_{TSS}(T_s) \\ &s.t. \ \ P_{error} \le \varepsilon \end{aligned} \quad (18)$$

where ε is the probability of error sensing threshold that the SU needs to achieve to protect the PU.

Substitution of (13) and (17) to (18), the problem formulation can be rewritten as follows

$$\begin{aligned} &\max_{T_s} \ R_{TSS}(T_s) = \left(1 - \frac{T_s}{T_p}\right) \cdot \left[(1 - P_f) P(H_0) C_0 + (1 - P_d) P(H_1) C_1 \right] \\ &s.t. \ \ P_{error} = P(H_1)(1 - P_d) + P(H_0) P_f \le \varepsilon \end{aligned} \quad (19)$$

In our discussion, we suppose the activity probability $P(H_1)$ of primary users is small, say less than 0.3, thus it is economically advisable to explore the secondary usage for that frequency band. Since $C_0 > C_1$, the first term in the right hand side of (13) dominates the achievable throughput. Therefore, the optimization problem can be approximated by

$$\begin{aligned} &\max_{T_s} \ R_{TSS}(T_s) = \left(1 - \frac{T_s}{T_p}\right) \cdot (1 - P_f) P(H_0) C_0 \\ &s.t. \ \ P_{error} = P(H_1)(1 - P_d) + P(H_0) P_f \le \varepsilon \end{aligned} \quad (20)$$

5 Numerical results and analysis

In this section, numerical results are presented to evaluate the sensing performance for the proposed scheme by using MATLAB tool. In order to provide sufficient protection to the primary user and obtain more opportunity to utilize the spectrum, simulations are carried out to investigate throughput under the probability of error sensing constraints. We assume that noise variance $\delta = 1$. The probabilities of PU's absence and existence are $P(H_0)$=0.7 and $P(H_1)$=0.3, respective.

In the following, we will evaluate the sensing performance comparisons for different sensing approaches. Suppose the SNR for secondary transmission is 5dB. Fig.2 shows the receive operating characteristic (ROC) curve of TSS sensing scheme, energy detection and first order cyclostationary feature detection, respectively. The result indicates that two-stage sensing outperforms the energy detection and first order cyclostationary feature scheme.

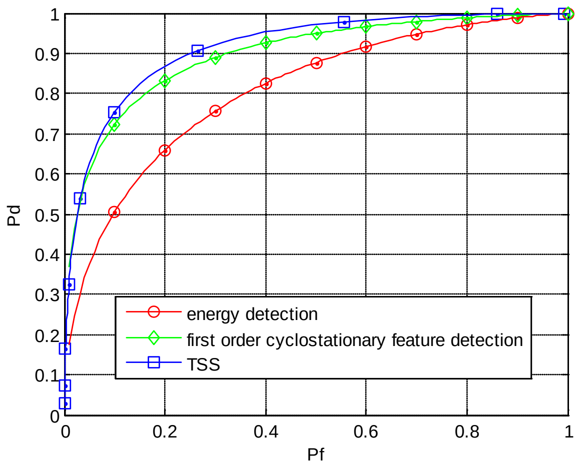

Fig.2 ROC comparisons for different Schemes

Fig.3 illustrates the probability of error sensing versus SNR under different sensing approaches. It can infer that when SNR is more than 12dB, the probability of error sensing for three schemes are very low. Besides, the proposed scheme has the lowest probability of error sensing compared to other schemes.

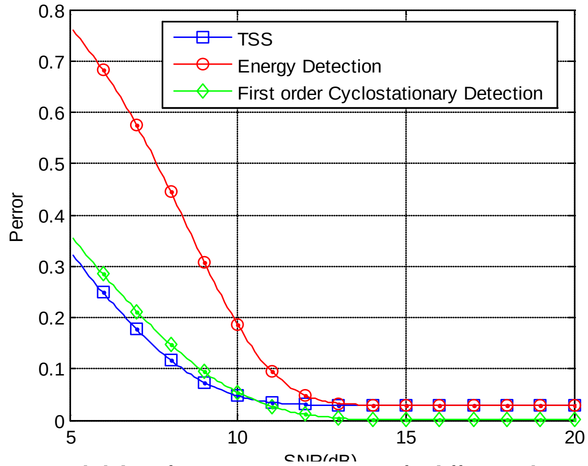

Fig.3 Probability of error sensing versus SNR for different Schemes

Fig.4 shows the throughput versus SNR for three sensing schemes. We assume that sensing time T_{s1}=2ms and T_{s2}=18ms for energy detection and first order cyclostationary feature detection, respectively.

As we can see, when SNR is less than 10dB, the TSS sensing scheme outperforms either energy detection or first order cyclostationary feature detection. The result indicates that the TSS approach not only has the lower probability of sensing error, but also has the good performance of throughput.

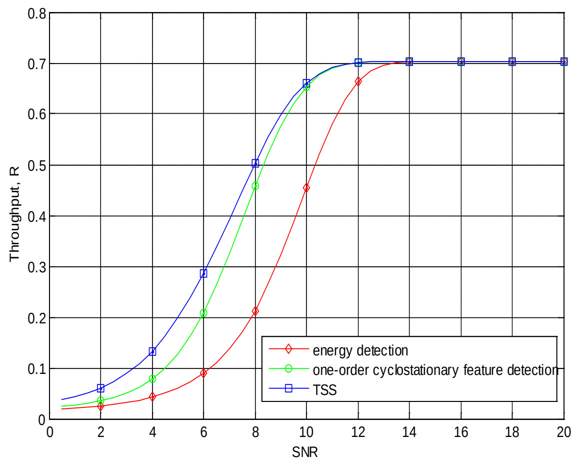

Fig.4 Throughput versus SNR for different Schemes

6 Conclusion

In this paper, a two-stage spectrum sensing scheme is presented to meet the requirements to accuracy of sensing in cognitive radio networks. In special, the proposed approach combines energy detection and first order cyclostationary feature detection. Numerical results indicate that the proposed scheme not only can guarantee a reliable sensing under the probability of sensing error constraints, but also has good performance of throughput compared to one stage sensing scheme.

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