Proactive Detection of Spectrum Holes in Cognitive Radio[†]

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***Abstract*— Most of existing works on spectrum sensing detect primary transmitters while the purpose of spectrum sensing is to avoid interfering with *primary receivers* (PRs). Therefore, it is more important to detect PRs. In this paper, we propose a proactive spectrum sensing method that detects whether a PR is within the coverage or the interference range of a CR transmitter by exploiting the *close-loop power control* policy in primary systems. With the proposed scheme, the CR user may still access the spectrum band even though a primary signal is present as long as its transmission does not interfere with the PR. Simulation results show the advantages of the proposed method.**

***Index Terms*— Cognitive radio, Spectrum Sensing, Receiver Detection.**

I. INTRODUCTION

Cognitive radio (CR) [1] enables a much higher spectrum efficiency by opportunistic spectrum access. Therefore, it is an attractive technology for future wireless communications. In CR, unlicensed users, also called secondary users, operate in licensed spectrum bands when interference to licensed users, also called primary users, is below a given threshold. Therefore, CR users are able to access licensed spectrum bands and coexist with primary users on a non-interference basis.

Spectrum sensing plays a significant role in CR. Generally, there are two kinds of spectrum sensing, *local sensing* [2][3] and *cooperative sensing* [4][5]. A comprehensive overview on spectrum sensing has been provided in [6]. In local sensing, three traditional signal detection techniques, matched filter, energy detector, and cyclostationary feature detector, have been introduced in [2]. Performance of energy detection over fading channel has been analyzed in [3]. Fading and shadowing in wireless channels usually degrade the performance of local sensing [2]. Therefore, cooperative spectrum sensing has been proposed to improve detection capabilities by exploiting spatial diversity in wireless networks. It has been shown in [4][5] that cooperative sensing increases detection sensitivity significantly. A soft combiner in centralized CR networks has been proposed in [7] and a cooperative sensing method based on *amplify-and-forward* (AF) techniques has been developed in [8][9].

All above techniques are to detect *primary transmitters* (PTs). However, the purpose of spectrum sensing is to avoid interfering with PRs. Cognitive users can transmit simultaneously with PTs as long as interference to PR is below an acceptable threshold [10]. In other words, without interfering with PR, CR users can still work even though the primary signal is detected on licensed spectrum band. Therefore, it will be more effective and efficient to detect PR. There have been some works considering PR detection. By exploiting local oscillator leakage emitted by *radio-frequency* (RF) front end, a direct sensing method has been developed in [11]. However, this approach is limited by a short sensing range due to the weak leakage signal. Another method introduced in [6] converts PR detection into PT detection by reciprocity of *time-division duplex* (TDD) primary systems. However, in *frequency division duplex* (FDD) systems, it is hard to detect PRs in downlink channel even through the uplink channel may be identified.

In this paper, we will develop a proactive spectrum sensing method to detect PR indirectly by exploiting the *close-loop power control* (CLPC) policy, which has been widely used in many wireless systems [12]. Different from traditional sensing methods [2]-[10] that detect spectrum holes by only *listening* to the signal form a PT, the method proposed in this paper finds spectrum holes by sending a sounding signal and observing possible corresponding power fluctuations of the primary signal due to CLPC in primary systems. By appropriately choosing the power of the sounding signal, the interference to PRs caused by the sounding signal is ensured below a tolerable threshold.

The rest of this paper is organized as follows. In Section II, we present system model and describe the problem of PR detection. In Section III, we develop the proactive spectrum sensing method and analyze its performance. Then we investigate the interference to PRs caused by the proactive spectrum sensing in Section IV. Simulation results are presented in Section V to demonstrate the advantages of the proposed method. Section VI concludes the paper.

II. SYSTEM MODEL AND PROBLEM DESCRIPTION

Before describing the problem of PR detection, we briefly introduce the simplest spectrum sensing scheme, energy de-

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tection. Also, we model the CLPC that exists in many wireless systems and will be used in our proposed sensing method.

A. Energy Detection

Conventionally, spectrum sensing is to decide whether a spectrum band is currently occupied by observing whether a primary signal is present or not. The received signal of a CR user can be expressed as

$$y(t) = \begin{cases} n(t), & \mathcal{H}_I, \\ hs(t) + n(t), & \mathcal{H}_B, \end{cases} \tag{1}$$

where $s(t)$ is the transmit signal of a PT, h denotes the channel coefficient between the PT and the CR user, and $n(t)$ represents *additive white Gaussian noise* (AWGN) with zero mean and variance σ_n^2. $\mathcal{H}_I$ and $\mathcal{H}_B$ denote that the spectrum band is idle (unoccupied) and busy (occupied), respectively.

The energy detector decides whether $s(t)$ is present or not based on the energy of $y(t)$ within a duration of T. It calculates the energy of the received signal by

$$Y = \frac{1}{\sigma_n^2} \int_t^{t+T} |y(t)|^2 dt, \tag{2}$$

where $\sigma_n^2 = 2WN_0$, W is the system bandwidth, and N_0 is the power spectral density of the noise. As shown in [3], when the primary signal is absent, Y follows a central chi-square (χ^2) distribution with M degrees of freedom, where $M = 2TW$. When the primary signal is present, Y follows a non-central χ^2 distribution with M degrees of freedom and a non-centrality parameter,

$$\gamma = \frac{h^2 \sum_{k=0}^{M-1} |s(\frac{kT}{M})|^2}{\sigma_n^2}, \tag{3}$$

which equals the *signal-to-noise ratio* (SNR). In summary,

$$Y \sim \begin{cases} \chi_M^2, & \mathcal{H}_I, \\ \chi_M^2(\gamma), & \mathcal{H}_B. \end{cases} \tag{4}$$

B. Channel Model and Close-Loop Power Control

Wireless channels usually experience both large-scale and small-scale fading [12]. As the dominant component, large-scale fading contains *path-loss* and *shadowing*. For simplicity, we ignore the shadowing throughout this paper and only consider the path-loss of wireless channels, which can be modeled as

$$G_{PL} = \frac{C}{r^\alpha}, \tag{5}$$

where C is a constant, α is the path-loss exponent, and r is the distance between the transmitter and the receiver. Given a transmit power, P_{tx}, the average received power can be expressed as

$$P_{rx} = G_{PL} \cdot P_{tx} = \frac{CP_{tx}}{r^\alpha}. \tag{6}$$

Denote P_n and P_i as the noise and interference power, respectively, then the *signal-to-interference-plus-noise ratio* (SINR) at the receiver is given by

$$\text{SINR} = \frac{P_{rx}}{P_i + P_n}. \tag{7}$$

The goal of CLPC is to minimize the transmission power while maintaining an acceptable signal quality of the receiver, which also reduces co-channel interference and improves channel reuse. Therefore, it has been widely used in wireless systems [12]. If the SINR at the receiver is below a certain threshold, $\overline{SINR}$, CLPC will adjust the transmit power to compensate the energy loss caused by path-loss or interference and vice versa. With CLPC, the transmit power can be obtained by

$$P_t = \frac{\overline{SINR}(P_i + P_n)}{G_{PL}}. \tag{8}$$

C. Problem Description

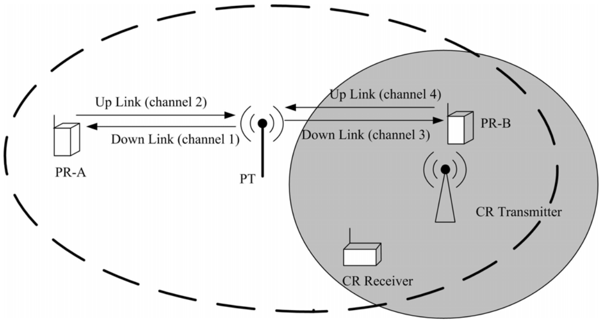

Fig. 1. Scenario of a cellular system with CR.

Figure 1 shows the scenario of a CR application in a cellular primary system[*]. We assume that a PT and a *primary receiver A* (PR-A) are communicating with each other by FDD. As indicated in Figure 1, Channels 1 and 2 are used for downlink and uplink transmissions between the PT and PR-A, respectively. A CR transmitter is in the coverage of the PT and intends to communicate with the CR receiver by Channel 1 if it does not cause unacceptable interference to PR-A. If the coverage of the CR communication is the shaded area as shown in the figure, the CR user may still use Channel 1 even though the channel is already occupied by the primary user because PR-A is beyond the range of the CR communication. In this scenario, we refer to PR-A as an *exposed terminal* since it is out of CR's coverage. In contrast, the *primary receiver B* (PR-B) in the figure is called a *hidden terminal*. Assume that PR-B is using Channels 3 and 4 for downlink and uplink transmissions, respectively. Since PR-B is within the coverage of the CR transmitter, the CR user is not allowed to use Channel 3 that is assigned to PR-B. The purpose of proactive spectrum sensing scheme proposed in this paper is to distinguish the exposed terminals from the hidden ones. Therefore, when an exposed terminal is identified, the

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[*] While we only consider a cellular primary system for simplicity, the developed algorithm in this paper can also be applied to other wireless networks.

CR user is able to communicate on the licensed downlink spectrum band.

III. PROACTIVE SPECTRUM SENSING

In this section, we will present the principle of our proactive spectrum sensing and then analyze its performance.

A. Principle of Proactive Spectrum Sensing

The basic idea of proactive spectrum sensing is to let a CR user transmit a sounding signal in sensing period and observe the response of a PT that is controlled by CLPC. To control the interference to PRs caused by the proactive spectrum sensing, the power of the sounding signal must satisfy a certain interference constraint.

As indicated before, the transmission power of a primary system with CLPC varies with the interference power, P_i, at the PR so as to maintain the quality of the received signal, which can be used to detect whether a PR is within the coverage of the CR user or not. When a CR user is close to a PR, the sounding signal from the CR user will change the interference environment of the PR and cause the PT to change its transmission power accordingly through CLPC. If the received power of the CR user from the PT goes down when its sounding signal turns, from on to off, then, with a high probability, the CR transmission causes interference to the PR. Thus, the CR user needs to vacate the spectrum band as soon as possible. This case is referred to hypothesis $\mathcal{H}_B$, which means the licensed channel is busy for the CR user. If, on the other hand, the power fluctuation of the signal from the PT is trivial no matter whether the sounding signal are on or off, then the PR is out of the coverage of the CR user. So it may coexist with the primary user at the same time. This case is referred to hypothesis $\mathcal{H}_I$, which means the licensed channel is idle and can be exploited by the CR user.

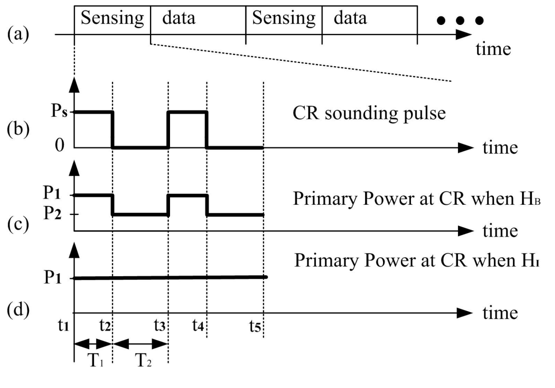

Fig. 2. Timing of the proactive spectrum sensing .

Figure 2 illustrates the principle of the proactive spectrum sensing scheme. Figure 2(a) shows the frame structure of a general CR system with periodic spectrum sensing. Figure 2(b) shows the fluctuations of the power of a sounding signal. Figures 2(c) and (d) show the waveforms of the primary signal power under $\mathcal{H}_B$ and $\mathcal{H}_I$, respectively. In practical systems, the signal of the PT may appear at any time within the CR frame. For simplicity, we assume that the PT turns on at the beginning of the sensing period of the CR user, t_1.

As shown in the figure, the CR user first transmits the sounding signal between t_1 and t_2 with a duration of T_1 and a certain power P_s, then the CR user keeps silent between t_2 and t_3 with a duration of T_2. So the *duty cycle* of the sounding signal, which is the proportion of time when the CR user is on, is given by $\nu = T_1/(T_1+T_2)$. When the energy detector is adopted, the CR user measures the energy of the signal from the PT between t_1 and t_2 by

$$Y_1 = \frac{1}{N_0}\int_{t_1}^{t_2} |y(t)|^2 dt. \tag{9}$$

From Y_1, the CR user makes a decision on whether the spectrum band is used by primary users or not, which is the same as the conventional energy detection schemes. But in our scheme, if the primary signal is detected, we need to further determine whether the PR is an exposed or a hidden terminal. To that end, the CR user measures the energy of the PT signal between t_2 and t_3 by

$$Y_2 = \frac{1}{N_0}\int_{t_2}^{t_3} |y(t)|^2 dt. \tag{10}$$

Denote P_1 and P_2 as the received powers from the PT when CR's sounding signal is on and off, respectively, which can be obtained from Y_1 and Y_2. Then, if $\mathcal{H}_B$ is true, $P_1 > P_2$. However, if $\mathcal{H}_I$ is true, $P_1 = P_2$.

As indicated in II-A, Y_1 follows a non-central χ^2 distribution with M degrees of freedom, that is,

$$Y_1 \sim \chi_M^2(\gamma_1), \tag{11}$$

where $\gamma_1 = E_{s1}/N_0$ is the non-central parameter and E_{s1} is the transmit energy during T_1. Similarly, Y_2 also follows a non-central χ^2 distribution with M degrees of freedom and a different non-central parameter depending on the hypothesis, i.e.,

$$Y_2 \sim \begin{cases} \chi_M^2(\gamma_1), & \mathcal{H}_I, \\ \chi_M^2(\gamma_2), & \mathcal{H}_B, \end{cases} \tag{12}$$

where $\gamma_2 = E_{s2}/N_0$ is the non-central parameter and E_{s2} is the transmit energy during T_2.

Because of CLPC in primary systems, the transmit power may be changed according to the power of the sounding signal from the CR user. Therefore, the CR user could distinguish two hypotheses, $\mathcal{H}_B$ or $\mathcal{H}_I$, based on Y_1 and Y_2. To improve detection performance, more sounding cycles can be sent as shown in Figure 2 so that we can get more accurate measurements. In this case, Y_1 and Y_2 will be the summations of the energies in multiple sounding and silent periods, respectively.

B. Performance Analysis

Denote $\theta = \gamma_1 - \gamma_2$, then the detection problem involves detecting whether θ is zero ($\mathcal{H}_I$) or positive ($\mathcal{H}_B$). We further assume $a = \frac{T_1}{T}$ and $b = \frac{T_2}{T}$. According to the *central limited theory* (CLT), Y_1 and Y_2 are approximately Gaussian when M

is large, i.e.,

$$Y_1 \sim \mathcal{N}\left[M+\gamma, \frac{2(M+2\gamma)}{a}\right], \tag{13}$$

$$Y_2 \sim \mathcal{N}\left[M+\gamma-\theta, \frac{2(M+2(\gamma-\theta))}{b}\right], \tag{14}$$

where $\mathcal{N}(\mu, \sigma^2)$ represents normal distribution with mean μ and variance σ^2. Define $Y = Y_1 - Y_2$, then

$$Y \sim \mathcal{N}\left[\theta, \frac{2(M+2\gamma)}{a} + \frac{2(M+2\gamma-2\theta)}{b}\right]. \tag{15}$$

Obviously, the duty cycle of the sounding signal is

$$\nu' = \frac{a}{a+b}. \tag{16}$$

Denote $K = 2(M+2\gamma)$, then

$$Y \sim \begin{cases} \mathcal{N}\left[0, K(\frac{1}{a}+\frac{1}{b})\right], & \mathcal{H}_I\ (\theta=0), \\ \mathcal{N}\left[\theta, K(\frac{1}{a}+\frac{1}{b}) - \frac{4\theta}{b}\right], & \mathcal{H}_B\ (\theta>0). \end{cases} \tag{17}$$

Thus, the probabilities of false alarm and missed detection can be expressed as

$$P_f = Q\left(\frac{\lambda}{\sqrt{K(\frac{1}{a}+\frac{1}{b})}}\right), \tag{18}$$

and

$$P_m = 1 - P_d = 1 - Q\left(\frac{\lambda-\theta}{\sqrt{K(\frac{1}{a}+\frac{1}{b}) - \frac{4\theta}{b}}}\right), \tag{19}$$

respectively. Eliminating λ by combining (18) and (19), we can find P_f for given a, b, and P_m as follows,

$$P_f = Q\left(\frac{Q^{-1}(1-P_m)\sqrt{K(\frac{1}{a}+\frac{1}{b}) - \frac{4\theta}{b}} + \theta}{K(\frac{1}{a}+\frac{1}{b})}\right), \tag{20}$$

where $Q^{-1}(\cdot)$ represents the inverse Q-function.

IV. INTERFERENCE ANALYSIS AND SOUNDING POWER DESIGN

In the proposed proactive spectrum sensing method, there are some inevitable interference to PRs if the sounding signal is with overmuch power. In this section, we will analyze this interference and investigate the allowable transmit power of a CR user for a given interference constraint.

A. Sounding Power in Single Sensing Period

As shown in Figure 3, we consider the area inside a circle of radius R with a CR transmitter at the center. Suppose that there are N PRs randomly distributed within the circle. Obviously, the interference power to a PR, P_i, caused by the CR user, decreases with the distance between them, r. Therefore, the probability that a CR user interferes with a PR can be expressed as

$$\varphi = \frac{\pi r'^2}{\pi R^2} = \left(\frac{r'}{R}\right)^2, \tag{21}$$

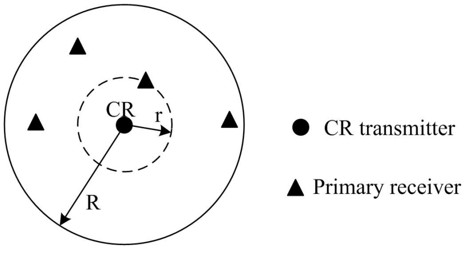

Fig. 3. Interference analysis diagram

where r' is the radius of the interference boundary for a CR user. Given the maximum tolerable interference power, $P_{i'}$, the sounding power can be expressed as

$$P_s = \frac{P_{i'}}{G_{r'}} = \frac{P_{i'} \cdot r'^{\alpha}}{C} = \frac{P_{i'} \cdot (R\sqrt{\varphi})^{\alpha}}{C}, \tag{22}$$

where $G_{r'}$ denotes the path-loss due the to the distance r'.

B. Consequential Power Adaptation in Multi-Sensing Periods

When a spectrum hole is identified in a CR system, it can be utilized by the CR user in subsequent data slot. However, the power of the CR transmission must be limited so as not to generate harmful interference to PRs, which may lead to decrease the performance of CR communication. Thus we will briefly introduce the concept of consequential power adaptation strategy in our proactive sensing method to identify the maximum allowable transmission power of a CR user or the equivalent size of the spectrum hole.

In a CR system, sensing and data slots usually appear alternatingly so as to protect primary systems [13], which is also called periodic spectrum sensing. In our proactive spectrum sensing scheme, the CR user can try to transmit with more sounding power in the next sensing slot if the current result is idle. With this way, the transmission power of a CR user can be adjusted accordingly to achieve better communication performance.

V. SIMULATION RESULTS

In this section, we will present numerical results to demonstrate the detection performance of the proposed proactive spectrum sensing. In our numerical examples, a PT is communicating with its receiver and a CR user tries to sense whether the spectrum is available or not. We assume that the time bandwidth product of the CR system is $M = 10$.

Figures 4 shows the *receiver operating characteristic* (ROC) for different power variation of a PT, θ, caused by a sounding signal, where $SNR = 20$dB and the duty cycle of the sounding signal equals 0.5, where $a = b = 1$. From the figure, ROC performance increases with θ. Also, the figure indicates that the ROC performance gain decreases as θ increases.

Figure 5 demonstrates the ROC performance in different SNRs at a CR user, γ, where $\theta = 5$ dB. From the figure, the ROC performance improves as γ goes up. Also, the higher γ is, the more ROC benefit could be gotten. Furthermore, the SNR at the CR user dramatically affects the ROC.

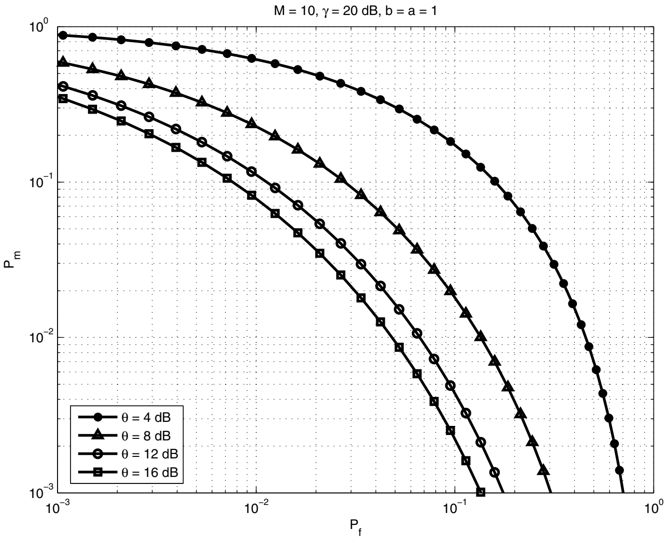

Fig. 4. ROC of the detector for different θ

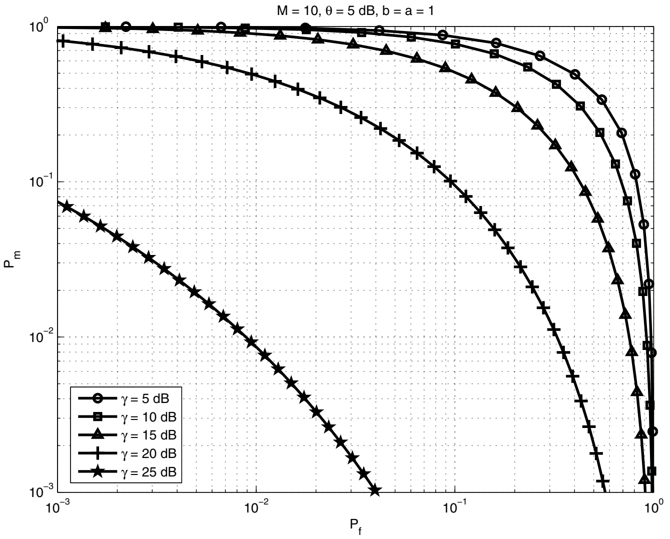

Fig. 5. ROC of the detector for different γ

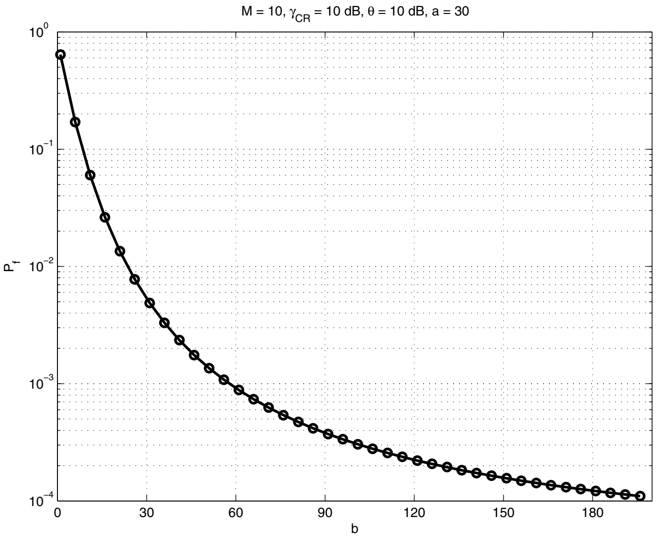

Fig. 6. P_f versus the required relative measuring period

Figure 6 shows the probability of false alarm, P_f, versus the required relative measure time, b, when the CR user is silent, where $a = 30$, SNR at the CR user is $\gamma = 10$ dB, the power fluctuation of CLPC at PT is $\theta = 10$ dB, and the threshold is selected so as to $P_m \approx 0.01$. From the figure, P_f decreases as b increases and $P_f \approx 0.01$ when $b > 25$.

VI. CONCLUSION

In this paper, we have proposed a proactive spectrum sensing method by detecting PR to enable a CR system to coexist with a primary system. Different from conventional spectrum sensing methods which have to vacate the spectrum band when a primary signal is detected, our proposed scheme enables a CR user to use the spectrum band assigned to *exposed terminals* and adjust its sounding power to achieve the maximum allowable transmit power. Therefore, more opportunities and a larger communication range can be achieved. Simulation results demonstrate the detection performance and the advantages of our method.

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