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Transmission Power-Based Spectrum Sensing for Cognitive Ad Hoc Networks

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Abstract

In spectrum sensing, there is a tradeoff between the probability of missed detection and the probability of a false alarm according to the value of the sensing threshold. Therefore, it is important to determine the sensing threshold suitable to the environment of cognitive radio networks. In this study, we consider a cognitive radio-based ad hoc network where secondary users directly communicate by using the same frequency band as the primary system and control their transmit power on the basis of the distance between them. First, we investigate a condition in which the primary and the secondary users can share the same frequency band without harmful interference from each other, and then, propose an algorithm that controls the sensing threshold dynamically on the basis of the transmit power of the secondary user. The analysis and simulation results show that the proposed sensing threshold control algorithm has low probabilities of both missed detection and a false alarm and thus, enables optimized spectrum sharing between the primary and the secondary systems.

Index Terms: Cognitive radio, Sensing threshold, Spectrum sensing, Transmit power control

I. INTRODUCTION

Cognitive radio is a paradigm for wireless communication in which either a network or a wireless node changes its transmission or reception parameters to communicate efficiently by avoiding interference with licensed or unlicensed users. This alteration of parameters is based on the active monitoring of several factors in the external and the internal radio environment, such as the radio frequency spectrum, user behavior, and network state. As a key technology enabling the cognitive radio, spectrum sensing plays an important role in the detection of an occurrence of an incumbent or available radio frequency [1].

Cognitive radio technology makes it possible to share the same spectrum band temporally or spatially between heterogeneous systems in order to improve the utilization of the spectrum [2]. However, the secondary system should not cause harmful interference to the primary system. Therefore, spectrum sensing is per-formed by the secondary signal to check whether the primary signal occurs or not. The performance of spectrum sensing is evaluated by using the probability of missed detection (P_{MD}) and the probability of false alarm (P_{FA}) [3, 4]. P_{MD} denotes the probability that the secondary signal does not detect a primary signal even though the primary signal exists. Thus, the secondary signal causes a severe interference to the primary signal. On the other hand, P_{FA} denotes the probability that the secondary signal detects a primary signal even though the primary signal does not exist. In this case, the utilization of the spectrum decreases as the secondary signal does not use the

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current band anymore. It has been known that there is a tradeoff between P_{MD} and P_{FA} according to the sensing threshold [5-7]. If the sensing threshold is increased, P_{MD} is increased, but P_{FA} is decreased. Therefore, it is important to determine a suitable value of the sensing threshold for the cognitive radio environment.

In an ad hoc network, a communication node controls its own transmit power according to the distance to its correspondent node [8]. If an ad hoc node uses the band of the primary system as the secondary system, the amount of interference from the ad hoc node to the primary system depends on the strength of the transmit power of the ad hoc node. Moreover, in spectrum sensing, the sensing threshold is a criterion to judge whether the primary system receives harmful interference or not; thus, we can expect the sensing threshold to be related to the transmit power of the secondary system. Therefore, in this study, we focus on the determination of the sensing threshold in a cognitive radio-based ad hoc network environment. First, we model a cognitive radio system in the ad hoc network and present a condition in which the primary and the secondary systems can coexist on the same channel without harmful interference from each other. Then, we derive a suitable value of the sensing threshold for efficient spectrum sharing and decide the sensing time required for reliable spectrum sensing against channel fading.

The rest of this paper is organized as follows: in Section II, the system model and the operation of the proposed sensing threshold control algorithm are presented. In Section III, the performance of the proposed scheme is analyzed. In Section IV, numerical and simulation results are presented. Section V concludes this paper.

II. PROPOSED SPECTRUM SENSING ALGORITHM

A. System Model

Fig. 1 illustrates a system model for the considered cognitive radio ad hoc network. The primary system is regarded as a one-way broadcast system, such as a wireless microphone; therefore, a primary receiver (PR) always receives the signal from a primary transmitter (PT). As the secondary system, we consider a pair of ad hoc nodes. Namely, two secondary users (SU) perform peer-to-peer communication by using the same frequency band as the primary system and use a transmit power control (TPC) mechanism according to the distance between them.

We define some parameters as follows:

r_p: radius of PT coverage.
r_s: radius of SU coverage.
d: distance between SU and PR.
P_p: transmit power of PT.

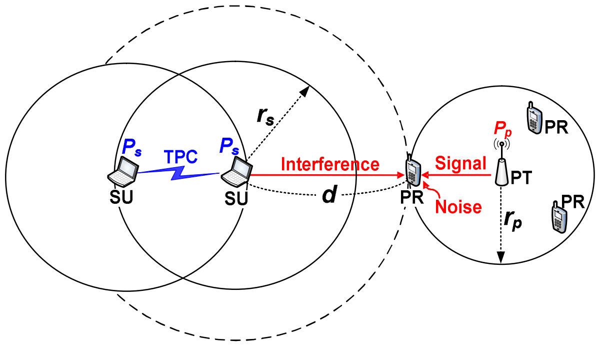

Fig. 1. System model for cognitive radio ad hoc network. SU: secondary user, PR: primary receiver, PT: primary transmitter, TPC: transmit power control.

P_s: transmit power of SU.
P_n: background thermal noise power.
γ_{rx}: signal-to-interference-plus-noise ratio (SINR) received at PR.
γ_{req}: minimum required SINR at PR.
λ: sensing threshold of SU.

B. Transmit Power-Based Sensing Threshold Control

Previous studies have dealt with issues of TPC for spectrum sharing in a cognitive radio system [9-13]. As a common approach, an SU first senses the power level of a PU and then controls its transmission power within a specified range such that the SU does not interfere with the PU. However, the SU sometimes cannot decrease its transmission power below a certain power level to guarantee the transmission rate required by the quality-of-service (QoS). In this case, the SU should change the currently used channel to another one in order to not interfere with the PU. Unlike the above scenario, in our approach, the SU first controls its transmission power according to the QoS requirement and then senses the PU signal. In order that the SU's transmission has no influence on the PU, the SU decides a sensing threshold based on the predetermined transmission power and performs spectrum sensing by using the decided sensing threshold.

As shown in Fig. 1, when the primary and the secondary systems use the same channel, the PR receives interference from the SU. Nevertheless, if only the SINR received at the PR is greater than the minimum SINR required for decoding, the interference from the SU is tolerable for the PR. On the basis of this underlying concept [14], we suppose the worst case scenario because we do not know the location of the PR practically. The worst case corresponds to when the PR is located on the boundary of the PT coverage and the nearest position to the SU, as shown in Fig. 1. In this case, the PR has the lowest SINR and this SINR should be greater than γ_{req} for the primary and the secondary systems to share the same spectrum band. Therefore, the following condition is formed (there might be multiple ad hoc connections. For the sake of simplicity, in this paper, we assume that multiple ad hoc connections can use different channels through their control signaling and each ad hoc connection uses a half-duplex mode. Therefore, only one SU can be an interferer at any given point of time):

$$\gamma_{rx}^{worst} = \frac{P_p L(r_p)}{P_s L(d) + P_n} = \frac{P_p r_p^{-\alpha}}{P_s d^{-\alpha} + P_n} \geq \gamma_{req}, \quad (1)$$

where the function of path loss is given by $L(x) = x^{-\alpha}$ where α denotes the path loss exponent and x represents the distance between the transmitter and the receiver.

From (1), we can derive the minimum distance between the SU and the PR required for them to share the same spectrum. The minimum distance, d_{min}, is calculated as

$$d_{min} = \exp\left\{\frac{1}{\alpha}\ln\left(\frac{P_s\gamma_{req}}{P_p r_p^{-\alpha} - P_n\gamma_{req}}\right)\right\}. \quad (2)$$

That is, spectrum sharing is possible only if the distance between the SU and the PR is longer than d_{min}. Under this optimized coexistence condition, the signal power that the SU receives from the PT becomes $P_pL(d_{min}+r_p)$; thus, this value can be used as a criterion to judge whether spectrum sharing is possible or not. Therefore, the proposed sensing threshold of SU, λ_{prop}, is determined as

$$\lambda_{prop} = P_p L(d_{\min} + r_p) = \frac{P_p}{(d_{\min} + r_p)^{\alpha}} = \frac{P_p}{\left[\exp\left\{\frac{1}{\alpha}\ln\left(\frac{P_s\gamma_{req}}{P_p r_p^{-\alpha} - P_n\gamma_{req}}\right)\right\} + r_p\right]^{\alpha}}. \quad (3)$$

The regulation for a shared spectrum provides information about the primary system, such as P_p, r_p, and γ_{req} [15]. In addition, the SU can estimate the path loss exponent α and the noise power level P_n in a given channel [16]. Therefore, the sensing threshold λ_{prop} given by (3) depends only on the transmit power of the SU, P_s. In other words, the sensing threshold should be decreased as the transmit power is increased, which implies that the SU should detect the primary signal more sensitively as it causes more interference by increasing its transmit power.

For spectrum sensing, the overall procedure of the SU can be summarized as follows:

1) The SU decides its transmit power by TPC considering the distance with the other SU.
2) The SU decides its sensing threshold by using (3).
3) The SU performs spectrum sensing (e.g., energy detection) by using the decided sensing threshold.
4) If the detected power is greater than the sensing threshold, the SU does not use the current channel and changes to another channel immediately.
5) If the detected power is smaller than the sensing threshold, the SU continues to use the current channel and performs spectrum sensing next time.
6) Every time the SU changes its transmit power, it recalculates the sensing threshold.

III. PERFORMANCE ANALYSIS

For the performance evaluation, we constructed an analysis model as shown in Fig. 2. We can consider an one-dimensional analysis because the algorithm depends only on the distance between the SU and the PT. Suppose that there is an X-axis and the origin is the SU; then, a PT can be located at any point on the X-axis. The detection range in which the SU can detect the primary signal varies according to its sensing threshold λ. For example, when the SU sets its sensing threshold to the proposed sensing threshold (i.e., $\lambda = \lambda_{prop}$), its detection range becomes $d_{min}+r_p$, which is the minimum distance between the SU and the PT required for spectrum sharing. However, if the sensing threshold increases (i.e., $\lambda > \lambda_{prop}$), then the detection range of the SU shrinks and the SU may not detect the PT signal even though the PR receives harmful interference from the SU (i.e., the missed detection occurs).

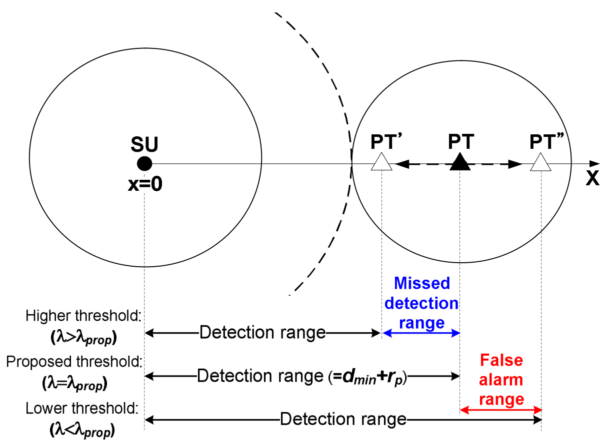

Fig. 2. Analysis model for performance evaluation. SU: secondary user, PT: primary transmitter.

In contrast, if the sensing threshold decreases (i.e., $\lambda < \lambda_{prop}$), the detection range extends and the SU may detect the PT signal unnecessarily although the PR is not interfered by the SU (i.e., a false alarm occurs).

If we consider a radio propagation model with lognormal slow fading (in spectrum sensing, the instantaneous received signal is averaged to decide its strength; therefore, fast fading can be neglected on average), the signal power that the SU receives from the PT is expressed as

$$R(x) = P_p x^{-\alpha} 10^{Z/10}, \tag{4}$$

where x denotes the distance between the SU and the PT, and Z represents a Gaussian random variable with zero mean and standard deviation σ.

Missed detection occurs when the received signal power is less than the sensing threshold in spite of the requirement that the SU must detect the PT signal. Therefore, P_{MD} at a distance x is defined as

$$P_{MD}(x) = \Pr\{R(x) < \lambda \mid \lambda > \lambda_{prop}\}. \tag{5}$$

Then, the average probability of missed detection is calculated as

$$\begin{aligned} \overline{P}_{MD} &= \int_0^\infty P_{MD}(x)dx \\ &= \int_0^{d_{\min}+r_p} \Pr(R(x) < \lambda)\, dx \\ &= \int_0^{d_{\min}+r_p} Q\left(\frac{10\log\left(\frac{P_p}{x^\alpha \lambda}\right)}{\frac{\sigma}{\sqrt{m}}} \right) dx \end{aligned}, \tag{6}$$

where Q(·) represents a Q-function defined as $Q(x) = 1/\sqrt{2\pi}\int_x^\infty \exp(-u^2/2)du$ and m denotes the number of sensing operations for decision making. On the other hand, P_{FA} at a distance x is defined as

$$P_{FA}(x) = \Pr\{R(x) > \lambda \mid \lambda < \lambda_{prop}\}. \tag{7}$$

Therefore, the average probability of a false alarm is obtained by

$$\begin{aligned} \overline{P}_{FA} &= \int_0^\infty P_{FA}(x)dx \\ &= \int_{d_{\min}+r_p}^\infty \Pr(R(x) > \lambda)\, dx \\ &= \int_{d_{\min}+r_p}^\infty 1 - Q\left(\frac{10\log\left(\frac{P_p}{x^\alpha \lambda}\right)}{\frac{\sigma}{\sqrt{m}}} \right) dx \end{aligned}. \tag{8}$$

Notice that the average probabilities of missed detection and false alarm ($\overline{P}_{MD}$ and $\overline{P}_{FA}$) are the function of m (i.e., the number of sensing operations for averaging). Since the channel fluctuation (i.e., fading) deteriorates the sensing performance, we need to consider temporal averaging to mitigate the fading effect. In other words, the sensing time should be increased according to the fading level in order to satisfy the requirements of missed detection and false alarm. Therefore, the total sensing time, T_S, is determined as

$$\begin{aligned} m_1 &= \arg\max_{m_1 \in Z} \overline{P}_{MD}(m_1) \quad s.t.\ \overline{P}_{MD} < \varepsilon_1,\ m_1 > 0 \\ m_2 &= \arg\max_{m_2 \in Z} \overline{P}_{FA}(m_2) \quad s.t.\ \overline{P}_{FA} < \varepsilon_2,\ m_2 > 0 \\ T_S &= t_s \cdot \max(m_1, m_2) \end{aligned}, \tag{9}$$

where ε_1 and ε_2 denote the sensing constraints of missed detection and false alarm, respectively, and t_s indicates the time needed for one sensing operation.

IV. RESULTS AND DISCUSSION

For the results, we use the parameters listed in Table 1. We consider a wireless microphone as the primary system. The wireless microphone operates on the bandwidth of 200 kHz and requires an SINR of more than 20 dB for normal decoding [17]. The SU varies its transmit power from 0 to 30 dBm. Both the primary and the secondary systems are in the same channel environment, and the related parameters are set up taking into account the indoor wireless channel [18]. Here, three sensing operations for the decision of the sensing threshold satisfy the condition that both P_{MD} and P_{FA} need to be less than 0.1 [13]. In addition, we perform a Monte Carlo simulation to validate the numerical analysis.

Fig. 3 shows the proposed sensing threshold versus the transmit power of the SU according to the minimum required SINR for PR (γ_{req}). As shown, the proposed sensing threshold decreases with an increase in the transmit power of the SU. Since the higher the transmit power of the SU, the greater is the amount of interference with the primary

Table 1. Parameter setup

Parameter	Value
P_p	30 dBm
P_s	0–30 dBm
P_n	-174 + *NF* + 10log(Δf) (dBm)
Δf	200 kHz
Noise figure (*NF*)	10 dB
r_p	100 m
γ_{req}	20–40 dB (default = 20 dB)
α	3
σ	4 dB
ε_1, ε_2	0.1
m	3

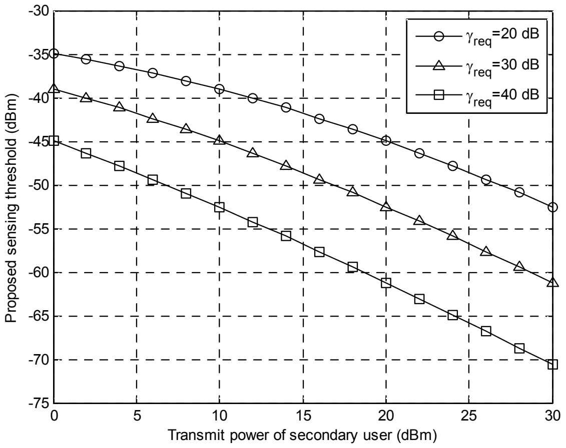

Fig. 3. Proposed sensing threshold vs. transmit power of the secondary user according to γ_{req}.

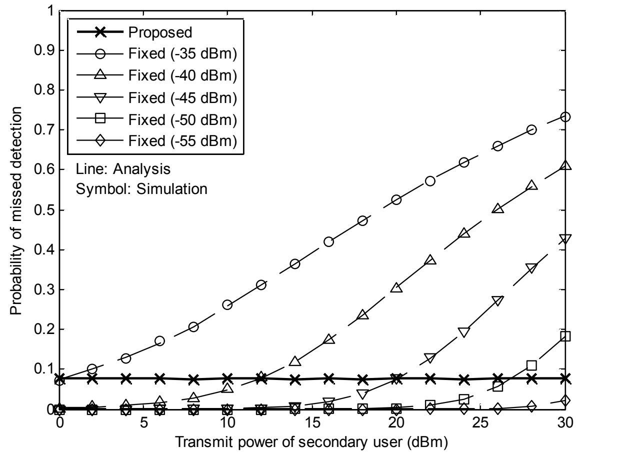

Fig. 4. Probability of missed detection vs. transmit power of the secondary user (γ_{req} =20 dB).

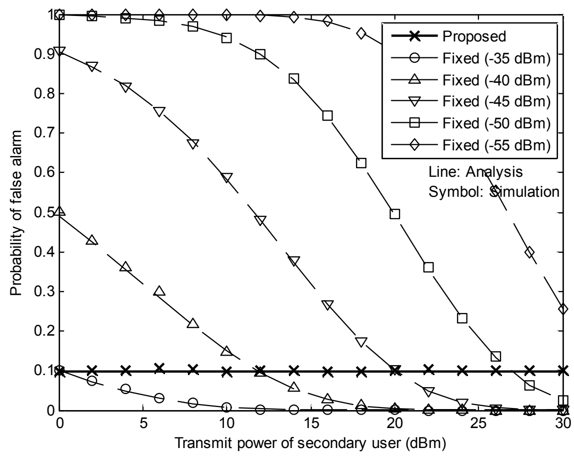

Fig. 5. Probability of false alarm vs. transmit power of the secondary user (γ_{req} =20 dB).

system, the SU should detect the PT signal more carefully, and thus, the sensing threshold should be lower. In addition, the sensing threshold decreases with an increase in the minimum required SINR for the PR. Because the amount of interference allowed by the PR decreases as γ_{req} increases, the minimum distance between the SU and the PR required for the coexistence should be longer and the sensing threshold should be reduced.

As shown in (3), the sensing threshold is related to not only the transmit power of the SU but also the minimum required SINR for the PR; therefore, it should be controlled adaptively taking into account these system parameters for efficient coexistence.

Fig. 4 shows the probability of missed detection versus the transmit power of the SU. In the case of a fixed threshold (in the conventional approach, the sensing threshold is decided as a constant according to the noise level of the sensing channel without considering the variation of the transmit power of the secondary users [12]), the probability of missed detection increases as the transmit power of the SU increases. Since the higher the transmit power of the SU, the severer is the interference, the fixed threshold may not detect whether the PR receives interference from the SU and missed detection occurs. However, the proposed algorithm maintains a constant probability of missed detection because it changes the sensing threshold dynamically according to the variation of the transmit power of the SU. The missed detection in the proposed method is affected only by the fading effect.

Fig. 5 shows the probability of false alarm versus the transmit power of the SU. Unlike the probability of missed detection, the probability of false alarm is decreased as the transmit power of SU is increased in the case of a fixed threshold. In other words, the results show that there is a tradeoff between the false alarm and the missed detection. The fixed sensing threshold shows a high probability of false alarm when the transmit power of the SU is low, because the SU does not cause a severe interference to the PU at the low transmit power. However, the proposed algorithm shows a constant probability of false alarm irrespective of the transmit power of the SU because it adaptively selects the sensing threshold suitable to its transmit power. The proposed algorithm shows that its probability of false alarm is a little greater than the probability of missed detection under the same condition. This is because the fading effect is more dominant in the case of the probability of false alarm than in the case of the probability of missed detection.

Fig. 6 shows the coexistence probability versus the transmit power of the SU. We define the coexistence probability as a probability that both the primary and the secondary systems utilize a co-channel at the same time without interfering with each other. Therefore, it is given by $1–P_{MD}–P_{FA}$.

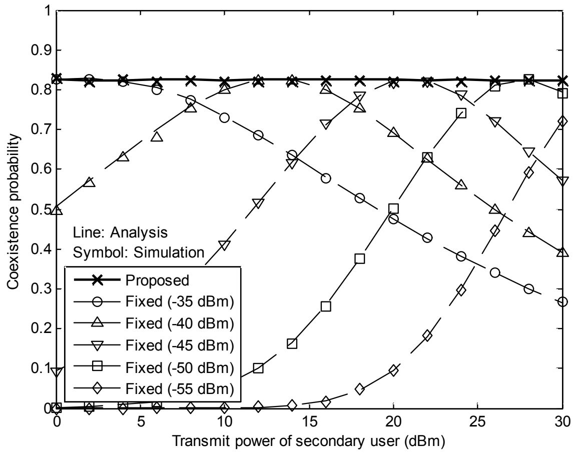

Fig. 6. Coexistence probability vs. transmit power of the secondary user (γ_{req} =20 dB).

The coexistence probability of the fixed threshold method increases with an increase in the transmit power of the SU, but eventually decreases as the transmit power becomes higher. However, the proposed algorithm maintains a constant probability, which follows the peak performance of each method using the fixed threshold. This is because the proposed scheme optimally adjusts the sensing threshold according to the transmit power of the SU.

V. CONCLUSIONS

In this paper, we investigated how the sensing threshold of energy detection should be determined for efficient spectrum sharing in the cognitive ad hoc network. The results show that the value of the sensing threshold is closely related to the transmit power of the SU. In the ad hoc network, the transmit power is a prior requirement for the SU to guarantee its quality of service. Therefore, it is desirable that the SU first determines its transmit power and then controls its sensing threshold dynamically according to the predetermined transmit power. We believe that the proposed dynamic sensing threshold control mechanism can be used for determining an optimized sensing threshold that minimizes both missed detection and false alarm in various cognitive radio environments.

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