The Impact of Sensing Range on Spatial-Temporal Opportunity

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Abstract. *In this paper, we study the impact of secondary user (SU) sensing range on spectrum access opportunity in cognitive radio networks. We first derive a closed-form expression of spectrum access opportunity by taking into account the random variations in number, locations and transmitted powers of primary users (PUs). Then, we show how SU sensing range affects spectrum access opportunity, and the tradeoff between SU sensing range and spectrum access opportunity is formulated as an optimization problem to maximize spectrum access opportunity. Furthermore, we prove that there exists an optimal SU sensing range which yields the maximum spectrum access opportunity, and numerical results validate our theoretical analysis.*

Keywords

Cognitive radio, spectrum access opportunity, spatial false alarm, optimal SU sensing range.

1. Introduction

In cognitive radio networks, secondary user (SU) can utilize a licensed channel of primary user (PU) when there is no active PU within a certain sensing range. SU equipped with frequency-agile radio is capable of sensing a given channel locally and deciding whether the channel is available or not. Conventionally, it is considered that the occurrence of false alarm is caused by the intrinsic feature of radio channel and noise in temporal domain [1] [2]. However, when there is no active PU within SU sensing range, SU can still detect the presence of signal of PU locating outside of SU sensing range due to the signal characteristic in spatial domain. Accordingly, spectrum access opportunity will be lost. This phenomenon has been termed as spatial false alarm [3] [4].

For a given channel, spectrum access opportunity can be characterized as spatial and temporal. Recently, there are several studies devoted to the researches of spectrum sensing taking into account of spatial and temporal characteristics. [3] discussed spectrum sensing from a spatial-temporal domain perspective, and presented unified spatial-temporal metrics to evaluate the performance of spectrum sensing. [4] considered the scenario that a single PU locating in a circular region uniformly and quantified spatial false alarm by a closed-form expression. In [4], the occurrence of spatial false alarm is caused by an active PU locating outside SU sensing range. [5] investigated the occurrence of spatial spectrum opportunity through a careful examination of the definition of spectrum access opportunity, and demonstrated the difference between detecting the signal of PU and detecting spectrum access opportunity.

However, most studies focused on the performance analysis of spectrum sensing taking into account spatial and temporal characteristics, but ignored the impact of SU sensing range. Specifically, SU sensing range not only affects SU coverage area, which can be considered as SU capacity, but also the performance analysis of spectrum access opportunity at SU. From the detection's perspective, the physics meaning of SU sensing range is a certain configuration of detector for a given requirement on system performance. We will discuss it in detail in Section 3. Furthermore, the impact of SU sensing range on spectrum access opportunity will be more complicated especially for a random PU network with multiple PUs due to spatial false alarm. Therefore, it is critical to understand the impact of SU sensing range on spectrum access opportunity, which is the main work of this paper.

In this paper, we first present the quantitative analysis of spectrum access opportunity taking into account the spatial and temporal characteristics with random variations in the number, locations and transmitted powers of PUs. Through modeling PU network in terms of stochastic geometry, a closed-form expression of spectrum access opportunity is derived. Modeling PU network in terms of stochastic geometry seems particularly tractable. Then, we show how SU sensing range affects spectrum access opportunity, and formulate the fundamental tradeoff between SU sensing range and spectrum access opportunity as an optimization problem. Finally, we prove that there indeed exists an optimal SU sensing range which yields the maximum spectrum access opportunity. A list of the key mathematical symbols used in this paper is given in Tab. 1.

2. System Model

2.1 Stochastic Geometric Network Model for PU Network

Generally, classical analysis methods are insufficient to analyze spectrum access opportunity with random PU networks for the following reasons: (i) It is impossible for SU to know or predict the number and locations of all but perhaps a few PUs. (ii) The received signal power at SU is a function of PU network geometry which the pass-loss and fading characteristics are dependent upon. Stochastic geometry [6] has been proved to be helpful in circumventing the above difficulties. Stochastic geometry provides a natural way of defining and computing macroscopic properties of random network.

In this paper, we consider a single SU located at $s \in \mathbb{R}^2$, within a decentralized random PU network, as depicted in Fig. 1. Consider a marked Point Process (P.P) $\tilde{\prod}_{S_{all}} = \{x_i, p_i\}$ with points on the plane $\prod_{S_{all}} = \{x_i\} \in \mathbb{R}^2$ and marks $p_i \in \mathbb{R}^+$, where points represent the locations of active PUs and marks represent PUs transmitted powers at any given time instant in the area of PU network S_{all} [7]. Standard stochastic scenarios are considered for marked point process: (i) $\tilde{\prod}_{S_{all}}$ is a stationary independently marked point process with the location of PU $\{x_i\}$ and intensity λ_p; (ii) The mark (transmitted power) p_i does not depend on the location of PU [8]. The intensity λ_p means that the average number of PU for unit area is λ_p. For a given area of primary network, corresponding average number of PU can be obtained.

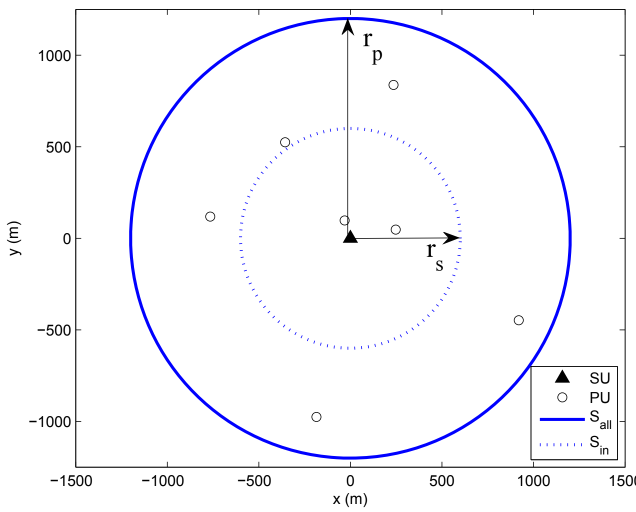

Fig. 1. A snapshot of network topology.

2.2 Channel Model

The propagation power loss from location x_i of PU i to s is modeled by $g_i l(\|s - x_i\|)$, where g_i is a random variable that characterizes the cumulative effect of shadowing and fading. $l(\|s - x_i\|)$ is the distance-dependent path-loss [9]. g_i is assumed to be independent and identically distributed (i.i.d.) across different users and also independent of PU's location, with probability density function (PDF) $f_G(g_i)$. l is modeled as a power law, $l(\|s - x_i\|) = C\|s - x_i\|^{-\alpha}$, where $\alpha > 2$ is the pass-loss exponent and C is a constant [10]. Moreover, such model holds for $\|s - x_i\| \geq 1$, and in the remainder of this paper we will only consider the case of $\|s - x_i\| \geq 1$ [9] [11]. Therefore, the received signal power at SU from PU i can be denoted as $P_i = C p_i g_i \|s - x_i\|^{-\alpha}$ [9].

Symbol	Definition
PU	Primary User
SU	Secondary User
P.P	Point Process
PPP	Poisson Point Process
S_{all}	Area of PU network
S_{in}	Area of SU sensing range
S_{out}	The rest area of S_{all} excluding S_{in}
s	Location of SU
x_i	Location of PU i
p_i	Transmitted power of PU i
λ_p	Intensity of PU network
g_i	Cumulative effect of shadowing and fading
$l(\|\|)$	Distance-dependent path-loss
$f_G(g_i)$	Probability density function of g_i
C	Constant
α	Path-loss exponent
P_i	Received signal power at SU from PU i
M	Number of samples
W	Bandwidth of channel
T	Sensing time
$B(s, r_s)$	Disk centered at SU location s with radius r_s
P_{Opp}	Probability of spectrum access opportunity
$P(s)$	Total received power from all PUs to SU at s
$\gamma_{H_0^+}$	Average received SNR at SU

Tab. 1. List of symbols.

2.3 Energy Detection

Energy detection is the most widely used method for detecting the presence of PU signal in a particular frequency channel [12]. Energy detector simply measures the energy received on the licensed channel during a sensing time and compares it with a sensing threshold. Energy detector will declare a spectrum access opportunity if the measured energy is less than the sensing threshold. Let $M = WT$ be the number of samples (bandwidth time product) where W is the bandwidth of the channle and T is the sensing time (sample time) in energy detector. The test statistic for energy detector at SU is $T(y) = \sum_{m=1}^{M} |y(m)|^2 \big/ M$, where $y(m)$ is the received signal sample at SU. A binary hypothesis test for temporal-spatial spectrum sensing [4] at SU is denoted as follows:

$$H_0 : \text{opportunity}, \begin{cases} H_0^- : & \prod_{S_{all}} = \phi \\ H_0^+ : & \prod_{S_{in}} = \phi \cap \prod_{S_{out}} \neq \phi \end{cases} \tag{1}$$
$$H_1 : \text{no opportunity}, \prod_{S_{in}} \neq \phi$$

where ϕ is the null set. Here, $S_{in} = B(s, r_s) \in \mathbb{R}^2$ is the area of SU sensing range, where $B(s, r_s)$ denotes the disk centered at SU location s with radius r_s. S_{all} is the area of PU network, S_{out} is the rest area of S_{all} excluding S_{in}, namely $S_{all} = S_{in} + S_{out}$. $\prod_{S_{in}}$ is corresponding P.P consisting of PUs' locations within S_{in}, and $\prod_{S_{all}}$ and $\prod_{S_{out}}$ are similarly defined [13]. Therefore, the received signal at SU $y(m)$ can be represented as

$$\begin{aligned} H_0 : y(m) &= \begin{cases} H_0^- : n(m), \\ H_0^+ : \sum\limits_{i \in \prod_{S_{out}} \neq \phi} \sqrt{P_i} s_i(m) + n(m), \end{cases} \\ H_1 : y(m) &= \sum_{i \in \prod_{S_{in}} \neq \phi} \sqrt{P_i} s_i(m) + n(m) \end{aligned} \tag{2}$$

where $m = 1, 2, \ldots, M$ and $n(m)$ is AWGN with power spectral density N_0.

3. Closed-Form Expression of Spectrum Access Opportunity

SU is permitted to access the channel as long as there is no active PU within SU sensing range. However, for energy detection, false alarm which may result from noise or the signal of PU outside of SU sensing range will affect the sensing performance. Thus, it is necessary to take the impact of false alarm into account when analyzing the probability of spectrum access opportunity. Note that false alarm has temporal and spatial characteristics which are produced under different two hypotheses, i.e., H_0^- and H_0^+. Thus, the probability of spectrum access opportunity P_{Opp} is the combination of spectrum opportunity probabilities under the hypothesis H_0^- and H_0^+. Consequently, the probability of spectrum access opportunity P_{Opp} can be denoted as

$$P_{Opp} = P(H_0^-)(1 - P(H_1|H_0^-)) + P(H_0^+)(1 - P(H_1|H_0^+)) \tag{3}$$

where $P(H_0^-)$ and $P(H_0^+)$ represent the probabilities of H_0^- and H_0^+, respectively. $P(H_1|H_0^-)$ is the conventional (temporal) false alarm probability and $P(H_1|H_0^+)$ denotes the spatial false alarm probability.

In this paper, we consider the case where underlying independently marked PP is Poisson (PPP). According to the proprieties of PPP [8], $P(H_0^-)$ is given as

$$P(H_0^-) = \Pr\{\prod_{S_{all}} = \phi\} = e^{-S_{all}\lambda_p}. \tag{4}$$

Similar to $P(H_0^-)$, $P(H_0^+)$ can be denoted as

$$P(H_0^+) = \Pr\{\prod_{S_{in}} = \phi, \prod_{S_{out}} \neq \phi\}. \tag{5}$$

Note that PUs are independent of each other according to the property of PPP, thus we have

$$\begin{aligned} P(H_0^+) &= \Pr\{\prod_{S_{in}} = \phi\} \Pr\{\prod_{S_{out}} \neq \phi\} \\ &= e^{-S_{in}\lambda_p}(1 - e^{-S_{out}\lambda_p}). \end{aligned} \tag{6}$$

From (2), we know that under hypothesis H_0^-, the received noise power is WN_0. Thus, as applying central limit theorem (CLT) and the formula of false alarm probability in [12], for a given sensing threshold ε, we have

$$P(H_1|H_0^-) = Q\left(\left(\frac{\varepsilon}{WN_0} - 1\right)\sqrt{M}\right) \tag{7}$$

where $Q(\cdot)$ is the normal Q-function.

For energy detection, under hypothesis H_0^+, quantitative analysis on detection performance needs the knowledge of the average total received signal power. From the definition of the received signal power p_i from PU i, we can have the total received signal power from all PUs to SU under hypothesis H_0^+ denoted as

$$P(s) = \sum P_i = \sum_{(x_i, p_i) \in \prod_{S_{out}} \neq \phi} p_i g_i l(\|s - x_i\|). \tag{8}$$

Applying Campbell's theorem [8], the Laplace transform of $P(s)$ at SU is

$$\mathcal{L}_{P(s)}(t) = \exp\left\{2\pi\lambda_p \int_G \int_{r_s}^{r_p} r f_G(g)(\exp(j\omega p_p g r^{-\alpha}) - 1) dr dg\right\} \tag{9}$$

where $p_i = p_p$ is the constant transmitted power of PU.

To make the model concrete, we consider the disk model for PU network, namely $S_{all} = B(s, r_p) \in \mathbb{R}^2$, so that it will lead to clean tractable solution that highlight the main characteristic regarding spectrum access opportunity. Thus, the average received signal power at SU under hypothesis H_0^+ is obtained by

$$\begin{aligned} E[P(s)] &= \frac{1}{P(H_0^+)}\left[\frac{\partial \mathcal{L}_P(t)}{\partial t}\right]_{t=0} \\ &= \frac{2\pi\lambda_p \hat{C}(r_s^{2-\alpha} - r_p^{2-\alpha})}{(\alpha - 2)(1 - e^{\pi r_s^2 \lambda_p - \pi r_p^2 \lambda_p})} \end{aligned} \tag{10}$$

where $\hat{C} = C p_p \int_G g f_G(g) dg$. Consequently, the average received signal-to-noise ratio (SNR) $\gamma_{H_0^+}$ at SU is denoted as

$$\gamma_{H_0^+} = \frac{E[P(s)]}{WN_0} = \frac{2\pi\lambda_p \hat{C}(r_s^{2-\alpha} - r_p^{2-\alpha})}{(\alpha - 2)(1 - e^{\pi r_s^2 \lambda_p - \pi r_p^2 \lambda_p})WN_0}. \tag{11}$$

Thus, based on the test static $T(y)$, $P(H_1|H_0^+)$ is denoted as

$$P(H_1|H_0^+) = Q\left(\left(\frac{\varepsilon}{WN_0} - \gamma_{H_0^+} - 1\right)\sqrt{\frac{M}{2\gamma_{H_0^+} + 1}}\right). \tag{12}$$

Subsequently, substituting (4-6) and (12) into (3) yields the probability of spectrum access opportunity as

$$\begin{aligned} P_{Opp} = {} & e^{-\pi r_p^2 \lambda_p}\left(1 - Q\left(\left(\frac{\varepsilon}{WN_0} - 1\right)\sqrt{M}\right)\right) + (e^{-\pi r_s^2 \lambda_p} \\ & - e^{-\pi r_p^2 \lambda_p})\left(1 - Q\left(\left(\frac{\varepsilon}{WN_0} - \gamma_{H_0^+} - 1\right)\sqrt{\frac{M}{2\gamma_{H_0^+} + 1}}\right)\right) \end{aligned} \tag{13}$$

Note that the probability of total false alarm including temporal (7) and spatial (12) has a direct relationship with SU sensing range. Thus, when designing energy detector to satisfy the requirement on the false alarm probability, we should take SU sensing range into account. From the perspective of energy detector, the detection performance of false alarm is determined by the sensing threshold. Thus, the physics meaning of SU sensing range can be considered as the sensing threshold in energy detector. In other words, the requirement on the detection performance can be achieved by adjusting the sensing threshold in energy detector to different SU sensing ranges.

4. Tradeoff Between SU Sensing Range and Spectrum Access Opportunity

In this section, the characteristics of the impact of SU sensing range on spectrum access opportunity are identified as following.

Proposition 1: Without considering the effect of false alarm, $P(H_0)$ decreases exponentially with r_s^2.

Proof: Spectrum access opportunity for SU means that no active PU is within SU sensing range. Obviously, for a given intensity λ_p of active PU, the larger r_s, the larger the area of S_{in}, which corresponds to the case that no active PU is within SU sensing range with a smaller probability.

Mathematically, the probability of spectrum access opportunity resulting from (1) without considering the effect of false alarm can be denoted as

$$P(H_0) = P(H_0^-) + P(H_0^+) = e^{-\pi r_s^2 \lambda_p}, \tag{14}$$

which is exponentially decreasing with r_s^2, as shown in Fig. 2.

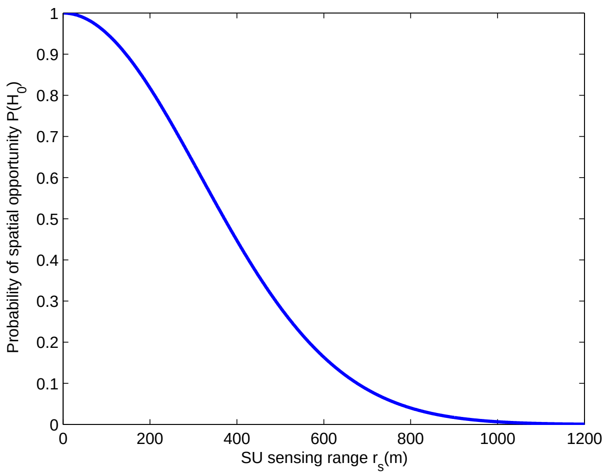

Fig. 2. $P(H_0)$ versus r_s without considering the effect of false alarm. To show all range of $P(H_0)$, the parameters of PU network are chosen as $r_p = 1200$ m and $\lambda_p = 6 \times 10^{-7}$.

In contrast, from the perspective of SU capacity, r_s should be designed as large as possible (the area of S_{in} can be considered as SU capacity to a certain extent). Thus, there should exist a tradeoff between SU capacity and r_s.

Proposition 2: With the increase of r_s, the impact of spatial false alarm $P(H_1|H_0^+)$ will be mitigated.

Proof: For a given S_{all}, S_{out} decreases with the increase of S_{in}. Correspondingly, the received signal power from PUs in S_{out}, which induces spatial false alarms, will also be decreasing.

We quantitatively characterize the probability of spatial false alarm (12) as a function of $\gamma_{H_0^+}$. From (12), we have $P(H_1|H_0^+)$ is an increasing function of $\gamma_{H_0^+}$. Moreover, the expression of $\gamma_{H_0^+}$ (11) is a decreasing function of r_s. Thus, we can conclude that the probability of spatial false alarm $P(H_1|H_0^+)$ is a decreasing function of r_s. In other words, the impact of spatial false alarm will be mitigated with the increase of r_s.

Based on *Proposition* 1 and 2 mentioned above, we have the following theorem regarding the tradeoff between r_s and spectrum access opportunity.

Theorem 1. *Under the disk propagation model, for $\lambda_p \ll 1$, there exists an optimal r_s^* which yields the maximum spectrum access opportunity for SU.*

Proof: Note that $P(H_0^+) = e^{-\pi r_s^2 \lambda_p} - e^{-\pi r_p^2 \lambda_p}$ is a decreasing function of r_s. Furthermore, since only the second term of (13), denoted as $P_O = P(H_0^+)(1 - P(H_1|H_0^+))$, is affected by r_s, then we adopt P_O here as the performance measure. Therefore, the problem of maximizing spectrum access opportunity can be formulated as follows:

$$\begin{aligned} r_s^* &= \arg\max_{r_s} \{P_O\}, \\ s.t. 1 &\le r_s \le r_p. \end{aligned} \tag{15}$$

Differentiating P_O with respect to r_s gives:

$$P_O' = P(H_0^+)' \left(1 - P(H_1|H_0^+)\right) + P(H_0^+) \left(1 - P(H_1|H_0^+)\right)'. \tag{16}$$

From (6), we have $\lim_{r_s \to 1} P(H_0^+)' = -2\pi\lambda_p e^{-\pi\lambda_p} \approx 0$ due to $\lambda_p \ll 1$. For $r_s \to 1$, $P(H_0^+) = e^{-\pi\lambda_p} - e^{-\pi r_p^2 \lambda_p} > 0$ and $0 < 1 - P(H_1|H_0^+)$ according to (12). From *Proposition* 2, we know $\lim_{r_s \to 1} \left(1 - P(H_1|H_0^+)\right)' > 0$.

Therefore, substituting into (16), we have

$$\lim_{r_s \to 1} P_O' > 0. \tag{17}$$

Obviously, similar to the case of $r_s \to 1$, $\lim_{r_s \to r_p} P(H_0^+)' < 0$, and $\lim_{r_s \to r_p} \left(1 - P(H_1|H_0^+)\right) > 0$. Furthermore, it can be verified that $\lim_{r_s \to r_p} P(H_0^+) = 0$. Thus, we have

$$\lim_{r_s \to r_p} P_O' < 0. \tag{18}$$

In summary, (17) and (18) mean that P_O increases when r_s approaches 1 and decreases when r_s approaches r_p. Hence, there is a maximum point of P_O within interval $(1, r_p)$, as depicted in Fig. 3.

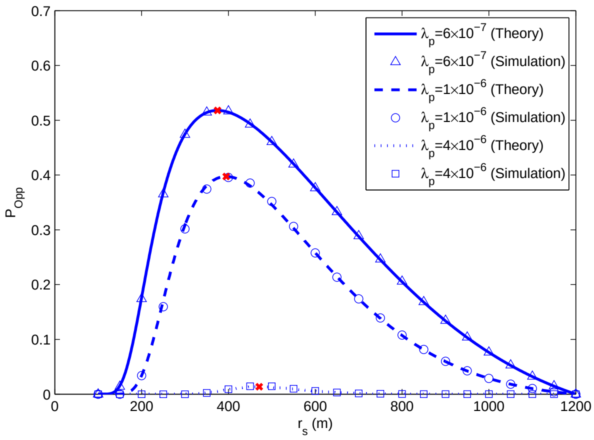

Fig. 3. The theory and simulation results on P_{Opp} versus r_s. The parameters of network are $T = 2$ ms, $W = 6$ MHz, $N_0 = -174$ dBm, $\alpha = 4$ and $\hat{C} = 1$. The red markers x represent the maximum P_{Opp} with respect to the optimal r_s.

In Fig. 3, the experiment parameters are defined as following: the sensing time $T = 2$ ms is chosen according to [12] and the bandwidth $W = 6$ MHz is the standard bandwidth of DTV [12]. The noise power spectral density $N_0 = -174$ dBm is the most used value in common environment [7].

Furthermore, it can be further proved that P_O is concave for a certain range of r_s in which $P_O'' < 0$. This make the maximum point of P_O unique in this range. In this case, efficient search algorithms can then be developed, like convex optimization. Otherwise, exhaustive search is needed in order to find the optimal sensing range. The detail of search algorithm is omitted here for the general case.

Lemma 1. *For a large λ_p, the impact of r_s on P_{Opp} can be ignored due to severe spatial false alarms. Accordingly, local energy detection will be insufficient to detect spectrum access opportunity.*

Fig. 3 also depicts P_{Opp} versus r_s under different values of λ_p. It is seen that for both theory and simulation quantities, there exists an optimal r_s^* which yields the maximum P_{Opp}. We notice that for $\lambda_p = 4 \times 10^{-6}$, the corresponding average number of PUs in S_{all} is $\pi r_p^2 \lambda_p \approx 18.09$, and P_{Opp} is so small that the impact of r_s can be ignored. This is because when the number of PUs is large, local energy detection will always detect the presences of signals of PUs and the impact of spatial false alarm will result in severe loss of spectrum access opportunity. Thus, local energy detection is insufficient to detect spectrum access opportunity for a large λ_p, and other detection schemes should be used to improve the performance of spectrum sensing, for instance using the position information of PUs and SU or cooperative sensing, which are worthy to investigate in future study.

5. Conclusion

In this paper, we quantified spectrum access opportunity by a closed-form expression through modeling PU network in terms of stochastic geometry. This will provide a metric to evaluate sensing performance. Moreover, the impact of SU sensing range on spectrum access opportunity was considered, and the existence of optimal SU sensing range which yields the maximum spectrum access opportunity was also proved. The optimal SU sensing range will provide a fundamental framework for designing SU network.

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