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A spectrum hole detection mechanism in cognitive radio networks applied in typical scenarios

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Abstract: A novel spectrum hole detection mechanism is proposed to improve the detection probability in cognitive radio networks for several typical scenarios. By removing the influence of the spatial false alarm (SFA), the spectrum hole detection probability of the secondary user under path loss and multi-path fading is derived. Meanwhile, the spectrum hole detection probability of multi-users cooperative sensing and that of single-user sensing in multi-bands are derived for comparison. Theoretical analyses and simulation results show that the spectrum hole detection probability of the proposed mechanism is inversely proportional to the sampling times and the area of the sensing region. The detection performance of the multi-users sensing is better than that of single-user sensing when with the AND logic fusion rule but worse when with the OR logic fusion rule. The detection probability is further decreased in the Rayleigh fading channel but it is greatly increased in multi-bands.

Key words: spectrum hole; spectrum sensing; multi-users sensing; spatial false alarm (SFA)

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Pushed by the increasing demand on the frequency spectrum, a survey of the spectrum utilization processed by the Federal Communications Commission (FCC) indicates that the licensed spectrum is rarely used in huge temporal and geographic dimensions[1]. Under such circumstances, a new working group on wireless regional area networks has been formed by IEEE to develop the related standards[2]. The cognitive radio technology is different from the fixed spectrum assignment policies, and it can access the frequency bands of the primary user while keeping the quality of service (QoS) of the whole network[3].

In dynamic spectrum access (DSA), the secondary user dynamically detects and accesses the spectrum of the primary user in two main modes, i. e., the underlay mode and the overlay mode. As it is known to all, the idle spectrum of the primary user borrowed by the secondary user is declared as the spectrum hole and how to maximize the spectrum hole detection probability is important no matter which mode is used. Therefore, the overlay mode is studied in this paper and the issue termed as the spatial false alarm (SFA) problem is considered. SFA means that a secondary user mistakes a non-interfered primary user which is spatial far away for an interfered one with a certain probability. Considering SFA, a spectrum hole detection mechanism for cognitive radio is proposed in this paper and the spectrum hole detection probability is deduced.

In the previous cognitive radio studies, the detection accuracy is discussed and distributed cooperative sensing is applied to deal with the multi-path fading and hidden terminal problem without analyzing system performance[4-5]. In Refs. [6 - 7], the time gain is derived to reduce the secondary system sensing time through relaying. In Refs. [8 - 9], the sensing time tradeoff is studied and its optimal value to maximize the system capacity is derived while interferences to the primary user are kept under an acceptable level. In Ref. [10], the joint spatial-temporal sensing is discussed for cognitive radio networks without considering the number of transmitter-receiver pairs as a Poisson random variable. In those papers, the networks model is assumed to be static. In the work of Gupta and Kumar[11], the stochastic geometry theory is shown as a very powerful mathematical tool for performance evaluation of wireless networks. The Poisson point process distribution is applied in Refs. [12 - 13] to study the system performance. In Ref. [14], the spatial capacities of narrowband versus ultra wideband in cognitive radio networks are discussed under the Poisson point process distribution without considering SFA. In Ref. [15], the accessing probability of the secondary user is studied by considering SFA, but cooperative sensing and multi-path fading problems are not discussed. In this paper, the primary user location following the two-dimensional homogeneous Poisson process and the SFA are defined as the same as those in Ref. [15]. The spectrum hole detection probability calculated in this mechanism is higher than that in the conventional way. The spectrum

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hole detection probabilities of different sensing schemes in typical scenarios are derived. Simulation results show the spectrum hole detection probability is inversely proportional to the sampling times and the area of the sensing region. It also shows that the single-user sensing is superior to the multi-users sensing with the OR logic fusion rule but inferior to that with the AND logic fusion rule. The spectrum hole detection probability further decreases in the Rayleigh fading but increases in multi-bands.

1 System Model and Analysis

1.1 System model

The system model to sense the spectrum of the primary system is shown in Fig. 1. The cognitive radio networks consist of the primary system and the secondary system. In Fig. 1, R_s is the radius of the secondary system sensing region and R is the distance from the primary user to the secondary user. The secondary user senses the region around itself to avoid interfering with the primary user within this area. It means that the secondary user will interfere with the primary user inside the region when they transmit at the same time. However, the communication of the primary user will not be interfered with anyway as long as it is outside of this region. Some secondary users which are close to each other can sense the same region to offer multi-users diversity to improve detection accuracy when facing fading and hidden terminal problems.

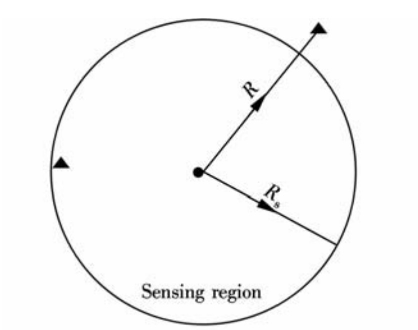

Fig. 1 System model to sense the spectrum of primary system

1.2 Analysis of spectrum hole detection probability

The conventional spectrum sensing objective is to figure out the on-off status of the primary user inside the sensing region ($R < R_s$), we have

$$\begin{aligned} &\text{A: } y(m) = n(m) \qquad m = 1, 2, \ldots, M-1 \\ &\text{B: } y(m) = hs(m) + n(m) \qquad m = 1, 2, \ldots, M-1 \end{aligned} \tag{1}$$

where A denotes the event that the primary user is inactive; B denotes the event that the primary user is active; $y(m)$ is the received signal at the secondary user; $s(m)$ is the signal from the primary user located at the edge of the sensing region; M is the number of samples. The parameter is $h = g/R^{\alpha}$, where α denotes the path loss exponent and g denotes the multi-path fading factor. The primary transmit power is denoted by p_s and the noise power is denoted by p_n. The target average primary-signal-to-noise-ratio (PSNR) at the secondary detector is given by $\bar{\gamma} = E\left(\left(\frac{p_s}{p_n}\right)\frac{g}{R^{\alpha}}\right)$.

In the energy detection case, the test statistics is expressed by $T(y) = \sum_{0}^{M-1}[y(m)]^2/M$, and it is an estimate of the signal power by scaling the energy detector with sensing time. It also subjects to a normal distribution in two hypotheses when the sampling number is big enough.

$$\begin{aligned} &\text{A: } T \sim N\left(p_n, \sqrt{\frac{2}{M}}p_n\right) \\ &\text{B: } T \sim N\left(p_n + p_n\bar{\gamma}, \sqrt{\frac{2}{M}}(p_n + p_n\bar{\gamma})\right) \end{aligned} \tag{2}$$

The spectrum hole detection probability calculated in the conventional way can be denoted as

$$P_{cd} = P(\text{A})(1 - P(\text{B} \mid \text{A})) \tag{3}$$

where $P(\text{A})$ is the probability of the primary user spectrum being idle and $P(\text{B} \mid \text{A})$ is the conventional false alarm probability.

Using the same practical scenario in Ref. [15], there exists a primary user in a circular observed window, of which the area is πd^2, $d > R_s$. The primary user outside of the sensing region ($R > R_s$) can be detected by the secondary user; i. e., the SFA problem occurs and the spectrum hole detection probability of the sensing region ($R < R_s$) is lost because the secondary user cannot tell the location of the primary user and consider that the primary user is active inside the sensing region. Following the same procedure in Ref. [15], we have

$$\begin{aligned} &\text{C: } \begin{cases} y(m) = n(m) & m = 1, 2, \ldots, M-1 \\ y(m) = hs_{\text{out}}(m) + n(m) & m = 1, 2, \ldots, M-1 \end{cases} \\ &\text{D: } y(m) = hs_{\text{in}}(m) + n(m) \qquad m = 1, 2, \ldots, M-1 \\ &\text{E: } y(m) = hs_{\text{out}}(m) + n(m) \qquad m = 1, 2, \ldots, M-1 \end{aligned} \tag{4}$$

where C denotes that the spectrum hole within the sensing region is existent, and D denotes that the spectrum hole within the sensing region is nonexistent. Additionally, state C consists of A and E, which represents that the primary user is inactive and the primary user is transmitting outside the sensing region, respectively. $s_{\text{in}}(m)$ denotes the signal of the primary user which is active inside the sensing region, and $s_{\text{out}}(m)$ denotes the signal of the primary user which is active outside the sensing region. For the secondary user, the lost quantity of the spectrum hole detection probability caused by the SFA is denoted as

$$P_{\mathrm{ld}} = P(\mathrm{B})P(\mathrm{A} \mid \mathrm{E}) \tag{5}$$

The mechanism to calculate the spectrum hole detection probability can be derived [15] as

$$P_{\mathrm{nd}} = P_{\mathrm{cd}} + P_{\mathrm{ld}} = P(\mathrm{A})(1 - P(\mathrm{B} \mid \mathrm{A})) + P(\mathrm{B})(P(\mathrm{A} \mid \mathrm{E})) = (1-p)(1-P_{\mathrm{f}}) + p\int_{R_{\mathrm{s}}}^{d}\int_{0}^{+\infty}(1 - P_{\mathrm{d}}(R,\gamma))f(\gamma)f(R)\mathrm{d}\gamma\mathrm{d}R \tag{6}$$

where p is the activity probability of the primary user; γ is the instantaneous signal-to-noise-ratio (SNR) with the multi-path fading factor g; P_{f} is the conventional system false alarm probability; $P_{\mathrm{d}}(R,\gamma)$ is the conventional system detection probability under path loss as well as multi-path fading; $f(R)$ is the probability density function (PDF) of the primary user location, which is given by $f(R) = 2R/d^2$; and $f(\gamma)$ is the PDF of the instantaneous SNR with multi-path fading factor g.

Comparing Eq. (6) and Eq. (3), it shows that the spectrum hole detection probability calculated in this mechanism is higher than the spectrum hole detection probability calculated in the conventional way. The available spectrum hole probability provided by the primary system is derived as

$$P(\mathrm{C}) = P(\mathrm{A}) + P(\mathrm{E}) = (1-p) + p\int_{R_{\mathrm{s}}}^{d} f(R)\mathrm{d}R = (1-p) + p\int_{R_{\mathrm{s}}}^{d}\left(\frac{2R}{d^2}\right)\mathrm{d}R = (1-p) + p\left(1 - \frac{R_{\mathrm{s}}^2}{d^2}\right) = 1 - \frac{pR_{\mathrm{s}}^2}{d^2} \tag{7}$$

Substituting $f(R)$ and Eq. (7) into Eq. (6), we have

$$P_{\mathrm{nd}} = 1 - (1-p)P_{\mathrm{f}} - (1 - P(\mathrm{C}))\cdot\left(1 + \frac{2}{R_{\mathrm{s}}^2}\int_{R_{\mathrm{s}}}^{R_{\mathrm{s}}\sqrt{p/(1-P(\mathrm{C}))}}\int_{0}^{+\infty}P_{\mathrm{d}}(R,\gamma)f(\gamma)R\mathrm{d}\gamma\mathrm{d}R\right) \tag{8}$$

When the false alarm probability P_{f} and the detection probability $P_{\mathrm{d}}(R_{\mathrm{s}})$ in the sensing region are given, the radius of sensing region R_{s} can be determined according to $P_{\mathrm{d}}(R_{\mathrm{s}})$ and P_{f}. Therefore, the spectrum hole detection probability can be calculated by Eq. (8).

2 Expressions in Typical Scenarios

2.1 Multi-users cooperative sensing under path loss

In order to derive the spectrum hole detection probability under multi-users cooperative sensing, the simple logic fusion OR and AND rules are applied.

We assume that each single user has the same false alarm probability P_{f} and detection probability P_{d} under uncooperative situations. According to Eq. (2), we have

$$P_{\mathrm{f}} = Q\left(\frac{\lambda - \mu_0}{\sigma_0}\right) \tag{9}$$

$$P_{\mathrm{d}}(R) = Q\left(\frac{\lambda - \mu_1}{\sigma_1}\right) \tag{10}$$

where $\mu_0 = p_{\mathrm{n}}$, and $\sigma_0 = \sqrt{\frac{2}{M}}p_{\mathrm{n}}$; $\mu_1 = p_{\mathrm{n}} + \frac{p_{\mathrm{s}}}{R^{\alpha}}$, and $\sigma_1 = \sqrt{\frac{2}{M}}\left(p_{\mathrm{n}} + \frac{p_{\mathrm{s}}}{R^{\alpha}}\right)$; λ is the detection threshold.

The system false alarm probability and the system detection probability of OR and AND rules are denoted as G_{fo}, G_{fa} and G_{do}, G_{da}, respectively.

$$G_{\mathrm{fa}} = P_{\mathrm{f}}^n = Q\left(\frac{\lambda - \mu_0}{\sigma_0}\right)^n \tag{11}$$

$$G_{\mathrm{da}} = P_{\mathrm{d}}(R_{\mathrm{s}})^n = Q\left(\frac{\lambda - \mu_1}{\sigma_1}\right)^n \tag{12}$$

$$G_{\mathrm{fo}} = 1 - (1 - P_{\mathrm{f}})^n = 1 - \left(1 - Q\left(\frac{\lambda - \mu_0}{\sigma_0}\right)\right)^n \tag{13}$$

$$G_{\mathrm{do}} = 1 - (1 - P_{\mathrm{d}}(R_{\mathrm{s}}))^n = 1 - \left(1 - Q\left(\frac{\lambda - \mu_1}{\sigma_1}\right)\right)^n \tag{14}$$

where n is the number of the cooperative secondary users. Substituting Eqs. (11) to (14) into Eq. (8), the spectrum hole detection probability of cooperative sensing with the logic fusion OR and AND rules under path loss can be derived as

$$P_{\mathrm{ndo}} = 1 - (1-p)\left(1 - \left(1 - Q\left(\frac{\lambda - \mu_0}{\sigma_0}\right)\right)^n\right) - (1 - P(\mathrm{C}))\cdot\left(1 + \frac{2}{R_{\mathrm{s}}^2}\int_{R_{\mathrm{s}}}^{R_{\mathrm{s}}\sqrt{p/(1-P(\mathrm{C}))}}\left(1 - \left(1 - Q\left(\frac{\lambda - \mu_1}{\sigma_1}\right)\right)^n\right)R\mathrm{d}R\right) \tag{15}$$

$$P_{\mathrm{nda}} = 1 - (1-p)Q\left(\frac{\lambda - \mu_0}{\sigma_0}\right)^n - (1 - P(\mathrm{C}))\cdot\left(1 + \frac{2}{R_{\mathrm{s}}^2}\int_{R_{\mathrm{s}}}^{R_{\mathrm{s}}\sqrt{p/(1-P(\mathrm{C}))}}Q\left(\frac{\lambda - \mu_1}{\sigma_1}\right)^n R\mathrm{d}R\right) \tag{16}$$

2.2 Single-user sensing under path loss with Rayleigh

Taking the Rayleigh fading into consideration with path loss fading, the PDF of the SNR under the Rayleigh fading with mean u obeys the exponential distribution. We have

$$f(\gamma) = u\mathrm{e}^{-u\gamma} \tag{17}$$

Substituting Eq. (17) into Eq. (8), the spectrum hole detection probability of the single-user sensing under path loss as well as the Rayleigh fading is derived as

$$P_{\mathrm{ndr}} = 1 - (1-p)P_{\mathrm{f}} - (1 - P(\mathrm{C}))\cdot\left(1 + \frac{2}{R_{\mathrm{s}}^2}\int_{R_{\mathrm{s}}}^{R_{\mathrm{s}}\sqrt{p/(1-P(\mathrm{C}))}}\int_{0}^{\infty}Q\left(\frac{\lambda - \mu}{\sigma}\right)u\mathrm{e}^{-u\gamma}R\mathrm{d}\gamma\mathrm{d}R\right) \tag{18}$$

where $\mu = p_n + \frac{p_n \gamma}{R^\alpha}$, $\sigma = \sqrt{\frac{2}{M}}\left(p_n + \frac{p_n \gamma}{R^\alpha}\right)$.

2.3 Single-user sensing under path loss in multi-bands

We assume that the multi-bands consists of k sub-bands. Each sub-band activity probability is p and it is detected by different secondary users. There is a coordinating center to collect the on-off information of all the sub-bands and allocate the available bands to the secondary user. The false alarm probability and the detection probability in each sub-band are the same as those in the narrow band situation. The spectrum hole detection probability of single-user sensing under path loss in multi-bands is derived:

$$P_{\text{ndkm}} = 1 - (1-p^k)Q\left(\frac{\lambda-\mu_0}{\sigma_0}\right)^k - (1-P_k(\text{C})) \cdot \left(1 + \frac{2}{R_s^2}\int_{R_s}^{R_s\sqrt{p^k/(1-P_k(\text{C}))}} Q\left(\frac{\lambda-\mu_1}{\sigma_1}\right)^k R\text{d}R\right) \tag{19}$$

where $P_k(\text{C}) = 1 - p^k R_s^2/d^2$.

The spectrum hole detection probability exists as long as one sub-band is idle and is correctly detected. Besides, it exists when all the sub-bands are occupied but at least one of them is detected to be idle by mistake.

For comparision, the spectrum hole detection probability in the narrow band with the same available spectrum hole probability $P_k(\text{C})$ is denoted as

$$P_{\text{ndk}} = 1 - (1-p^k)Q\left(\frac{\lambda-\mu_0}{\sigma_0}\right) - (1-P_k(\text{C})) \cdot \left(1 + \frac{2}{R_s^2}\int_{R_s}^{R_s\sqrt{p^k/(1-P_k(\text{C}))}} Q\left(\frac{\lambda-\mu_1}{\sigma_1}\right) R\text{d}R\right) \tag{20}$$

3 Simulation and Results

For simulation, it is assumed that the primary user signal is a digital television (DTV) signal which is the same as in Ref. [15]. The sampling frequency of the primary system is 6 MHz, $M = 28\,000$, SNR is -16 dB, $\alpha = 3.5$, $p = 0.7$, $P_f = 0.1$, $P_d(R_s) = 0.95$, and the noise power density is -174 dbm/Hz.

As shown in Fig. 2, given the same available spectrum hole probability, the primary user activity probability, the sensing region, the false alarm probability and the detection probability, the spectrum hole detection probability of the secondary user under path loss fading is inversely proportional to the sampling times; i. e., the fewer the sampling times are, the higher the spectrum hole detection probability is. The results in Fig. 2 show that the missed detection probability will increase when the sampling times decrease. It means that more spectrums will be taken by the secondary user as the spectrum hole.

The spectrum hole detection probability of the secondary

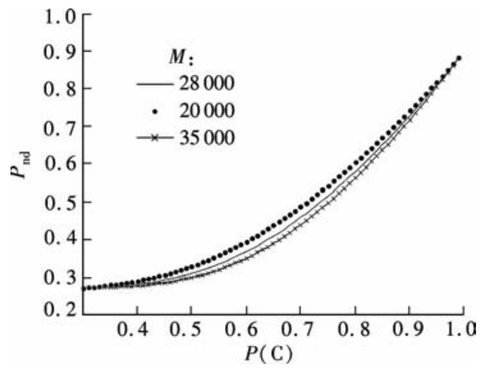

Fig. 2 P_{nd} vs. $P(\text{C})$ with different sampling times when R_s is fixed

user and the available spectrum hole probability provided by the primary user are compared in Fig. 3. Obviously, the detection probability of the secondary user is always less than the available spectrum hole probability provided by the primary user. It means that part of the available spectrum hole probability still gets lost due to the false alarm probability and the missed detection probability. Both probabilities decrease as the radius ratio increases. When the radius ratio R_s/d is 0, the outside space of the sensing region is far larger than the space of the sensing region, so the probabilities under both situations approach 1. Contrarily, if $R_s/d = 1$, the sensing region is very large, and the probabilities approach $1-p$, which is the idle probability of the primary user.

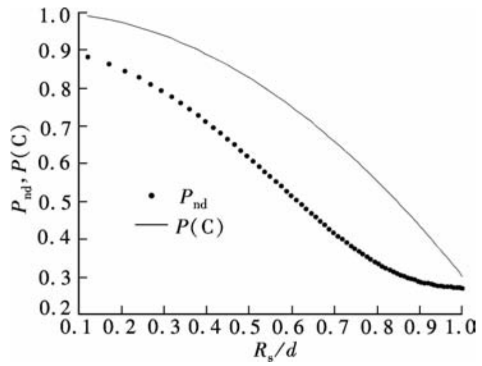

Fig. 3 P_{nd} and $P(\text{C})$ vs. space ratio

The impact of cooperative sensing on the spectrum hole detection probability is shown in Fig. 4. Because the spectrum hole detection probability is the main focus, each independent secondary user is assumed to have the identical sensing ability; i. e., the false alarm probability is the same among local users, and the local false alarm probability under a cooperative sensing situation is the same as that under a single-user sensing situation. So is the detection probability. The number of the cooperative secondary users is four, only when the path loss fading is taken into consideration. When the logic OR fusion rule is applied, the lost spectrum detection probability increases because the system false alarm probability and the system detection probability both get increased, so the spectrum hole detection probability of the secondary user is decreased. When the logic AND fusion rule is applied, the lost spectrum hole detection probability decreases because the system false alarm probability and the detection probability both get decreased, so the spectrum hole detection probability of the secondary user is increased. It is actually a trade-off between the QoS and the spectrum utilization. When the OR rule cooperation sensing increases the system detection probability and the system false alarm probability, the primary user will face fewer interferences, but the secondary user will lose more spectrum hole. On the contrary, when the AND rule cooperation decreases the system detection probability and the system false alarm probability, the primary system will face more interferences, but the secondary user will find more spectrum hole.

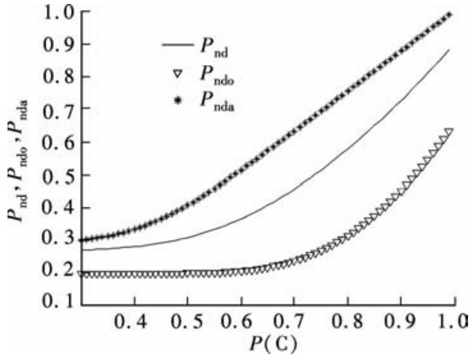

Fig. 4 P_{nd}, P_{ndo} and P_{nda} vs. $P(C)$

The comparison between the spectrum hole detection probability of single-user sensing under pure path loss and the spectrum hole detection probability of single-user sensing under path loss as well as the Rayleigh fading is shown in Fig. 5. The mean of the Rayleigh fading is 1. Given the same network parameters, it shows that the extra multi-path fading further wears down the spectrum hole detection probability.

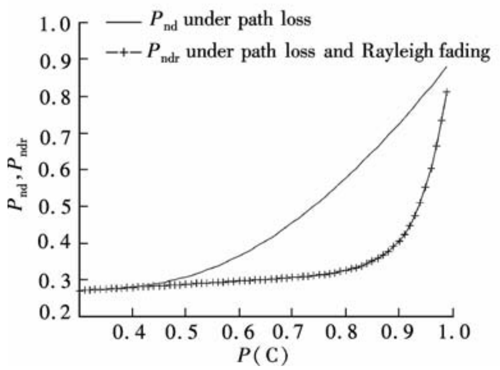

Fig. 5 P_{nd} and P_{ndr} vs. $P(C)$

The spectrum hole detection probability of single-user sensing under path loss in multi-bands and the spectrum hole detection probability of single-user sensing under path loss in the narrow band is shown in Fig. 6. The results show that when the multi-bands situation is considered, more spectrum hole will be found by the secondary user in the frequency domain, and the spectrum hole detection probability will further increase when the number of sub-bands is three, which consequently leads to increasing the system complexity and expenses.

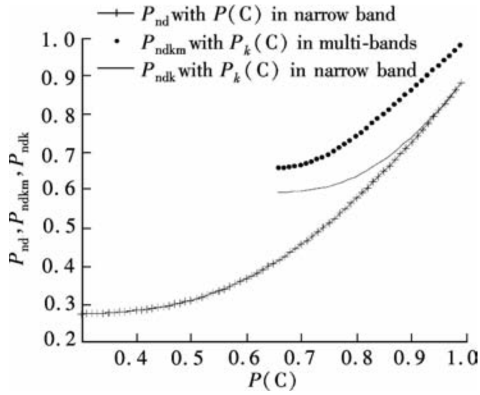

Fig. 6 P_{nd}, P_{ndkm} and P_{ndk} vs. $P(C)$

4 Conclusion

In this paper, a spectrum hole detection mechanism for cognitive radio without the SFA is proposed. The spectrum hole detection probability of multi-users cooperative sensing, single-user sensing and single-user sensing in multi-bands are derived under several typical scenarios. The spectrum hole detection probability calculated in this mechanism is higher than the one calculated in the conventional way. Simulation results show that the spectrum hole detection probability is inversely proportional to the sampling times and the area of the sensing region. It also shows that the multi-users sensing with the AND logic fusion rule is superior to the single-user sensing, and the multi-users sensing with the OR logic fusion rule is inferior to the single-user sensing when the local secondary user sensing ability is identical. The spectrum hole detection probability under path loss as well as the Rayleigh fading is lower than the spectrum hole detection probability only under path loss; the spectrum hole detection probability of single-user sensing in multi-bands is higher than the one in the narrow band.

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适用于认知无线电网络典型场景的空闲频谱检测方法

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摘要:针对认知无线网络若干典型场景,提出一种新的空闲频谱检测方法以提高其检测概率. 通过消除空间虚警对频谱感知的影响,得到认知用户在路径损耗和多径衰落作用时的空闲频谱检测概率,同时得到多用户合作检测以及单用户在宽带环境检测时的空闲频谱检测概率并进行对比. 理论分析和仿真结果表明:所提方法的空闲频谱检测概率与采样次数以及检测区域面积成反比;采用"与"融合规则进行多用户检测时效果好于单用户检测,采用"或"融合规则时则相反;瑞利衰落会使检测概率进一步减小,而增加带宽则会使其大大提高.

关键词:空闲频谱;频谱检测;多用户检测;空间虚警概率

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