Optimum Detection Location-Based Cooperative Spectrum Sensing in Cognitive Radio

Hongtao ZHANG[1], Xiaoxiang WANG[1], Geng-Sheng KUO[2], Thomas Michael BOHNERT[3]

[1]Key Laboratory of Universal Wireless Communication, Ministry of Education,
Beijing University of Posts and Telecommunications, Beijing 100876, P.R.China
[2]National Chengchi University, Taipei, Taiwan
[3]SAP Research CEC Zurich, Switzerland

htzhang@bupt.edu.cn

Abstract. *Cognitive radio arises as a hot research issue in wireless communications recently, attributed to its capability of enhancing spectral efficiency and catering for the growing demand for bandwidth. As a good embodiment of cognitive radio's unique feature, i.e. making use of every bit spectral resource, spectrum sensing plays a vital role in the implementation of cognitive radio. To alleviate negative effect on cooperative spectrum sensing brought by bit errors, we introduce a novel concept, i.e. Optimum Detection Location (ODL) and present two algorithms of different computational complexity for locating ODL, together with an ODL-Based cooperative spectrum sensing scheme, with the motivation to exploit the gain derived from geographic advantages and multiuser diversity. Numerical and simulation results both demonstrate that our proposed spectrum sensing scheme can significantly improve the sensing performance in the case of reporting channel with bit errors.*

Keywords

Cognitive radio, spectrum sensing, Wireless Region Area Network (WRAN), Optimum Detection Location (ODL).

1. Introduction

Recently, the misconception that there is scarcity of spectrum for wireless communication is provoked mostly by the intense competition for spectrum usage. However, studies from the Federal Communication Commission (FCC) show that the utilization of licensed spectrum only ranges from 15% to 85% [1]. In order to use this spectrum (white space) to the largest extent, IEEE 802.22 Wireless Region Area Network (WRAN) Group is chartered with the development of a CR-based standard for wireless regional area networks (WRAN) [2].

In cognitive radio systems, secondary users can use the licensed spectrum as long as the primary user is absent. Therefore spectrum sensing plays an important role in the implementation of cognitive radio. To improve the sensing reliability, cooperative spectrum sensing has been proposed to exploit multiuser diversity in sensing process [3]. It is usually performed in two successive stages: sensing and reporting. In the sensing stage, every cognitive user performs spectrum sensing individually. In the reporting stage, all the local sensing observations are reported to a common receiver and the latter will make a final decision on the absence or the presence of the primary user.

To the best of our knowledge, most works concerning cooperative spectrum sensing are based on the assumption of ideal reporting channels [4]-[6]. In practice, bit errors are unavoidable due to adverse factors introduced along transmission path, and they will cause negative impact to the performance of cooperative spectrum sensing. In this paper, we will take bit errors in reporting channels into account and propose an optimum detection location-based cooperative spectrum sensing scheme to improve the sensing performance. Our proposed cooperative spectrum sensing scheme is based on a novel concept, i.e. Optimum Detection Location (ODL) brought up in this paper, which represents the location where the secondary user has the best sensing performance. Besides, we provide two algorithms for fixing on ODL.

The rest of the paper is organized as follows. In Section 2, system model, energy detection and cooperative spectrum sensing with reporting are studied. In Section 3, we propose two algorithms to find the optimum detection location. In Section 4, the ODL-based cooperative spectrum sensing scheme is proposed and OR fusion rule scheme is analyzed theoretically. Simulation results are shown and discussed in Section 5. Finally, we draw our conclusions in Section 6.

2. Cooperative Spectrum Sensing

2.1 System Model

In this paper, we adopt the system model based on the IEEE 802. 22 WRAN deployment scenario, as is illustrated in Fig. 1. The system model includes a TV broadcast station as the primary user, a WRAN base station (BS) as the secondary base station and customer-premises equipments (CPEs) as the secondary users. The primary user and the secondary BS are far apart and the secondary users are uniformly randomly distributed within the coverage radius of the secondary BS.

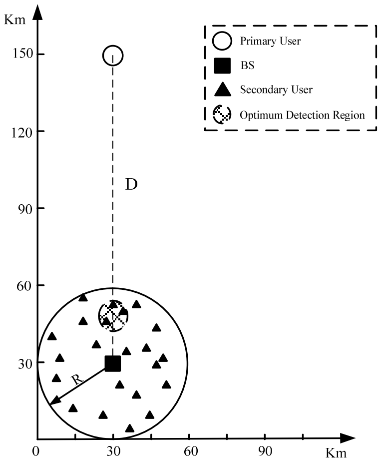

Fig. 1. The topology of WRAN.

For simplicity, we assume that all channels only experience path loss. Thus the primary user's signal to the noise ratio received at each secondary user is computed by,

$$\gamma_{1,i} = \frac{P_u \beta}{\sigma^2 d_{1,i}^{\ \alpha}} \quad \text{for } i = 1, 2, \ldots, M \tag{1}$$

where M is the total number of CPEs in the network. Likewise, i-th secondary user's signal to the noise ratio received at BS is computed by

$$\gamma_{2,i} = \frac{P_s \beta}{\sigma^2 d_{2,i}^{\ \alpha}} \quad \text{for } i = 1, 2, \ldots, M \tag{2}$$

where $d_{1,i}$ is the distance between PU and i-th secondary user, and $d_{2,i}$ is the distance between BS and i-th secondary user. P_u and P_s is the signal power of PU and secondary user respectively. Noise power σ^2 is identical in WRAN system, and α is the path loss exponent factor and β is a scalar.

2.2 Energy Detection

Energy detection is suboptimal but is simple to implement. For implementation simplicity, we restrict ourselves to energy detection in the spectrum sensing. The test statistic for energy detector is given by

$$T(y) = \frac{1}{N}\sum_{n=1}^{N} | y(n) |^2 \tag{3}$$

where $y(n)$ denotes the sampled received signal at secondary user. Under H_0, i.e. the absence of PU, $y(n)$ equals noise $u(n)$, which is Gaussian iid random process with zero mean and variance σ^2. For a large N, PDF of $T(y)$ can be approximated by a Gaussian distribution using central limit theorem. For a chosen threshold, the probability of false alarm is given by

$$P_f(\varepsilon) = P_r(T(y) > \varepsilon \mid H_0) = Q\left[(\frac{\varepsilon}{\sigma^2} - 1)\sqrt{N} \right]. \tag{4}$$

Under H_1, i.e. the presence of PU, $y(n)$ is the sum of PU's signal $s(n)$ and noise $u(n)$. Assume $s(n)$ is a complex PSK modulated signal and we defined $\gamma_1 = \sigma_s^2/\sigma^2$ as the primary user's signal power to noise ratio received at the secondary user. For a chosen threshold, the probability of detection is given by

$$P_d(\varepsilon) = P_r(T(y) > \varepsilon \mid H_1) = Q\left[(\frac{\varepsilon}{\sigma^2} - \gamma_1 - 1)\sqrt{\frac{N}{2\gamma_1 + 1}} \right]. \tag{5}$$

Note that PU's signal power is especially weak at secondary users in cognitive radio networks [7], so $2\gamma_1+1$ can be neglected in (5), and (5) can be rewritten as

$$P_d(\varepsilon) = Q\left[(\frac{\varepsilon}{\sigma^2} - \gamma_1 - 1)\sqrt{\frac{N}{2\gamma_1 + 1}} \right] \approx Q\left[(\frac{\varepsilon}{\sigma^2} - \gamma_1 - 1)\sqrt{N} \right]. \tag{6}$$

2.3 Cooperative Spectrum Sensing with Reporting Errors

Cooperative spectrum sensing is usually employed in cognitive radio networks to overcome hidden node problem and improve sensing reliability. To minimize transmission overhead of sensing data, we assume that CPEs perform energy detection independently and then forward their one-bit decision to BS. In practice, the reporting channels may suffer from bit errors which will deteriorate the performance of cooperative spectrum sensing. For brevity, we will start to deal with this problem in the case when there is only one CPE in the WRAN. Assuming BPSK, the bit-error rate P_b is given by

$$P_b(\gamma_2) = Q(\sqrt{2\gamma_2}) \tag{7}$$

where $Q(.)$ is the Q-function. γ_2 stands for the secondary user's signal to the noise ratio received at BS, which is expressed as

$$\gamma_2 = \frac{P_s \beta}{\sigma^2 d_2^{\alpha}}. \tag{8}$$

Therefore, we can derive the probability of detection P_d^s in WRAN as

$$P_d^s = \left(1 - P_d\right) P_b + P_d \left(1 - P_b\right) = P_d + P_b - 2P_d P_b. \tag{9}$$

Similarly, the probability of false alarm P_f^s is given by

$$P_f^s = P_f + P_b - 2P_f P_b. \tag{10}$$

Combining P_f, P_d in (4), (6) respectively, we have

$$P_f = Q\left[(\frac{\varepsilon}{\sigma^2}-1)\cdot\sqrt{N}\right]+Q(\sqrt{2\gamma_2}) -2Q\left[(\frac{\varepsilon}{\sigma^2}-1)\cdot\sqrt{N}\right]\cdot Q(\sqrt{2\gamma_2}) \tag{11}$$

$$P_d = Q\left[(\frac{\varepsilon}{\sigma^2}-\gamma_1-1)\cdot\sqrt{N}\right]+Q(\sqrt{2\gamma_2}) -2Q\left[(\frac{\varepsilon}{\sigma^2}-\gamma_1-1)\cdot\sqrt{N}\right]\cdot Q(\sqrt{2\gamma_2}) \tag{12}$$

3. Optimum Detection Location

According to the two stages in cooperative spectrum sensing, system sensing performance in a WRAN is determined by two factors: one is the performance of single node spectrum sensing; the other is the bit-error rate of reporting channels. Since both of the two factors are impacted by signal to noise ratio, hence the veracity of every CPE's sensing result received by BS varies according to their deployment location in the network. Here, we define the location where CPE has the best performance as ODL.

3.1 ODL Modeling

Lemma. Given that ODL exists in the network, it must situate in the line which connects PU and BS.

Proof: Convert P_d^s in (9) to

$$P_d^s = P_d + P_b - 2P_d P_b = P_b + P_d\cdot(1-2P_b)$$

with d_2 fixed, γ_2 and P_b is constant, and

$$\because\ P_b \le 0.5\ ,\forall\gamma_2\ge 0$$

$$\therefore\ (1-2P_b)\ge 0$$

Since $Q(x)$ is a decreasing function of x, P_d is monotonous increasing function of γ_1, and a monotonous decreasing function of d_1. For a specific d_2, it is obvious that we have the minimum d_1 when CPE lies in the straight line connecting PU and BS.

Thus, the searching region for ODL can be limited in the straight line mentioned above. From the secondary users' perspective, a guaranteed low P_f is desired so that they will have a high capacity. Thus we fix the P_f of the network at their desired value and then maximize P_d as much as possible.

Under this constant false alarm rate (CFAR) requirement, the optimization problem for locating ODL is expressed as

$$\max\quad P_d = Q\left[(\frac{\varepsilon}{\sigma^2}-\gamma_1-1)\cdot\sqrt{N}\right]+Q(\sqrt{2\gamma_2}) -2Q\left[(\frac{\varepsilon}{\sigma^2}-\gamma_1-1)\cdot\sqrt{N}\right]\cdot Q(\sqrt{2\gamma_2}) \tag{13}$$

s.t.

$$P_f = Q\left[(\frac{\varepsilon}{\sigma^2}-1)\cdot\sqrt{N}\right]+Q(\sqrt{2\gamma_2}) -2Q\left[(\frac{\varepsilon}{\sigma^2}-1)\cdot\sqrt{N}\right]\cdot Q(\sqrt{2\gamma_2}) = \overline{P}_f \tag{14}$$

$$d_1+d_2 = D\,,\quad 0\le\ d_2\le R \tag{15}$$

$$\gamma_1 = \frac{P_u\beta}{d_1^{\ \alpha}}\,, \tag{16}$$

$$\gamma_2 = \frac{P_s\beta}{d_2^{\ \alpha}}\,. \tag{17}$$

3.2 An Optimum Algorithm for Solving ODL

The classical method for the above constrained optimization problem is the standard Lagrange multiplier algorithm. We have the Lagrange function for the problem as

$$\Omega = P_d - \rho_1\cdot(P_f-\overline{P}_f)-\rho_2(d_1+d_2-D) \tag{18}$$

where ρ_1 and ρ_2 are multipliers. Then, we differentiate Ω with respect to γ_1, γ_2 and ε, and can obtain equations (19)-(21)

$$\frac{\partial\Omega}{\partial\gamma_1} = \sqrt{\frac{N}{2\pi}}\cdot EXP(-\frac{N(\frac{\varepsilon}{\sigma^2}-\gamma_1-1)^2}{2})\cdot\left[1-2Q(\sqrt{2\gamma_2})\right] -\rho_2\cdot\frac{(P_u\beta)^{1/\alpha}}{\alpha}\cdot\gamma_1^{-(\frac{1}{\alpha}+1)} \tag{19}$$

$$\frac{\partial\Omega}{\partial\gamma_2} = \sqrt{\frac{1}{\gamma_2\pi}}\cdot EXP(-\gamma_2)\cdot\left\{Q[(\frac{\varepsilon}{\sigma^2}-\gamma_1-1)\cdot\sqrt{N}] -\rho_1\cdot Q\left[(\frac{\varepsilon}{\sigma^2}-1)\cdot\sqrt{N}\right]+\frac{\rho_1-1}{2}\right\}-\rho_2\cdot\frac{(P_s\beta)^{1/\alpha}}{\alpha}\cdot\gamma_2^{-(\frac{1}{\alpha}+1)} \tag{20}$$

$$\frac{\partial\Omega}{\partial\varepsilon} = \frac{1}{\sigma^2}\sqrt{\frac{N}{2\pi}}\cdot\left[1-2Q(\sqrt{2\gamma_2})\right]\cdot[EXP(-\frac{N(\frac{\varepsilon}{\sigma^2}-\gamma_1-1)^2}{2}) -\rho_1\cdot EXP(-\frac{N(\frac{\varepsilon}{\sigma^2}-1)^2}{2})] \tag{21}$$

Forcing $\partial\Omega/\partial\gamma_1$, $\partial\Omega/\partial\gamma_2$, $\partial\Omega/\partial\varepsilon$ to be zero, with constraints (14)-(17), we can convert the optimization problem to

$$\frac{\partial\Omega}{\partial\gamma_1}=0,\ \ \frac{\partial\Omega}{\partial\gamma_2}=0,\ \ \frac{\partial\Omega}{\partial\varepsilon}=0\,, \tag{22}$$

$$s.t.\quad P_f = \overline{P}_f\,, \tag{23}$$

$$d_1+d_2 = D\,,\ \ 0\le\ d_2\le R\,, \tag{24}$$

$$\gamma_1 = \frac{P_u\beta}{d_1^{\ \alpha}}\,, \tag{25}$$

$$\gamma_2 = \frac{P_s\beta}{d_2^{\ \alpha}}\,. \tag{26}$$

First, we will start with the range of γ_2, which is greatly associated with the objective of our optimization d_2. From $P_f = \overline{P}_f$, we have

$$\sqrt{N}\left(\frac{\varepsilon}{\sigma^2}-1\right) = Q^{-1}\left(\frac{\overline{P}_f - Q(\sqrt{2\gamma_2})}{1-2Q(\sqrt{2\gamma_2})}\right). \quad (27)$$

Since the range of x in $Q^{-1}(x)$ is (0, 1), then

$$\frac{\overline{P}_f - Q(\sqrt{2\gamma_2})}{1-2Q(\sqrt{2\gamma_2})} \in (0,1) \;\Rightarrow\; \gamma_2 \in \left(\frac{\left(Q^{-1}(P_f)\right)^2}{2}, +\infty\right). \quad (28)$$

Equation (28) implies that the constraint $P_f = \overline{P}_f$ requires γ_2 to be large enough, i.e. CPE should not locate far apart from BS. On the other hand, the topology limit of WRAN, i.e. $0 < d_2 < R$, is expressed by

$$\gamma_2 \in \left(\frac{P_s\beta}{R^\alpha}, +\infty\right). \quad (29)$$

Taking these two aspects in (28)-(29) into account, the range of γ_2 can be denoted as $\gamma_2 \in \Upsilon$, where

$$\Upsilon = \begin{cases} \left(\frac{\left(Q^{-1}(P_f)\right)^2}{2}, +\infty\right), & \text{if } \frac{\left(Q^{-1}(P_f)\right)^2}{2} \ge \frac{P_s\beta}{R^\alpha} \\ \left(\frac{P_s\beta}{R^\alpha}, +\infty\right) & \text{otherwise} \end{cases} \quad (30)$$

For notation brevity, we convert variables ε, γ_1, ρ_1, ρ_2 into the function of $F_1(\gamma_2)$, $F_2(\gamma_2)$, $F_3(\gamma_2)$, and construct a function from (19) and (20) as

$$\begin{aligned} G(\gamma_2) &= \gamma_2^{-(\frac{1}{\alpha}+1)} \cdot P_s^{1/\alpha} \cdot \frac{\partial\Omega}{\partial\gamma_2} - \gamma_1^{-(\frac{1}{\alpha}+1)} \cdot P_u^{1/\alpha} \cdot \frac{\partial\Omega}{\partial\gamma_1} \\ &= \gamma_2^{\frac{1}{\alpha}+1} \cdot P_s^{1/\alpha} \sqrt{\frac{1}{\gamma_2\pi}} \cdot EXP(-\gamma_2) \cdot \Big\{ Q[F_1(\gamma_2) - \sqrt{N}F_2(\gamma_2)] \\ &\quad -\frac{1}{2} + F_3(\gamma_2) \cdot \left\{\frac{1}{2} - Q\left[F_1(\gamma_2)\right]\right\}\Big\} - P_u^{1/\alpha} \cdot [F_2(\gamma_2)]^{\frac{1}{\alpha}+1} \sqrt{\frac{N}{2\pi}} \\ &\quad \cdot EXP\left(-\frac{\left(F_1(\gamma_2) - \sqrt{N} \cdot F_2(\gamma_2)\right)^2}{2}\right) \cdot \left[1 - 2Q(\sqrt{2\gamma_2})\right] \end{aligned} \quad (31)$$

where

$$\sqrt{N}\left(\frac{\varepsilon}{\sigma^2}-1\right) = F_1(\gamma_2) = Q^{-1}\left(\frac{P_f - Q(\sqrt{2\gamma_2})}{1-2Q(\sqrt{2\gamma_2})}\right),$$

$$\gamma_1 = F_2(\gamma_2) = \left(\frac{D}{(P_u\beta)^{1/\alpha}} - \left(\frac{P_s}{P_u \cdot \gamma_2}\right)^{1/\alpha}\right)^{-\alpha},$$

$$\begin{aligned} \rho_1 = F_3(\gamma_2) &= EXP\left(-\frac{N(\frac{\varepsilon}{\sigma^2} - \gamma_1 - 1)^2}{2}\right) / EXP\left(-\frac{N(\frac{\varepsilon}{\sigma^2} - 1)^2}{2}\right) \\ &= EXP\left[\frac{\sqrt{N} \cdot F_2(\gamma_2)}{2} \cdot (2F_1(\gamma_2) - \sqrt{N} \cdot F_2(\gamma_2))\right], \end{aligned}$$

$$\begin{aligned} \rho_2 = F_4(\gamma_2) &= \gamma_2^{\frac{1}{\alpha}+1} \sqrt{\frac{1}{\gamma_2\pi}} \cdot EXP(-\gamma_2) \\ &\quad \cdot \left\{ Q[F_1(\gamma_2) - \sqrt{N}F_2(\gamma_2)] - \frac{1}{2} + F_3(\gamma_2) \cdot \left\{\frac{1}{2} - Q\left[F_1(\gamma_2)\right]\right\}\right\}. \end{aligned}$$

The discussion of solving γ_2 from (31) can be divided into three circumstances as follows:

i. If (19)-(20) are satisfied in the range of γ_2, that is

$$G(\gamma_2) = \gamma_2^{-(\frac{1}{\alpha}+1)} \cdot P_s^{1/\alpha} \cdot \frac{\partial\Omega}{\partial\gamma_2} - \gamma_1^{-(\frac{1}{\alpha}+1)} \cdot P_u^{1/\alpha} \cdot \frac{\partial\Omega}{\partial\gamma_1} = 0. \quad (32)$$

We will have $(\gamma_2^1, \gamma_2^2, \ldots, \gamma_2^n) = G^{-1}(0)$, where γ_2^i, $(i = 1, 2, \ldots, n)$ is the solution to $G(\gamma_2) = 0$. Because the extremum of γ_2 derived from Lagrange multiplier algorithm must contain the one leading to the maximum of P_d, thus it is feasible to find out $\hat{\gamma}_2$ corresponding to $P^1_{d\max}$ by substituting γ_2^i, $(i = 1, 2, \ldots, n)$ into (12) and searching for the one that gets the maximum value of P_d. The comparison process can be presented by

$$\begin{aligned} \hat{\gamma}_2 = \underset{i=1,2,\ldots,n}{\arg\max} \Big\{ & Q\left[F_1(\gamma_2^i) - \sqrt{N}F_2(\gamma_2^i)\right] + Q\left(\sqrt{2\gamma_2^i}\right) \\ & -2 \cdot Q\left(\sqrt{2\gamma_2^i}\right) \cdot Q\left[F_1(\gamma_2^i) - \sqrt{N}F_2(\gamma_2^i)\right] \Big\} \end{aligned} \quad (33)$$

and

$$\begin{aligned} P^1_{d\max} = & Q\left[F_1(\hat{\gamma}_2) - \sqrt{N}F_2(\hat{\gamma}_2)\right] + Q\left(\sqrt{2\hat{\gamma}_2}\right) \\ & -2 \cdot Q\left(\sqrt{2\hat{\gamma}_2}\right) \cdot Q\left[F_1(\hat{\gamma}_2) - \sqrt{N}F_2(\hat{\gamma}_2)\right] \end{aligned} \quad (34)$$

The $\hat{d}_2$ corresponding to ODL is

$$\hat{d}_2 = \left(\frac{P_s\beta}{\hat{\gamma}_2}\right)^{1/\alpha}. \quad (35)$$

ii. If $G(\gamma_2) = \gamma_2^{-(\frac{1}{\alpha}+1)} \cdot P_s^{1/\alpha} \cdot \frac{\partial\Omega}{\partial\gamma_2} - \gamma_1^{-(\frac{1}{\alpha}+1)} \cdot P_u^{1/\alpha} \cdot \frac{\partial\Omega}{\partial\gamma_1} > 0, \forall\gamma_2 \in \Upsilon$, it is obvious that $\partial\Omega/\partial\gamma_2 > 0$, $\partial\Omega/\partial\gamma_1 < 0$, implying that the targeted function Ω is a monotonous increasing function of γ_2. The P_d is also a monotonous increasing function of γ_2 in the fact that $\Omega = P_d$. Hence P_d will approach its maximum value when $\gamma_2 \to +\infty$,

$$P^2_{d\max} \to Q(Q^{-1}(P_f) - P_u\beta D^{-\alpha}). \quad (36)$$

In this case, $\hat{d}_2$ corresponding to ODL is denoted by

$$\hat{d}_2 \to 0. \quad (37)$$

iii. If $G(\gamma_2) = \gamma_2^{-(\frac{1}{\alpha}+1)} \cdot P_s^{1/\alpha} \cdot \frac{\partial\Omega}{\partial\gamma_2} - \gamma_1^{-(\frac{1}{\alpha}+1)} \cdot P_u^{1/\alpha} \cdot \frac{\partial\Omega}{\partial\gamma_1} < 0, \forall\gamma_2 \in \Upsilon$, we can easily obtain that P_d is a monotonous decreasing function of γ_2.

$$P_{d\ \max}^{3} \rightarrow \begin{cases} Q\left[\dfrac{\left(Q^{-1}(P_f)\right)^2}{2}\right], & if\ \dfrac{\left(Q^{-1}(P_f)\right)^2}{2} \geq \dfrac{P_s\beta}{R^\alpha} \\ \Theta, & otherwise \end{cases} \tag{38}$$

where

$$\begin{aligned}\Theta = Q\Bigg[& Q^{-1}\left(\frac{P_f - Q(\sqrt{2P_s\beta / R^\alpha})}{1-2Q(\sqrt{2P_s\beta / R^\alpha})}\right) \\ & -\sqrt{\mathrm{N}}\cdot\left(\frac{D}{(P_u\beta)^{1/\alpha}} - \left(\frac{R^\alpha}{P_u\cdot\beta}\right)^{1/\alpha}\right)^{-\alpha}\Bigg] + Q\left(\sqrt{2\frac{P_s\beta}{R^\alpha}}\right) \\ & -2\cdot Q\Bigg[Q^{-1}\left(\frac{P_f - Q(\sqrt{2P_s\beta / R^\alpha})}{1-2Q(\sqrt{2P_s\beta / R^\alpha})}\right) \\ & -\sqrt{\mathrm{N}}\cdot\left(\frac{D}{(P_u\beta)^{1/\alpha}} - \left(\frac{R^\alpha}{P_u\cdot\beta}\right)^{1/\alpha}\right)^{-\alpha}\Bigg]\cdot Q\left(\sqrt{2\frac{P_s\beta}{R^\alpha}}\right)\end{aligned}$$

In this case, $\hat{d}_2$ corresponding to ODL is denoted as

$$\hat{d}_2 \rightarrow \begin{cases} \left(\dfrac{2P_s\beta}{\left(Q^{-1}(P_f)\right)^2}\right)^{1/\alpha}, & if\ \dfrac{\left(Q^{-1}(P_f)\right)^2}{2} \geq \dfrac{P_s\beta}{R^\alpha} \\ R, & otherwise \end{cases} \tag{39}$$

It is worth noting that the ODL obtained in Case ii and Case iii is infinitely close to BS and the edge of WRAN district respectively. In practice, we can select somewhere near the BS or the edge of WRAN district as ODL, as long as the error produced by such approximation can be tolerated.

3.3 A Full Searching Algorithm for Locating ODL

Although the standard Lagrange multiplier algorithm can obtain the optimum solution, it is of high computational complexity and is difficult to be implemented. Herein, full searching algorithm which has relatively low complexity is a promising candidate for locating ODL. For simplicity, we neglect the edge of d_2's range, and constrain the searching space of d_2 to (0, d_2_Range), where

$$d_2\_\text{Range}= \min\left(R,\ \left(\frac{2P_s\beta}{\left(Q^{-1}(P_f)\right)^2}\right)^{1/\alpha}\right).$$

The scouting interval is set to Δd, and the error of searching result won't exceed $\pm\Delta d$. If Δd is small enough, the ODL acquired from this algorithm infinitely approaches its theoretical value. The flow chart of the full searching algorithm is shown in Fig. 2.

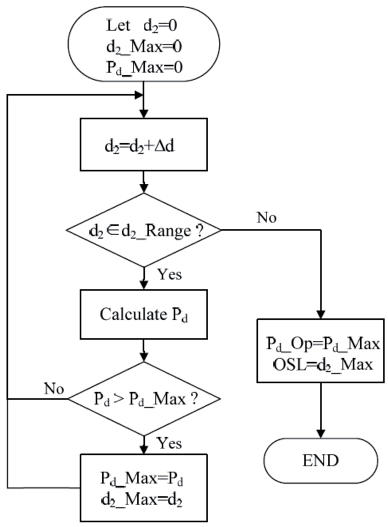

Fig. 2. Flow chart of full searching algorithm.

4. ODL-Based Cooperative Spectrum Sensing

4.1 ODL-Based Cooperative Spectrum Sensing

Aiming to alleviate the negative impact brought by reporting errors and improve sensing performance, we propose an ODL-based cooperative spectrum sensing.

We defined Optimum Detection Region (ODR) as a disc with ODL as its center and r as its radius, where $r << R$, as shown in Fig. 1. Notate the member set of CPEs located in ODR as **U**, and the upper limit number of users for cooperative spectrum sensing as L.

The ODL-based cooperative spectrum sensing is conducted through the following steps:

Step 1: BS calculates ODL and ascertains L according to information such as channel states information. Then, BS broadcasts ODR-related information to all CPEs;

Step 2: After every CPE$_i$ (i=1, 2, …, M) receiving this message, it subsequently makes a judgment of whether itself is in ODR via positioning devices. If CPE$_i \in \mathbf{U}$(i=1, 2, …, M), it will send back ACK_i ,or $NACK_i$ otherwise;

Step 3: If $|\mathbf{U}|$=0, no spectrum sensing is conducted, BS randomly selects H_0 or H_1 as the final sensing result;

Step 4: If $0 < |\mathbf{U}| \leq L$, BS organizes all the CPEs in ODR to perform cooperative spectrum sensing using some kind of fusion rule;

Step 5: If |**U**| > L, BS randomly selects L CPEs from **U**, to perform cooperative spectrum sensing using some kind of fusion rule.

By means of the above information exchanges, BS is able to pick out a specific number of CPEs situated in the vicinity of ODL. Evidently, these CPEs have better sensing performance compared with others in the network, so the veracity of our proposed sensing scheme can be greatly improved. The setting of upper limit number of users for cooperative spectrum sensing L should strike the balance of channel status, communication load caused to WRAN, and QoS requirement, etc.

4.2 Theoretical Performance Analysis of ODL-OR

Different decision rules can be applied to our proposed cooperative spectrum sensing scheme. Here, we adopt OR decision fusion rule to further evaluate the system performance of ODL-based cooperative spectrum sensing. We call this scheme ODL-OR.

In OR fusion rule, when at least 1 out of K secondary users detect the primary users, the final decision declares a primary user is present. Assume that the threshold ε in energy detection is identical for all CPEs, then the system false alarm probability $P_F^{ODR\text{-}OR}$ and detection probability $P_D^{ODR\text{-}OR}$ of the final decision are therefore, respectively

$$P_F^{ODR-OR} = 1 - \left(1 - P_f^{ODR-OR}\right)^K, \tag{40}$$

$$P_D^{ODR-OR} = 1 - \left(1 - P_d^{ODR-OR}\right)^K \tag{41}$$

where $P_{f,i}^{ODR\text{-}OR}$ is the probability of false alarm of CPE$_i$ (i=1, 2, …, K) who is situated in ODR, and $P_{d,i}^{ODR\text{-}OR}$ is the corresponding probability of detection. The second assumption mentioned above can lead to $P_{f,i}^{ODR\text{-}OR} = P_{f,j}^{ODR\text{-}OR} = P_f^{ODR\text{-}OR}$ and $P_{d,i}^{ODR\text{-}OR} = P_{d,j}^{ODR\text{-}OR} = P_d^{ODR\text{-}OR}$ (i, j =1, 2, …, K, $i \neq j$).

Evidently, CPEs in ODR have the optimum sensing performance compared with other CPEs, that is

$$\begin{aligned} &P_d^{ODR-OR} \geq P_{d,i}^{OR}, \quad i = 1,\ 2,\ ...,\ K \\ s.t.\quad &P_F^{ODR-OR} = P_F^{OR} = \overline{P}_F \end{aligned} \tag{42}$$

where $P_{d,i}^{OR}$ (i = 1, 2,…, K) stands for the probability of detection of arbitrary K CPEs randomly chosen from the network. Hereby, one can easily prove that

$$1 - \left(1 - P_d^{ODR-OR}\right)^K \geq 1 - \prod_{i=1}^{K}\left(1 - P_{d,i}^{OR}\right), \tag{43}$$

$$P_D^{ODR-OR} \geq P_D^{OR}. \tag{44}$$

Equation (44) implies that ODL-OR is capable to provide better protection to the primary user compared with other OR-rule sensing schemes.

Theorem 1: In WRAN scenario, assuming that M CPEs are uniformly distributed, the total number of CPEs in ODR will vary with the time. On the assumption that the area of WRAN and ODR is A and a respectively, the total number of CPEs in ODR at a given time conforms to a Poisson process with parameter λa, where $\lambda = M/A$ stands for the average number of CPEs per unit area.

As we can see from Theorem 1, the number of cooperative users in ODR, denoted as K, conforms to a Poisson process with parameter λa. So the system detection probability bears statistical significance, and it can be characterized as the average probability of detection. Therefore, with Poisson distribution expression, the average probability of detection for WRAN is formulated as

$$\begin{aligned} P_d^{Ave-OR} &= 0.5 \cdot \Phi(k=0) + \sum_{K=1}^{L} \Phi(k=K) \cdot \left[1 - \left(1 - P_d^{ODR-OR}\right)^K\right] \\ &\quad + \sum_{K=L}^{\infty} \Phi(k=K) \cdot \left[1 - \left(1 - P_d^{ODR-OR}\right)^L\right] \\ &= 0.5 \cdot e^{-\lambda a} + \sum_{K=1}^{L} \frac{e^{-\lambda a}(\lambda a)^K}{K!} \cdot \left[1 - \left(1 - P_d^{ODR-OR}\right)^K\right] \\ &\quad + \sum_{K=L}^{\infty} \frac{e^{-\lambda a}(\lambda a)^K}{K!} \cdot \left[1 - \left(1 - P_d^{ODR-OR}\right)^L\right] \end{aligned} \tag{45}$$

Equation (45) reveals that the sensing performance of ODL-OR is influenced by two variables: L and λa. When upper limit number of users for cooperative spectrum sensing L and the density of users in WRAN is getting larger, our proposed scheme will have better performance.

Under the CFAR, owing to ensure the utilization of idle channels, the average false alarm probability of ODL-OR is defined as the constant target value $\overline{P}_f^{Ave}$. It is assumed that the mapping relationship between $P_d^{ODR\text{-}OR}$ and $P_f^{ODR\text{-}OR}$ is defined as $P_d^{ODR\text{-}OR} = \Psi(P_f^{ODR\text{-}OR})$.

From (11)-(12), the mapping function Ψ is expressed as

$$\begin{aligned} P_d^{ODR-OR} &= \Psi(P_f^{ODR-OR}) \\ &= Q\left[Q^{-1}\left(\frac{P_f^{ODR-OR} - Q(\sqrt{2\gamma_2})}{1 - 2Q(\sqrt{2\gamma_2})}\right) - \sqrt{N} \cdot \gamma_1\right] \\ &= Q\left[Q^{-1}\left(\frac{1 - (1 - \overline{P}_f^{Ave})^{1/L} - Q(\sqrt{2\gamma_2})}{1 - 2Q(\sqrt{2\gamma_2})}\right) - \sqrt{N} \cdot \gamma_1\right]. \end{aligned} \tag{46}$$

Under the constraint of $\overline{P}_f^{Ave}$, and according to equations (40)-(41), when the number of cooperative user is K, the detection probability of final decision is derived as

$$\begin{aligned} P_D^{ODR-OR} &= 1 - \left(1 - \Psi(P_f^{ODR-OR})\right)^K \\ &= 1 - \left[1 - \Psi\left(1 - (1 - \overline{P}_f^{Ave})^{1/K}\right)\right]^K \end{aligned} \tag{47}$$

Theorem 2: Let $\Lambda(K) = 1 - \left[1 - \Psi\left(1 - (1 - \overline{P}_f^{Ave})^{1/K}\right)\right]^K$, $\Lambda(K)$ is a monotonously increasing function according to K, and the upper bound of $\Lambda(K)$ is 1.

According to (45), when the average number of user in ODR is satisfied as $\lambda a \to \infty$, the average probability of decision is existed that

$$\lim_{\lambda a \to \infty} \sum_{K=0}^{L-1} \frac{e^{-\lambda a} (\lambda a)^K}{K!} = 0, \tag{48}$$

then
$$\lim_{\lambda a \to \infty} \sum_{K=L}^{\infty} \frac{e^{-\lambda a} (\lambda a)^K}{K!} = \lim_{\lambda a \to \infty} \sum_{K=0}^{\infty} \frac{e^{-\lambda a} (\lambda a)^K}{K!} = 1. \tag{49}$$

When the number of average user in ODR is satisfied as $\lambda a \to \infty$, the average probability of decision is derived as

$$\lim_{\lambda a \to \infty} P_d^{Ave} = 1 - \left(1 - P_d^{ODR-OR}\right)^L. \tag{50}$$

If $\lambda a \to \infty$, the number of cooperative user tends to the upper bound value L. Owing to the Theorem 2, we can obtain that the average probability of decision is a monotonous increasing function according to the number of average users in ODR and the number of cooperative users. So if $\lambda a \to \infty$ and $L \to \infty$, the average probability of decision tends to the performance upper bound, and is expressed as

$$\begin{aligned} \lim_{L\to\infty} \lim_{\lambda a \to \infty} P_d^{Ave} &= \lim_{L \to \infty} 1 - \left(1 - P_d^{ODR-OR}\right)^L \\ &= \lim_{L\to\infty} 1 - \left[1 - \Psi\left(1 - (1 - \overline{P}_f^{Ave})^{1/L}\right)\right]^L = 1 \end{aligned} \tag{51}$$

5. Simulation Results

We study some simulation results to demonstrate the performance of the ODL-based cooperative spectrum sensing. The radius of WRAN and ODR is set to 33 km and 0.33 km respectively, while BS is 120 km away from the primary user. During the sensing time, the number of received signal samples at each secondary user is set as 6000 samples. The path loss exponent factor α, in (1) and (2), is set to be 3. The β and P_u are set at a value such that the primary user's signal to noise ratio at the secondary BS is -16 dB. For notation brevity, we refer to P_d as the average probability of detection for WRAN.

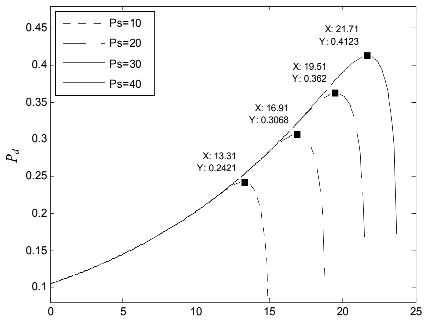

Fig. 3. Tendency of ODL under different CPE transmission power.

In Fig. 3, we show the tendency of P_d versus the distance between BS and a CPE d_2 under different CPE transmission power. Under the CFAR requirement, the desired P_f is set as 0.1%. We observe that there does exist an optimum detection location in the line connecting BS and PU. When transmission power P_s increases, ODL moves forward to the edge of WRAN, and the sensing performance improves gradually. This phenomenon can demonstrate that it's feasible to ameliorate the sensing performance of WRAN system by enlarging transmission power of CPEs as long as it doesn't exceed the interference threshold tolerated by the primary user.

Fig. 4 shows the P_d of WRAN system with the total number of CPEs in the network increasing when using ODL-OR scheme under the constraint of P_f =0.1%. It illustrates that the P_d increases as M and L grows, which tallies with our analysis in Section 4.

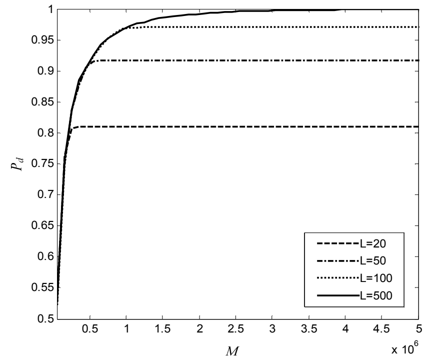

Fig. 4. The P_d of ODL-OR versus the total number of CPEs M in the network under different upper limit number of users for cooperative spectrum sensing L.

Fig. 5 compares the sensing performance of ODL-OR with conventional sensing scheme using OR-fusion rule. We suppose that the conventional sensing scheme randomly chooses 20 users for collaboration during one startup of cooperative spectrum sensing. For fairness, we set the upper limit number of users for cooperative spectrum sensing L in ODL-OR as 20. The P_f is also fixed on 0.1%, and the total number of CPEs M is assumed to be 2×10^5. In Fig. 5, the P_d of both schemes increases as P_S growing. However, conventional OR fusion scheme is inferior to ODL-OR scheme throughout the simulation range of P_s. When P_s= 0 dB, the ODL achieves the P_d of 80%, while that of conventional OR fusion scheme is only slightly above 10%. In other words, the probability of detection can be enhanced by as much as 70% by our proposed scheme. Notably, when P_S is larger than 5 dB, ODL-OR scheme even outperforms conventional OR fusion scheme with no reporting errors. This phenomenon can be attributed to the exploitation of geographic advantages in user selection.

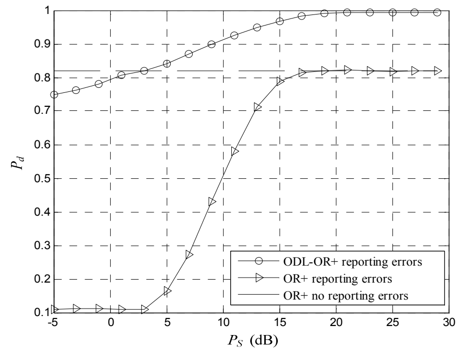

Fig. 5. The comparisons of P_d as the transmission power P_s increases under CFAR requirement.

Fig. 6 shows the complementary ROC curves, i.e. the probability of loss detection P_m versus the probability of false alarm P_f under CFAR requirement. The P_f is set to 0.1%, the transmission power is 10 dB, M is assumed to be 2×10^5. Fig. 6 demonstrates that the P_m of ODL-OR is much smaller than that of conventional OR fusion scheme, which again verifies the superiority of our proposed scheme over conventional sensing.

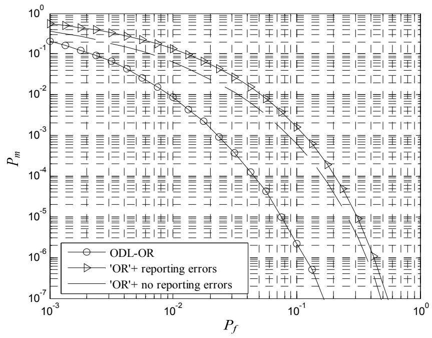

Fig. 6. The Complementary ROC curves (the probability of loss detection P_m versus the probability of false alarm P_f) under CFAR requirement.

6. Conclusion

In this paper, we proposed an optimum detection location-based cooperative spectrum sensing scheme to improve the sensing performance in the case of imperfect reporting channels. To exploit the geographic advantages to overcome the negative impact caused by reporting errors, we modeled the cooperative spectrum sensing process using energy detection and found out a specific location in WRAN where the CPE will have the optimum sensing performance using two algorithms. Numerical and simulation results both show that the sensing performance of our proposed scheme is improved considerably compared with conventional spectrum sensing.

Appendix

Proof of Theorem 1:

The distribution of M CPEs is uniform, so the probability P_n of every CPE$_i$ ($i = 1, 2, \ldots, M$) that falls into ODR is equal, and can be expressed as the following

$$P_n = \frac{a}{A} \tag{52}$$

where $A = \pi R^2$ is the area of WRAN. Thus the probability of K CPES that fall into ODR is

$$\Phi(K) = C_M^K \cdot P_n^K \cdot (1-P_n^K)^{M-K}\,. \tag{53}$$

According to Poisson Theorem, we obtain

$$\Phi(K) \approx e^{-\lambda a}(\lambda a)^K / K!\,. \tag{54}$$

The total number of CPEs in ODR at a given time conforms to a Poisson process with parameter λa, where $\lambda = M/A$ stands for the average number of CPEs per unit area.

Proof of Theorem 2:

Firstly, we proof that $\Lambda(K)$ is a monotonously increasing function according to K, we can get the derivative of the function $\Lambda(K)$

$$\frac{d\Lambda(K)}{dK} = \Lambda(K)\cdot\ln\left[1-\Psi\left(1-(1-\bar{P}_f^{Ave})^{1/K}\right)\right] \cdot\frac{d\Psi\left(1-(1-\bar{P}_f^{Ave})^{1/K}\right)}{dK} \tag{55}$$

where

$$\frac{d\Psi\left(1-(1-\bar{P}_f^{Ave})^{1/K}\right)}{dK} = -\frac{\exp\left[-\left(Q^{-1}\left(\frac{1-(1-\bar{P}_f^{Ave})^{1/K}-Q(\sqrt{2\gamma_2})}{1-2Q(\sqrt{2\gamma_2})}\right)-\sqrt{N}\cdot\gamma\right)^2/2\right]}{\sqrt{2\pi}} \cdot\frac{dQ^{-1}\left(\frac{1-(1-\bar{P}_f^{Ave})^{1/K}-Q(\sqrt{2\gamma_2})}{1-2Q(\sqrt{2\gamma_2})}\right)}{dx}$$

and

$$\frac{dQ^{-1}\left(\frac{1-(1-\bar{P}_f^{Ave})^{1/K}-Q(\sqrt{2\gamma_2})}{1-2Q(\sqrt{2\gamma_2})}\right)}{dx} = \frac{\sqrt{2\pi}(1-\bar{P}_f^{Ave})^{1/K-1}}{L(1-2Q(\sqrt{2\gamma_2}))} \Big/ \exp\left[-\left(Q^{-1}\left(\frac{1-(1-\bar{P}_f^{Ave})^{1/K}-Q(\sqrt{2\gamma_2})}{1-2Q(\sqrt{2\gamma_2})}\right)\right)^2/2\right] > 0$$

According to the range of Q function, we can obtain

$$\because 0 < 1-\Psi\left(1-(1-\bar{P}_f^{Ave})^{1/K}\right) < 1\,, \tag{56}$$

$$\therefore \ln\left[1-\Psi\left(1-(1-\bar{P}_f^{Ave})^{1/K}\right)\right] < 0\,. \tag{57}$$

According to (55)-(57), we can proof that $d\Lambda(K)/dK > 0$, $\Lambda(K)$ is a monotonous increasing function according to K, in the following we will proof that the upper bound of $\Lambda(K)$ is 1.

For $\Lambda(K)$ is a monotonously increasing function according to K, the proof of the upper bound of $\Lambda(K)$ is 1 equals to proof as following

$$\lim_{K\to\infty}\left[1-\Psi\left(1-(1-\bar{P}_f^{Ave})^{1/K}\right)\right]^K = 0\,. \tag{58}$$

Let $\Phi(K) = K\cdot\ln\left[1-\Psi\left(1-(1-\bar{P}_f^{Ave})^{1/K}\right)\right]$, then

$$\lim_{K\to\infty}\Phi(K) = \lim_{K\to\infty}\frac{\ln\left[1-\Psi\left(1-(1-\bar{P}_f^{Ave})^{1/K}\right)\right]}{\frac{1}{K}}\,. \tag{59}$$

The limit of $\Psi\left(1-(1-\bar{P}_f^{Ave})^{1/K}\right)$ is expressed as

$$\lim_{K\to\infty}\Psi\left(1-(1-\bar{P}_f^{Ave})^{1/K}\right)=$$

$$\lim_{K\to\infty}Q\left[Q^{-1}\left(\frac{P_f^{ODR-OR}-Q(\sqrt{2\gamma_2})}{1-2Q(\sqrt{2\gamma_2})}\right)-\sqrt{N}\cdot\gamma_1\right]$$

$$=\lim_{K\to\infty}Q\left[Q^{-1}\left(\frac{1-(1-\bar{P}_f^{Ave})^{1/K}-Q(\sqrt{2\gamma_2})}{1-2Q(\sqrt{2\gamma_2})}\right)-\sqrt{N}\cdot\gamma_1\right] \quad (60)$$

where $0<\frac{1-(1-\bar{P}_f^{Ave})^{1/K}-Q(\sqrt{2\gamma_2})}{1-2Q(\sqrt{2\gamma_2})}<1$.

Since $\lim_{K\to\infty}1-(1-\bar{P}_f^{Ave})^{1/K}=0$, we can obtain $Q(\sqrt{2\gamma_2})\to 0$.

Let $x=\frac{1-(1-\bar{P}_f^{Ave})^{1/K}-Q(\sqrt{2\gamma_2})}{1-2Q(\sqrt{2\gamma_2})}$, then $x\to 0$.

Substituting into (60), we obtain

$$\lim_{K\to\infty}\Psi\left(1-(1-\bar{P}_f^{Ave})^{1/K}\right)=\lim_{x\to 0}Q\left[Q^{-1}(x)-\sqrt{N}\cdot\gamma_1\right]=0. \quad (61)$$

Equation (59) is the type of 0/0, by Los Hospital Rule, we obtain

$$\lim_{K\to\infty}\frac{\ln\left[1-\Psi\left(1-(1-\bar{P}_f^{Ave})^{1/K}\right)\right]}{\frac{1}{K}}$$

$$=\lim_{K\to\infty}\frac{K^2}{1-\Psi\left(1-(1-\bar{P}_f^{Ave})^{1/K}\right)}\cdot\frac{d\Psi\left(1-(1-\bar{P}_f^{Ave})^{1/K}\right)}{dK}. \quad (62)$$

According to (55), we obtain

$$\lim_{K\to\infty}\frac{d\Psi\left(1-(1-\bar{P}_f^{Ave})^{1/K}\right)}{dK}=\lim_{K\to\infty}-\frac{\sqrt{2\pi}(1-\bar{P}_f^{Ave})^{1/K-1}}{K(1-2Q(\sqrt{2\gamma_2}))}$$

$$\cdot\exp\left[\left(Q^{-1}\left(\frac{1-(1-\bar{P}_f^{Ave})^{1/K}-Q(\sqrt{2\gamma_2})}{1-2Q(\sqrt{2\gamma_2})}\right)-\sqrt{N}\cdot\gamma_1\right)\cdot\frac{\sqrt{N}\cdot\gamma_1}{2}\right]. \quad (63)$$

Substituting (63) into (62), we obtain

$$\lim_{K\to\infty}\Phi(K)=\lim_{K\to\infty}\frac{K^2}{1-\Psi\left(1-(1-\bar{P}_f^{Ave})^{1/K}\right)}$$

$$\cdot\frac{d\Psi\left(1-(1-\bar{P}_f^{Ave})^{1/K}\right)}{dK}=-\infty \quad (64)$$

Thus, (58) is valuable, and $\Lambda(K)$ is a monotonous increasing function according to K, and the upper bound is 1, the proposition holds.

Acknowledgements

This work was supported by the National High Technology Research and Development Programme of China (No. 2009AA01Z247) and the National Natural Science Foundation of China under Grants No. 60972076, 61072052.

References

[1] FCC, Spectrum Policy Task Force Report. *ET Docket No. 02-155*, Nov. 2002.

[2] CORDEIRO, C., CHALLAPALI, K., BIRRU, D. IEEE 802.22: the first worldwide wireless standard based on cognitive radio. In *Proc. of 1st IEEE Symp. New Frontiers in Dynamic Spectrum Access Networks,* Baltimore, Maryland, Nov. 2005, p. 328-337.

[3] MISHRA, S. M., SAHAI, A., BRODERSEN, R. W. Cooperative sensing among cognitive radios. In *Proc. of IEEE Int. Conf. on Communications.* Istanbul (Turkey), 2006, vol. 4, p. 1658-1663.

[4] THOMOPOULOS, S. C. A., VISWANATHAN, R., BOUGOULIAS, D. C. Optimal decision fusion in multiple sensor systems. *IEEE Trans. Aerosp. Electron. Syst.,* 1987, vol. 23, p. 644-653.

[5] VISWANATHAN, R., AALO, V. On counting rules in distributed detection. *IEEE Trans. on Signal Processing*, 1989, vol. 37, p. 772-775.

[6] CHEN, B., JIANG, R., KASETKASEM, T., et al. Channel aware decision fusion in wireless sensor networks. *IEEE Trans. on Signal Processing,* 2004, vol. 52, p. 3454-3458.

[7] CABRIC, D., MISHRA, S. M., BRODERSEN, R. W. Implementation issues in spectrum sensing for cognitive radios. In *Proceedings of Asilomar Conf. on Signals, Systems, and Computers.* Pacific Grove (CA), 2004, vol. 1, p. 772-776.

About Authors ...

Hongtao ZHANG was born in 1980. He received his Ph.D. degree in Communication and Information system from Beijing University of Posts and Telecommunications in 2008. His research interests include cooperative communications, wideband wireless network and signal processing.

Xiaoxiang WANG was born in 1969. Prof. Wang is doctor supervisor in the School of Information and Telecommunication Engineering. She received her Ph.D. degree from BIT in 1998, and once was a visit scholar in Austria University of Technology in Vienna from 2001 to 2002. Her research is now supported by the National 863 Program and the National Natural Science Foundation, with 4 patents and more than 50 papers published in the area of Co operative Communication, MIMO OFDM and Cooperative Position Locating area.

Gengsheng (G.S.) KUO was born in 1950. He received his Ph.D. degree in Systems Engineering, Case Western Reserve University, USA in 1983. From 2001 to 2002, he was Editor-in-Chief of IEEE Communications Magazine. From 2000 to 2001, he was Director of Communications Switching & Routing Technical. He is Editor-in-Chief of China Communications from 2003 to now; IEEE Communications Society. Now he is Vice-Director of Asia Pacific Board for IEEE Communications Society.

Thomas Michael BOHNERT was born in 1973. He received his Ph.D. degree in Electronic Engineering from University of Coimbra in 2006. His research interests include wireless communications, Wimax networks and signal processing.