Distributed Selection and Optimization of Threshold of Energy Detection for Cooperative Spectrum Sensing

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Abstract—**Spectrum detection is the prerequisite for the Cognitive Radio. Energy detection is often used to sense the spectrum hole in Cognitive Radio network, and the threshold plays a vital role. In this paper, a method of setting threshold is proposed. In the low SNR environment, to protect the primary user, each secondary user observes the environment adaptively and then sets the threshold independently. The simulation results prove that, under the method proposed in this paper, the detection performance can be greatly improved, comparing with the traditional one, i.e., the threshold is set by the spectrum broker and all the secondary users have a same fixed threshold.**

Keywords—Cognitive radio; Energy detection; Threshold; Cooperative sensing.

I. INTRODUCTION

In recent years, with the rapid development of radio services, more and more wireless spectrum resources are needed to meet the communication requirements. However, because of the fixed spectrum allocation scheme and the spectrum monopolized principle, the spectrum resources are believed to be scarce resources. Although there are some measures such as Frequency Division Multipexing (FDM), Time Division Multipexing (TDM), Code Division Multiplexing (CDM), etc., to improve the spectrum utilization, but these can not ultimately solve the lack of spectrum resources. As a result, the technology of Cognitive Radio (CR) emerges as the times require. It proposes a opportunists way to share the frequency spectrum, under the premise of not disturbing PU. This method can open the spectrum resources and improve spectrum utilization effectively.

The core ideology of CR is that the unlicensed user (secondary user, SU) senses the radio environment automatically, adjusts the system parameters intelligently to adapt to the changes in the environment, and uses idle spectrum resources to do some communications without disturbing licensed user (primary user, PU). Therefore, idle spectrum sensing is a critical task for CR networks [1][2].

There have been many kinds of classic spectrum sensing technologies, such as energy detection, match filter detection and cyclic-feature detection. However, energy detection is the most commonly used method to estimate if there are any PUs, because of its simple and practical operation.

In the actual communication environments, there are shadowing, fading and other adverse factors which would greatly deteriorate the SU's local decisions. So, the cooperative spectrum sensing is always used in CR network to improve the detection performance, that is, on the base of local detection, all the SUs transmit their local decisions to the spectrum broker through error-free channels, the spectrum broker analyses these data and makes the final decision.

In energy detection, how to set the threshold is very crucial, as the threshold would influence the local decision of SU, and then influence the performance of the system. There have been some studies about how to set the threshold in energy detection [3-7]. In [3], the authors, combining with cooperative sensing, proposed a method to determine the threshold, and the proposed optimal threshold which is decided by spectrum broker minimizes the probability of global error. However, this threshold is not the best one for various SUs who are in different environments. In [4], the authors, combining with the K/N voting rule, discussed the optimal threshold. Depending on K, they only proposed the range of the threshold instead of the exact value. In [5], a tradeoff threshold is proposed, and when the system has a higher requirment of protecting PU, it will set an actual value which is higher than the proposed optimal one to obtain a higher detection probability. In [6], the authors suggested a double-threshold based energy sensing algorithm to improve the performance of the local detection. Under the restriction of the two thresholds, the results of local detection can be more credible, but the authors only considered that all the SUs sensed the idle spectrum over Additive White Gaussian Noise (AWGN) channels, and not taken the fading channels into account. However, in [7], the authors provided a method about how to set a double-threshold in fading channel, and the simulation results proved that the double-threshold proposed can improve the sensing performance.

The detection thresholds mentioned above are all set by the spectrum broker, the spectrum broker bases on some rules to set the threshold uniformly and then distributes it to every SU, each SU, who takes part in cooperation owns a same threshold. However, SUs are in different environments, and they catch PU signals of different intensity. Those ways mentioned above did not take this problem into consideration, but generalized, Thus, all the SUs had a same threshold, which wound reduce the local detection performance.

In this paper, in order to protect the interests of PU in the low SNR environments, a threshold setting way to improve the performance of local energy detection is proposed. SUs monitor and estimate their radio environments, and then set their own optimal thresholds independently. This optimal one maximizes the difference of SU's the local detection probability and the local false-alarm probability. That is to say, in this way, the system protects the interests of PU to greatest extent, when it allows SUs to share the spectrum resource. The simulation results prove that this method of setting threshold improves the performance of detection significantly, comparing with the traditional method, i.e., the threshold is set by the spectrum broker and all the SUs have a same fixed detection threshold. In addition, the SUs do not need to transmit their signal-to-noise (SNR) radio and some other reliable information to the spectrum broker, so it is also an effective way to save the sensing time and the channel bandwidth.

The remainder of this paper is organized as follows. The energy detection is introduced in Section Ⅱ. The issue about setting threshold uniformly is discussed in Section Ⅲ. The new distributed setting threshold method is described in Section Ⅳ. Simulation results, conclusion and future work are given in Section Ⅴ and Section Ⅵ, respectively.

II. Energy Detection and Performance Criteria

Energy detection is the most commonly used method to estimate if there are any PUs, because of its simple and practical operation.

H_0 denotes PU absent and H_1 denotes PU existing. $y(t)$ is the signal which SU receives. $y(t)$ is denoted by [1]:

$$y(t)=\begin{cases} n(t) & H_0 \\ h(t)\cdot x(t)+n(t) & H_1 \end{cases}, \tag{1}$$

where $x(t)$ is the PU signal, $n(t)$ is the additive white gaussian noise, and $h(t)$ is the complex channel gain of the sensing channel. The SU lets $y(t)$ pass the bandpass filter (BPF) to filter the out-of-band noise and adjacent signals, and then pass the A/D converter, the squarer and the summation device, then the test statistic Y is obtained [2]:

$$Y \rightarrow \begin{cases} \chi^2{}_{2TW} & H_0 \\ \chi^2{}_{2TW}(2\gamma) & H_1 \end{cases}, \tag{2}$$

where γ is the instantaneous SNR at the secondary node, TW is the product of observation time and interested bandwidth, it is usually written as $m=TW$, and m is an integer. As shown in (2), when PU is absent, Y obeys the central chi-square distribution with $2TW$ degrees of freedom, when the PU is present, Y obeys the noncentral chi-square distribution with $2TW$ degrees of freedom and a non-centrality parameter 2γ.

Letting Y compare to a pre-set threshold λ, SU can decide whether PU is present or not. If Y is bigger than the threshold λ, then SU makes the judgment that PU is working, otherwise, SU believes PU do not occupy this licensed band, and then uses it to do some its own communications. Thus, how to select the threshold is very critical and it influences the local decision of SU immediately, thereby, influences the performance of the system.

In an AWGN environment where the complex channel gain $h(t)$ is constant, the probability of detection, the probability of false-alarm and the probability of missed detection are shown as follows [1]:

$$p_d = p\left\{Y>\lambda \middle| H_1\right\} = Q_m\left(\sqrt{2\gamma},\sqrt{\lambda}\right), \tag{3}$$

$$p_f = p\left\{Y>\lambda \middle| H_0\right\} = \frac{\Gamma\left(m,\frac{\lambda}{2}\right)}{\Gamma(m)}, \tag{4}$$

$$p_m = p\left\{Y\le\lambda \middle| H_1\right\} = 1-p_d, \tag{5}$$

where $\Gamma(.,.)$ is the incomplete gamma function, $Q(\ )$ is the generalized Marcum Q-function, $I_{m-1}(\ )$ is the first modified Bessel function with $m-1$ order. In a fading environment, the complex channel gain $h(t)$ varies with the decline, the SU's average probability of detection is [1]:

$$p_d = \int_x^\infty Q_m\left(\sqrt{2\gamma},\sqrt{\lambda}\right) f_\gamma(x)\,dx, \tag{6}$$

where $f_\gamma(x)$ is the probability distribution function of SNR in the fading environment.

In the actual communication environments, fading and shadowing, etc., would deteriorate the local spectrum sensing performance of the SU, so, multiple SUs are needed to sense the idle spectrum cooperatively, that is the cooperative spectrum sensing. In cooperative spectrum sensing, each SU who takes part in collaboration makes a binary judgment according to the local observation (0 or 1, 0 stands for the absence of PU, and 1 stands for the existence of PU), and then sends the decision to the spectrum broker through ideal channels, the spectrum broker applies the classic K/N voting rule (when K=N, the rule is the AND rule; when K=1, the rule is OR rule) to fuse all the results, and then makes the final decision [2]:

$$\Omega = \sum_{i=1}^{N} D_i \begin{cases} \ge K & H_1 \\ \le K & H_0 \end{cases}, \tag{7}$$

where N is the number of SUs who participate in the cooperation, D_i is the local decision of i th SU. When the number of the SU whose decision is 1, is more than K, the final result is H_1, that is to say the spectrum broker would believe PU is presence, otherwise, the result is H_0, the PU is absence. Under this voting rule, the false-alarm probability of cooperative spectrum sensing and the detection probability of cooperative spectrum sensing is [8]:

$$Q_f = \sum_{j=K}^{N} \sum_{\sum D_i = j} \prod_{i=1}^{N} \left(p_{fi}\right)^{D_i}\left(1-p_{fi}\right)^{1-D_i}, \tag{8}$$

$$Q_d = \sum_{j=K}^{N} \sum_{\sum D_i = j} \prod_{i=1}^{N} (p_{di})^{D_i} (1-p_{di})^{1-D_i} , \tag{9}$$

where p_{fi} and p_{di} are the false-alarm probability and the detection probability of i th SU respectively.

III. The Issue about Setting Threshold Uniformly by Spectrum Broker

How to set the threshold in energy detection is very critical. The threshold can influence the false-alarm probability and the detection probability at the same time, when it is set too high, the false-alarm probability would reduce and so does the detection probability. The decrease of the false-alarm probability would increase the radio frequency spectrum utilization, but the decrease of the detection probability would increase the probability of disturbing PU.

As shown in Figure 1, SU1, SU2 and SU3 are all affected by shadowing; SU4 is out of the coverage of the PU transmitter. They can not capture the PU signal no matter it exists or not, and then, they may make error decisions. Although collaborative spectrum sensing can be applied to ameliorate the performance, but the authors of [8] have proved that collaborative spectrum sensing can do little improvement to the performance in the case that secondary nodes are all in harsh environments. In some low SNR environments, SUs would be easy to interfere PU, but the precondition of CR network is that SUs share the spectrum resources without bothering PU. So, In some low SNR environments, especially, in some systems which need to put the interests of PU to the first place, more attention must be paid to protect the interests of PU.

In [3], the authors based on collaborative spectrum sensing, and proposed a method to set the threshold of energy detection. In that way, the threshold (λ^*) minimizes the total error probability (the sum of the missed detection probability and the false-alarm probability). Shown as the following equations:

$$\begin{aligned} \lambda^* &= \arg\min_{\lambda}(Q_f + Q_m) \\ &= \arg\min_{\lambda}(Q_f + 1 - Q_d) \\ &= \arg\min_{\lambda}(Q_f - Q_d) \\ &= \arg\max_{\lambda}(Q_d - Q_f) \\ &= \arg\max_{\lambda}(Q_{diff}) \end{aligned} \quad , \tag{10}$$

where $Q_m = 1 - Q_d$ is the system missed detection probability, $Q_{diff} = Q_d - Q_f$ is the difference of the system detection probability and the system false-alarm probability.

Six SUs are assumed to join in the collaborative spectrum sensing, and their SNR are -10dB, -5dB, -3dB, -1dB, 0dB, 1dB respectively, the OR rule is applied to fuse data at the spectrum broker. Letting threshold be the abscissa, the difference of the detection probability and the false-alarm probability (Q_{diff}) be the ordinate, the simulation figure about the relationship between the threshold and the difference of detection probability and false-alarm probability can be obtained, shown as Figure 2. From Figure 2, it is easy to see that the difference of the detection probability and the false-alarm probability varies with the threshold, and a optimal one (λ^*), which maximizes the difference of the detection probability and the false-alarm probability can be obtained. That is to say, according to [3], when the SUs who take part in cooperation all let λ^* be their threshold of energy detection, it would provide the uttermost protection of PU, comparing with some other threshold setting methods.

However, because of the adverse factors such as interference, noise and temperature, the SUs who join in cooperation are in different environments. The threshold mentioned in [3] is set by spectrum broker, and then the spectrum broker distributed it to SUs uniformly, but this threshold is not the optimal one to each SU who is with

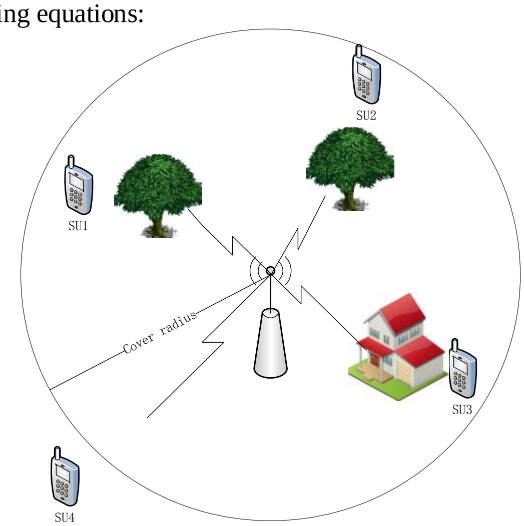

Figure 1. The actual sensing environment

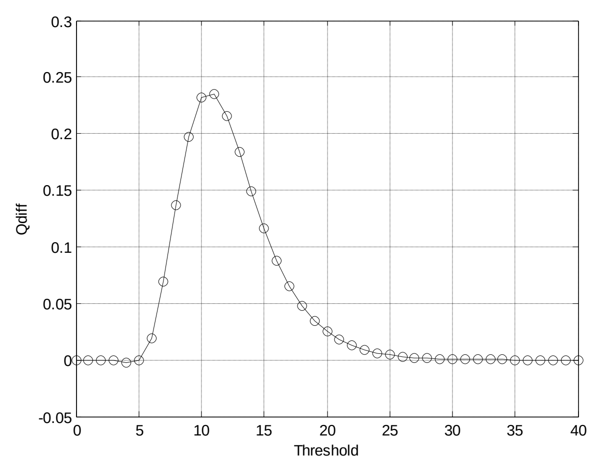

Figure 2. The relationship between the threshold and difference of detection probability and false-alarm probability

different SNR.So, in order to provide better protection to PU, SUs according to their environments, set their own thresholds by maximizing the difference of the detection probability and the false-alarm probability [9], and then make their own optimal decisions independently, that is the distributed setting threshold algorithm. In some harsh environments, this distributed setting threshold method can improve the detection probability, and then achieve the purpose of protecting PU.

IV. THE NEW DISTRIBUTED SETTING THRESHOLD METHOD

We will present the new distributed setting threshold method.

A. The Setting Threshold Method

The following gives a method to set the threshold of energy detection. SUs set their own thresholds according to their environments, and then make their own optimal decisions independently, after that, transmit their decisions to the spectrum broker to complete collaborative spectrum sensing. If the distributed setting threshold method is applied, SUs do not need to convey the SNR and some other reliable informations to the spectrum broker in advance [9][10], and do not need to wait for the uniform fixed threshold which is made by the spectrum broker to finish the energy detection. Obviously, this method can not only save the sensing time, but the bandwidth, more importantly, it can improve the system detection probability, reduce the risk of disturbing PU.

The number of secondary users who participate in collaborative spectrum sensing is N, the SNR of i th SU is assumed to be γ_i $(i=1,2...N)$, the instantaneous detection probability and the instantaneous false-alarm probability of i th SU are shown as follows:

$$p_{\mathrm{d}i} = Q_m\left(\sqrt{2\gamma_i}, \sqrt{\lambda_i}\right), \tag{11}$$

$$p_{fi} = \frac{\Gamma\left(m, \frac{\lambda_i}{2}\right)}{\Gamma(m)}, \tag{12}$$

where λ_i is the threshold of i th SU. The difference of the detection probability and the false-alarm probability of i th SU is:

$$\begin{aligned} p_{diff} &= p_{di} - p_{fi} \\ &= Q_m\left(\sqrt{2\gamma_i}, \sqrt{\lambda_i}\right) - \frac{\Gamma\left(m, \frac{\lambda_i}{2}\right)}{\Gamma(m)} \end{aligned}. \tag{13}$$

In order to maximize P_{diff}, we take the derivative with respect to λ_i on the both sides of (13), and let it be zero,

$$\begin{aligned} \frac{\partial p_{diff}}{\partial \lambda_i} &= \frac{\partial\left(p_{di} - p_{fi}\right)}{\partial \lambda_i} \\ &= \frac{\partial p_{di}}{\partial \lambda_i} - \frac{\partial p_{fi}}{\partial \lambda_i} \\ &= 0 \end{aligned}, \tag{14}$$

that is:

$$\frac{\partial p_{di}}{\partial \lambda_i} = \frac{\partial p_{fi}}{\partial \lambda_i}, \tag{15}$$

where,

$$\frac{\partial p_{fi}}{\partial \lambda_i} = -\frac{1}{(m-1)!}\frac{\lambda_i^{m-1}}{2^m} e^{-\frac{\lambda_i}{2}}. \tag{16}$$

$$\frac{\partial p_{di}}{\partial \lambda_i} = -\frac{\lambda_i^{\frac{m-1}{2}}}{2(2\gamma_i)^{\frac{m-1}{2}}}\exp\left(-\frac{\lambda_i + 2\gamma_i}{2}\right) I_{m-1}\left(\sqrt{2\lambda_i\gamma_i}\right). \tag{17}$$

Putting the (16), (17) into (15), and then the optimal threshold which maximize the difference of the detection probability and the false-alarm probability of i th SU can be obtained.

In Rayleigh fading channel, the signal envelope obeys the Rayleigh distribution, the probability density function of γ is:

$$f(\gamma) = \frac{1}{\bar{\gamma}}\exp\left(-\frac{\gamma}{\bar{\gamma}}\right), \gamma \ge 0. \tag{18}$$

Putting (18) into (6), the average detection probability of i th SU can be obtained:

$$\begin{aligned} \overline{p_{di\,Ray}} &= e^{-\frac{\lambda_i}{2}}\sum_{k=0}^{m-2}\frac{1}{k!}\left(\frac{\lambda_i}{2}\right)^k + \left(\frac{1+\bar{\gamma}_i}{\bar{\gamma}_i}\right)^{m-1} \\ &\times\left(e^{-\frac{\lambda_i}{2(1+\bar{\gamma}_i)}} - e^{-\frac{\lambda_i}{2}}\sum_{k=0}^{m-2}\frac{1}{k!}\left(\frac{\lambda_i\bar{\gamma}_i}{2(1+\bar{\gamma}_i)}\right)^k\right) \end{aligned}. \tag{19}$$

According to (19),

$$\frac{\partial \overline{p_{di\,Ray}}}{\partial \lambda_i} = \frac{1}{2(1+\bar{\gamma})}\left(\frac{\Gamma\left(m-1, \frac{\lambda}{2}\right)}{(m-2)!} - \overline{p_{di\,Ray}}\right). \tag{20}$$

Putting (20) into (15), the optimal threshold of i th SU over Rayleigh channel can be obtained.

B. Performance Analyse

SUs set their own thresholds independently according to their environments, and then make their own optimal decisions independently, after that, transmit their decisions to spectrum broker to complete collaborative spectrum detection. Because the issue we study is how to set the threshold to achieve the goal, and the goal is that we not only allow SUs to share spectrum resources, but protect the interests of PU as far as possible. So we apply the OR rule to fuse data in spectrum broker, and devote to improve the probability of detection.

If the SNR of each SU is assumed to be a instantaneous value, and SUs use the independent setting threshold method to complete energy detection, the system detection probability is:

$$\begin{aligned} Q_d &= 1-\prod_{i=1}^{N}\left(1-p_{di}\right) \\ &= 1-\prod_{i=1}^{N}\left(1-Q_m\left(\sqrt{2\gamma_i},\sqrt{\lambda_i}\right)\right) \end{aligned}, \tag{21}$$

where λ_i and γ_i is the threshold and the instantaneous SNR of i th SU respectively.

If the signal envelope obeys the Rayleigh distribution, and SUs use the independent setting threshold method to complete energy detection, system detection probability is:

$$\begin{aligned} Q_d &= 1-\prod_{i=1}^{N}\left(1-\overline{p}_{di\,Ray}\right) \\ &= 1-\prod_{i=1}^{N}\left(\begin{array}{l} 1-e^{-\frac{\lambda_i}{2}}\sum_{k=0}^{m-2}\frac{1}{k!}\left(\frac{\lambda_i}{2}\right)^k+\left(\frac{1+\overline{\gamma_i}}{\overline{\gamma_i}}\right)^{m-1}\times \\ \left(e^{-\frac{\lambda_i}{2\left(1+\overline{\gamma_i}\right)}}-e^{-\frac{\lambda_i}{2}}\sum_{k=0}^{m-2}\frac{1}{k!}\left(\frac{\lambda_i\overline{\gamma_i}}{2\left(1+\overline{\gamma_i}\right)}\right)^k\right) \end{array}\right) \end{aligned}, \tag{22}$$

where λ_i and $\overline{\gamma_i}$ is the threshold and the average SNR of i th SU respectively.

Over AWGN channel, each SU owns a same SNR value, that is to say $\gamma_1=\gamma_2=......=\gamma_N=\gamma$, and they can get a same optimal threshold value ($\lambda^{'}$), through the independent setting threshold method, and the system detection probability over AWGN channel is:

$$\begin{aligned} Q_d &= 1-\prod_{i=1}^{N}\left(1-p_{di}\right) \\ &= 1-\left(1-Q_m\left(\sqrt{2\gamma},\sqrt{\lambda^{'}}\right)\right)^N \end{aligned}. \tag{23}$$

V. SIMULATION RESULTS

The number of the SUs who participate in collaborative spectrum sensing is assumed to be $N=6$, and the simulations are did to compare the unified setting threshold method in [3] with the distributed setting threshold method (the algorithm mentioned in this paper) over 10 kinds of environments (the average SNR is -5dB，-4dB，-3dB，-2dB，-1dB，0dB，1dB，2dB，3dB，4dB respectively). The relationships of their system detection probability are shown as Figure 3，Figure 4 and Figure 5.

Figure 3 shows the relationship between the system detection probability and the average SNR under the two methods. From Figure 3, under the distributed setting threshold method, the system detection probability is improved significantly, that is to say, the method proposed in this paper can provide better protection to PU system, comparing with the unified setting threshold method.

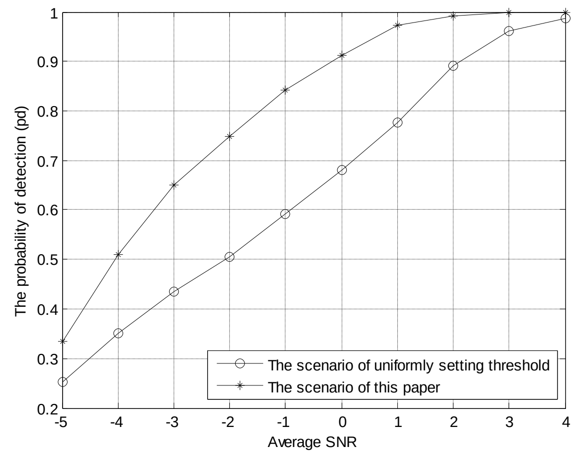

Figure 3. Considering the instantaneous signal-to-noise, the relationship between global detection probability and the average signal-to-noise

Figure 4 and Figure 5 show the simulations over Rayleigh channel and additive white gaussian noise (AWGN) channel respectively. Form the figures, the distributed setting threshold method proposed in this paper is equally applicable to the Rayleigh channel and AWGN channel, this method can also improve the system detection probability, reduce the risk of bothering PU, and achieve the goal of protecting PU.

VI. CONCLUSION AND FUTURE WORKS

When all the SUs are in low SNR environments, collaborative spectrum sensing can do little improvement to the performance of the system, in this case, we should devote to improve the local detection performance of SU, and then improve the global detection performance. In this paper, each SU according to its environment sets the most suitable threshold independently, and then makes the optimal local decision. The simulation results prove that, under the method proposed in this paper, the local detection

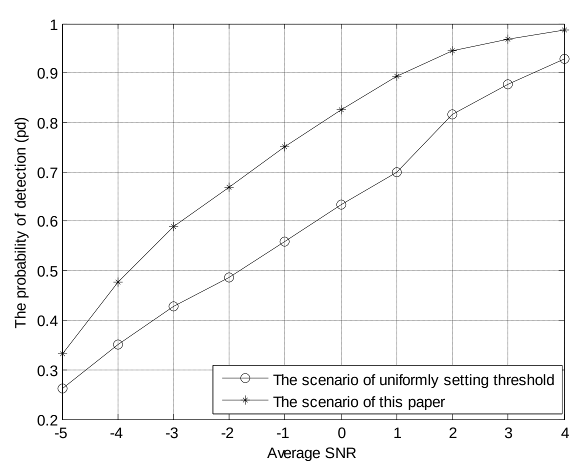

Figure 4. Over Rayleigh channel, the relationship between global detection probability and the average signal-to-noise

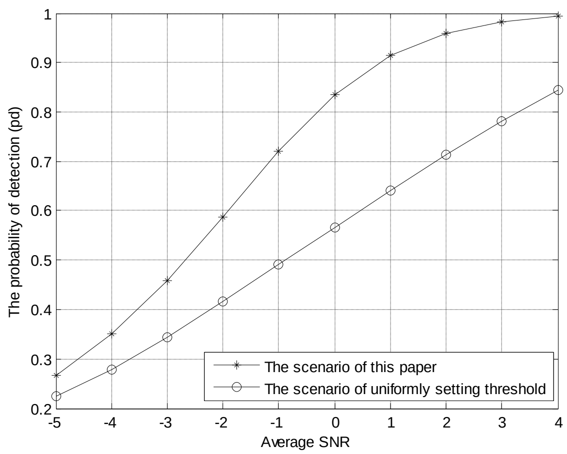

Figure 5. Over AWGN channel, the relationship between global detection probability and the average signal-to-noise

probability is improved, after collaborative detection, the system detection probability is improved too; so, the risk of disturbing PU is reduced. In future work, we will devote to find a more effective way to improve the detection performance of system.

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