Selective Cooperative Spectrum Sensing for Cognitive Radio System

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***Abstract*—Spectrum sensing is the basis of cognitive radio technology. Cooperative spectrum sensing has been shown to increase the reliability of spectrum sensing. To reduce sensing overhead and total energy consumption, it is recommended that the users with good performance should be selected to increase the sensing reliability. However, which of the cognitive users have the best detection performance is not known a priori. In this paper, a selective cooperative sensing strategy and a user selection method based on B value are proposed so as to increase the sensing reliability and reduce sensing overhead. Simulations are used to evaluate and compare the B value method with other methods. Simulation results show that B value selection has the same sensing performance with signal-to-noise ratio (SNR) selection. B value selection obviously outperforms the simple counting selection in the presence of noise uncertainty. In general, the SNRs of all cognitive users are not known a priori and there must be certain noise uncertainty, in this sense, B selection is a simple, feasible and effective selection method.**

***Index Terms*—selective cooperative sensing, spectrum sensing, user selection method, cognitive radio**

I. INTRODUCTION

With the rapid development of communication technology and industries, spectrum resource is becoming increasingly scarce. Recently, cognitive radio (CR) technology is considered to be an effective method to solve the lack of spectrum resources. The main idea is to allow cognitive users (non-authorized users) to share spectrum resources without causing any harmful interference to those primary users (authorized users). Spectrum sensing is one of the key technologies. According to the rule of IEEE 802.22 WLAN, the cognitive users system should be far away from the primary user system to ensure that the primary users (PUs) are kept away from interference produced by CR transmitter. In that case, CR node will sense the primary user signal with low signal-to-noise ratio (SNR). In addition, in a fading environment, the channel uncertainty due to the deep fading and shadow challenges the spectrum sensing. To combat multi path and shadow effect of spectrum sensing, cooperative spectrum sensing has been shown to increase the reliability of sensing [1-5]. However, a large number of cooperating CRs typically lead to more energy consumption of the system. During cooperative spectrum sensing, each CR implements local spectrum sensing independently, then sends the result to Fusion Center (FC) and waits for the final system judgment. While waiting for the judgment, all CRs cannot send and receive their own data, which reduces the average system throughput. In addition, the fusion principle which is widely used by fusion center is not optimized, when the users with poor performance participate in cooperative sensing, they actually degrade the system sensing performance [6-9].

Study [10] showed that cooperative sensing among the CRs with high SNR could obtain the best performance. However, in general, the SNRs of all CRs are not known a priori, the base station or fusion center cannot select cooperating CRs basing on their SNRs. Study [11] proposed an iterative algorithm to estimate detection probability and false alarm probability for each CR and selected the cooperating CRs basing on the estimated detection probability and false alarm probability. Study [12] proposed a sensor selection method based on the knowledge of sensor positions. Study [13] proposed one method to select the CRs basing on Simple Counting (SC) in the case of ignoring noise uncertainty. In general, the noise uncertainty certainly always exists and causes counting error, so degrades the sensing performance. The authors of [14] solved the problem of uncorrelated user selection in mobile cognitive radio ad hoc networks. The authors of [15] developed a distributed sensor selection mechanism utilizing non-cooperative game theory.

This paper presents a new method for selecting cooperating CRs. During the selecting period, every CR

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calculates each B value of the received signal and passes it to the fusion center. Fusion center selects the cooperating CRs based on their B values.

The main contributions of this paper can be described as follows:

1) We propose a selective cooperative sensing strategy in which a selecting slot is designed before the sensing slot. Only the users with good performance are selected to cooperate sensing so as to increase the sensing reliability and reduce sensing overhead.

2) A method based on B value for selecting the cognitive users with the best detection performance is proposed. Simulation results show that B value selection has the same sensing performance with SNR selection. In general, the SNRs of all CRs are not known and meanwhile there must be certain noise uncertainty. In this case, B selection is a simple, feasible and effective selection method.

This paper is organized as follows: Section 2 describes the system model of the selective cooperative sensing and section 3 presents B value selection method. Section 4 analyzes the selective performance of the model. Section 5 gives the results of simulation and analysis in order to evaluate the performance of this approach. Finally, section 6 gives the conclusions of the article.

II. System Model

The system model used in this paper is based on the IEEE 802.22 WRAN deployment scenario. A centralized CR network (CRN) is illustrated in Fig.1, which consists of M CRs and a fusion center (FC). For primary user (PU) network, we assume that it consist of a primary transmitter denoted as base station (BS) and several receivers, e.g., a TV radio station and many TV radio receivers. The FC is far away from the primary user BS. All CRs are independently and randomly distributed in a circle centered at the FC with radius RS. The received power of the CR i is

$$P_i = \frac{P_{pu}}{d_i^{\alpha}} \mu \tag{1}$$

where P_{pu} is the PU's signal power, d_i is the actual distance from the CR i to the PU, α is the path loss exponent factor and μ is a scalar.

In this CRN, CR needs to detect the activities of PU before its transmissions. If PU is detected, CR will defer its transmissions and then try again in the next transmission phase, otherwise, CR is allowed to send its messages. However, if PU is undetected when it is actually present, CR may affect the operations of PU. To improve the detection performance of CR and well-protect primary transmissions, the cooperative CRs should assist PU to monitor the spectrum.

It assumes that all CRs operate in a fixed time division multiple access (TDMA) manner. In 802.22 WRAN, each medium access control (MAC) frame consists of two consecutive durations called sensing slot and data transmission slot [16], as depicted in Fig. 2 (a).

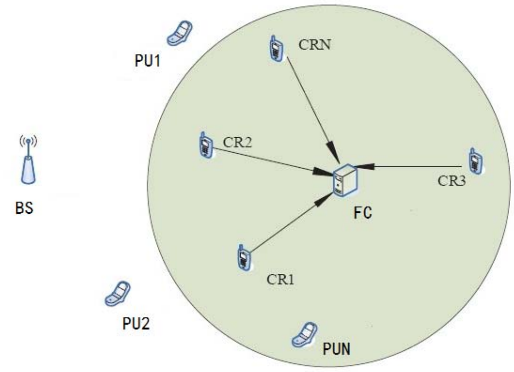

Figure.1 Simulation scenario in CR networks

In traditional strategy, all CRs independently detect PU's states in the sensing slot at the beginning of each MAC frame and then each cooperative CR reports its local 1-bit hard decision to the FC.

We further propose a frame structure of selective cooperative detection as depicted in Fig.2 (b). A selecting slot is designed before the sensing slot.

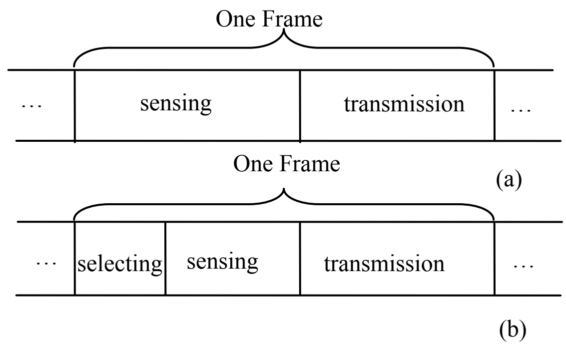

Figure.2 (a) Frame structure of traditional cooperative detection; (b) Frame structure of selective cooperative detection.

In selecting slot every CRs calculates the specific parameter of the received signal and transfer the parameter to the FC. At the end of the selecting slot, basing on the all parameters, the FC selects the best CRs to cooperate sensing based on the proposed selection methods.

At the start of each cognitive radio selection round, i.e., at the very start of selecting period, the FC assigns an identity number to each cognitive radio. The FC grants a contention free channel to individual cognitive radios by polling them (using their identity numbers) for transmitting their parameters. At the end of the selecting period, only the cognitive radios with the best detection performance are selected. Mobility of CRs can cause changes to the probability of detection. Slow mobility can be taken into account by periodically performing the CR selection process.

In sensing slot, all selected CRs independently detect PU's state and then each cooperative CR reports its local 1-bit hard decision to the FC. We use the method given in [17] to transmit and receive the local decisions. Specifically, each cooperative CR encodes its local decision by a cyclic redundancy code (CRC) and then sends the CRC-encoded indicator signal to FC where CRC checking is performed. Finally, only the successfully decoded outcomes are used for fusion. Typically, after FC makes a global decision, it should broadcast a message containing PU's state information to notify its neighboring CRs. Like many existing works, it is assumed that the final decision notification can be correctly received by cooperative CRs, where the details of final decision declaring is out of scope of this paper and thus not discussed.

III. User Selection Method

In this section, SNR selection and SC selection two methods are introduced and analyzed firstly. Then B value method is proposed to select the cooperative users with the best detection performance.

A. Related Work

It is shown that the optimum (best) detection performance is usually achieved by cooperating only with the CRs that have the highest *SNR* values [10]. However, in general the *SNR* of a CR is not known, so it is not known a priori which CR have the best detection performance.

Simple Counting (SC) method mentioned in the literature [13] is as follows: in a given time slot, denote the sensing decision of the CR *i* by $\delta_i \in \{0,1\}$, and the real state of the PU by $\rho \in \{0,1\}$. The probability that the CR *i* declares the PU to be present is given as:

$$\Pr(\delta_i = 1) = (1 - P_{H_1})P_{f,i} + P_{H_1}P_{d,i} \qquad (2)$$

In (2), the probability of PU present is P_{H_1} and the probability of PU absent is 1-P_{H_1}. $P_{f,i}$ is the false alarm probability and $p_{d,i}$ is the detection probability of the CR *i*. P_{H_1} and $P_{f,i}$ are assumed the same for every CR. When $p_{d,i}$ is high, $\Pr(\delta_i = 1)$ is also high. In this case, the CRs with high $\Pr(\delta_i = 1)$ are selected as cooperating CRs.

The false alarm probability $P_{f,i}$ in (2) is assumed the same for every CR. While in practice, there is certain noise uncertainty. Due to noise uncertainty, the estimated noise power may be different from the real noise power, thus, the actual false alarm probability $P_{f,i}$ will be somewhat different from each other. High $P_{f,i}$ must lead to high $\Pr(\delta_i = 1)$. In this case, the user selection based on $\Pr(\delta_i = 1)$ must bring about the risk of increasing the system false alarm probability and cause possible harmful interference to the PU.

B. Proposed B Value Selection Method

Let us consider D consecutive samples and define the received signal as $x_i(n)$. B value selection algorithm is as follows.

Step 1) Every CR user calculates the autocorrelations of the received signal $x_i(n)$ according to (3). Parameter L is the maximum time delay factor and it is any integer less than D.

$$C_i(l) = \frac{1}{D}\sum_{n=0}^{D-1} x_i(n)x_i(n-l),\ l = 0,1,\cdots,L-1,\ \text{L<D} \quad (3)$$

Step 2) The sample autocorrelation $C_i(l)$ form the matrix Rx_i as

$$Rx_i = \begin{bmatrix} C_i(0) & C_i(1) & \cdots & C_i(L-1) \\ C_i(1) & C_i(0) & \cdots & C_i(L-2) \\ \vdots & \vdots & \ddots & \vdots \\ C_i(L-1) & C_i(L-2) & \cdots & C_i(0) \end{bmatrix} \qquad (4)$$

Step 3) Every CR calculates the performance parameters B_i according to formula (5) and then sends B_i to the Data Fusion Center.

$$B_i = \sum_{j=1}^{L}\sum_{k=1}^{L}|r_{jk}| \Big/ \sum_{j=1}^{L}|r_{jj}| \qquad (5)$$

where r_{jk} represents the elements of the sample autocorrelation matrix Rx_i.

Step 4) FC selects K cognitive users according to B_i value from big to small and then informs them to cooperate local sensing.

As in (5), $\sum_{j=1}^{L}\sum_{k=1}^{L}|r_{jk}|$ represents the autocorrelation extent of $x_i(n)$ and it is influenced by channel fading and received *SNR*. In (5), $\sum_{j=1}^{L}|r_{jj}|$ is the autocorrelation of additive white Gaussian Noise and this value increases with the growth of the noise power. The B_i value represents the sensing performance of the CR *i*. The greater the B_i value is, the better sensing performance of the CR *i* will have. Therefore, in the scenario of having no prior knowledge of the *SNR*s, B_i value can be used as criterion for selecting cooperative sensing users.

IV. Performance Analysis

Let us now analyze the performance of the selective cooperative sensing. In particular, we are interested in two performance measures. First, it is the performance, in terms of the detection and false alarm probabilities, at the node level. Second it is the detection and false alarm probabilities at the FC side. These performance metrics will be defined and derived in the following subsections.

The local spectrum sensing is accomplished by energy detection. We use the energy detection to evaluate the performances of traditional and proposed selective cooperative sensing. Since we want to show the advantages of proposed selective cooperative sensing based user selection, the choice of detector is not critical. Thus, the results obtained in this paper can be easily extended to other detector cases.

The channels are modeled as Rayleigh fading, which are independent with each other. Suppose that the additive white Gaussian noise (AWGN) at the receivers of CRs, PUs and FC.

A. Probability of Detection and False Alarm at the node level

Let H_0 and H_1 denote two standard hypotheses used in spectrum sensing. By definition, false alarm means that PU is detected under H_0 and detection indicates that PU is detected under H_1. Besides, miss detection is defined as that PU is undetected under H_1. For energy detector in Rayleigh fading channel, if we choose the detection threshold as λ, the probability of false alarm P_{fa} is then given by [16]:

$$\begin{aligned} P_{f,i} &= P(\Delta > \lambda | H_0) \\ &= Q\left(\frac{\lambda - \sigma_{w,i}^2}{\sigma_{w,i}^2 / \sqrt{N}}\right) \end{aligned} \tag{6}$$

where Δ represents the detection statistics, $Q(\cdot)$ is the complementary distribution function of the standard Gaussian, i.e.,

$$Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-\frac{\mu^2}{2}} d\mu \tag{7}$$

If the probability of false alarm of sensing system is given, according to (6), threshold λ is set as

$$\lambda = \left(\frac{\sigma_{w,i}^2}{\sqrt{N}}\right) Q^{-1}(P_{fa}) + \sigma_{w,i}^2 \tag{8}$$

where $Q^{-1}(\cdot)$ denotes the inverse function of $Q(x)$, $\sigma_{w,i}^2$ presents the noise power at the CR *i*.

The detection probability is given by

$$\begin{aligned} P_{d,i} &= P(\Delta > \lambda | H_1) \\ &= Q\left(\frac{\lambda - (1+\gamma_i)\sigma_{w,i}^2}{\sigma_{w,i}^2 \sqrt{(1+2\gamma_i)}} \sqrt{N}\right) \end{aligned} \tag{9}$$

where *N* represents the number of sampling points, γ_i presents the received SNR at the CR *i* under the hypothesis H_1. Obviously γ_i is equal to $\gamma_i = \frac{E_p |h_i|^2}{\sigma_{w,i}^2}$, E_p is the PU's transmit power.

B. Detection and False Alarm Probabilities at the FC Side

Since some of the CRs which are not selected to cooperate sensing will not make local sensing, only the subset of the selected CRs will cooperate sensing and report to the FC. This subset is denoted Cr, where the number of its elements ranges from 1 to K, i.e. 1 ⩽ |Cr| ⩽ K. Every CR i ∈ Cr sends its local decision to the FC through its CRi-FC link experiencing flat Rayleigh fading.

FC attempts to decode the CR *i* and perform CRC checking, where only the successfully decoded outcomes are pooled at FC. If the CRC checking fails to pass, FC deems that PU is undetected by the CR *i*. In an information-theoretic sense [18], if the channel capacity falls below a predefined data rate, an outage occurs and then the CRC checking will fail at the receiver. However, due to the many channel impairments like fading, shadowing, path loss etc, some of the local decisions may get corrupted when decoded by the FC. Hence, the probability that the CR *i* successfully reports a 1 to the BS can be written as

$$\begin{aligned} P_{re,i} &= P(r_{re,i} \geq r_{th}) \\ &= \int_{r_{th}}^\infty r_{re,i}^{-1} e^{-r/r_{re,i}} dr \\ &= e^{-r_{th}/r_{re,i}} \end{aligned} \tag{10}$$

where $\gamma_{th} = 2^Q - 1$ and Q is the spectral efficiency in bits per second per Hertz. The $\gamma_{re,i}$ is the instantaneous *SNR* of the CR-FC link and $\gamma_{re,i} = SNR_f |h_{re,i}|^2$, where SNR_f is the transmit *SNR* of the CR *i* (assumed equal for all CRs), $|h_{re,i}|^2$ is the channel gain of the CR i-FC link.

For the purpose of comparison, the performance of traditional OR-based cooperative detection is also analyzed. Different from existing works, we analyze the detection performance of traditional strategy with consideration of reporting channel errors due to both the Rayleigh fading.

$$\begin{aligned} P_d^{sel} &= P(\Delta_g > \lambda_g | H_1) \\ &= 1 - \prod_{CR_i \in CR} [1 - P_{re} P_{d,i}] \end{aligned} \tag{11}$$

$$\begin{aligned} P_f^{sel} &= P(\Delta_g > \lambda_g | H_0) \\ &= 1 - \prod_{CR_i \in CR} [1 - P_{re} P_{f,i}] \end{aligned} \tag{12}$$

where $CR = \{CR_i | i = 1, \cdots, k\}$. From (12), we can write the overall miss detection probability of traditional OR-based strategy as $P_m^{sel} = 1 - P_d^{sel}$.

V. Simulation Results

To verify the above proposed selection method by Monte Carlo simulation, we use BPSK as the primary user signal. The sampled observation data has length N=6000, there are ten CRs in the network and their *SNR*s randomly distribute between $-18dB$ and $-10dB$. The targeted system false alarm probability is set to 0.05. In following figures, D represents the length of signal which is used to compute B value and select cooperative user, L represents the maximum time delay and only "OR" fusion criterion is used.

Assume that the noise is white Gauss noise and noise power is σ_w^2. If the noise uncertainty is x dB, the actual estimated noise power is random variables in the range of the $[10^{-x/10}\sigma_w^2, 10^{x/10}\sigma_w^2]$ [19].

A. Performance Comparison between B Selection and Random Selection

Fig.3 shows the B value of the signal versus under different noise uncertainty. D=600 and L=10. As you can see that B value almost linearly increases with the *SNR* improvement. When the *SNR* is same, B value decreases along with the noise uncertainty increasing, which indicates that the B value can reflect the influence of *SNR* and the noise uncertainty. So B value can be used as selecting criterion to select cooperative users.

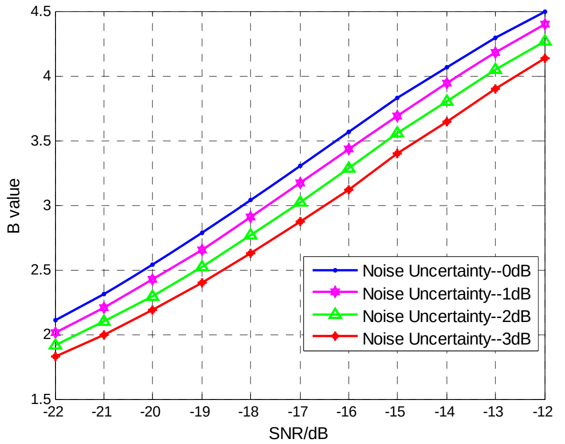

Figure 3. B value versus SNR under different noise uncertainty

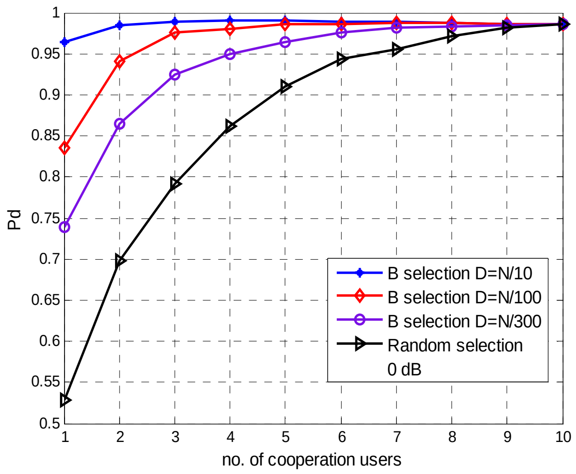

Figure 4. Detection probability comparison between B selection under different D and random selection, noise uncertainty is 0dB

Fig.4 shows the detection probability comparison between random selection and B selection under different D . L=10. D is respectively equal to N/10=600, N/100=60 and N/300=20. It can be seen that different D has different selective result. For the same number of cooperating users, the bigger the value of D is, the better detection probability of cooperative spectrum sensing will have. As we can see, for the same number of cooperative users, the system detection probability P_d under B selection is obviously higher than that P_d under random selection. Even when D=20, B selection detection probability is still higher than that P_d of random selection. There are ten CRs in the network, of course, when all ten cognitive users in network are involved in cooperative sensing, the result under random selection is as the same as that under B selection.

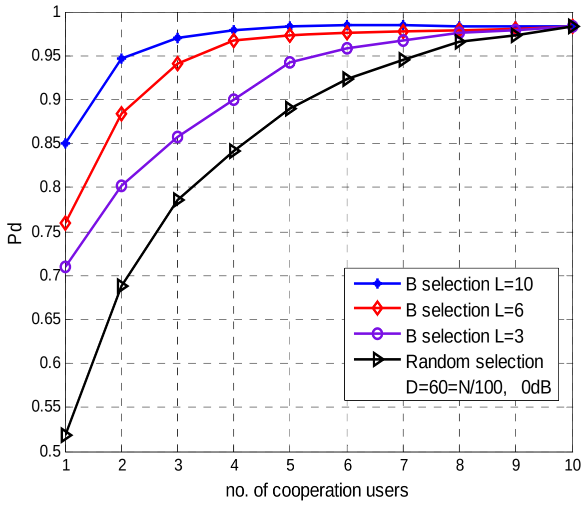

Figure 5. Detection probability comparison between B selection under different delay L and random selection, noise uncertainty is 0dB

Fig.5 shows the detection probability comparison between random selection and B selection under different delay L. When D=N/100=60, L is respectively equal to L=10, L=6 and L=3. It can be seen that different L has different selecting result. For the same number of cooperating users, the bigger the value of L is, the better detection probability of cooperating spectrum sensing will have. For the same number of cooperating users, the system detection probability P_d under B selection is obviously higher than that P_d under random selection. Even when L=3, B selection detection probability is still higher than that P_d of random selection. Of course, when all cognitive users in network are involved in cooperative sensing, the result under random selection is as the same as that under B selection.

Fig.6 and Fig.7 show the error detection probability comparison between random selection and B selection under different noise uncertainty, L=10. Fig.6 shows the performance comparison in the case of ignoring noise uncertainty, where noise uncertainty is 0dB. Fig.7 shows the performance comparison in the presence of noise uncertainty and noise uncertainty is 0.1dB. The probability of error detection P_e is the sum of the false alarm probability and missing probability. It can be seen that the P_e of B selection is lower than random selection. Because cognitive users using the energy sensing method, the sensing performance of two methods all decrease due to the noise uncertainty influence. In the case of considering noise uncertainty in Fig.7, the sensing performance of both methods all degrade, while the error detection probability of B selection is still lower than that P_e of random selection.

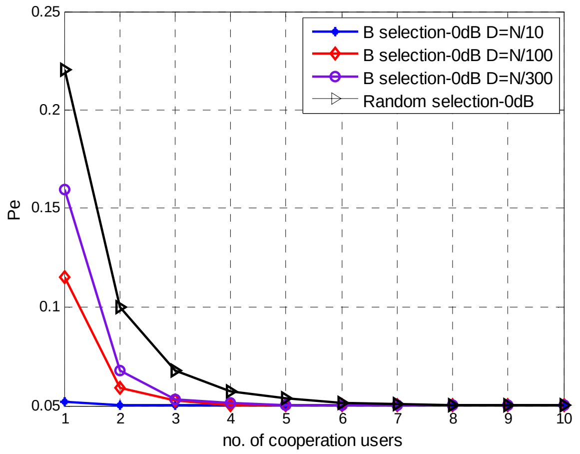

Figure 6. Error detection probability comparison between B selection under different D and random selection, noise uncertainty is 0dB

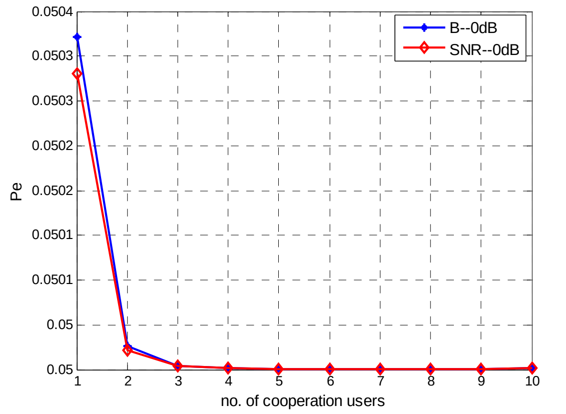

Figure 8. Error detection probability comparison between B selection and SNR selection, noise uncertainty is 0dB

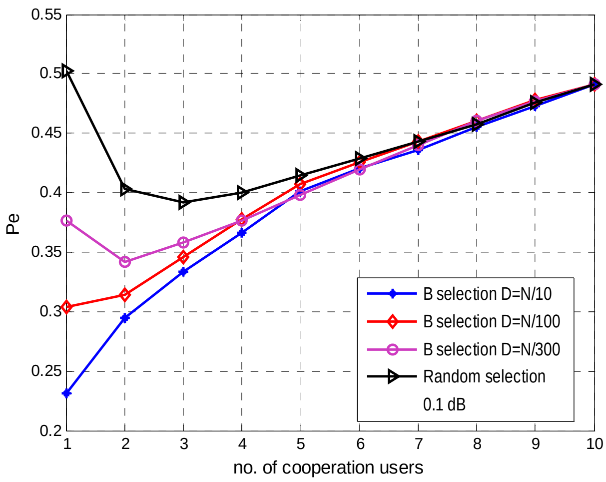

Figure 7. Error detection probability comparison between B selection under different D and random selection, noise uncertainty is 0.1dB

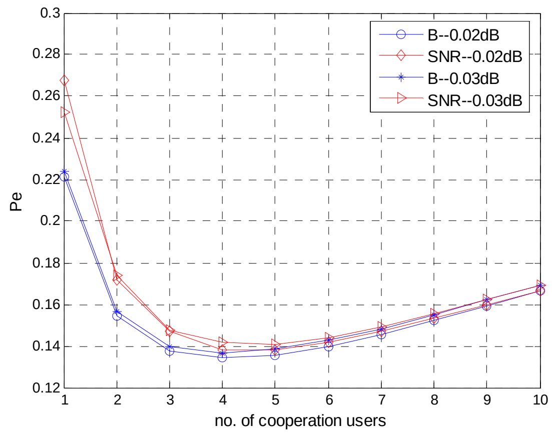

Figure 9. Error detection probability comparison between B selection and SNR selection with different noise uncertainty

B. Comparison with SNR Selection

As mentioned in [10], the user selection based on *SNR* can obtain the best sensing performance, which must have *SNR*s knowledge a prior. Assuming *SNR*s are known a prior, Fig.8 and Fig.9 show the performance comparison between B selection and *SNR* selection.

Fig.8 shows that B selection has nearly the same performance with *SNR* selection in the case of ignoring noise uncertainty.

Fig.9 shows the performance comparison between B selection and *SNR* selection in the presence of noise uncertainty. It can be seen that B selection has litter better performance than the *SNR* selection method in the presence of noise uncertainty.

C. Comparison with SC Selection

Fig.10 and Fig.11 compares the performance between the B selection and Simple Counting (SC) selection. Assuming the possibility of the PU present is $P_{H_1} = 0.2$. In Fig.10, we can see that both performances are very close in the case of no noise uncertainty.

Fig.11 shows the performance comparison between the B value and SC selection in the case of noise uncertainty. It can be seen that when the number of cooperation users is 4, the noise uncertainty equals to 0.02dB, P_e of SC selection is about 0.081, while P_e of B selection is 0.06, the P_e of B selection counts down about 25% comparing with SC selection. When the noise uncertainty equals to 0.03dB, P_e of SC selection is about 0.09, while P_e of the B selection is about 0.07, the P_e of the B selection counts down about 22% comparing with SC selection. Fig.10 and Fig.11 shows that the B selection outperforms the SC selection in the presence of noise uncertainty.

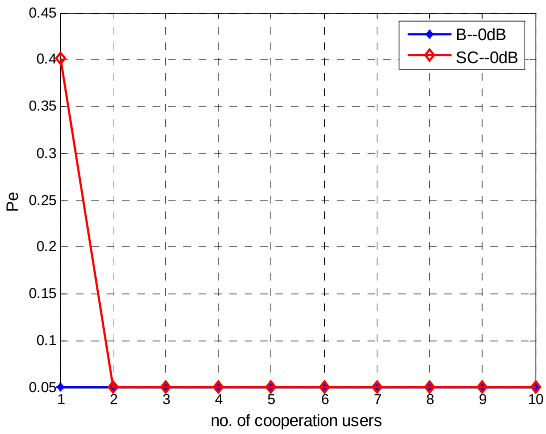

Figure 10. Performance comparison between B selection and SC selection, noise uncertainty is 0dB.

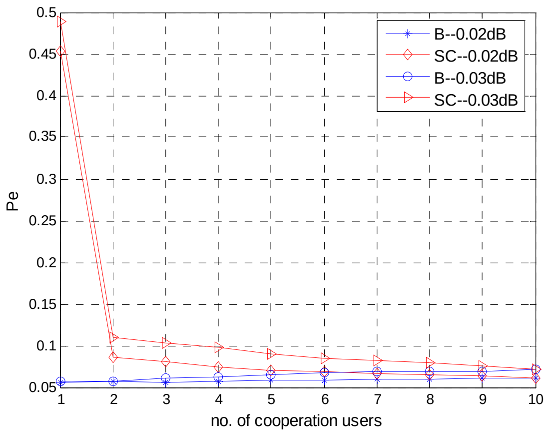

Figure 11. Performance comparison between B selection and SC selection with different noise uncertainty.

VI. CONCLUSIONS

In this paper, a selective cooperative sensing strategy and a user selection method based on B value are proposed. B value selection method is presented to select cooperating sensing CRs. B value selection is compared with the *SNR* selection and SC selection. The simulation results show that B selection has the same sensing performance as *SNR* selection no matter or not noise uncertainty exists. B value selection obviously outperforms the SC selection in the presence of noise uncertainty. In general, the *SNR*s of different cognitive users are not known, and there must be certain noise uncertainty, in this sense, B selection method is a feasible, simple and effective selection method.

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