Optimization of Collaborating Secondary Users in a Cooperative Sensing under Noise Uncertainty

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***Abstract*—Cooperative spectrum sensing is employed in Cognitive Radio (CR) networks to reliably detect Primary User (PU) transmissions by fusing the sensed data of multiple Secondary Users (SUs). The local detection reliability of an individual SU is closely related to its channel condition. In this paper, we propose a scheme that uses SNR to evaluate the reliability of each individual SU's local decision. We optimize the number of SUs for the sensing based on their channel conditions to achieve the optimal global detection probability at the fusion centre. Simulation results show that the proposed algorithm is robust against noise uncertainty with the optimal number of SUs and better receiver operating characteristic (ROC) performance is obtained in comparison to conventional schemes.**

I. Introduction

Cognitive radio (CR) is proposed to opportunistically access the underutilized spectrum [1], [2]. CR employs spectrum sensing to determine unused frequency bands and utilizes these idle bands without causing harmful interference to PUs. Many sensing algorithms have been proposed to enhance the sensitivity of spectrum sensing [3]–[5]. Energy detection is most commonly researched as it does not require prior information of PU signals. Specifically, an energy detector can calculate the energy of the received PU signal through FFT computations with low complexity, and then compare the energy with a threshold. The result is then recorded with a binary value (0 or 1) locally. However, energy detection is based on the assumption that the noise is independent and identically Gaussian distributed at each SU. In practice, the noise power changes with time and radio environment, which is commonly modelled as noise uncertainty. The noise uncertainty greatly lowers the sensing reliability of energy detection [6] and a new challenge emerges for CR communications to be robust against the noise uncertainty.

Mathematic modelling of noise uncertainty [7] shows that there are SNR walls under which a reliable detection cannot be achieved even when the sample number is increased to infinite. Noise uncertainty may cause inaccurate local decision of SUs, and thus affect the final global decision precision in the fusing centre [8]. To solve this problem, a cooperative spectrum sensing scheme with a double-threshold is proposed to detect weak signals of unknown formats and cope with hidden primary receiver problem [9], [10]. By introducing multiple SUs in the spectrum sensing, it provides multiple independent local detections of PUs' frequency bands utilization. The spatial diversity of SUs helps cooperative spectrum sensing improve detection performance by reducing error detection probability caused by shadowing and multipath fading [11]. However, it has been assumed that all SUs share an identical SNR [10]. In practical scenarios, however, different SUs would have different SNR values. Meanwhile, the extra transmission of unreliable decisions from low SNR SUs can also introduce overhead of control signaling, which lowers spectrum efficiency and increases energy consumption [12].

To reduce the sensing energy, many cooperative sensing schemes have been proposed to reduce the number of SUs. In [13], a clustering scheme is proposed to minimize the energy consumed in spectrum sensing. But it requires the formulation of appropriate clusters, selecting cluster head according to prior information and aggregating sensing data of SUs to the cluster head. Consequently, it takes extra time for collecting data from all SUs and adds complexity to deal with diverse scenarios in reality. A cooperative sensing technique to select part of SUs to minimize the detection error probability in WIFI networks is proposed in [14]. However, this paper assumes that all SUs have the same SNR, and the noise is independent and identically Gaussian distributed at each SU. In practice, each SU has different channel conditions and encounters different fading channels. Therefore, it should take both noise uncertainty and different SNRs at each SU into consideration for the cooperative sensing.

Furthermore, the local detection precision of an SU is closely related to its SNR value [15]. When the SU experiences a highly destructive channel fading and shadowing, its local decision is actually less reliable and affects the final global decision at fusion centre [16]. Therefore, for cooperative spectrum sensing, it is necessary for the fusion centre to incorporate SNR conditions at each SU to achieve a reliable fusion result [17].

In this paper, we propose a scheme considering both noise uncertainty and different channel conditions at each SU. The reliability of the SUs' local decisions is evaluated and prioritized by their SNRs. Both the analytical study and simulations show that the number of collaborating SUs can be optimized upon their channel conditions while maintaining the high detection performance at the fusion centre.

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The rest of this paper is organized as follows: the proposed cooperative spectrum sensing system model based on energy detection with a double-threshold under noise uncertainty is described in Section II. In Section III, the number of collaborative SUs based on their channel conditions is derived in terms of the local detection probability and global false alarm probability under noise uncertainty. Simulation results are analyzed and compared with a conventional scheme in Section IV. Finally, conclusions are drawn in Section V.

II. The Proposed Spectrum Sensing Model under Noise Uncertainty

In CR networks, spectrum sensing can be formulated as a binary hypothesis testing model,

$$x(t) = w(t), \qquad H_0 \tag{1}$$

$$x(t) = s(t) \cdot h(t) + w(t), \qquad H_1 \tag{2}$$

where $s(t)$ denotes the signal sent by PU, $w(t)$ is the addictive white Gaussian noise distributed independently and identically , $x(t)$ is the signal received at SU, and $h(t)$ represents the channel coefficient between PU and SU. Hypothesis H_0 implies the absence of PU signal and H_1 represents the presence of PU signal.

In our system model, SUs employ energy detection. The test statistics for the energy detector at each SU is computed as the sum of the received signal energy over an interval of N samples, and is defined as [3]:

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

where N is the number of samples in the PU's band in each detection. According to the central limit theorem, when N is large enough (e.g. $N \geq 10$), the value of T follows the Gaussian distribution.

$$T \sim N(\sigma_n^2, \frac{2\sigma_n^4}{N}), \qquad H_0 \tag{4}$$

$$T \sim N(\sigma_s^2 + \sigma_n^2, \frac{2(\sigma_s^2+\sigma_n^2)^2}{N}), \qquad H_1 \tag{5}$$

where σ_s^2 is signal power, and σ_n^2 is noise power [7].

The performance of the detection scheme can be evaluated by two metrics: probability of detection P_d and probability of false alarm P_f. For energy detection, the probabilities P_f and P_d can be calculated as [3]:

$$P_f = P(T > \lambda|H_0) = Q\left(\frac{\lambda - \sigma_n^2}{\sigma_n^2\sqrt{\frac{2}{N}}}\right) \tag{6}$$

$$P_d = P(T > \lambda|H_1) = Q\left(\frac{\lambda - (\sigma_s^2+\sigma_n^2)}{(\sigma_s^2+\sigma_n^2)\sqrt{\frac{2}{N}}}\right) \tag{7}$$

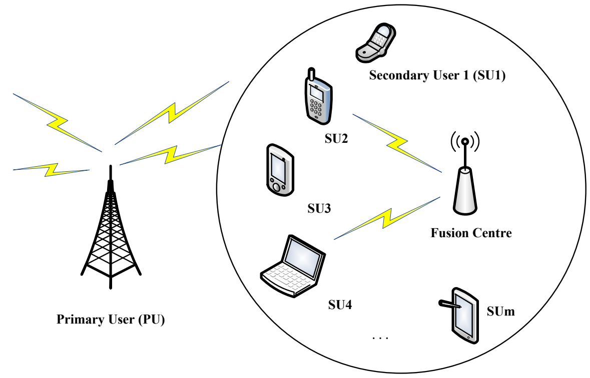

Fig. 1: Cooperative spectrum sensing model for a CR network.

where $Q(x)$ is the standard Gaussian Complementary Distribution Function (CDF). Using $\gamma = \sigma_s^2/\sigma_n^2$ to denote the signal to noise ratio (SNR), equation (7) can be rewritten as,

$$P_d = P(T > \lambda|H_1) = Q\left(\frac{\lambda - \sigma_n^2(\gamma+1)}{\sigma_n^2(\gamma+1)\sqrt{\frac{2}{N}}}\right) \tag{8}$$

Hence, the individual detection probability P_d is conditional probability upon SNR γ, sample points N and noise σ_n^2 at each SU.

The CR network model adopted in this paper is shown in Fig. 1. The SUs employ energy detection to perform the spectrum sensing. During the cooperative sensing process, SUs sense the signal from a targeted PU through a sensing channel. After comparing the local observation with the threshold, each SU makes a one-bit hard decision on the absence or presence of the primary user, and then sends this one bit (0 or 1) to the fusion centre through a reporting channel. Finally, the fusion centre will make a final global detection decision.

The literature proposes many sensing schemes [3], [16] assuming that the noise is additive white Gaussian noise (AWGN) with mean and variance known exactly to derive the value of false alarm and detection probability through equation (6) and (7). In practice, however, noise is not perfectly Gaussian distributed due to the channel fading. This makes it hard for the SU to obtain the full information, and therefore the noise uncertainty should be considered in each SU's local detection decision. In [7], [10], the distribution of noise power can be modelled as

$$\delta_n^2 \in [(\frac{1}{\rho})\sigma_n^2, \rho\sigma_n^2] \tag{9}$$

where ρ indicates the degree of uncertainty, and δ_n^2 is the actual noise variance by taking the noise uncertainty into account.

To make detections more accurate, double thresholds (λ_l and λ_h) of each SU can be set in the comparison. Based on equation (6) and (9), the thresholds can be calculated by:

$$\lambda_l = (\sqrt{\frac{2}{N}}Q^{-1}(P_f) + 1)(\frac{1}{\rho})\sigma_n^2 \tag{10}$$

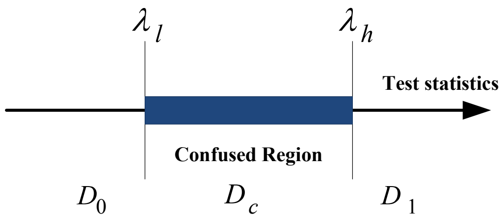

Fig. 2: The double-threshold scheme.

$$\lambda_h = \left(\sqrt{\frac{2}{N}}Q^{-1}(P_f) + 1\right)\rho\sigma_n^2 \tag{11}$$

Fig. 2 shows two thresholds for $P_f = 0.5$. The test in the confusing region is caused by the noise uncertainty. Decision in that region is not reliable. The decision can be obtained as $D_0 : T_i \leq \lambda_{l,i}$, $D_c : \lambda_{l,i} \leq T_i \leq \lambda_{h,i}$, and $D_1 : T_i \geq \lambda_{h,i}$, where T_i and λ_i represents the test statistic and threshold of the i-th SU, and D_0 and D_1 represent PU is absent and present, respectively. D_c indicates that test statistics falls into a confusing region. To save bandwidth used for reporting channels, it is not necessary to transmit the confused decision D_c. Finally, the received local decisions are all D_0 or D_1.

Under the noise uncertainty, the detection probability and false alarm probability with the double-threshold scheme at each SU can be defined as:

$$\begin{aligned} P_{d,i} &= P(Y_i \geq \lambda_{h,i}|H_1) \\ &= \int_{(\frac{1}{\rho})\sigma_n^2}^{\rho\sigma_n^2} Q\left(\frac{\lambda_{h,i} - \sigma_n^2(\gamma+1)}{\sigma_n^2(\gamma+1)\sqrt{\frac{2}{N}}}\right) f(\delta_n^2)d\delta_n^2 \end{aligned} \tag{12}$$

$$\begin{aligned} P_{f,i} &= P(Y_i \geq \lambda_{h,i}|H_0) \\ &= \int_{(\frac{1}{\rho})\sigma_n^2}^{\rho\sigma_n^2} Q\left(\frac{\lambda_{h,i} - \sigma_n^2}{\sigma_n^2\sqrt{\frac{2}{N}}}\right) f(\delta_n^2)d\delta_n^2 \end{aligned} \tag{13}$$

where $f(\delta_n^2)$ is the probability density function of the noise power.

After assigning a double-threshold for each SU to remove the decision confusion caused by the noise uncertainty, the cooperative spectrum sensing scheme is employed. There are several fusion rules addressed for cooperative sensing (AND-rule, OR-rule, K-out-of-N rule) [18]. The OR-rule is adopted in this paper as it has higher detection probability when SUs experience different SNRs, which is helpful to minimize the interference to licensed users [17]. For the OR-rule, the fusion centre determines the presence of PU when at least one SU detects the PU. This can be characterized as follows:

$$Q_d = 1 - \prod_{i=1}^{M}(1 - P_{d,i}),\ i = 1, 2, ..., m \tag{14}$$

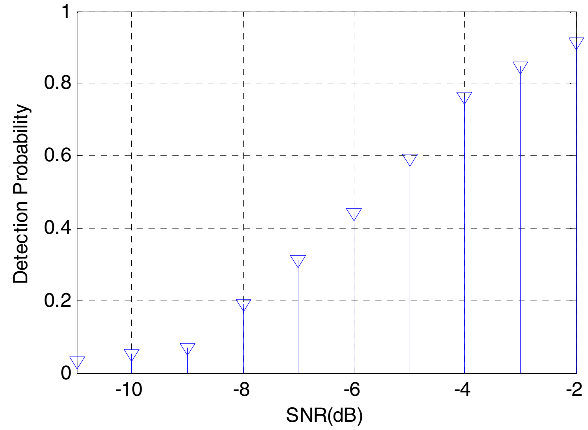

Fig. 3: The relationship between detection probability of a single SU and different SNRs under equal noise uncertainty.

$$Q_f = 1 - \prod_{i=1}^{M}(1 - P_{f,i}),\ i = 1, 2, ..., m \tag{15}$$

where Q_d denotes the global detection probability and Q_f denotes the global false alarm probability at the fusion centre. M is the number of SUs in a CR network.

III. Optimization of Collaborating SUs

In realistic CR systems, the global false alarm probability Q_f is often predefined to 10% or lower in order to limit the waste of band resource. Based on the fixed global false alarm, the objective is to maximize the global detection probability Q_d as much as possible.

In [10], it is assumed that the channel fading is independent for each SU in the network, and the identical SNR is assigned to each of the SUs. In practical scenarios, however, the channel gain $h_i(t)$ for an i-th SU is varying due to the channel fading and $P_{d,i}$ becomes a conditional probability being dependent on the received SNR at i-th SU, as shown in Fig. 3. SUs with low SNRs would transmit unreliable decisions to the fusion centre, so that the final global detection performance at the fusion centre is degraded. This is even worse when the noise uncertainty is involved [8].

Considering the scenario in Fig. 1, there are 15 SUs in the CR network, and each SU being assigned with randomly uniform SNRs from -20dB to 5dB. The number of sample points is set to 10 and noise uncertainty is 1dB for all SUs. The global sensing decision are then calculated by equation (14) after receiving all the local sensing decisions from each SU. Fig. 4 shows that the cooperative sensing is superior to that of a single node. However, the global detection probability does not always increase as more SUs join in the sensing process in the fusion centre. The detection of SU_1, SU_2, SU_3 and SU_4 can achieve better performance than that of SU_1, SU_2,..., and SU_{10} or that of all SUs. This could be caused by inaccurate decisions from the SUs with low SNRs.

The different SUs have different detection reliability due to variable channel conditions. The SU with better channel

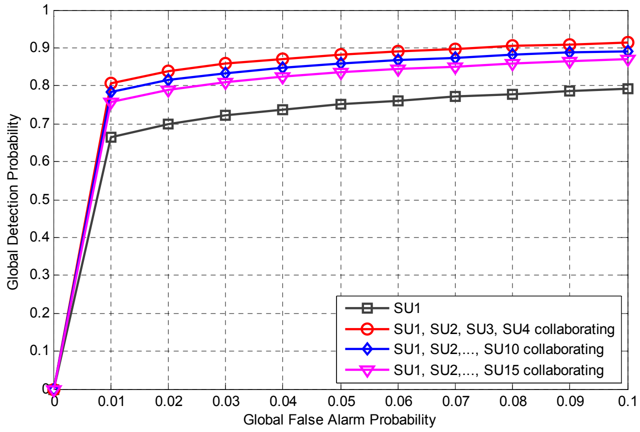

Fig. 4: Cooperative sensing comparison with equal noise uncertainty.

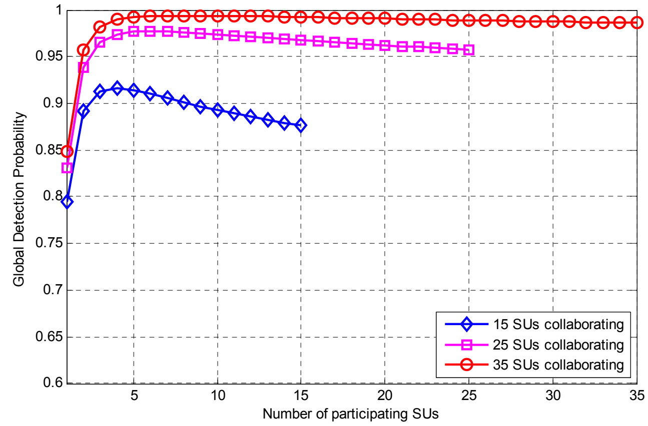

Fig. 5: Global detection probability with different number of SUs collaborating in the cooperate sensing.

condition has higher detection probability and therefore can improve the reliability of global detection at the fusion centre. The set of SUs with higher SNRs are encouraged to join the cooperative sensing in the first place. However, the SUs with low SNRs could degrade the global detection probability. Therefore, in order to achieve optimal fusion performance and save the reporting channel bandwidth, it would be more efficient for the fusion centre to collect the SNR information for each SU to decide which group of SUs gives better global sensing performance. The SNR of each SU can be obtained via reference signal received power (RSRP) as it has been employed in the measurement report of a 3GPP Long Term Evolution (LTE) network [19]. The question now is to determine how many SUs should be involved in the global detection process.

As equation (15) indicates, to achieve desired value of Q_f under OR fusion rule, the individual false alarm probability of each SU can be computed as,

$$P_f^Q = 1 - \sqrt[\widetilde{M}]{1 - Q_f}, \ \widetilde{M} = 1, 2, ..., m \qquad (16)$$

where $\widetilde{M}$ is the number of SUs selected to participate in the cooperative spectrum sensing. By taking equation (11) and (16) into (12), we can derive the relationship between the local detection probability and global false alarm probability under the noise certainty at each SU as:

$$P_{d,i}^Q = \int_{\frac{1}{\rho}\sigma_n^2}^{\rho\sigma_n^2} Q\left(\frac{\rho(Q^{-1}(P_f^Q) + \sqrt{N/2})}{\gamma_i + 1} - \sqrt{\frac{N}{2}}\right) f(\delta_n^2) d\delta_n^2 \qquad (17)$$

With a given Q_f and N, the local detection probability of each SU $P_{d,i}^Q$ can be obtained against SNRs. It can been seen from equation (17) that an increase in either P_f^Q or γ_i leads to an increase in $P_{d,i}^Q$. P_f^Q allocated to each SU is upon the global false alarm probability Q_f and the number of collaborating SUs $\widetilde{M}$. For the predefined Q_f, when the number of SUs $\widetilde{M}$ increases, P_f^Q allocated to each SU decreases, and thus $P_{d,i}^Q$ decreases. However, as equation (14) indicates, the global detection probability Q_d is the increasing function with the number of collaborative SUs $\widetilde{M}$. Therefore, as the number of participating SUs $\widetilde{M}$ increases, the global detection probability Q_d increases at first, and then falls after reaching the peak point as P_f^Q of each SU decreases. To achieve the maximum global detection probability, we need to find out the optimum number of collaborative SUs $\widetilde{M}$.

In our proposed cooperative sensing scheme, SNRs of all SUs will be collected via RSRP at the fusion centre first, and then the fusion centre sort SNRs in a descending order. To detect the existence of primary users reliably, SU with the highest SNR will be chosen first, then the second highest one, and so on. As the number of joining SUs increases, SNR decreases, $P_{d,i}^Q$ also decreases as indicated in (17). Therefore, the global detection probability Q_d is expected to increase at first, and then fall as the number of SU M increases. At the turning point, the iterative calculation process ceases and the maximized Q_d would be achieved. In this process, the high detection performance can be achieved at the fusion centre with a optimal number of SUs joint in the sensing process.

IV. Simulation and Analysis

Consider a CR network with M SUs and the predefined global false alarm probability $Q_f = 0.1$. To evaluate the detection performance of the whole CR network, we set the number of sample points $N = 10$ and assume the SNR value of all SUs in the network are randomly distributed from -20dB to 5dB and noise uncertainty is 1dB for all SUs. The number of SUs M equals 15, 25 and 35, respectively. The results are shown in Fig. 5.

It is evident that in each case, the global detection probability increases with the number of participating SUs at first, and then falls after reaching a peak value. This is consistent with the analytical study in section III and indicates that the optimal number of participating SUs is about 5-8 out of 15-35

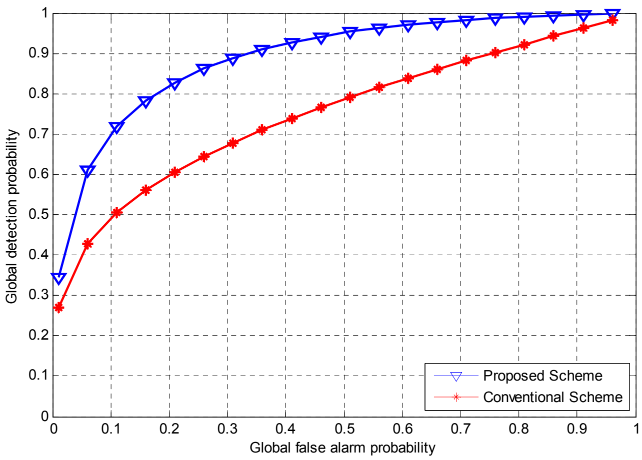

Fig. 6: Comparison of ROC curves between the proposed scheme and conventional scheme.

SUs. Therefore, it largely reduces the number of low SNR SUs in which the local sensing is not required. Therefore, energy conservation for those SUs can be achieved by the proposed cooperative spectrum sensing algorithm.

As shown in Fig. 5, at a predefined false alarm probability Q_f, by taking a part of SUs with higher SNRs for the fusion centre, the global detection probability can be improved by about 1%-5% in comparison with the case of all SUs in the CR network collaborating in the global sensing process. Applying this scheme to the CR spectrum sensing scenario, we could estimate the minimum number of SUs joint in sensing to enhance the detection performance with the energy conservation for low SNR SUs.

For the purpose of evaluation, we take the conventional scheme proposed in [10] for comparison. As discussed in section II, the fusion rule adopted in this paper is the OR-rule. Assuming the number of SUs M is 5, noise uncertainty = 0.1, 0.5, 0.5, 1.0, 2.0dB, N = 20, and SNR = -2, -10, -12, -15, -20dB, the ROC curves for both conventional and proposed schemes are obtained in Fig. 6. It is shown that considering the different channel conditions of different SUs, choosing the minimal number of SUs with higher SNRs for detection instead of all SUs in the CR network can improve the final reliability of detection at the fusion centre, and performs better than the conventional scheme.

V. Conclusion

In a cooperative sensing scheme, choosing the optimal number of SUs for the global detection at the fusion centre is important for the energy conservation for each sensing node. In this paper, based on an adaptive double-threshold cooperative sensing under noise uncertainty, we proposed a scheme to optimize the number of participating SUs in the cooperative process based on their SNR conditions to achieve the high global detection probability at the fusion centre. The obtained results showed that the optimal number of collaborating SUs was about 5-8 out of 15-35 SUs. The global detection performance of the proposed scheme was better than that of the conventional scheme.

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