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Cooperative Spectrum Sensing with Realistic Reporting Channel

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***Abstract*— In cooperative spectrum sensing, each *cognitive radio* (CR) user needs to report its local sensing results to a common CR user for a final decision. Most of existing contributions assume that such a reporting is perfect, i.e., there always exists an idle channel to accomplish an error free reporting. However, it is not true in practice since the reporting actually belongs to secondary transmission and may cause interference to primary users. In this paper, we propose a practical reporting approach in cooperative spectrum sensing, called "Listen-Before-Reporting", which considers both the availability and the reliability of the reporting channels. We design the detectors at the FC in both single and multiple realistic reporting bands. Simulation results demonstrate that the proposed scheme performs fairly well under imperfect reporting channels.**

I. INTRODUCTION

Cognitive radio (CR) [1] improves spectrum efficiency by enabling CR users to opportunistically reuse the idle spectrum bands of licensed users, i.e., primary users. To avoid causing interference to the primary users, spectrum sensing, which detects idle licensed bands, is one of the most important issues. There are plenty of contributions [2] in spectrum sensing, including both local sensing and cooperative sensing. The former conducts spectrum sensing by a single CR user, while the latter performs spectrum sensing with multiple CR users. It shows that the performance of local sensing is degraded severely due to channel fading, shadowing, noise uncertainty, and hidden terminal problem [2]-[3]. Therefore, cooperative spectrum sensing [4] is introduced to enhance the performance by combining the sensing results from different CR users.

Cooperative spectrum sensing involves two stages. First, each CR user detects the spectrum opportunity individually based on its own received signal, which is called *local sensing stage*. Then, all the sensing results are sent to a common CR user for a final decision, which is called *global reporting stage*. In the local sensing stage, the channels from the primary users to each CR user are known as *sensing channels*. In the global reporting stage, the channels from CR users to the common CR user are known as *reporting channels*. Most existing works on cooperative sensing consider fading and shadowing of sensing channels under the assumption of perfect reporting channels. In other words, they only consider the imperfect sensing channels, i.e., they assume there is always an idle channel for reporting the local sensing results and such a reporting channel is error-free. However, the assumptions are not valid in practice because the reporting channel is a secondary link as well. It is not available all the time and the channel fading and shadowing lead to reporting errors, which degrades the overall sensing performance.

In this paper, we propose a practical cooperative sensing approach considering both the availability and the reliability of the reporting channels. For each CR user, whether to report and how to report are based on their local sensing results. Each CR user needs to "listen" to the primary user first, and then "report" its local sensing result. Thus, we call our approach as "Listen-Before-Reporting" (LBR), which is different from existing works [5][6] only considering the reliability of reporting channels. In [5], the authors discuss correlated channel shadowing among different reporting channels. In [6], a cognitive space-time-frequency coding technique is proposed to reduce the impact of fading in the reporting channels.

The rest of the paper is organized as follows. In Section II, we describe the problem of cooperative spectrum sensing in realistic reporting channel. In Section III, we propose a reporting method based on local sensing in one spectrum band case, and then extend the method to multiple band case. In Section IV, we provide simulation results to demonstrate the performance of the proposed methods. Finally, we conclude the paper in Section V.

II. SYSTEM MODEL AND PROBLEM DESCRIPTION

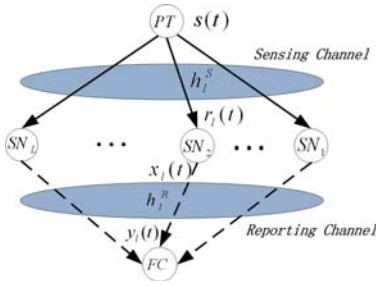

Fig. 1. Principle of cooperative sensing

Figure 1 illustrates the system model of the cooperative spectrum sensing, where a CR system consisting of *L Sensing Nodes* (SNs) and a *Fusion Center* (FC) senses the activity of the *Primary Transmitter* (PT). Both the SNs and the FC are CR nodes. We consider that both shadowing and small scale fading of the sensing channels are statistically independent, since different CR users have different channel environments, e.g., some SNs have light-of-sight path while the others have not.

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As for the reporting channels, we only consider independent small scale fading because SNs and the FC are usually with short distances, i.e., the wireless channels among them experience the same shadowing. To be more specific, we consider that the small scale fading subjects to Rayleigh distribution and the shadowing subjects to Log-Normal distribution.

A. Local Spectrum Sensing

As shown in Fig. 1, the PT's signal, $s(t)$, goes through the sensing channels, h_l^S, between the PT and the lth SN, which suffers from fading and shadowing. Here, we define the "on" and "off" state of the PT as $\mathcal{H}_1$ and $\mathcal{H}_0$, respectively. Then the received signal at the lth SN can be expressed as

$$r_l(t) = \begin{cases} n_l(t), & \mathcal{H}_0, \\ h_l^S s(t) + n_l(t), & \mathcal{H}_1, \end{cases} \tag{1}$$

where $l = 1, 2, \ldots, L$ and $n_l(t)$ denotes *additive white Gaussian noise* (AWGN) with zero mean and variance σ^2, i.e., $n_l(t) \sim \mathscr{N}(0, \sigma^2)$.

In spectrum sensing, the detection aims at finding the spectrum opportunity, i.e., the case when PT is off. Then the detection probability can be defined as follows,

$$P_d = Pr\{\mathcal{H}_0 \mid \mathcal{H}_0\}. \tag{2}$$

On the other hand, if the PT is on and the decision result is idle, the interference to the primary users will be introduced, which is defined as false alarm. The probability that the false alarm happens can be expressed as

$$P_f = Pr\{\mathcal{H}_0 \mid \mathcal{H}_1\}. \tag{3}$$

To simplify the analysis, we consider energy detection. Each SN calculates the power of the received signal in an observing duration T, which can be obtained by

$$q_l = \frac{1}{T} \int_0^T r_l^2(t) dt. \tag{4}$$

By comparing the receive power with a threshold λ_l, the local decision at the lth SN as follows,

$$D_l \mid_{local} = \begin{cases} \mathcal{H}_0, & q_l < \lambda_l, \\ \mathcal{H}_1, & q_l \geq \lambda_l. \end{cases} \tag{5}$$

In order to fully exploit the spectrum opportunities with limited interference to the primary users, Neyman-Pearson criterion is used for determining the threshold in (5), i.e., the probability of detection P_d is maximized subject to a constant false alarm probability P_f.

B. Global Reporting and Problem Description

In the global reporting stage, the local sensing results, $D_l \mid_{local}$, need to be forwarded through the reporting channels to the FC for the final decision. If there are idle and perfect reporting channels, the FC is able to gather the local decisions from the SNs correctly. Then the virtues of cooperative spectrum sensing can be achieved by using some fusion rules, such as OR rule, AND rule, and "N-out-of-K" rule [6].

In practice, however, the reporting channels many not exist especially when a cognitive system has been just setup. At the very beginning of a secondary transmission, the availability of the channels are not known to the SNs. To obtain the availability of a certain spectrum band, the local sensing results need to be reported to the FC. However, such a reporting, in turn, needs at least one available band. This becomes a "Chicken and Egg" problem. In other words, cooperative spectrum sensing depends on a successful global reporting, whereas the successful global reporting relies on the cooperative spectrum sensing result. In the following, we will deal with such a problem by introducing a new reporting approach in the cooperative spectrum sensing.

III. LISTEN-BEFORE-REPORTING

As addressed before, the reporting channel is a secondary link. To avoid interfering with the primary user, each SN is allowed to report its sensing result to the FC only when the channel is idle. Before reporting, each SN has to "listen" to the primary signal to judge the availability of the sensing channel first. If the sensing channel is decided to be idle, the SN can inform the FC the availability of the primary channels. However, when the channel is decided to be busy, such a reporting will be disabled.

It is reasonable to assume that the PT's "on" status is a default hypothesis at the FC, i.e., if no reporting signal is received from the lth SN, the FC regards the sensing result of the SN as busy ($\mathcal{H}_1$). By contrast, if the FC receives the reporting signal from the lth SN, it indicates that the sensing result of the SN is idle ($\mathcal{H}_0$). In this way, the FC can obtain the local sensing result for final decision in both "on" and "off" scenarios.

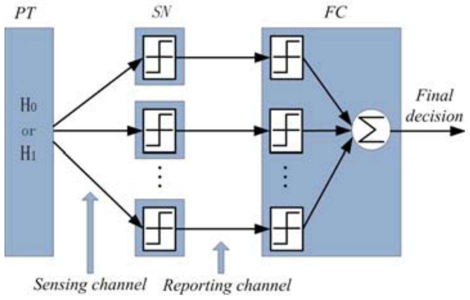

Fig. 2. Architecture of the proposed LBR approach

Figure 2 shows the architecture of our LBR cooperative spectrum sensing approach, where each SN has one detector and the FC consists of L detectors with a combiner. The detector at each SN is to judge the availability of the reporting channels, the decision result of which is actually the same as that of the local sensing. Its performance determines the interference to the primary system. The detectors at the FC are to decide the activity of the PT by combing the local sensing results from different SNs*. In Section II A, we have

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*Here, the performance of the detector at each SN affects the performance of the detectors at the FC, which will be discussed later.

introduced the detectors at each SN, which are done in the local sensing stage. Next, we will develop the detectors at the FC in the global reporting stage.

A. Detector Design in Realistic Reporting Channels

In the global reporting stage, we use code division multiple access to distinguish the reporting signals from different SNs, where L reporting signals $\mathbf{c}_l$ are assigned to different SNs. They are assumed to satisfy the following conditions,

$$\mathbf{c}_i^T \mathbf{c}_j = 0,\ \mathbf{c}_i^T \mathbf{c}_i = 1,\quad i \neq j,\quad 0 < i, j < L, \tag{6}$$

where $\mathbf{c}_i^T = [c_i(1), c_i(2), \ldots c_i(M)]$ is a code vector of length M. In our scheme, whether to report is based on the local sensing results. If a SN believes that the reporting channel is unavailable, the SN will keep silence and then the power of the reporting signal is zero. Otherwise, if the SN finds that the reporting channel is available, it transmits the reporting signal with power $P^{\dagger}$.

In practice, when the PT turns off, the sensing result of each SN may be either busy or idle, which is determined by the missed-detection probability and the detection probability at the SN, respectively. In other words, even when the PT is on, the power of the reporting signal at a SN may be either P or 0. Therefore, the power of the reporting signal is related to the detection performance of SN. To model the transmit power for the reporting signal, we introduce a random variable E_1, which follows Binomial distribution as

$$Pr\{E_1 = 1\} = P_d \quad \text{and} \quad Pr\{E_1 = 0\} = 1 - P_d. \tag{7}$$

Then the reporting signal power can be expressed as $E_1 P$ when the PT turns off. Similarly, when the PT is on, we introduce a random variable E_2 as well, which follows Binomial distribution as

$$Pr\{E_2 = 1\} = P_f \quad \text{and} \quad P\{E_1 = 0\} = 1 - P_f. \tag{8}$$

Then the power of the reporting signal is $E_2 P$.

Finally, we can equivalently represent the reporting signal vector of the lth SN as

$$\mathbf{x}_l = p_l \mathbf{c}_l, \tag{9}$$

where

$$p_l = \begin{cases} E_1 P, & \mathcal{H}_0, \\ E_2 P, & \mathcal{H}_1. \end{cases} \tag{10}$$

Since the reporting signal is in the same frequency band as that of the PT's, the FC may receive the PT's signal as well. The received signal at the FC becomes

$$\mathbf{y} = \begin{cases} \sum_{l=1}^{L} h_l^R \mathbf{x}_l + \mathbf{n}, & \mathcal{H}_0, \\ \sum_{l=1}^{L} h_l^R \mathbf{x}_l + h_0 \mathbf{s} + \mathbf{n}, & \mathcal{H}_1, \end{cases} \tag{11}$$

where $\mathbf{n} = [n(1), n(2), \ldots n(M)]^T$ is the AWGN vector at the FC, $n(m) \sim \mathcal{N}(0, \sigma^2)$ for $1 \leq m \leq M$, $\mathbf{s} = [s(1), s(2), \ldots, s(M)]^T$ is the PT's signal vector, and h_0 is the the sensing channel coefficient between the PT and the FC.

Since the reporting signals at the SNs are orthogonal, we can separate the reporting signals from different SNs. Assume that the FC has the perfect channel information of all the reporting channels. Then the decision variable at the FC for the lth SN that maximizes the *signal-to-noise ratio* (SNR) can be obtained by

$$\widetilde{y}_l = w_l \mathbf{c}_l^T \mathbf{y}, \tag{12}$$

where $w_l = \frac{h_l^{R*}}{\|h_l^R\|^2}$ is actually a maximal ratio combiner.

According to (6), (9), (11) and (12), we can obtain the decision variable for the lth SN as

$$d_l = \begin{cases} E_1 P + w_l \mathbf{c}_l^T \mathbf{n}, & \mathcal{H}_0, \\ E_2 P + w_l \mathbf{c}_l^T (h_0 \mathbf{s} + \mathbf{n}), & \mathcal{H}_1. \end{cases} \tag{13}$$

Analogous to the detector at each SN for local sensing, the threshold can be obtained by using Neyman-Pearson criterion given a false alarm probability. After each detector at the FC yields a decision, the final decision can be obtained by various fusion rules [6].

B. Extension to Multiple Spectrum Bands

When a cognitive system can sense multiple spectrum bands simultaneously, which belong to different primary users, the LBR approach is still applicable by operating in each band independently. However, this may increase the potential interference to the primary users. To further improve the performance of the cooperative spectrum sensing, we will discuss the extension of the LBR sensing approach to the multiple spectrum bands case.

As the number of spectrum bands grows, it has a higher probability that at least one of the spectrum bands is available for reporting. Therefore, each SN can use only one spectrum band to report the sensing results of all the spectrum bands. In this way, the interference to the primary users is significantly reduced since the reporting only happens in one band rather than all bands. Furthermore, if the number of the sensing bands is large, there may always exists available reporting channels. That is, reliable reporting will be achieved, which enables soft combination at the FC. In the following, we will introduce a LBR approach in multiple band scenario.

When there are multiple bands to be sensed, the orthogonal sequences $\mathbf{c}_{k,l}$ need to distinguish the reporting signals from different SNs as well as the sensing results from different spectrum bands. Consider that there are K spectrum bands, the reporting signal vector for the lth SN is

$$\mathbf{x}_l = \Sigma_{k=1}^{K} q_{k,l} \mathbf{c}_{k,l}, \tag{14}$$

where $q_{k,l}$ is the power of the primary signals in the kth band. If the lth SN selects the band k^l for reporting, the received signal at the FC can be expressed as

$$\mathbf{y}_{k^l} = \begin{cases} \sum_{l=1}^{L} h_{k^l,l}^R \mathbf{x}_l + \mathbf{n}_{k^l}, & \mathcal{H}_0, \\ \sum_{l=1}^{L} h_{k^l,l}^R \mathbf{x}_l + h_{k^l,0} \mathbf{s}_{k^l} + \mathbf{n}_{k^l}, & \mathcal{H}_1, \end{cases} \tag{15}$$

where $\mathbf{n}_{k^l}^T$ and $\mathbf{s}_{k^l}^T$ are respectively the AWGN vector and the

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†The reporting signal power P needs to be below the interference tolerance of the primary user.

PT's signal vector in band k^l, and $h_{k^l,l}$ is the reporting channel coefficient for the lth SN in band K^l. Then the local sensing result for the lth SN at the kth band can be obtained by $\widetilde{y}_{k,l}^{k^l} = w_{k^l,l}\mathbf{c}_{k,l}^T\mathbf{y}_{k^l}$, where $w_{k^l,l} = \frac{h_{k^l,l}^{R*}}{\|h_{k^l,l}^R\|^2}$ can be obtained from (III-A). Then, we have

$$\widetilde{y}_{k,l}^{k^l} = \begin{cases} q_{k,l} + w_{k^l,l}\mathbf{c}_{k,l}^T\mathbf{n}_{k^l}, & \mathcal{H}_0, \\ q_{k,l} + w_{k^l,l}\mathbf{c}_{k,l}^T(h_{k^l,0}\mathbf{s}_{k^l} + \mathbf{n}_{k^l}), & \mathcal{H}_1. \end{cases} \tag{16}$$

For the kth band, by summing up the sensing results for all L SNs, we obtain the final decision variable as $d_k = \sum_{l=1}^{L} \widetilde{y}_{k,l}^{k^l}$. The threshold can be obtained by using the same method as that in the previous subsection.

IV. SIMULATION RESULTS

In this section, we present simulation results to demonstrate the performance of the proposed LBR approach in both single band and multiple band cases, where P_f of the detectors at the SNs is set to be 0.1 for local decisions. The availability of each reporting channel depends on the activity of the primary users, whereas the reliability of the reporting channels relies on the channel conditions. We assume that the primary user's "on" and "off" are with equal probability and the reporting channels subject to Rayleigh fading. Furthermore, we consider both Rayleigh fading and Log-Normal shadowing with standard deviation 3.7 in the sensing channels. Two SNs are considered in the simulation and our results are based on 10^5 Monte-Carlo trails.

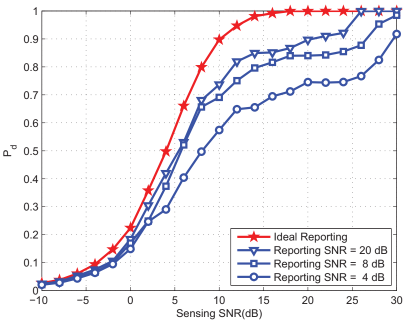

Fig. 3. Detection performance of LBR in single band case

Figure 3 compares the detection performance of the LBR method in realistic reporting channels with the performance of the cooperative sensing method in perfect reporting channels, where *1 out of K* rule is used at the FC. We set P_f of the detectors at the FC to be 0.1, in which condition the overall P_f is 0.01 accordingly. Walsh sequence is used with the length of 16. From the figure, it shows that the detection performance increases as the sensing SNR and the reporting SNR grow. It also indicates that the LBR method has performance loss compared to the ideal reporting method. As expected, the loss decreases as the reporting SNR increases.

Figure 4 shows the detection performance of LBR in the multiple band case, where 15 bands are considered and Walsh sequence of length 32 is used. We deploy soft combination at the FC and set the overall P_f for soft combination to be 0.01, which is the same as that in single band case. From Fig. 4, it can be found that in the low sensing SNR region, i.e., from -10dB to 8dB, the detection performance of LBR is much worse than that with perfect reporting channel. This is because the detectors at SNs can not find reporting channel when sensing SNR is low, which actually disables the cooperative sensing. This also leads to the performance degradation of the multiple band sensing at low sensing SNR, which is shown by comparing the results of Fig. 4 and Fig. 3. However, with the sensing SNR increasing, the LBR in the multiple band case outperforms the single band case.

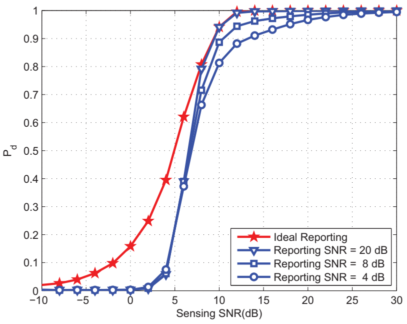

Fig. 4. Detection performance of LBR in multiple band case

V. CONCLUSIONS

In this paper, we have addressed the "Chicken and Egg" problem brought by the realistic reporting channels in cooperative spectrum sensing, and proposed listen-before-reporting sensing schemes for both single band and multiple band cases. With the proposed methods, cooperative sensing is able to operate in practice with fairly good performance, where reporting is a secondary transmission. Our simulation results show that even though sensing multiple spectrum bands will degrade the sensing performance at low sensing SNR, the sensing performance improves significantly as the sensing SNR increases.

REFERENCES

[1] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE J. Select. Areas Commun.*, vol. 23, No. 2, pp. 201-220, Feb. 2005.

[2] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *IEEE Commun. Surveys & Tutorials*, vol. 11, no. 1, pp. 116-130, First Quarter, 2009.

[3] J. Ma, G. Zhao, and Y. (G.) Li, "Soft combination and detection for cooperative spectrum sensing in cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 11, pp. 4502-4507, Nov. 2008.

[4] A. Ghasemi and E. Sousa, "Collaborative spectrum sensing for opportunistic access in fading environment," *Proc. IEEE DySPAN*, Nov. 2005, pp. 131-136.

[5] M. D. Renzo, L. Imbriglio, F. Graziosi, and F. Santucci, "Distributed date fusion over correlated Log-Normal sensing and reporting channels: Application to cognitive radios networks," *IEEE Tran. Wireless Commun.* Vol. 8, No. 12, pp. 5813-5821, Dec. 2009.

[6] K. B. Lataief, W. Zhang, "Cooperative communications for cognitive radio networks," *IEEE Proc.* Vol.97, No. 5, pp. 878-893, May. 2009.