Exploiting Multiuser Diversity for Spectrum Sensing in Cognitive Radio Networks

Tuan T. Do and Brian L. Mark*

Dept. of Electrical and Computer Engineering
George Mason University, MS 1G5, 4400 University Drive, Fairfax, VA
*Correspondent: tel 703-993-4069; fax 703-993-1601; email bmark@gmu.edu

***Abstract*— We consider wireless system consisting of secondary users equipped with cognitive radios that attempt to access radio spectrum that is not being used by the primary licensed users. To avoid causing harmful interference to the primary users, the secondary users perform spectrum sensing to determine spectrum hole opportunities for channel access. Due to multipath fading, users in the network experience peak channel quality at different times. We propose a cooperative spectrum sensing strategy for cognitive radio networks that exploits the fading diversity among secondary users to improve the probability of correct detection of a primary transmitter. Our simulation results show that the proposed scheme significantly outperforms previous schemes that do not exploit multiuser diversity.**

***Index Terms*— Cognitive radio, dynamic spectrum access, hypothesis testing, multiuser diversity, spectrum sensing.**

I. INTRODUCTION

In traditional wireless systems, spectrum or frequency is allocated to licensed users over a geographic area. Within these constraints, spectrum is considered a scarce resource due to static spectrum allocation. Recent empirical studies of radio spectrum usage have shown that licensed spectrum is typically highly underutilized [1], [2]. To recapture the so-called "spectrum holes," various schemes for allowing unlicensed or secondary users to opportunistically access unused spectrum have been proposed. Opportunistic or dynamic spectrum access is achieved by cognitive radios that are capable of sensing the radio environment for spectrum holes and dynamically tuning to different frequency channels to access them. Such radios are often called *frequency-agile* or *spectrum-agile*.

Spectrum sensing can be performed either at individual secondary node or by a group of cooperative secondary nodes. Cooperative sensing has been studied in a number of papers [3]–[5]. Cooperation between secondary nodes can mitigate the effects of low signal to noise ratio (SNR), shadowing, and hidden terminals [5]. In cooperative sensing, secondary users at different locations sense the channel independently and send their observations to a fusion center. The observation could be a soft value or a one-bit hard decision [6].

In a wireless network with fading, different users experience different channel fading conditions during the same observation period. Multiuser diversity can be exploited by scheduling users to transmit when their channel conditions are favorable [7]. For example, Qin and Berry [8] propose a distributed approach for exploiting multiuser diversity based on a protocol channel-aware slotted ALOHA wherein each user decides, based on the channel state, in which slot to transmit and how much power to use.

In this paper[1], we propose a distributed approach to spectrum sensing that exploits multiuser diversity among secondary users to improve sensing capability in cognitive radio networks. We adopt a cooperative sensing framework to overcome low SNR and shadowing. Unlike traditional multiuser diversity schemes for wireless networks, fairness and delay issues (cf. [9]) can be ignored in spectrum sensing scenarios because the only performance metric of interest is the detection probability. Our numerical results show that the proposed spectrum sensing scheme achieves significantly better performance compared to dynamic spectrum access schemes that do not exploit multiuser diversity.

The remainder of the paper is organized as follows. Section II describes the system model. Section III proposes the distributed scheme for exploiting multiuser diversity to improve spectrum sensing capability. Finally, the paper is concluded in Section V.

II. SYSTEM MODEL

We consider a discrete-time system model with a single primary transmitter and S secondary users equipped with frequency-agile cognitive radios. Each user makes a local decision about the presence of the primary user and communicates a one-bit hard decision to a fusion center, which then makes the final decision. Due to communication constraints, not all the secondary users are able to communicate their decisions to fusion center. We assume that N out of S secondary users are able to communicate with the fusion center. Because of multiuser diversity, each of the S secondary users has different fading channel parameters during a given observation time period.

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We adopt a spectrum sensing model similar to that in [6]. Each secondary user uses M samples for energy detection. We define two hypotheses: H_1 is the hypothesis that the primary is ON and located close to the secondary nodes and H_0 is the hypothesis that the primary is OFF or far away. In other words, H_0 is the hypothesis that the spectrum hole exists and the frequency channel is available for reuse by secondary users. The observed energy value at the jth user is given by

$$Y_j = \begin{cases} \sum_{i=1}^{M} n_{ji}^2, & \text{under } H_0, \\ \sum_{i=1}^{M} (s_{ji} + n_{ji})^2, & \text{under } H_1, \end{cases} \tag{1}$$

where n_{ji} is the white noise signal in the ith sample of the jth user and s_{ji} denotes the received primary signal at each secondary user, $1 \leq j \leq N$, $1 \leq i \leq M$. The noise samples n_{ji} are assumed to be independently and identically distributed (i.i.d.) Gaussian random variables with zero mean and unit variance.

The instantaneous SNR of the jth secondary user is defined as

$$\gamma_j \triangleq \frac{1}{M} \sum_{i=1}^{M} s_{ji}^2.$$

Following [6], we assume that the total energy of the transmitted primary signal is constant within each observation blocks. Thus, the γ_j's represent the power of the instantaneous channel gain and can be modeled by a Rayleigh or Nakagami distribution [10] and are i.i.d. over different secondary users j and observation block. Within a given observation block, multiuser diversity exists because of the differences in γ_j across users.

If the primary user is absent or in the OFF state, Y_j can be modeled as a central chi-square random variable with M degree of freedom. Otherwise, if the primary user is in the ON state, Y_j follows a non-central chi-square distribution with M degrees of freedom and a non-centrality parameter $\lambda_j = M\gamma_j$ [6]: A weighted sum of Y_j's is computed at the fusion center as follows:

$$Y = \sum_{j=1}^{N} \omega_j Y_j, \tag{2}$$

where ω_j is the weight associated with the jth observation. For large M, the distribution of Y can be approximated by a Gaussian distribution as follows:

$$\begin{aligned} H_0 :\ & Y \sim \mathcal{N}\left(M \sum_{j=1}^{N} \omega_j, 2M \sum_{j=1}^{N} \omega_j^2 \right), \\ H_1 :\ & Y \sim \mathcal{N}\left(M \sum_{j=1}^{N} (1 + \mu_j), 2M \sum_{j=1}^{N} \omega_j^2 (1 + \mu_j) \right). \end{aligned} \tag{3}$$

The fusion center chooses hypothesis H_1 if $Y > \tau_f$ and H_0 otherwise, where τ_f is the decision threshold at the fusion center. The performance metrics of interest are the false alarm probability P_F and the detection probability P_D:

$$P_F \triangleq \Pr\{Y > \tau_f | H_0\}, \quad P_D \triangleq \Pr\{Y > \tau_f | H_1\}.$$

For a given false alarm probability, the objective is to maximize the probability of (correct) detection. The performance of different sensing schemes can be evaluated by comparing the values of P_D at a given P_F value.

III. MULTIUSER DIVERSITY SPECTRUM SENSING

In this section, we develop a multiuser diversity spectrum sensing scheme for cognitive radio networks. We assume that there are S secondary nodes equipped with identical energy detectors and the shadow fading noise processes between secondary nodes are i.i.d. For simplicity, we also assume a perfect MAC (Medium Access Control) protocol that coordinates transmissions between the secondary nodes and the fusion center on a dedicated control channel.

A. Soft combination

Let τ_l and τ_u be predefined lower and upper thresholds, respectively, where $\tau_l < \tau_u$. In the proposed scheme, a node j ($j = 1, \ldots, S$) with received energy level satisfying

$$Y_j > \tau_u \quad \text{or} \quad Y_j < \tau_l \tag{4}$$

sends its observation to the fusion center. As stated earlier, we assume that communication capacity of the channel between the secondary nodes and the fusion center is limited such that only N out of S nodes can communicate with the fusion center. If the number of nodes with received energy level satisfying (4) is $\tilde{N} < N$, then $N - \tilde{N}$ nodes are randomly chosen to communicate theirs observations to the fusion center. This guarantees that the total number of observation sent to fusion center is always equal to N.

To understand the benefit of exploiting multiuser diversity, we consider a simple soft information equal gain combining (EGC) strategy at the fusion center, i.e., the weights ω_j are set equal to one in (2). For $S \gg N$, the thresholds τ_l and τ_u can be chosen such that

$$\Pr(Y_j < \tau_l | H_1) \approx 0, \ \Pr(Y_j > \tau_u | H_0) \approx 0, \ j = 1, \ldots S.$$

Suppose that $\tilde{N} > 0$ nodes satisfy (4) and denote their received energy levels by $\tilde{Y}_j$, $j = 1, \ldots \tilde{N}$. Under hypothesis H_1, the following inequality holds almost surely (a.s.):

$$\sum_{j=1}^{\tilde{N}} \tilde{Y}_j \geq \sum_{j=1}^{\tilde{N}} Y_j,$$

where $\{Y_j\}_{j=1}^{N}$ a set of observations from a randomly selected subset of N out of the S nodes. Hence,

$$\tilde{Y} = \sum_{j=1}^{\tilde{N}} \tilde{Y}_j + \sum_{j=\tilde{N}+1}^{N} Y_j \geq Y = \sum_{j=1}^{N} Y_j, \ \text{a.s.} \tag{5}$$

Thus,

$$P_{\mathrm{mud}} \triangleq \Pr\{\tilde{Y} > \tau_f\} \geq \Pr\{Y > \tau_f\} \triangleq P_c \qquad (6)$$

where P_{mud} and P_c denote the detection probability of the multiuser diversity spectrum sensing scheme and a conventional scheme, respectively. Therefore, multiuser diversity spectrum sensing results in a superior detection probability compared to conventional spectrum sensing. A similar approach can be applied for hypothesis H_0. In this case, the false alarm probability of the multiuser diversity spectrum sensing scheme can be shown to be smaller than that of a conventional scheme.

The optimal weights for soft combination are derived in [6] as $\omega_j = \frac{\gamma_j}{\sqrt{\sum_{k=1}^{N}\gamma_k^2}}$, $j = 1, \ldots, N$, where γ_j is the instantaneous SNR, and the soft combination rule is given by (2). Since the optimal weights are similar to those for *maximal ratio combining* (MRC), we refer to this approach as the MRC scheme. In this case, the fusion center compares the obtained soft combination metric Y in (2) with a predetermined threshold τ_f and decides on hypothesis H_1 if $Y > \tau_f$ and H_0 otherwise. The value of τ_f is determined by simulation [6] such that the probability of interference is smaller than or equal to a threshold on the probability of false alarm, P_F.

B. Hard combination

The soft combination scheme may be impractical due to the overhead of sending the observation data to the fusion center. As an alternative, a hard combination scheme could be adopted, whereby each node compares its observation Y_j with a given threshold τ_n and sends a hard decision $U_i \triangleq I_{\{Y_i > \tau_n\}}$ to the fusion center, where I_A denotes the indicator function on the event A. Two fusion rules that could be applied are: 1) 1 out of N (OR) rule; 2) Counting rule. In the OR rule, hypothesis H_1 is selected if $U_i = 1$ for any user $i = 1, \ldots, N$, while in the counting rule, the decision is made by comparing the sum $\sum_{i=1}^{N} U_i$ to a threshold. In both cases, the thresholds are determined by simulation (cf. [5]).

C. CSMA-based MAC protocol

We briefly describe a MAC protocol for coordinating communications between the secondary nodes and the fusion center over a dedicated control channel. The proposed MAC protocol adopts the exponential backoff scheme in the IEEE 802.11 standard with a modification to exploit multiuser diversity. Each user j generates a backoff time that is chosen at random in the range $(0, w_j - 1)$, where w_j is the contention window size. At the first transmission attempt or after a successful transmission, $w_j = \mathrm{CW}_1$ if the observation Y_j satisfies (4); otherwise $w_j = \mathrm{CW}_2$. After each failed transmission, i.e., more than one user transmits during a time slot, w_j is doubled until it reaches $\mathrm{CW}_{\max}$, where $\mathrm{CW}_{\max} = 2^m \mathrm{CW}_1$ if Y_j satisfies (4); otherwise, $\mathrm{CW}_{\max} = 2^m \mathrm{CW}_2$. The backoff time counter is decremented as long as the channel is sensed idle and frozen when the channel is busy. When the backoff time counter reaches zero, the user transmits its observation to the fusion center. We choose $\mathrm{CW}_1 \ll \mathrm{CW}_2$ such that users for which (4) is satisfied will have access to the channel with high probability.

IV. NUMERICAL RESULTS

In this section, we compare the performance of the proposed multiuser diversity spectrum sensing scheme with a conventional scheme that does not exploit multiuser diversity. The simulations were carried out in MATLAB and the following parameters were used:

- False alarm probability requirement $\tau_{\mathrm{FA}} = 0.01$;
- Number of samples $M = 6$;
- Number of secondary nodes $N = 4$;
- $\mathrm{CW}_1 = 8$, $\mathrm{CW}_2 = 64$, $m = 3$.

In Fig. 1-3, 95% confidence intervals are omitted to maintain clarity of the performance curves.

In Fig. 1, we compare the performance of multiuser diversity spectrum sensing with conventional spectrum sensing when soft optimal combination and the OR rule are used at the fusion center. Here, the total number of users is $S = 12$. We reproduce the results for conventional OR rule and optimal soft combination considered in [6] and compare with the corresponding results from the multiuser diversity scheme. The thresholds τ_u and τ_l are chosen to satisfy

$$P(Y < \tau_l | H_0) \approx \frac{N}{S} \text{ and } P(Y > \tau_u | H_1) \approx \frac{N}{S}. \qquad (7)$$

These thresholds can be calculated using (3) for the case $N = 1$, $\omega_1 = 1$. The threshold τ_n is set by simulation to meet the false alarm probability requirement. Observe that the detection probability performance of the proposed scheme is much better than that of the conventional scheme especially when the SNR is relatively small. For $S = 12$ and $N = 4$, the OR rule with multiuser diversity outperforms the optimal soft combination scheme.

Fig. 2 compares the performance of the multiuser diversity scheme with conventional optimum soft combination and the OR rule with different values of S at SNR$=0$ dB. The thresholds τ_u and τ_l are similar to those used in the simulation of Fig. 1 at SNR$=0$ dB. When the total number of users S increases, the detection probability of multiuser diversity spectrum sensing increases. When $S \geq 8$, the multiuser diversity based OR rule outperforms the soft optimal combination scheme studied in [6].

Fig. 3 compares the performance of the conventional and multiuser diversity spectrum sensing schemes with the counting rule at the fusion center. All of the schemes meet the requirement of τ_{FA} at the fusion center, but only the counting rule satisfies the τ_{FA} requirement at both the nodes and the fusion center. The performance of the

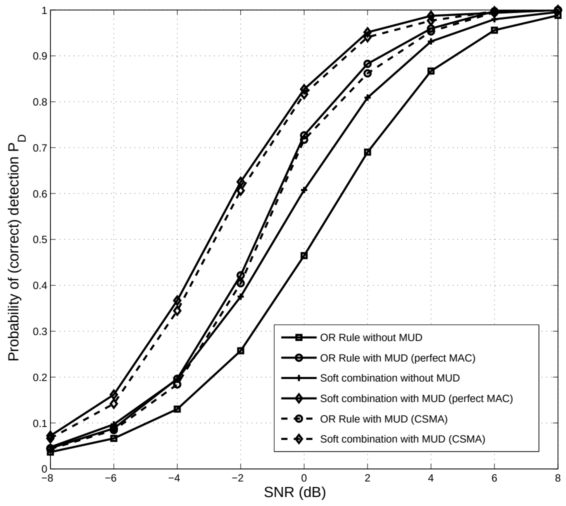

Fig. 1. Performance of 1 out N rule (OR) rule and soft combination with multiuser and conventional spectrum sensing.

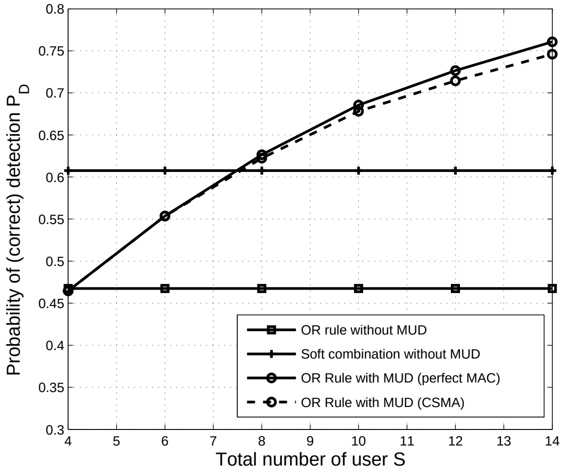

Fig. 2. Performance of conventional OR rule, soft combination, and OR rule with multiuser diversity vs. total number of users S.

OR rule is better than that of the conventional counting rule because it results in higher false alarm probability at each node [11]. At low SNR, single user detection can outperform the counting rule because of the effect of fading; nodes which experience severe fading can generate wrong local decisions.

V. CONCLUSION

We proposed a cooperative multiuser diversity spectrum sensing scheme that exploits the multiuser diversity inherent in the secondary network to improve the sensing capability of cognitive radio systems. The approach is distributed in the sense that each secondary user only has local knowledge about its observed energy. Our simulation results show a significant performance gain over sensing schemes that do not exploit multiuser diversity.

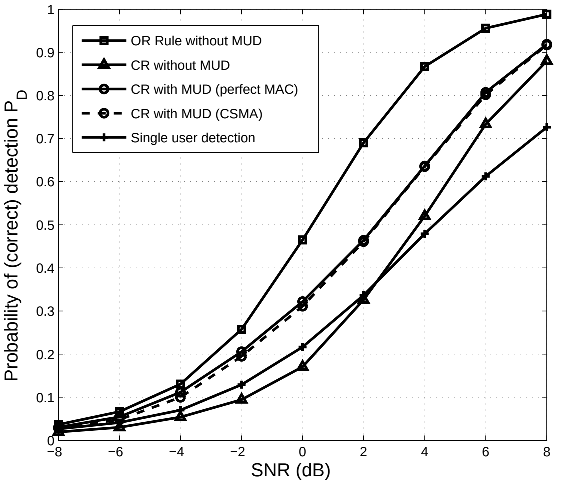

Fig. 3. Performance of Counting Rule (CR) with multiuser and conventional spectrum sensing.

REFERENCES

[1] M. McHenry, "Frequency agile spectrum access technologies," in *FCC Workshop on Cognitive Radio*, May 2003.

[2] R. W. Broderson, A. Wolisz, D. Cabric, S. M. Mishra, and D. Willkomm, "Corvus: A cognitive radio approach for usage of virtual unlicensed spectrum," White Paper, Univ. California Berkeley, Tech. Rep., Jul. 2004.

[3] S. Mishra, A. Sahai, and R. W. Brodersen, "Cooperative sensing among cognitive radios," in *Proc. IEEE Int. Conf. Communications*, vol. 4, Istanbul, Jun. 2006, pp. 1658–1663.

[4] E. Visotsky, S. Kuffner, and R. Peterson, "On collaborative detection of TV transmissions in support of dynamic spectrum sharing," in *Proc. DySPAN'05*, Nov. 2005, pp. 338–345.

[5] J. Unnikrishnan and V. Veeravalli, "Cooperative sensing for primary detection in cognitive radio," *IEEE J. Sel. Topics Signal Process.*, vol. 2, no. 1, pp. 18–27, Feb. 2008.

[6] J. Ma and Y. Li, "Soft combination and detection for cooperative spectrum sensing in cognitive radio networks," in *Proc. IEEE Globecom'07*, Nov. 2007, pp. 3139–3143.

[7] R. Knopp and P. Humblet, "Information capacity and power control in single-cell multiuser communications," in *Proc. IEEE Int. Conf. Comm. (ICC'95)*, Seattle, WA, Jun. 1995, pp. 331–335.

[8] X. Qin and R. A. Berry, "Distributed approaches for exploiting multiuser diversity in wireless networks," *IEEE Trans. Inf. Theory*, vol. 52, no. 2, pp. 392–413, Feb. 2006.

[9] P. Viswanath, D. N. C. Tse, and R. Laroia, "Opportunistic beamforming using dumb antennas," *IEEE Trans. Inf. Theory*, vol. 48, no. 6, pp. 1277–1294, 2002.

[10] F. F. Digham, M. S. Alouini, and M. K. Simon, "On the energy detection of unknown signals over fading channels," in *Proc. IEEE Int. Conf. on Comm. (ICC'03)*, May 2003, pp. 3575–3579.

[11] A. Ghasemi and E. S. Sousa, "Collaborative spectrum sensing for opportunistic access in fading enviroments," in *Proc. IEEE DySPAN'05*, Nov. 2005, pp. 131–136.