Improving Spectrum Sensing Performance by Exploiting Multiuser Diversity

Tuan Do[1] and Brian L. Mark[2]
[1]*Global Wireless Solutions, Inc., Dulles, Virginia*
[2]*Dept. of Electrical and Computer Eng. George Mason University, Fairfax, Virginia*
USA

1. 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 (Broderson et al., 2004; McHenry, 2003). 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*.

On a given frequency channel, a spectrum hole can be characterized as spatial or temporal. A *spatial* spectrum hole can be specified in terms of the maximum transmission power that a secondary user can employ without causing harmful interference to primary users that are receiving transmissions from another primary user that is transmitting on the given channel. Spectrum reuse in this context is similar to frequency reuse among cochannel cells in a cellular network. A *temporal* spectrum hole is a period of time for which the primary transmitter is idle. During such idle periods, a secondary user may opportunistically transmit on the given channel without causing harmful interference.

Various technologies have been proposed for spectrum sensing: matched filter, cyclostationary feature detector, and energy detector (Cabric et al., 2004). The matched filter maximizes the received signal-to-noise ratio, but requires demodulation of the primary user signal. To demodulate the primary signal, secondary users require prior knowledge of the primary signal at both PHY and MAC layers, e.g., modulation type and order and packet format. Moreover, demodulation requires timing and carrier synchronization with the primary signal. Cyclostationary feature detectors exploit the cyclostationary characteristics of the modulated signal to estimate signal parameters such as the carrier phase and pulse timing at the receiver. Assuming the modulation type is known, a cyclostationary feature detector can be used for detection of a random signal in noise and interference. In this chapter, we shall focus on spectrum sensing based on an energy detector, which uses noncoherent detection, and is applicable in a wide range of scenarios.

In a wireless network with fading, multiuser diversity is the phenomenon whereby different users experience different channel fading conditions during the same observation period. Multiuser diversity can be leveraged to achieve higher throughput by scheduling users to transmit when their channel conditions are favorable (Knopp & Humblet, 1995). Multiuser diversity systems can be centralized or distributed. In centralized systems, a central processor maintains channel state information for all users and always schedules the user with the best channel for transmission. In distributed multiuser diversity systems, each user has knowledge of its own channel state, but does not has knowledge of the fading levels of other users.

In this chapter, we propose a distributed approach to temporal spectrum sensing that exploits multiuser diversity among secondary users to improve sensing performance in a cognitive radio networks. Since our focus is on temporal spectrum sensing, we shall use the term spectrum sensing to mean *temporal* spectrum sensing, unless otherwise specified. Nevertheless, the proposed scheme can be integrated with spatial spectrum sensing to achieve a joint spatial-temporal spectrum sensing system (Do & Mark, 2009; 2010). The proposed multiuser diversity spectrum sensing scheme uses a cooperative sensing framework to overcome low signal-to-noise ratio (SNR) and shadowing. Unlike traditional multiuser diversity schemes for wireless networks, fairness and delay issues can be ignored in the spectrum sensing scenario because the only performance metric of interest is the detection probability given the false positive is the same.

We also propose a MAC protocol bases on carrier sense multiple access (CSMA) protocol to facilitate the transmission of observation from secondary users to fusion center. In this chapter, our proposed MAC protocol uses different backoff window to exploit the multiuser diversity inherent in secondary networks. We name our MAC protocol as cognitive CSMA MAC protocol which controls the communication between secondary users and fusion center. Our numerical results show that the proposed spectrum sensing scheme significantly outperforms schemes that do not exploit multiuser diversity. Furthermore, we show by simulation the benefit of using multiple antennas for spectrum sensing.

For our numerical and simulation results, we consider two main scenarios: 1) secondary users are equipped with single antenna and multiple antennas, and 2) channel between primary user and secondary users are Rayleigh with and without shadowing. We also study the performance of our multiuser diversity scheme in the context of IEEE 802.22 WRAN (Wireless Regional Area Network) standard (IEEE 802.22 Working Group, 2011) since it is the leading standard on the cognitive radio systems. The intention of the WRAN system is to provide internet services in rural area by utilizing unused TV white spaces.

The remainder of the chapter is organized as follows. In Section 2, we provide some background on spectrum sensing and discuss related work on multiuser diversity and IEEE 802.22. The system model considered in this chapter is detailed in Section 3. In Section 4, we develop a distributed scheme for exploiting multiuser diversity to improve spectrum sensing capability. In Section 5, we describe a practical MAC protocol to coordinate transmissions between the secondary users and fusion center. Simulation results are presented in Section 6. In Section 6, we also study the performance of our scheme in scenarios based on the IEEE 802.22 standard. Finally, the chapter is concluded with a summary and a discussion of future work in Section 7.

2. Background and related work

In this section, we provide a brief overview of spectrum sensing and the IEEE 802.22 standard. We then discuss related work on multiuser diversity and spectrum sensing techniques applied to IEEE 802.22.

2.1 Spectrum sensing

Spatial spectrum sensing is investigated (Mark & Nasif, 2009; Nasif & Mark, 2009), wherein the maximum interference-free transmit power (MIFTP) of a given secondary user is estimated based on signal strengths received by a group of secondary nodes. To calculate the MIFTP for a secondary node, estimates of both the location and transmit power of the primary transmitter are estimated collaboratively by a group of secondary nodes. Using these estimates, each secondary node determines its approximate MIFTP, which bounds the size of its spatial spectrum hole. The problem of detecting when the primary is ON or OFF is called *temporal* spectrum sensing (Unnikrishnan & Veeravalli, 2008). In (Do & Mark, 2009; 2010), a joint spatial-temporal spectrum sensing scheme is performed wherein the secondary node performs spatial sensing to determine its MIFTP when the primary transmitter is ON and uses localization information obtained in the process of spatial sensing to improve the performance of temporal sensing, which estimates the ON/OFF state of the primary transmitter. Joint spatial-temporal sensing has higher achievable capacity compared to pure spatial or pure temporal sensing (Do & Mark, 2010).

Cooperative sensing has been studied in a number of papers (Mishra et al., 2006; Unnikrishnan & Veeravalli, 2008; Visotsky et al., 2005). Cooperation between secondary nodes can mitigate the effects of low signal to noise ratio (SNR), shadowing, and hidden terminals Unnikrishnan & Veeravalli (2008). In cooperative sensing, secondary users at different locations sense the channel independently and send their observation to a fusion center. They can communicate either the soft information about the channel or a one-bit hard decision to the fusion center (Ma & Li, 2007). The optimum soft combination rule is derived in (Ma & Li, 2007), wherein the optimal weight coefficients are shown to be identical to those for *maximal ratio combining* (MRC).

2.2 IEEE 802.22

In Section 6.3, we study the performance of our proposed multiuser diversity spectrum sensing scheme in the context of the IEEE 802.22 WRAN (Wireless Regional Area Network) standard (Cordeiro et al., 2005; IEEE 802.22 Working Group, 2011). The 802.22 standard is currently the leading international standard for cognitive radio systems. The intention of the WRAN system is to provide broadband internet services in rural and remote areas by utilizing unused TV white spaces. While availability of broadband access may not be so critical in urban and suburban areas, this certainly is an issue in rural and remote areas. Therefore, this has triggered the FCC (Federal Communications Commission) to stimulate the development of new technologies based on cognitive radio that increase broadband availability in these markets (Challapali et al., 2004; Federal Communications Commission, 2004; 2005). In fact, broadband access in rural areas was one of the reasons why the FCC selected the TV bands for providing such service, as this lower spectrum of frequencies facilitates the propagation of wireless service to rural and remote areas. Moreover, studies of wireless spectrum occupancy have shown that many TV channels are largely unoccupied in many parts of the United States (McHenry, 2003).

Another motivation for the WRAN standard is that IEEE 802.22 devices in the TV band will be unlicensed, which will further lower cost, thus providing affordable wireless service. The commercial markets of 802.22 may include single-family residential, small office/home office (SOHO), small businesses, multi-tenant buildings, and public and private campuses. In the U.S., TV channels are in the VHF (Very High Frequency) and UHF (Ultra High Frequency) regions, i.e., from channel 2 to 69. All of these channels are 6 MHz wide and span from 54-72 MHz, 76-88 MHz, 174-216 MHz, and 470-806 MHz.

The 802.22 system specifies a fixed point-to-multipoint topology whereby a base station (BS) manages its own cell and all associated Consumer Premise Equipments (CPEs). The medium access control of all CPEs in a cell is controlled by the BS. In order to ensure the protection of primary user services, the 802.22 system follows a masters/slave relationship, wherein the BS performs the role of the master and the CPEs are the slaves. No CPE is allowed to transmit before receiving authorization from a BS. The BS also controls all the RF characteristics (e.g., modulation, coding) used by the CPEs. The IEEE 802.22 also manages distributed spectrum sensing which is needed to protect primary user services.

The 802.22 system specifies spectral efficiencies in the range of 0.5 bps/Hz up to 5 bps/Hz or an average of 3 bps/Hz. For 6 MHz TV channel, this would correspond to a total PHY data rate of 18 Mbps. In order to obtain the minimum data rate per CPE, a total of 12 simultaneous users have been considered which leads to a required minimum peak throughput rate at edge of coverage of 1.5 Mbps per CPE in the downstream direction. In the upstream direction, a peak throughput of 384 kbps is proposed, which is also comparable to DSL (Digital Subscriber Line) services. The BS coverage range of IEEE 802.22 can go up to 100 Km if power is not an issue (current specified coverage range is 33 Km at 4 Watts CPE EIRP). Compared to the existing 802.22 standards, WRANs have a much larger coverage range, which is primarily due to its higher power and the favorable propagation characteristics of TV frequency bands. This enhanced coverage range offers unique technical challenges as well as opportunities.

2.3 Multiuser diversity

Opportunistic MAC protocols which exploit multiuser diversity have been investigated in literature. In (Zhao & Tong, 2005), opportunistic CSMA for energy-efficient information retrieval in sensor networks is investigated. The key idea is to exploit the channel state information (CSI) in the backoff strategy of carrier sensing in which the backoff time is a decreasing function of CSI. This scheme ensures that only sensor with the best channel transmit. In (Hwang et al., 2006), the authors incorporate multiuser diversity into p-persistent CSMA. Each user sends a packet if the CSI is above threshold which is determined such that the probability of accessing the medium is p. The proposed opportunistic p-persistent CSMA has a significant capacity increase compare to traditional p-persistent CSMA. The paper by (Hwang & Cioffi, 2007) investigates opportunistic CSMA/CA to achieve multi-user diversity in a wireless LAN.

In (Qin & Berry, 2006), a distributed approach for exploiting multiuser diversity is proposed, based on a protocol called channel-aware slotted ALOHA wherein each user decides, based on the channel state, in which slot to transmit and how much power to use. The design of a multiuser diversity system should consider two important issues: fairness and delay

(Viswanath et al., 2002). In the ideal situation when users fading statistics are the same, the multiuser diversity maximizes not only the total capacity of the system but also the throughput of individual users. However, in reality, users that are closer to the base station have a better average SNR. Some users are stationary, while others are moving. A pure multiuser diversity strategy maximizes long-term average throughput, without regard to delay requirement.

2.4 Spectrum sensing for IEEE 802.22

Spectrum sensing with application to the IEEE 802.22 standard has been studied in (Cordeiro et al., 2007; Kim & Andrews, 2010; Lim et al., 2009; Shellhammer et al., 2006). The spectrum sensing approach proposed in (Kim & Andrews, 2010) uses a spectral covariance sensing algorithm which exploits different statistical correlations of the signal and noise in frequency domain. The spectral covariance sensing algorithm is studied in the context of IEEE 802.22 systems. The algorithm is shown to be very robust to noise uncertainty, which is one of the critical performance measures of spectrum sensing.

An overview of blind sensing techniques in IEEE 802.22 WRANs is provided in (Sai Shanka, 2008). Cooperative spectrum sensing for IEEE 802.22 is studied in (Lim et al., 2009), in which the authors proposed two data fusion schemes for cooperative spectrum sensing. The data fusion structure is appropriate for the WRAN system due to its centralized structure and it can provide reliable sensing performance. The proposed data fusion schemes improve sensing reliability by utilizing a confidence vector of the sensing results.

The performance of power detector sensors for digital TV signals in IEEE 802.22 is studied in (Shellhammer et al., 2006). The authors studied the performance of a power detector in various IEEE 802.22 scenarios such as the “keep out region,” also referred as the noise-limited contour. The use of multiple independent sensors is recommended to address the issue of shadow fading. Even with the use of multiple sensors, however, the power detector performance is strongly degraded by the effects of noise uncertainty at the sensors.

3. 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 local decisions about the presence of the primary user and communicate a one-bit hard or soft decision to the fusion center, which makes the final decision. Alternatively, the system can operate in a distributed manner wherein secondary users exchange their local decisions with each user. Without loss of generality, we shall assume a fusion center in this chapter.

Due to communication constraints between secondary users and the fusion center, not all the secondary users are able to communicate their decisions to the 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.

We adopt a spectrum sensing model similar to that in (Ma & Li, 2007). 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(Ma & Li, 2007), 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 (Digham et al., 2003) and are i.i.d. over different secondary users j and observation blocks. Within a given observation block, multiuser diversity exists because of the differences in γ_j across users $j = 1, \ldots, N$.

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 degrees of freedom. Otherwise, if the primary user is in the ON state, Y_j follows a non-central chi-square distribution with M degree of freedom and a non-centrality parameter $\lambda_j = M\gamma_j$ (Ma & Li, 2007):

$$H_0 : Y_j = \chi_M^2,$$
$$H_1 : Y_j = \chi_M^2(\lambda_j).$$

For large M, Y_j can be approximated by a Gaussian distribution (Ma & Li, 2007):

$$\begin{aligned} H_0 &: Y_j \sim \mathcal{N}(M, 2M), \\ H_1 &: Y_j \sim \mathcal{N}(M(1+\gamma_j), 2M(1+\gamma_j)). \end{aligned} \tag{2}$$

In (Ma & Li, 2007), a Gaussian approximation of the received energy distribution is used to derived the optimal soft combination weights. The weighted summation at fusion center is given by

$$Y = \sum_{j=1}^{N} \omega_j Y_j. \tag{3}$$

where the optimal weight coefficients are given by(Ma & Li, 2007)

$$\omega_j = \frac{\gamma_j}{\sqrt{\sum_{k=1}^{N} \gamma_k^2}}. \tag{4}$$

where γ_j is the instantaneous SNR for node j. The distribution of Y can be approximated by a Gaussian distribution as follows: Under H_0,

$$H_0 : Y \sim \mathcal{N}\left(M\sum_{j=1}^{N}\omega_j, 2M\sum_{j=1}^{N}\omega_j^2\right),$$

$$H_1 : Y \sim \mathcal{N}\left(M\sum_{j=1}^{N}(1+\gamma_j), 2M\sum_{j=1}^{N}\omega_j^2(1+\gamma_j)\right). \tag{5}$$

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 and the detection probability, given respectively by

$$P_f \triangleq \Pr\{Y > \tau_f | H_0\},\ P_d \triangleq \Pr\{Y > \tau_f | H_1\}. \tag{6}$$

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

4. 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, which are equipped with identical energy detectors. The received signal powers between pairs of secondary nodes are i.i.d. with a Rayleigh or Nakagami fading distribution. We first consider the case of secondary users equipped with a single antenna and then address the case of multiple antennas.

4.1 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

$$Y_j > \tau_u \quad \text{or} \quad Y_j < \tau_l \tag{7}$$

is given priority to send its observation to the fusion center. As stated earlier, we assume that the 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. We assume that there exists a dedicated control channel for enabling the communication between secondary users and fusion center.

In a *perfect* Medium Access Control (MAC) protocol, a centralized scheduler selects N nodes to communicate their observations to the fusion center. Let $\tilde{N}$ denote the number of nodes with received energy levels that satisfy (7). If $\tilde{N} \geq N$, the centralized scheduler (randomly) selects N out of the $\tilde{N}$ nodes to send their observations to the fusion center. Otherwise, if $\tilde{N} < N$, the N nodes selected by the scheduler consists of the $\tilde{N}$ nodes plus an additional $N - \tilde{N}$ nodes randomly selected from among the remaining nodes. Thus, the total number of observations sent to the fusion center is always equal to N. A practical, distributed MAC protocol for coordinating communications between the secondary nodes and the fusion center, based on CSMA, is proposed in Section 5.

To understand the benefit of exploiting multiuser diversity, we consider a simple soft information equal gain combining (EGC) strategy at the fusion center:

$$Y = \sum_{j=1}^{N} Y_j.$$

The distribution of Y can be approximated by a Gaussian distribution as given in (5) with $\omega_j = 1, j = 1, 2 \ldots, N$ for EGC. For $S \gg N$, the thresholds τ_l and τ_u can be chosen such that

$$\Pr(Y_j < \tau_l | H_1) \approx 0, \ \Pr(Y_j > \tau_u | H_0) \approx 0, \ j = 1, 2, \ldots S.$$

Suppose that $\tilde{N} > 0$ nodes satisfy (7) and let their received energy levels be denoted by $\tilde{Y}_j$, $j = 1, \ldots \tilde{N}$. Under hypothesis H_1, the following inequality holds with probability one:

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

where $\{Y_j\}_{j=1}^{N}$ denotes a set of observations that does not exploit multiuser diversity; i.e., a set of N out of S nodes is randomly selected to send their observations to the fusion center. Hence,

$$\tilde{Y} = \sum_{j=1}^{\tilde{N}} \tilde{Y}_j + \sum_{j=\tilde{N}+1}^{N} Y_j \geq Y = \sum_{j=1}^{N} Y_j, \tag{8}$$

where the inequality is understood to hold almost surely. Thus,

$$P_{\text{mud}} \triangleq \Pr\{\tilde{Y} > \tau_f\} \geq \Pr\{Y > \tau_f\} \triangleq P_c \tag{9}$$

where P_{mud} and P_c denote the detection probability of the multiuser diversity spectrum sensing scheme and a conventional scheme, respectively. Therefore, the 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 the conventional scheme. Simulation results presented in Section 6 validate the benefit of exploiting multiuser diversity for spectrum sensing.

The optimal soft combination is derived in (Ma & Li, 2007), where the optimal weight coefficients are given by (4) and the soft combination rule is given by (3). Since ω_j, derived in (4), is similar to the weights used in *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 (3) 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 (Ma & Li, 2007) such that the probability of interference is smaller than or equal to a threshold on the probability of false alarm, P_F.

4.2 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 at the fusion center. In this scheme, each node compares its observation Y_j with a given threshold τ_n. If Y_j satisfies (7), the node will send a hard decision $U_i = 1$ to the fusion center if $Y_j > \tau_n$ and $U_i = 0$ otherwise:

$$U_i \triangleq I_{\{Y_i > \tau_n\}},$$

where I_A denotes the indicator function on the event A. At the fusion center two fusion rules that could be applied are:

1. 1-out-of-N (OR) rule (Ghasemi & Sousa, 2005): The primary signal will be declared present if any one of the cooperative users decides locally that the primary signal exists.
2. Counting rule: The final decision is made by comparing the sum $\sum_{i=1}^{N} U_i$ to a decision threshold. The value of this threshold is obtained through simulation (Unnikrishnan & Veeravalli, 2008).

The threshold at each node τ_n for the OR rule is also determined by simulation such that the constraint on the probability of false alarm is satisfied at the fusion center. However, OR rule tends to have a high probability of false alarm (Ghasemi & Sousa, 2005). Moreover, the OR rule may not be used in case communication is not available between the secondary nodes and the fusion center. The counting rule ensures that the constraint on the probability of false alarm is met both at individual nodes and at the fusion center. However, *randomization* between two fusion thresholds may be required at the fusion center in order for the counting rule to achieve the false alarm probability constraint (Unnikrishnan & Veeravalli, 2008).

4.3 Multiple antenna case

We now extend the preceding discussion for the case when each secondary user has N_t antennas. As before, we assume that the primary transmitter has a single antenna. An energy detector is used at each antenna of a secondary user. We assume that the distance between the antennas is sufficiently far that the fading for different the antennas may be considered i.i.d. Assume that M samples are collected at each detector. The observed energy from the kth antenna at a node j is given by

$$Z_{j,k} = \begin{cases} \sum_{i=1}^{M} n_{ji}^2, & \text{under } H_0, \\ \sum_{i=1}^{M} (s_{ji} + n_{ji})^2, & \text{under } H_1. \end{cases} \tag{10}$$

For a multiple-receive antenna system, *equal gain combination* (EGC) is used (Ma & Li, 2007):

$$Y_j = \sum_{k=1}^{N_t} Z_{j,k}, \; j = 1, \ldots, S, \tag{11}$$

where Y_j is the combined total received energy at the output of secondary user j.

Similar to the single antenna scenario, Y_j is compared against two thresholds $\tilde{\tau}_u$ and $\tilde{\tau}_l$. If Y_j satisfies

$$Y_j > \tilde{\tau}_u \quad \text{or} \quad Y_j < \tilde{\tau}_l, \tag{12}$$

node j will be given priority to communicate its observation to the fusion center. In the multiple antenna case, we assume that the each node sends a one-bit hard decision (if any) to the fusion center for hard combination. If the observation Y_j satisfies $Y_j > \tilde{\tau}_n$, node sends the value 1 to the fusion center and 0 otherwise. The OR rule or the counting rule can be used at fusion center as the detection rule. The threshold $\tilde{\tau}_f$ at the fusion center and the thresholds $\tilde{\tau}_n$ are determined by simulation to meet the false alarm probability requirement.

The MAC protocol selects a subset of N secondary nodes to transmit their hard decisions to the fusion center, based on the condition (12). Let $\tilde{N}$ denote the number of nodes with received energy levels satisfying (12). Similar to the single antenna case, a perfect, centralized MAC scheduler makes a (possibly random) selection of N out of $\tilde{N}$ nodes, if $\tilde{N} \geq N$. If $\tilde{N} < N$, the N nodes selected by the scheduler consists of the $\tilde{N}$ nodes satisfying (12) plus a random selection of $N - \tilde{N}$ additional nodes. A more practical, distributed MAC protocol based on CSMA is discussed next.

5. CSMA-based MAC protocol

In this Section, we develop MAC protocol based on Carrier Sense Multiple Access (CSMA) for secondary users to transmit their observations to the fusion center. The proposed MAC is used to enable communications between secondary users and the fusion center during spectrum sensing period. Clearly, a different MAC protocol may be used for communications between secondary users during the spectrum hole period. As mentioned earlier, we assume that there exists a dedicated control channel for secondary users to exchange information with the fusion center. Also, the physical layer between fusion center and user is assumed to be perfect, i.e., the fusion center receives what the users send without error. Our proposed MAC protocol based on the IEEE 802.11 MAC (IEEE 802.11 Working Group, 1997). In our scenario, the MAC protocol is used to enable communications from the secondary users to the fusion center. Since there is only one receiver in this scenario, i.e., the fusion center, there is no hidden terminal issue, and Request to Send/Clear to Send (RTS/CTS) packets are not needed.

Time is divided into slots and each user is allowed to transmit only at the beginning of each time slot. If a secondary user wishes to communicate its observation to the fusion center, it monitors the channel activity. If the channel is idle for a specified time period, i.e., the distributed interframe space (DIFS) in the 802.11 standard, the secondary user transmits. Otherwise, if the channel is busy, the user continues to monitor the channel until it remains idle for an interval of DIFS. In this case, the user generates a random backoff interval before transmitting, in accordance with the 802.11 collision avoidance feature.

We adopt the exponential backoff scheme in 802.11 standard with a modification to exploit multiuser diversity. User i generates a random backoff time which is drawn from the interval $(0, w_i - 1)$ according to a uniform distribution, where $w_i > 1$ is an integer called the contention window of user i. At the first transmission attempt or after a successful transmission, $w_i = CW_1$ if the observation Y_i satisfies the condition (7); otherwise, $w_i = CW_2$. After each failed transmission, i.e., when there is more than one user transmitting at the beginning of a time slot, w_i is doubled until it reaches CW_{max} where $CW_{max} = 2^m CW_1$ if Y_i satisfies the condition (7); otherwise, $CW_{max} = 2^m CW_2$.

The backoff time counter is decremented as long as the channel is sensed idle and is frozen when the channel is sensed busy. When the backoff time counter reaches zero, the user transmits its observation to the fusion center. We choose $CW_1 \ll CW_2$. Hence, users satisfying

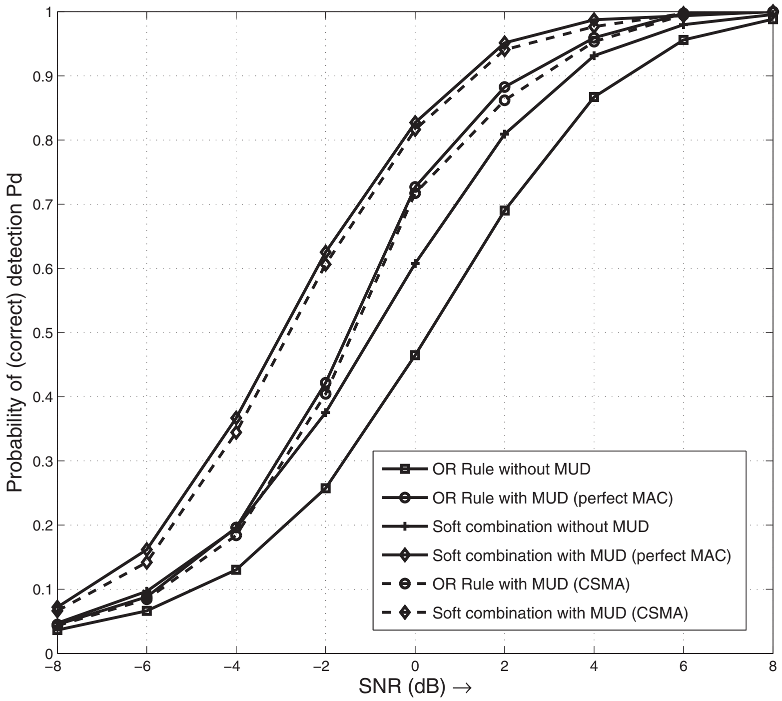


Fig. 1. Performance of OR rule rule and soft combination scheme with multiuser and conventional spectrum sensing.

condition (7) will likely have a smaller random backoff timer and will have channel access with higher probability. The fusion center will make the final decision whenever it receives the observations of N users. Once the fusion center receive observations from N nodes, it broadcasts a signal to stop the other nodes from transmitting further observations.

6. 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 following parameters are used for all simulations discussed in this Section.

- False alarm probability requirement $\tau_{FA} = 0.01$;
- Number of secondary nodes $N = 4$.
- $CW_1 = 8$, $CW_2 = 64$, $m = 3$

In addition, the number of samples $M = 6$ for the simulations corresponding to Fig. 1 through Fig. 6. For all of the simulation results, 95% confidence intervals were computed, but they have been omitted from the figures for clarity of presentation. For each simulation result, the width of the 95% confidence interval is less than 0.2 of a unit on the vertical scale.

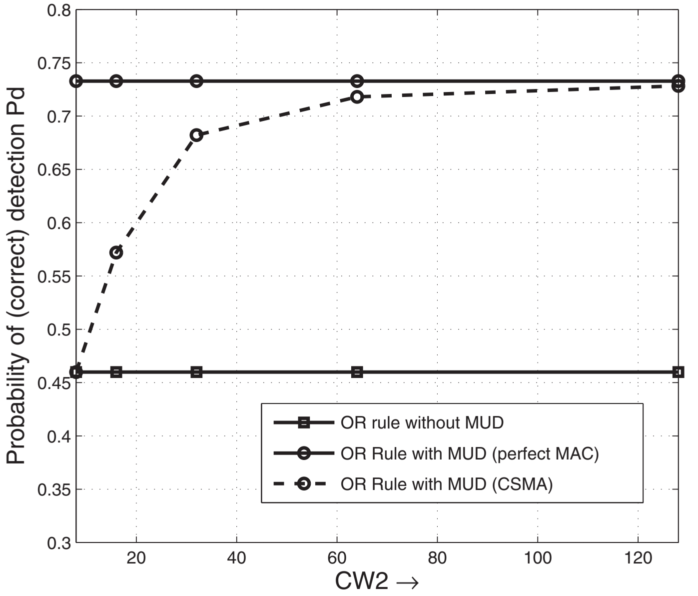


Fig. 2. Performance of OR Rule with perfect MAC and CSMA-based MAC vs. the contention window CW_2.

6.1 Spectrum sensing with Rayleigh fading only

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 the conventional OR rule and optimal soft combination considered in (Ma & Li, 2007) and compare with the corresponding results from the multiuser diversity scheme. The thresholds τ_u and τ_l are chosen to satisfy

$$P(Y_i < \tau_l | H_0) = \frac{N}{S} \text{ and } P(Y_i > \tau_u | H_1) = \frac{N}{S}. \tag{13}$$

These thresholds can easily be calculated using (2). The threshold τ_n is set by simulation to meet the false alarm probability requirement. Fig. 1 shows that the detection probability of our proposed scheme is much better than that of the conventional spectrum sensing scheme scheme especially when the signal-to-noise ratio (SNR) is relatively small. For $S = 12$ and $N = 4$, the hard combination (OR rule) with multiuser diversity can outperform the optimal soft combination scheme.

In Fig. 2, we compare the performance of CSMA-based MAC protocol described in Section 5 for different values of CW_2. The performance of the OR rule with the CSMA-based MAC approaches the performance of the OR rule with perfect MAC protocol (i.e., a centralized scheduler) at $CW_2 = 64$. However, as CW_2 increases, the MAC delay also increases.

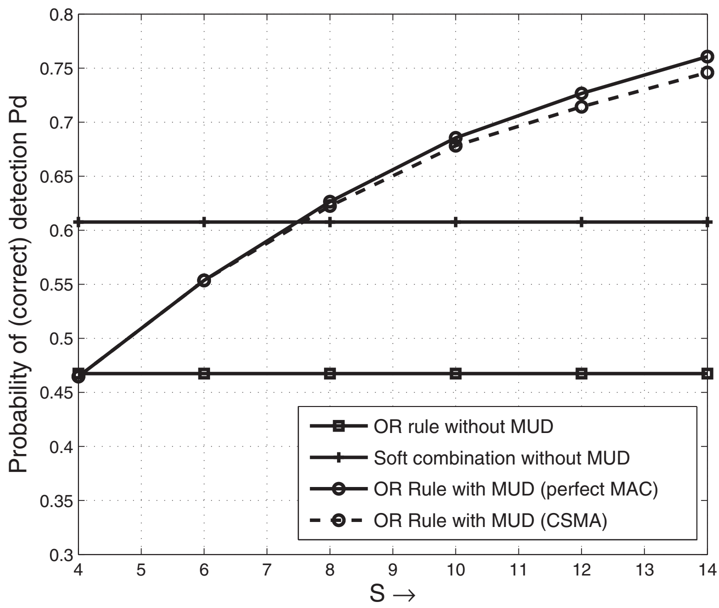


Fig. 3. Performance of conventional OR rule and soft combination scheme and OR rule with multiuser diversity vs. total number of users S.

In Fig. 3, we compare the performance of the multiuser diversity scheme with conventional optimum soft combination and the OR rule with different values of S with SNR $= 0$ dB. The thresholds τ_u and τ_l are similar to those used in the simulation of Fig. 1 with 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 hard combination based OR rule outperforms the conventional soft optimal combination studied in (Ma & Li, 2007).

In Fig. 4, we compare 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 both at the nodes and at the fusion center. The detection probability for the OR rule rule is higher than that of the conventional counting rule, but the OR rule also has a higher false alarm probability at each node (Ghasemi & Sousa, 2005). At low SNR, single user detection can outperform the counting rule because of the effect of fading. At low SNR, nodes that experience severe fading can make wrong decisions about the presence of a primary user. This may in turn result in a wrong decision produced at the fusion center.

In Fig. 5, we compare the performance gain of secondary users equipped with multiple antennas over those equipped with only a single antenna. Hard combination with the OR rule is used. Each multi-antenna user is equipped with $N_t = 2$ antennas. We consider $S = 12$ nodes and set the thresholds as $\tilde{\tau}_u$=2τ_u and $\tilde{\tau}_l$=2τ_l, where τ_u and τ_l are obtained from the simulation corresponding to Fig. 1. Fig. 5 clearly shows the benefit of multiple antennas over single antennas and also the benefit of multiuser diversity in multi-antennas systems.

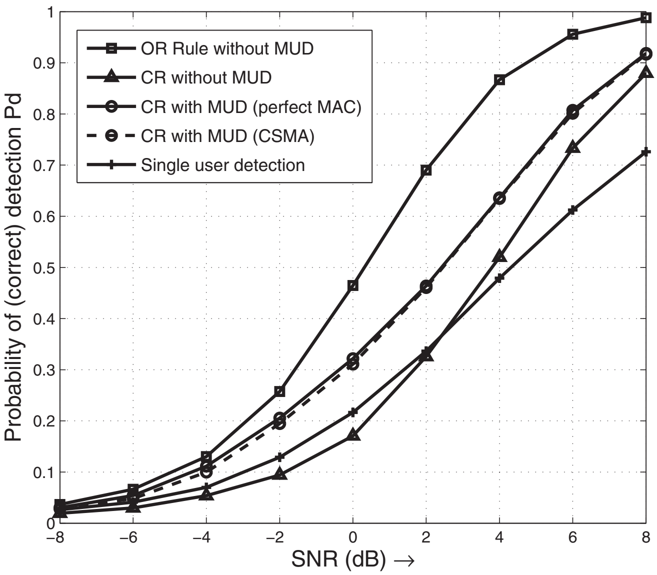


Fig. 4. Performance of Counting Rule (CR) with multiuser diversity and conventional spectrum sensing.

6.2 Spectrum sensing with Rayleigh fading and shadowing

In the previous simulation scenarios, we assumed that there was no shadowing in the received signal. In this Section, we consider the effect of both shadowing and small-scale fading on the received signal (Motamedi & Soleymani, 2007). In this case all users are affected by both large and small scale (Rayleigh) fading. The effect of shadowing causes random fluctuations in received power. These fluctuations can be modeled by multiplying the received power by a log-normal distributed random variable. The log-normal random variable w is specified by a mean μ_w (dB) and a standard deviation σ_w (dB). We have,

$$10 \log_{10} w \sim N(\mu_w, \sigma_w)$$

where $\mu_w = E[10 \log_{10} w]$ and $\sigma_w^2 = \mathrm{Var}[10 \log_{10} w]$. The probability density function (pdf) of w is given by (Motamedi & Soleymani, 2007)

$$P(w, \mu_w, \sigma_w) = \frac{1}{\sqrt{2\pi}\sigma_w} \exp[-(10 \log_{10} w - \mu_w)^2 / 2\sigma_w^2],\ w > 0. \tag{14}$$

In the presence of both shadowing and Rayleigh fading, the observed energy value at the jth user is given by

$$Y_j = \begin{cases} \sum_{i=1}^{M} n_{ji}^2, & \text{under } H_0, \\ \sum_{i=1}^{M} (s_{ji} w + n_{ji})^2, & \text{under } H_1, \end{cases} \tag{15}$$

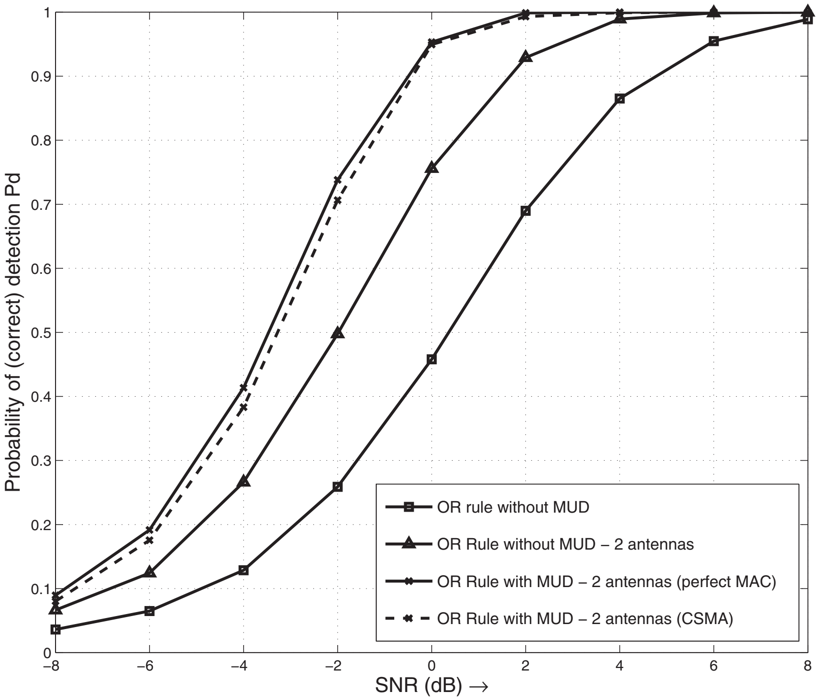


Fig. 5. Performance of OR rule with multiuser diversity and conventional spectrum sensing, 2 antennas used at secondary users.

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 and w denotes the shadowing noise. In our numerical results, we assume that the shadowing noise is Gaussian distributed with zero mean and a variance of 5.5 dB. Figure 6 shows that spectrum sensing with multiuser diversity significantly outperforms spectrum sensing without multiuser diversity, even in the presence of shadowing. In this simulation experiment, the number of sample $M = 4$, the CSMA-based MAC protocol is used with $W_1 = 8$ and $W_2 = 64$, and the threshold values are same as in the previous simulations without shadowing.

6.3 IEEE 802.22 WRAN

IEEE 802.22 requires a detection probability of 0.9 with the false alarm probability of 0.1 at SNR $= -22$ dB (Kim & Andrews, 2010; Lim et al., 2009) In all simulations, we use: Number of secondary nodes $N = 4$, contention window for MAC protocol $CW_1 = 8$, $CW_2 = 64$, $m = 3$, total number of secondary user $S = 24$. The shadowing fading is modeled by a log-normal distribution with zero mean and a variance of 5.5 dB (Shellhammer et al., 2006). The total

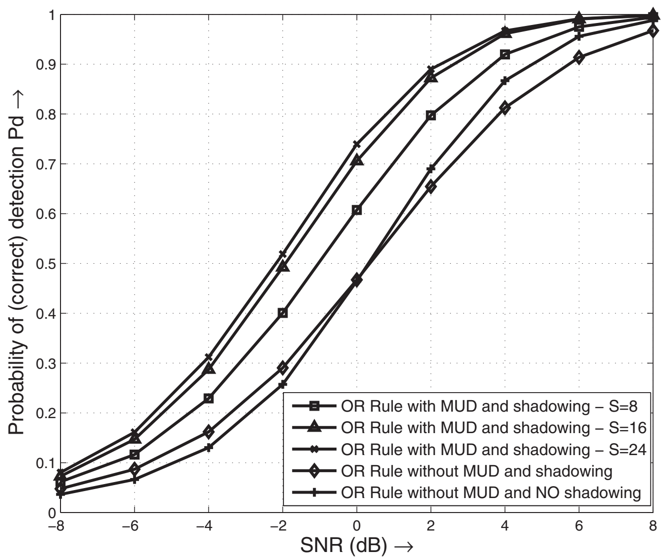


Fig. 6. Performance of OR rule with multiuser diversity and shadowing noise.

number of samples used by the energy detector is $M = 40$ except Fig. 10. The combination rule at fusion center is the OR rule.

In Fig. 7, the required probability of false alarm is $P_f = 0.01$. We compare the performance of our multiuser diversity spectrum sensing with spectrum sensing without multiuser diversity when only shadowing fading is assumed and no Rayleigh fading. As in Fig. 7, the multiuser spectrum sensing is outperformed the spectrum sensing without multiuser diversity. However, since it is assumed that there is no small-scale (Rayleigh) fading, the performance gain of multiuser diversity spectrum sensing is small. This result makes sense, since the degree of multiuser diversity is higher when small-scale fading is present among secondary users (Viswanath et al., 2002).

In Fig. 8, we compare the performance of multiuser diversity spectrum sensing with conventional spectrum sensing in the presence of both Rayleigh and shadowing fading. The simulation results show that multiuser diversity spectrum sensing significantly outperforms conventional spectrum sensing in this case. When SNR=-22 dB and $P_f = 0.1$, multiuser diversity spectrum sensing can achieve a detection probability close to 0.9, which is the spectrum sensing requirement of IEEE 802.22 when using only $M = 40$ samples. In this case, the detection probability for conventional spectrum sensing without multiuser diversity is only about 0.64,

In Fig. 9, we show the receiver operating characteristic (ROC) curve for energy detector with multiuser diversity spectrum sensing and conventional spectrum sensing without multiuser diversity. In Fig. 9, we use SNR=-21 dB, number of samples M = 40, both small scale fading (Rayleigh) and shadowing fading with zero mean and variance 5.5 dB. The ROC curve for spectrum sensing with multiuser diversity is much better than that of conventional spectrum

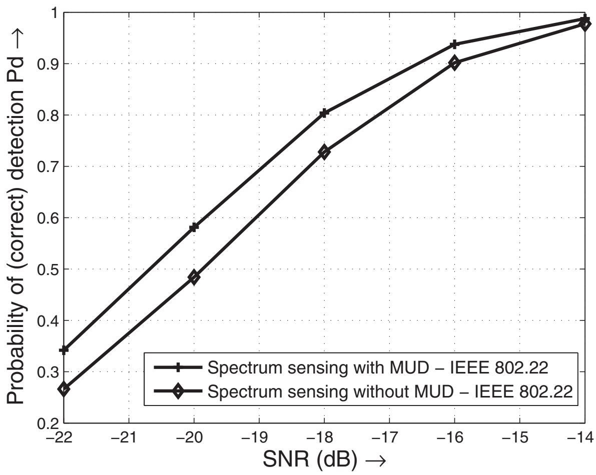


Fig. 7. Performance of OR rule without Rayleigh fading in IEEE 802.22: P_d vs. SNR.

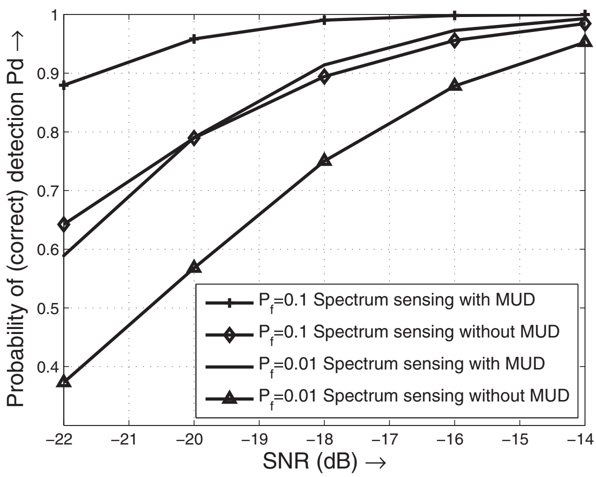


Fig. 8. Performance of OR rule with Rayleigh fading in IEEE 802.22: P_d vs. SNR.

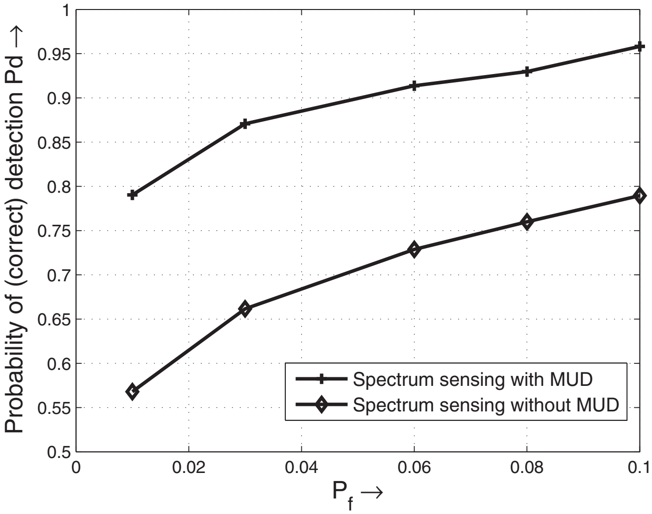


Fig. 9. IEEE 802.22 ROC curve with SNR=-21 dB

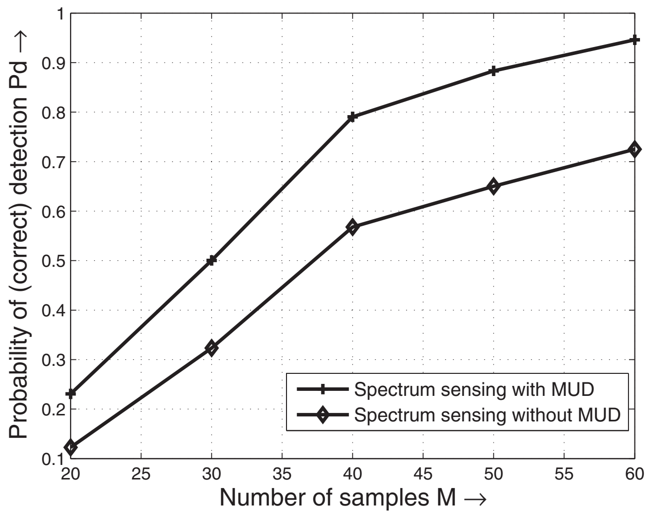


Fig. 10. Detection probability v.s. Number of sample M

sensing without multiuser diversity. In Fig. 10, the performance of the proposed multiuser diversity spectrum sensing scheme is compared with that of conventional spectrum sensing as the number of samples M is varied. We see that the detection probability for both schemes increase as M increases. For all values of M, the detection probability for multiuser diversity spectrum sensing is significantly higher than that of spectrum sensing without multiuser diversity.

7. Conclusion

We conclude this Chapter with a brief summary and a discussion of two topics for future work: sequential detection and multichannel systems.

7.1 Summary

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. We use a distributed approach in the sense that each secondary user only has local knowledge about its observed energy. We studied two detection rules for the fusion center, counting rule and the OR rule and also considered the case of users equipped with multiple antennas. We also proposed a CSMA-based MAC protocol for secondary users to communicate their observations to the fusion center.

We compared the performance of the proposed multiuser diversity spectrum sensing scheme and a conventional spectrum sensing scheme in a variety of scenarios. In particular, we studied the performance of the multiuser diversity scheme in the context of the IEEE 802.22 WRAN standard. Our simulation results showed that a substantial gain in spectrum sensing performance could be achieved by exploiting multiuser diversity, particularly in environments with both small-scale and large-scale fading.

7.2 Sequential detection

In spectrum sensing, detection delay is an important performance metric. When a primary user stops transmission, the secondary user should detect this event quickly in order to maximize its use of the newly created temporal spectrum hole. A small detection delay will allow secondary users to take advantage of short transmission opportunities. On the other hand, when the primary user starts transmission, the cognitive user should detect this event as quickly as possible in order to minimize interference to the primary user.

In this Chapter, the spectrum sensing decision is made after a fixed number of samples M. To improve detection delay performance, a *sequential* detection scheme could be incorporated into the multiuser diversity spectrum sensing scheme proposed in this Chapter. Sequential detection schemes exploit the fact that the number of samples required to achieve a given reliability level may well be dependent on the actual realization of the observed samples. For example, in a simple binary hypothesis testing context, Wald's sequential probability ratio test (SPRT) compares the likelihood ratio with two thresholds, and the decision is made as soon as the test statistic exceeds either one of the thresholds. It is known that SPRT minimizes the average sample number (ASN) among all tests with the same false alarm and detection probabilities. In (Kim & Giannakis, 2009), sequential sensing is proposed for orthogonal frequency division multiplexing (OFDM) cognitive radios. Lai *et al.* (Lai et al., 2008) develop a sequential sensing strategy based on a quickest detection framework.

7.3 Multichannel systems

In this Chapter, we focused on opportunistic spectrum access of a single channel. In multichannel cognitive radio networks, the licensed wireless spectrum consists of a set of N non-overlapping channels. Secondary users have the ability to access all of the available channels by switching frequencies. Multichannel cognitive radio networks have been studied in (Jiang et al., 2008; 2009; Kim & Giannakis, 2009; Min & Shin, 2008). For example, in (Jiang et al., 2008; 2009), a cognitive radio system with opportunistic transmissions is considered wherein the secondary user not only senses a channel to decide whether it is free, but also estimates the channel coefficients in order to determine the transmission rate. If a channel is sensed to be idle, but the channel quality between the secondary transceiver pair is not satisfactory, the secondary user may still skip this channel and keep sensing other channels.

A natural extension of the work presented in this Chapter would be to consider multiuser diversity spectrum sensing in a multichannel system. In such a system, the multiuser diversity principle could be exploited not only to improve spectrum sensing performance as studied in this Chapter, but also to improve the performance of opportunistic spectrum access when multiple channels are available.

8. References

Broderson, R. W., Wolisz, A., Cabric, D., Mishra, S. M. & Willkomm, D. (2004). Corvus: A cognitive radio approach for usage of virtual unlicensed spectrum, *Technical report*, Univ. California Berkeley.

Cabric, D., Mishra, S. & Brodersen, R. W. (2004). Implementation issues in spectrum sensing for cognitive radios, *Proc. 38th Asilomar Conf. on Signals, Systems and Computers '04*, pp. 772–776.

Challapali, K., Birru, D. & Mangold, S. (2004). Spectrum agile radio for broadband applications, *EE Times In-Focus* .
URL: *http://www.eetimes.com/design/other/4003528/Spectrum-Agile-Radio-for-Broadband -Applications*

Cordeiro, C., Challapali, K., Birru, D. & Shankar, N. S. (2005). IEEE 802.22: the first worldwide wireless standard based on cognitive radios, *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, New Orleans, pp. 328 – 337.

Cordeiro, C., Ghosh, M., Cavalcanti, D. & Challapali, K. (2007). Spectrum sensing for dynamic spectrum access of TV bands, *Cognitive Radio Oriented Wireless Networks and Communications (CROWNCom)*, pp. 225 – 233.

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

Do, T. & Mark, B. L. (2009). Joint spatial temporal spectrum sensing for cognitive radio networks, *Conference on Information Sciences and Systems - CISS 2009, submitted*, Baltimore, MD.

Do, T. & Mark, B. L. (2010). Joint spatial-temporal spectrum sensing for cognitive radio networks, *IEEE Trans. Veh. Technol.* 59(7): 3480–3490.

Federal Communications Commission (2004). Notice of proposed rule making, FCC - ET Docket no. 04-113.

Federal Communications Commission (2005). Report and order and memorandum opinion and order, FCC - ET Docket no. 05-56.

Ghasemi, A. & Sousa, E. S. (2005). Collaborative spectrum sensing for opportunitic access in fading enviroments, *Proc. IEEE DySPAN'05*, pp. 131–136.

Hwang, C.-S. & Cioffi, J. M. (2007). Using opportunistic CSMA/CA to achieve multi-user diversity in wireless LAN, *IEEE Globecom*, pp. 4952–4956.

Hwang, C.-S., Seong, K. & Cioffi, J. M. (2006). Opportunistic p-persistent CSMA in wireless networks, *IEEE Int. Conf. on Commun. (ICC)*, pp. 183–188.

IEEE 802.11 Working Group (1997). IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.

IEEE 802.22 Working Group (2011). IEEE 802.22 standard.

Jiang, H., Lai, L., Fan, R. & Poor, H. V. (2008). Cognitive Radio: How to Maximally Utilize Spectrum Opportunities in Sequential Sensing, *Proc. IEEE Globecom 2008*, pp. 4851–4855.

Jiang, H., Lai, L., Fan, R. & Poor, H. V. (2009). Optimal selection of channel sensing order in cognitive radio, *IEEE Trans. Wireless Commun.* 8(1): 297–307.

Kim, J. & Andrews, J. G. (2010). Spectral covariance for spectrum sensing, with application to IEEE 808.22, *IEEE International Conference on Acoustics Speech and Signal Processing (ICASSP)*.

Kim, S.-J. & Giannakis, G. B. (2009). Rate-optimal and reduced-complexity sequential sensing algorithms for cognitive OFDM radios, *EURASIP Journal on Advances in Signal Processing, Special Issue on Dynamic Spectrum Access for Wireless Networking* .

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

Lai, L., Fan, Y., & Poor, H. V. (2008). Quickest detection in cognitive radio: A sequential change detection framework, *Proc. IEEE Global Telecommunications Conference (GLOBECOM)*, New Orleans, LA, pp. 1–5.

Lim, S., Jung, H. & Song, M. S. (2009). Cooperative spectrum sensing for IEEE 802.22 WRAN system, *International Conference of Computer Communications and Networks (ICCCN)*.

Ma, J. & Li, Y. (2007). Soft combination and detection for cooperative spectrum sensing in cognitive radio networks, *Proc. IEEE Global Telecommun. Conf. (Globecom'07)*, pp. 3139–3143.

Mark, B. L. & Nasif, A. O. (2009). Estimation of maximum interference-free transmit power level for opportunistic spectrum access, *IEEE Trans. Wireless Commun.* 8(5): 2505–2513.

McHenry, M. (2003). Frequency agile spectrum access technologies, *FCC Workshop on Cognitive Radio*.

Min, A. W. & Shin, K. G. (2008). Exploiting multi-channel diversity in spectrum-agile networks, *Proc. IEEE Infocom 2008*, pp. 1921 – 1929.

Mishra, S., Sahai, A. & Brodersen, R. W. (2006). Cooperative sensing among cognitive radios, *Proc. IEEE Int. Conf. Communications*, Vol. 4, Istanbul, pp. 1658–1663.

Motamedi, Z. & Soleymani, M. R. (2007). For better or worse: The impact of shadow fading on the capacity of large MIMO networks, *IEEE Global Telecommunication Conference (Globecom 2007)*, pp. 3200 – 3204.

Nasif, A. O. & Mark, B. L. (2009). Opportunistic spectrum sharing with multiple cochannel primary transmitters, *IEEE Trans. Wireless Commun.* 8(11): 5702–5710.

Qin, X. & Berry, R. A. (2006). Distributed approaches for exploiting multiuser diversity in wireless networks, *IEEE Trans. Inf. Theory* 52(2): 392–413.

Sai Shanka, N. (2008). Overview of blind sensing techniques considered in IEEE 802.22 WRANs, *Sensor, Mesh and Ad Hoc Communications and Networks Workshops (SECON'08)*, pp. 1–4.

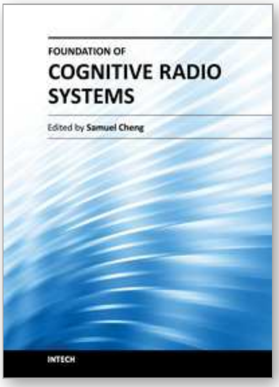
Shellhammer, S. J., Shankar, S., Tandra, R. & Tomcik, J. (2006). Performance of power detector sensors of dtv signals in IEEE 802.22 WRANs, *First International Workshop on Technology and Policy for Accessing Spectrum*.

Unnikrishnan, J. & Veeravalli, V. (2008). Cooperative sensing for primary detection in cognitive radio, *IEEE J. Sel. Topics Signal Process.* 2(1): 18–27.

Visotsky, E., Kuffner, S. & Peterson, R. (2005). On collaborative detection of TV transmissions in support of dynamic spectrum sharing, *Proc. DySPAN'05*, pp. 338–345.

Viswanath, P., Tse, D. N. C. & Laroia, R. (2002). Opportunistic beamforming using dumb antennas, *IEEE Trans. Inf. Theory* 48(6): 1277–1294.

Zhao, Q. & Tong, L. (2005). Opportunistic carrier sensing for energy-effcicient information retrieval in sensor networks, *EURASIP Journal on Wireless Communications and Networking* 2005(2): 231–241.



Foundation of Cognitive Radio Systems
Edited by Prof. Samuel Cheng

ISBN 978-953-51-0268-7
Hard cover, 298 pages
Publisher InTech
Published online 16, March, 2012
Published in print edition March, 2012