Transactions Letters

Cooperative Spectrum Sensing with Transmit and Relay Diversity in Cognitive Radio Networks

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***Abstract*—In the letter the problem of cooperative spectrum sensing is investigated in cognitive radio (CR) networks over Rayleigh fading channels. By taking into account the error effect on the decision reporting, a general performance analysis of cooperative spectrum sensing is given. The analytical detection results show that the performance of cooperative spectrum sensing is limited by the probability of reporting errors. To deal with this limitation, we propose a transmit diversity based cooperative spectrum sensing method. By regarding multiple CRs as a virtual antenna array, space-time coding and space-frequency coding are applied into CR networks over flat-fading and frequency-selective fading channels, respectively. Moreover, we propose a relay diversity based cooperative spectrum sensing approach to increase the diversity of detection when some CRs are in heavy shadowing. It is then shown that, when combined with algebraic coding, relay diversity can further improve the cooperative spectrum sensing performance.**

***Index Terms*—Cognitive radio, diversity technique, relay channels, space-frequency coding, space-time coding.**

I. Introduction

THE remarkable growth of wireless services over the last decade demonstrates the vast and increasing demand for radio spectrum. However, the spectrum resource is limited and most has been licensed exclusively to users which can work within a limited frequency band. Recent studies by the Federal Communications Commission (FCC) Spectrum Policy Task Force (SPTF) have demonstrated that the actual licensed spectrum is largely unoccupied most of the time [1]. Another recent work on spectrum occupancy measurements showed that the average spectrum occupancy from 30 MHz to 3 GHz over six cities is 5.2% and that the maximum total spectrum occupancy is 13.1% in New York City [2].

In order to deal with the imbalance between spectrum scarcity and spectrum under-utilization, *cognitive radio* (CR) has been proposed [3], [4]. By sensing and adapting to the environment, CR is able to fill in spectrum holes and serve its users without causing harmful interference to the licensed user. One of the great challenges of implementing spectrum sensing is the hidden terminal problem which occurs when the CR is shadowed, or degraded with high path loss while the primary user (PU) is still in operation. Cooperative spectrum sensing has been shown to greatly increase the probability of detecting the PU [5]–[9]. Cooperative spectrum sensing refers to the spectrum sensing methods where local spectrum sensing information from multiple CRs are combined for PU detection. In a centralized CR network, a common receiver plays a key role in collecting the local spectrum sensing information and detecting the spectrum holes. Usually, cooperative spectrum sensing requires two successive stages, *sensing* and *reporting*. The sensing channels between the PU and CRs are normally assumed as Rayleigh fading with additive white Gaussian noise (AWGN), whereas the reporting channels between the CRs and the common receiver are mostly assumed perfect (error-free) [5]–[9]. In practice, however, it is impossible for a common receiver to receive decisions from cooperative CRs without any error because the reporting channels also suffer some interferences or noise.

In this letter we consider cooperative spectrum sensing in a realistic environment where both the sensing channels and reporting channels are characterized by fading channels. By introducing a *probability of reporting error* in the CR network, we show that the cooperative spectrum sensing performance is limited by the imperfect reporting channels. Specifically, the probability of false alarm is lower bounded and the bound tends to be linearly increasing with the probability of reporting errors. In order to cope with this problem, we propose a transmit diversity based cooperative spectrum sensing method which applies some existing space-time (ST) coding and space-frequency (SF) coding for multiple antennas systems to the CR network by viewing CRs as distributed antenna arrays. We further propose a relay diversity technique with an algebraic coding approach to improve the performance of cooperative spectrum sensing when some CRs cannot forward decisions to the common receiver due to some heavy shadowing.

The rest of this letter is organized as follows. In Section II, spectrum sensing and cooperative spectrum sensing are briefly introduced. In Section III, a unified performance analysis of

Manuscript received October 20, 2006; revised April 26, 2007 and November 9, 2007; accepted January 19, 2008. The associate editor coordinating the review of this paper and approving it for publication was A. Sabharwal. This work was supported in part by the Hong Kong Research Grant Council under Grant No. N_ HKUST622/06.

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Digital Object Identifier 10.1109/T-WC.2008.060857

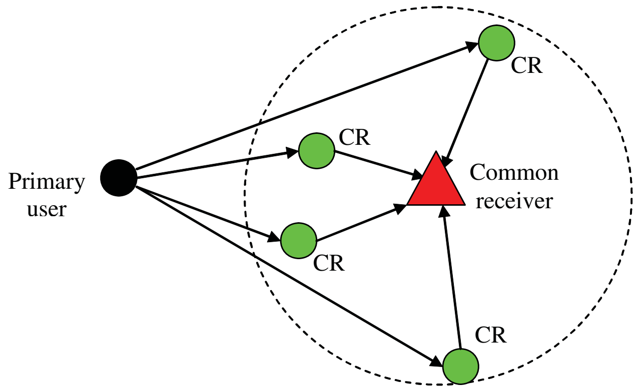

Fig. 1. Cognitive radio network with one common receiver and multiple cognitive radios (secondary users).

cooperative spectrum sensing over Rayleigh fading channels is given. In Section IV, an improved cooperative spectrum sensing with transmit diversity is proposed. In Section V, a relay-based cooperative spectrum sensing is proposed. Finally, in Section VI, we draw our conclusions.

II. Cooperative Spectrum Sensing

We consider a CR network composed of K CRs (secondary users) and a common receiver, as shown in Fig. 1. The common receiver functions as a base station (BS) which manages this CR network and all CRs.

To avoid causing harmful interference to a PU that is in operation, spectrum sensing is needed for the CRs. One of the great challenges of spectrum sensing is to detect the presence of the PU with little information about the channel and the signal transmitted from the PU. In such scenarios, one may choose the energy detector which measures the energy of the received signal in a fixed bandwidth W over an observation time window T. The performance of energy detection was studied for AWGN channels in [10], [11] and for a variety of fading channels in [5], [12], [13]. In the following, we focus on Rayleigh fading and briefly present the main results of [5], [12], [13].

One of the most challenging issues of spectrum sensing is the hidden terminal problem, which occurs when the CR is shadowed or in severe multipath fading. In this case, the CR cannot reliably detect the presence of the PU due to the very low SNR of the received signal. The CR can then assume that the observed frequency band is vacant and begins to access this band without noticing the presence of the PU. To address this issue, multiple CRs can be coordinated to perform spectrum sensing cooperatively. Several recent works have shown that cooperative spectrum sensing can greatly increase the probability of detection in fading channels [5]–[8]. In general, cooperative spectrum sensing is performed as follows:

- *Step 1*: Every CR performs local spectrum measurements independently and then makes a binary decision;
- *Step 2*: All of the CRs forward their binary decisions to a common receiver which is an AP in a wireless LAN or a BS in a cellular network;
- *Step 3*: The common receiver combines those binary decisions and makes a final decision to infer the absence or presence of the PU in the observed frequency band.

III. Performance Limits of Cooperative Spectrum Sensing

Previous works on cooperative spectrum sensing assume that the decision made by each CR is forwarded to BS without error. However, in practice it is impossible to transmit the decisions without errors over the wireless channels. Thus, it is of interest to examine the performance of cooperative spectrum sensing under realistic environments.

In the following, we assume that the common receiver is a BS. At first, one CR performs local spectrum sensing to get the local decision $H_0^{\rm CR}$ or $H_1^{\rm CR}$. Then, the local decision is reported to the BS through the reporting channels which are usually subject to fading and hence the local decision will be corrupted by the fading and additive noise. After signal recovery at the BS, $H_0^{\rm BS}$ or $H_1^{\rm BS}$ is decoded.

Definition 1: The probability of reporting errors of the ith CR, denoted by $P_{e,i}$, is defined as the error probability of signal transmission over the reporting channels between the ith CR and the common receiver.

Here we assume that the reporting channel is a binary symmetric channel (BSC) with an error probability $P_{e,i}$. This means that the probability of receiving H_1 (or H_0) at the common receiver (after the decision recovery) while H_0 (or H_1) is transmitted is $P_{e,i}$ for CR i.

Theorem 1: Let Q_f and Q_m denote the probability of false alarm and probability of missed detection of cooperative spectrum sensing, respectively. Then,

$$Q_f = 1-\prod_{i=1}^{K}\left[(1-P_{f,i})(1-P_{e,i})+P_{f,i}P_{e,i}\right], \quad (1)$$

$$Q_m = \prod_{i=1}^{K}\left[P_{m,i}(1-P_{e,i})+(1-P_{m,i})P_{e,i}\right], \quad (2)$$

where $P_{f,i}$ and $P_{m,i}$ are the false alarm probability and missed detection probability of the local spectrum sensing of the ith CR, respectively.

Proof is in Appendix I.

Corollary 1: Suppose that the local spectrum sensing conducted by CR i results in $P_{f,i}=P_f$ and $P_{m,i}=P_m$, for all $i=1,\cdots,K$, and that the probabilities of reporting errors are identical for all CRs, then

$$\begin{aligned} Q_f &= 1-\left[(1-P_f)(1-P_e)+P_fP_e\right]^K, \\ Q_m &= \left[P_m(1-P_e)+(1-P_m)P_e\right]^K. \end{aligned} \quad (3)$$

Furthermore, Q_f is bounded by

$$Q_f \geq \bar{Q}_f \triangleq \lim_{P_f\to 0} Q_f = 1-(1-P_e)^K \approx KP_e. \quad (4)$$

In Fig. 2, we shall investigate the performance of cooperative spectrum sensing with respect to the number of CRs for an SNR $\bar{\gamma}=10$ dB and $P_e=0.001$. It will be seen that cooperative spectrum sensing with more CRs has a better performance in most cases. But when Q_f decreases to a threshold, namely, the lower bound $\bar{Q}_f$, the probability

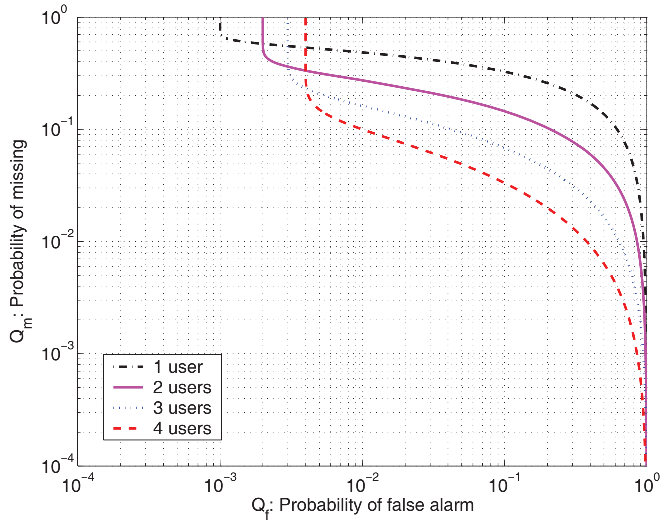

Fig. 2. Performance results (Q_m vs. Q_f) of cooperative spectrum sensing for different number of cooperative CRs. The average SNR of the sensing channels is $\bar{\gamma} = 10$ dB and the reporting error rate is 0.001.

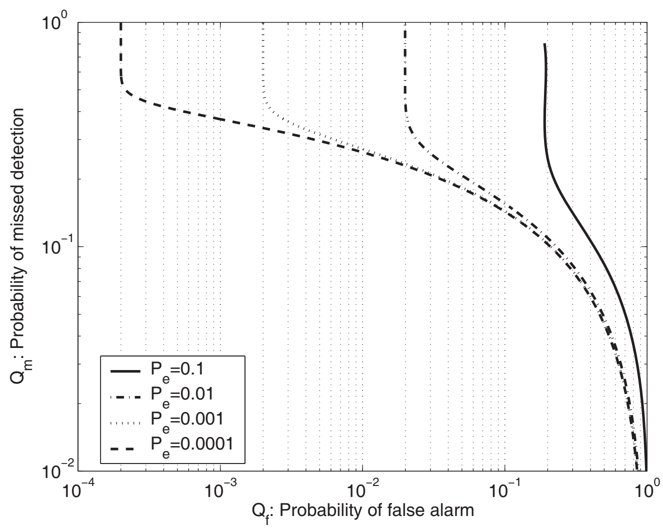

Fig. 3. Performance results (Q_m vs. Q_f) of cooperative spectrum sensing for two cooperative CRs and different reporting error rates $P_e = 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}$. The average SNR of the sensing channel is $\bar{\gamma} = 10$ dB.

of missed detection Q_m will drastically increase to one. Equivalently, the detection probability Q_d will quickly fall down to zero. Thus, cooperative spectrum sensing will be impractical when $Q_f \to \bar{Q}_f$. Moreover, $\bar{Q}_f$ increases with the increase of the number of CRs which is consistent with (4).

Fig. 3 compares the performance results under different probability of reporting errors for two CRs and $\bar{\gamma} = 10$ dB. It clearly demonstrates that the larger the probability of reporting errors is, the larger the bound of Q_f. Note that the false alarm probability Q_f is the probability of the event that the BS infers the presence of the PU while in fact the PU signal is not transmitted. In this case, the licensed frequency band is vacant but not utilized due to the false alarm. Therefore, Q_f can be interpreted as the bandwidth efficiency loss. From Fig. 3, we can conclude that the bandwidth efficiency loss increases with the increase of P_e.

IV. Cooperative Spectrum Sensing with Transmit Diversity

It has been shown that the use of multiple CRs may improve the detection probability over realistic sensing and reporting channels. But the performance is limited by the probability of reporting error P_e which is due to imperfect reporting channels. In this section, we will employ transmit diversity to improve the performance of cooperative spectrum sensing by reducing P_e.

A. Space-Time Coding for Cooperative Spectrum Sensing

We will describe the proposed cooperative spectrum sensing technique based on the use of a simple example of two CRs. The case of more than two CRs will be discussed later. Assume that the local spectrum sensing has been completed at each node and that the local decisions are denoted by D_1 and D_2 for CR 1 and CR 2, respectively. Instead of transmitting D_1 and D_2 to the BS directly, the two CRs are coordinated to form a transmit cluster in which ST block coding can be applied in order to achieve spatial diversity. Note that the *virtual* antenna array formed by user (CRs) cooperation is different from a *real* transmit antenna array formed by multiple antennas at one transmitter. This is because the inter-user channels of a virtual antenna array are noisy and might also be subject to fading. Therefore, ST coding cannot be easily employed across the two separated CRs unless the cooperative partners know each other's decision very well. In order to implement distributed ST coding, we require that each CR sends its own decision to each other. The information exchange can be performed through a similar protocol to the one used in wireless LAN by sending Receive-to-Send (RTS) and Clear-to-Send (CTS) frames. Then each CR checks if the received signal is correctly decoded. This can be realized by using cyclic redundancy check (CRC) for error detection. If both CRs correctly decode the signals transmitted from each others, then ST coding can be employed. In this case, CR 1 will send $\{D_1, D_2\}$ while CR 2 will send $\{-D_2, D_1\}$ to the BS. Otherwise, the CRs will continue to transmit their own decisions to the BS using the TDMA protocol. We should emphasize that the spectral environment does not change significantly and that the time consumed in the information exchange can then be ignored compared to the energy detection time.

Note in the proposed user cooperation protocol, the decisions are reported to the BS by using either direct transmission in TDMA or transmit diversity in ST coding, based on the quality of the inter-user channel. Let ϵ denote the error rate of the transmission over the inter-user channels between CR 1 and CR 2. Clearly, it is the same for the link CR 1 $\to$ CR 2 and the link CR 2 $\to$ CR 1 due to the channel reciprocity. Denote the error rate of BPSK using ST block coding and TDMA as P_e^{STBC} and P_e^{TDMA}, respectively. Then, the reporting error rate of the proposed user cooperation is given by

$$P_e = \alpha P_e^{\mathrm{STBC}} + (1-\alpha) P_e^{\mathrm{TDMA}} \qquad (5)$$

where $\alpha = (1-\epsilon)^2$ denotes the probability of the two CRs both correctly decoding the received signal coming from each other.

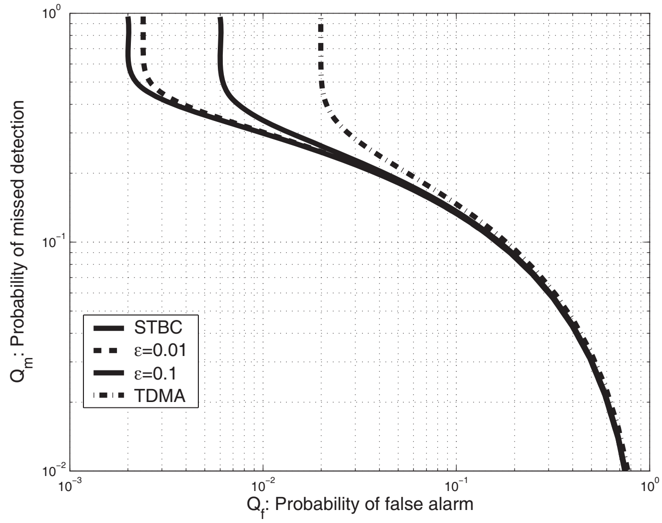

Fig. 4. Performance comparison (Q_m vs. Q_f) of cooperative spectrum sensing using transmit diversity technique for different inter-user channel qualities, $\epsilon = 0.01$ and 0.1. TDMA and STBC, which correspond to the case of $\epsilon = 1$ and 0, respectively, are also given. The sensing channels have average SNR $\bar{\gamma} = 10$ dB and reporting channels have average SNR $\bar{\eta} = 14$ dB.

When the inter-user channel is very good, i.e., it has a very high SNR, α approaches 1 and we simply have $P_e \approx P_e^{\mathrm{STBC}}$. This implies that the two CRs can always correctly decode the received signals due to the good inter-user channel and then can achieve transmit diversity by using ST coding in the reporting process. Hence, diversity gain can be achieved and the reporting error probability can be reduced greatly. On the other hand, when the inter-user channel is poor, for instance, when $\epsilon = 0.3$ which corresponds to $\alpha \approx 0.5$, P_e will be dominated by the term $(1-\alpha)P_e^{\mathrm{TDMA}}$ in (5). This indicates that the reporting error rate performance has no diversity gain, but is still better than TDMA with a coding gain of around 3 dB.

When there are more than two CRs in the network, some closely located CRs can be formed by pairs with two CRs per cluster while keeping the others isolated. Collaborative clusters can be formed either under the control of the BS or in an *ad hoc* fashion by negotiations among neighboring nodes without centralized control [14]. For different clusters, TDMA is used in the process of reporting. That is, each cluster will be assigned a time slot different from other clusters to report the decisions. Thus, the BS will receive signals from one cluster only in the given time slot without interference from other clusters.

Fig. 4 shows the performance comparison of cooperative spectrum sensing with two CRs for various inter-user channel qualities, $\epsilon = 0, 0.01, 0.1$ and 1. The sensing channels and the reporting channels both experience Rayleigh fading with an average SNR $\bar{\gamma} = 10$ dB and $\bar{\eta} = 14$ dB, respectively. It can be seen that STBC has a lower bound $\bar{Q}_f$, which is 0.002, whereas it is 0.02 for TDMA. For the case of $\epsilon = 0.01$, the performance is almost as good as STBC.

B. Space-Frequency Coding for Cooperative Spectrum Sensing

An OFDM-based CR system structure is considered by the IEEE 802.22 working group for WRAN. For OFDM-based CRs, a few subchannels are allocated for sending the local decisions to the BS. To avoid the interference coming from other CRs, each subchannel is assigned exclusively to one CR and different CRs should transmit through orthogonal subchannels. By doing so, the multiple-point to point (MP-P) access, i.e., CRs to BS, can be seen as an OFDM access (OFDMA). For instance, the FDMA of two CRs can be described as

$$\begin{pmatrix} D_1 & \\ & D_2 \end{pmatrix} \rightarrow \text{space} \quad \downarrow \text{subchannel (frequency)}.$$

It can be seen that the CRs send their decisions through orthogonal subchannels to the BS. Thus, similar to TDMA, FDMA cannot achieve the diversity gain.

Recently, it has been found that SF coding [15], [17] can achieve both space and frequency diversity by spreading codewords over multiple transmit antennas and OFDM subchannels. Here, we can regard the distributed CRs as a virtual antenna array and assume that the CRs can exchange their decisions. Instead of transmitting one symbol over one subchannel only for a CR, we use SF coding over several OFDM subchannels. An example of SF coding for two CRs can be described as follows,

$$\frac{1}{\sqrt{2}}\begin{pmatrix} D_1 & D_2 \\ -D_2 & D_1 \end{pmatrix} \rightarrow \text{space} \quad \downarrow \text{subchannel (frequency)}.$$

This shows that the decisions will be sent out from two subchannels simultaneously at each CR. By doing so, a frequency diversity gain of 2 can be achieved over frequency-selective fading channels. Therefore, by exploiting cooperative diversity among closely located CRs, we can reduce the reporting error probability and then enhance cooperative spectrum sensing performance.

V. Cooperative Spectrum Sensing with Relay Diversity

Assume that CR i fails to send its decision D_i to the BS due to heavy shadowing. This means that the received signal power is very weak so that the signal is merged into the noise. In this case, this CR is useless for cooperative spectrum sensing and the maximum diversity gain is reduced. To exploit full diversity gain, we propose a *censor-and-relay* method. Specifically, the BS should censor the SNR of the received signal to check whether this CR is reliable or not. If the SNR of the received signal from CR i is lower than a predesigned threshold, then CR i will be labeled as an unreliable one. Then, the unreliable CR will be instructed to relay its local spectrum sensing result to other neighboring CRs which have good channel conditions. Once a neighboring reliable CR j is found, then CR i will forward its decision D_i to CR j. In order to avoid the interference between the decision D_j made by CR j and the decision D_i coming from CR i, CR j will forward the two decisions to the BS through two orthogonal subchannels. Assume that CR i and CR j occupy subchannel $H_i(m_i)$ and $H_j(m_j)$ to transmit the decisions to the BS, respectively, where $m_i \neq m_j$ for $i \neq j$. If CR i needs to relay its decision D_i to CR j, then CR j will forward the decisions D_i and D_j at the same time through the subchannels $H_j(m_i)$ and $H_j(m_j)$ respectively, which are described as

$$\begin{pmatrix} D_i \longrightarrow H_j(m_i) \\ D_j \longrightarrow H_j(m_j) \end{pmatrix} \text{ at CR } j \text{ only.}$$

Now we can see that relay-assisted spectrum sensing is the same as FDMA with full cooperation. Suppose that M out of K CRs experience heavy shadowing. Without relaying, the *sensing diversity order* of cooperative spectrum sensing is only $(K - M)$. However, with the help of other relay CRs, it can be found that the maximum *sensing diversity order* K can be achieved after allocating all K decisions over K orthogonal subchannels among the $(K - M)$ reliable CRs.

The *sensing diversity order* of cooperative spectrum sensing in heavy shadowing can be improved by using some relay CRs, but the lower bound $\bar{Q}_f$ will also increase with the *sensing diversity order*, as seen from (4). To decrease the lower bound $\bar{Q}_f$ while achieving the maximum *sensing diversity order*, it is of interest to explore a coding approach combined with the relay diversity technique. In the following, we propose an algebraic coding approach to achieve signal space diversity for relay CRs.

Assume that CR i experiences heavy shadowing and CR j has a line-of-sight to the BS. In order to achieve the maximum *sensing diversity order*, CR i will relay its decision D_i to CR j. Then, the two decisions D_i and D_j which are BPSK symbols are encoded as $[\ C_i \quad C_j\ ]^{\mathcal{T}} = \mathbf{\Theta}[\ D_i \quad D_j\ ]^{\mathcal{T}}$, where $\mathbf{\Theta}$ is a 2×2 rotation matrix and the superscript $^{\mathcal{T}}$ denotes the transpose operation. We refer to the signal constellation rotation technique as algebraic coding. Subsequently, C_i and C_j are sent through orthogonal channels $H_j(m_i)$ and $H_j(m_j)$, respectively, as

$$\begin{pmatrix} C_i \longrightarrow H_j(m_i) \\ C_j \longrightarrow H_j(m_j) \end{pmatrix} \text{ at CR } j \text{ only.}$$

At the BS, the received symbols will be jointly decoded and the decoded decisions will then be forwarded to the fusion center.

It can be seen that the BPSK symbols $[\ D_i \quad D_j\ ]$ are rotated by the matrix $\mathbf{\Theta}$, which can be carefully designed in order to achieve a full diversity of codewords $[\ C_i \quad C_j\ ]$ over Rayleigh fading channels. The idea of rotating signal constellations to get a diversity was referred to as *signal space diversity* in [16] and was applied in MIMO systems [17]. Here, we exploit the signal space diversity and convert it into frequency diversity by transmitting two codewords through two orthogonal channels in the CR relay. Consequently, the probability of reporting errors is greatly reduced. Then, cooperative spectrum sensing can be further improved by lowering the bound $\bar{Q}_f$.

Fig. 5 shows the performance of cooperative spectrum sensing with the proposed relay diversity and algebraic coding for two CRs. The average SNRs of the sensing channels of the two CRs are both $\bar{\gamma} = 15$ dB and the average SNR of the reporting channel of the first CR is $\bar{\eta} = 14$ dB. The second CR is assumed to experience heavy shadowing in its reporting channel and cannot forward the decision to the BS. For comparison, we have also plotted the complementary receiver operating characteristics curve without the use of relays. It can be seen that the curve without relay has the worse performance among the three examined cases at a large value of Q_f. This implies that without relay the *sensing diversity order* of the cooperative spectrum sensing is lost under this scenario. Meanwhile the other two curves have a similar performance when Q_f is larger than their lower bounds. This indicates that the *sensing diversity order* of cooperative spectrum sensing can be retrieved by relaying the decision of the second CR to the first CR. However, it can be seen that the lower bound $\bar{Q}_f$ in the case of relay only is larger than that in the case of without relay. This substantiates (4) and indicates that cooperative spectrum sensing with many CRs will induce an increase of the lower bound of Q_f. The curve of relay with algebraic coding has the best performance in Fig. 5 and achieves both the *sensing diversity order* and the lower bound $\bar{Q}_f$. This is because relay diversity allows us to achieve maximum *sensing diversity order* and algebraic coding results in lowering the bound of Q_f.

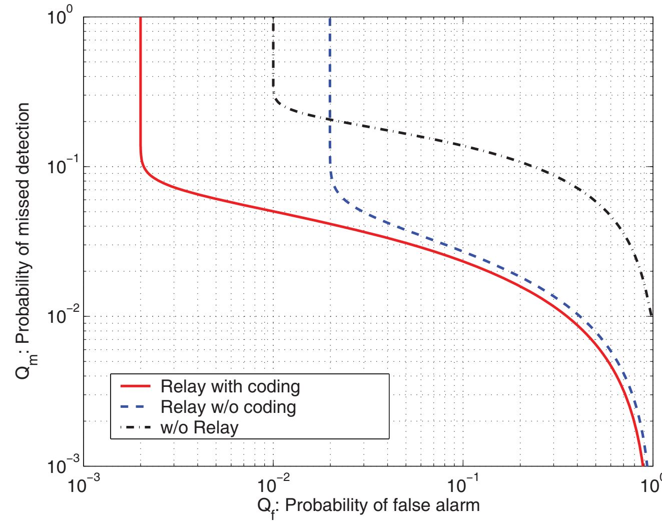

Fig. 5. Cooperative spectrum sensing performance with relay diversity and algebraic coding for two CRs. Both sensing channels have an average SNR $\bar{\gamma} = 15$ dB. The reporting channel of the first CR has average SNR $\bar{\eta} = 14$ dB. The reporting channel of the second CR experiences heavy shadowing.

VI. Conclusion

Cooperative spectrum sensing over Rayleigh fading channels in CR networks were studied. It was found that cooperative spectrum sensing with many CRs could increase the detection probability only within a limited range. To address the issue of performance limits, we proposed several robust cooperative spectrum sensing techniques which apply transmit diversity with space-time coding and space-frequency coding into CR networks over fading channels. Finally, when some CRs experience heavy shadowing, we proposed a relay diversity together with an algebraic coding to greatly improve the performance of cooperative spectrum sensing.

Appendix – Proof of Theorem 1

Proof: For notational brevity, we let H_j^{PU}, H_j^{CR} and H_j^{BS} denote $X_1 = H_j$, $X_2 = H_j$ and $X_3 = H_j$, respectively, for

$j = 0, 1$. Using the property of Markov chain, we obtain

$$\begin{aligned} \mathrm{Prob}\{H_0^{\mathrm{BS}}|H_0^{\mathrm{PU}}, H_0^{\mathrm{CR}}\} &= \mathrm{Prob}\{H_0^{\mathrm{BS}}|H_0^{\mathrm{CR}}\} \\ &= 1 - P_e, \end{aligned} \tag{6}$$

$$\begin{aligned} \mathrm{Prob}\{H_0^{\mathrm{BS}}|H_0^{\mathrm{PU}}, H_1^{\mathrm{CR}}\} &= \mathrm{Prob}\{H_0^{\mathrm{BS}}|H_1^{\mathrm{CR}}\} \\ &= P_e. \end{aligned} \tag{7}$$

Therefore,

$$\begin{aligned} & \mathrm{Prob}\{H_0^{\mathrm{BS}}|H_0^{\mathrm{PU}}\} \\ = \; & \mathrm{Prob}\{H_0^{\mathrm{CR}}|H_0^{\mathrm{PU}}\} \times \mathrm{Prob}\{H_0^{\mathrm{BS}}|H_0^{\mathrm{CR}}\} \\ + \; & \mathrm{Prob}\{H_1^{\mathrm{CR}}|H_0^{\mathrm{PU}}\} \times \mathrm{Prob}\{H_0^{\mathrm{BS}}|H_1^{\mathrm{CR}}\} \\ = \; & (1 - P_f)(1 - P_e) + P_f P_e. \end{aligned} \tag{8}$$

Likewise, we can get

$$\mathrm{Prob}\{H_0^{\mathrm{BS}}|H_1\} = P_m(1 - P_e) + (1 - P_m)P_e. \tag{9}$$

Next, we consider a CR network with K CRs. Hence,

$$\begin{aligned} Q_f &= \mathrm{Prob}\{\mathcal{H}_1|H_0\} \\ &= 1 - \mathrm{Prob}\{H_0^{\mathrm{BS},1}, \cdots, H_0^{\mathrm{BS},K}|H_0\} \\ &= 1 - \prod_{i=1}^{K} \mathrm{Prob}\{H_0^{\mathrm{BS},i}|H_0\}. \end{aligned} \tag{10}$$

By substituting (8) into (10), we get (1). Likewise,

$$\begin{aligned} Q_m &= \mathrm{Prob}\{\mathcal{H}_0|H_1\} \\ &= \mathrm{Prob}\{H_0^{\mathrm{BS},1}, \cdots, H_0^{\mathrm{BS},K}|H_1\} \\ &= \prod_{i=1}^{K} \mathrm{Prob}\{H_0^{\mathrm{BS},i}|H_1\}. \end{aligned} \tag{11}$$

Substituting (9) into (11) results in (2). ■

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