INVITED PAPER

Cooperative Communications for Cognitive Radio Networks

Distributed network users can collaborate to avoid the degrading effects of signal fading by automatically adjusting their coding structure with changes in the wireless environment.

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ABSTRACT | Cognitive radio is an exciting emerging technology that has the potential of dealing with the stringent requirement and scarcity of the radio spectrum. Such revolutionary and transforming technology represents a paradigm shift in the design of wireless systems, as it will allow the agile and efficient utilization of the radio spectrum by offering distributed terminals or radio cells the ability of radio sensing, self-adaptation, and dynamic spectrum sharing. Cooperative communications and networking is another new communication technology paradigm that allows distributed terminals in a wireless network to collaborate through some distributed transmission or signal processing so as to realize a new form of space diversity to combat the detrimental effects of fading channels. In this paper, we consider the application of these technologies to spectrum sensing and spectrum sharing. One of the most important challenges for cognitive radio systems is to identify the presence of primary (licensed) users over a wide range of spectrum at a particular time and specific geographic location. We consider the use of cooperative spectrum sensing in cognitive radio systems to enhance the reliability of detecting primary users. We shall describe spectrum sensing for cognitive radios and propose robust cooperative spectrum sensing techniques for a practical framework employing cognitive radios. We also investigate cooperative communications for spectrum sharing in a cognitive wireless relay network. To exploit the maximum spectrum opportunities, we present a cognitive space–time–frequency coding technique that can opportunistically adjust its coding structure by adapting itself to the dynamic spectrum environment.

KEYWORDS | Cognitive radio; cooperative communications; spectrum sensing; spectrum sharing

I. INTRODUCTION

As wireless technologies continue to grow, more and more spectrum resources will be needed. Within the current spectrum regulatory framework, however, all of the frequency bands are exclusively allocated to specific services, and no violation from unlicensed users is allowed. A recent survey of spectrum utilization made by the Federal Communications Commission (FCC) has indicated that the actual licensed spectrum is largely underutilized in vast temporal and geographic dimensions [1]. For instance, a field spectrum measurement taken in New York City has shown that the maximum total spectrum occupancy is only 13.1% from 30 MHz to 3 GHz [2], [3]. Similar results, obtained in the most crowded area of downtown Washington, D.C., indicated an occupancy of less than 35% of the radio spectrum below 3 GHz. Moreover, the spectrum usage varies significantly in various time, frequency, and geographic locations.

Spectrum utilization can be improved significantly by allowing a secondary user to utilize a licensed band when the primary user (PU) is absent. Cognitive radio (CR), as an agile radio technology, has been proposed to promote the efficient use of the spectrum [4]. By sensing and adapting to the environment, a CR is able to fill in spectrum holes and serve its users without causing harmful interference to the licensed user. To do so, the CR must continuously sense the spectrum it is using in order to detect the reappearance of the PU. Once the PU is detected, the CR should withdraw from the spectrum so as to minimize the interference it may

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possibly cause. This is a very difficult task, as the various PUs will be employing different modulation schemes, data rates, and transmission powers in the presence of variable propagation environments and interference generated by other secondary users. Another great challenge of implementing spectrum sensing is the hidden terminal problem, which occurs when the CR is shadowed, in severe multipath fading or inside buildings with a high penetration loss while a PU is operating in the vicinity.

Cooperative communications is an emerging and powerful solution that can overcome the limitation of wireless systems [5], [6]. The basic idea behind cooperative transmission rests on the observation that, in a wireless environment, the signal transmitted or broadcast by a source to a destination node, each employing a single antenna, is also received by other terminals, which are often referred to as relays or partners. The relays process and retransmit the signals they receive. The destination then combines the signals coming from the source and the partners, thereby creating spatial diversity by taking advantage of the multiple receptions of the same data at the various terminals and transmission paths. In addition, the interference among terminals can be dramatically suppressed by distributed spatial processing technology. By allowing multiple CRs to cooperate in spectrum sensing, the hidden terminal problem can be addressed [7]. Indeed, cooperative spectrum sensing in CR networks has an analogy to a distributed decision in wireless sensor networks, where each sensor makes a local decision and those decision results are reported to a fusion center to give a final decision according to some fusion rule [8]. The main difference between these two applications lies in the wireless environment. Compared to wireless sensor networks, CRs and the fusion center (or common receiver) are distributed over a larger geographic area. This difference brings out a much more challenging problem to cooperative spectrum sensing because sensing channels (from the PU to CRs) and reporting channels (from the CRs to the fusion center or common receiver) are normally subject to fading or heavy shadowing. In this paper, we propose several robust cooperative spectrum sensing techniques to address these challenging issues.

With fast and agile sensing ability, CR can opportunistically fill in spectrum holes to improve the spectrum occupancy utilization. However, once the PU returns to access the licensed band, the CR should immediately stop operating in the PU licensed band. This fast switching off of the CR can guarantee minimum interference to the primary system. However, from the point of view of the cognitive system, the interruptive transmissions will lead to a discontinuous data service and intolerable delay. To cope with this problem, we propose a cognitive relay network in which distributed cognitive users collaborate with each other so that they can share their distinct spectrum bands. By utilizing a cognitive space–time–frequency (STF) coding in the cognitive relay network, seamless data transmission within the cognitive system can also be realized.

The remainder of this paper is organized as follows. In Section II, the CR and cooperative communication technologies will be briefly reviewed. In Section III, spectrum sensing techniques for CR are surveyed and compared. In Section IV, cooperative spectrum sensing is considered and performance analysis will be given. The limitation of cooperative spectrum sensing in realistic cognitive wireless networks is then derived. In Section V, several robust cooperative spectrum sensing techniques are proposed. In Section VI, cooperative spectrum sharing is investigated and a new cognitive wireless relay network proposed. In particular, a cognitive STF coding technique is proposed to realize high-data-rate seamless service for cognitive wireless networks. In Section VII, we draw our conclusions.

II. PRELIMINARY

A. Cognitive Radio

As the demand for additional bandwidth continues to increase, spectrum policy makers and communication technologists are seeking solutions for the apparent spectrum scarcity [9], [10]. Meanwhile, measurement studies have shown that the licensed spectrum is relatively unused across many time and frequency slots [3]. To solve the problem of spectrum scarcity and spectrum underutilization, the use of CR technology is being considered because of its ability to rapidly and autonomously adapt operating parameters to changing requirements and conditions. Recently, the FCC has issued a Notice of Proposed Rulemaking regarding CR [11] that requires rethinking of the wireless communication architectures so that emerging radios can share spectrum with PUs without causing harmful interference to them.

In the pioneering work [4], Mitola and Maguire stated that "radio etiquette is the set of RF bands, air interfaces, protocols, and spatial and temporal patterns that moderate the use of radio spectrum. CR extends the software radio with radio-domain model-based reasoning about such etiquettes."

In Haykin's paper [12], it was stated that "cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., its outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming radio frequency (RF) stimuli by making corresponding changes in certain operating parameters (e.g., transmit power, carrier frequency, and modulation strategy) in real time, with two primary objectives in mind: 1) Highly reliable communications whenever and wherever needed; and 2) Efficient utilization of the radio spectrum."

Another CR description is found in Jondral's paper [13], which states that "an SDR that additionally senses its environment, tracks changes, and reacts upon its findings."

More specifically, the CR technology will enable the users to [14]:

- determine which portions of the spectrum are available and detect the presence of licensed users

when a user operates in a licensed band (spectrum sensing);
- select the best available channel (spectrum management);
- coordinate access to this channel with other users (spectrum sharing);
- vacate the channel when a licensed user is detected (spectrum mobility).

IEEE has also endeavored to formulate a novel wireless air interface standard based on CR. The IEEE 802.22 working group aims to develop wireless regional area network physical (PHY) and medium access control (MAC) layers for use by unlicensed devices in the spectrum allocated to TV bands [15], [16].

For an overview of recent advances in CR, readers are referred to [17]–[21].

B. Cooperative Communications

Traditional wireless networks have predominantly used direct point-to-point or point-to-multipoint (e.g., cellular) topologies. In contrast to conventional point-to-point communications, cooperative communications and networking allows different users or nodes in a wireless network to share resources and to create collaboration through distributed transmission/processing, in which each user's information is sent out not only by the user but also by the collaborating users [22]. Cooperative communications and networking is a new communication paradigm that promises significant capacity and multiplexing gain increase in wireless networks [23], [24]. It also realizes a new form of space diversity to combat the detrimental effects of severe fading [25].

There are mainly three relaying protocols: amplify-and-forward (AF), decode-and-forward (DF), and compress-and-forward (CF). In AF, the received signal is amplified and retransmitted to the destination. The advantage of this protocol is its simplicity and low cost implementation. But the noise is also amplified at the relay. In DF, the relay attempts to decode the received signals. If successful, it reencodes the information and retransmits it. Lastly, CF attempts to generate an estimate of the received signal. This is then compressed, encoded, and transmitted in the hope that the estimated value may assist in decoding the original codeword at the destination.

In [5] and [6], Sendonaris *et al.* introduced and examined the concept of user cooperation diversity. The implemented strategy uses a pair of transmitting, full-duplex users who cooperate in sending independent data from both users to a common destination. In essence, each user is acting as a relay for others while using the AF relaying strategy. The DF and CF strategies are thoroughly examined for wireless channels in [24]. In addition to providing a thorough survey of relay networks, [24] showed that under certain conditions, the DF strategy is capable of achieving rates of up to the ergodic capacity of the channel.

Cooperative techniques have already been considered for wireless and mobile broadband radio [26] and also have been under investigation in various IEEE 802 standards. The IEEE 802.11 standard is concerned with wireless local-area networks (WLANs) in unlicensed bands in indoor environments. A recent evolution of IEEE 802.11 using mesh networking, i.e., 802.11s is considering the update of 802.11 MAC layer operation to self-configuration and multihop topologies [27]. The mesh point that has the ability to function as the 802.11 access point collects the information about the neighboring mesh points, communicating with them and forwarding the traffic. The IEEE 802.16 standard is an orthogonal frequency-division multiplexing (OFDM), orthogonal frequency-division multiple access (OFDMA), and single-carrier based fixed wireless metropolitan-area network in licensed bands of 10–66 GHz. As an amendment of 802.16 networks, IEEE 802.16j is concerned with multihop relay to enhance coverage, throughput, and system capacity [28].

III. SPECTRUM SENSING TECHNIQUES

One of the most important components of CR is the ability to measure, sense, learn, and be aware of the parameters related to the radio channel characteristics, availability of spectrum and power, interference and noise temperature, radio's operating environment, user requirements, and applications [29]. In CR, the PUs are referred to those users who have higher priority or legacy rights on the usage of a part of the spectrum. Spectrum sensing is a key element in CR communications, as it enables the CR to adapt to its environment by detecting spectrum holes. The most effective way to detect the availability of some portions of the spectrum is to detect the PUs that are receiving data within the range of a CR. However, it is difficult for the CR to have a direct measurement of a channel between a primary transmitter and receiver. Therefore, most existing spectrum sensing algorithms focus on the detection of the primary transmitted signal based on the local observations of the CR. In the following, we denote $x(t)$ the received signal at the CR.

To enhance the detection probability, many signal-detection techniques can be used in spectrum sensing. In this section, we give an overview of some well-known spectrum sensing techniques.

1) Matched Filter Detection: When a secondary user has a prior knowledge of the PU signal, the optimal signal detection is a matched filter, as it maximizes the signal-to-noise ratio (SNR) of the received signal. A matched filter is obtained by correlating a known signal, or template, with an unknown signal to detect the presence of the template in the unknown signal. This is equivalent to convolving the unknown signal with a time-reversed version of the template. The main advantage of matched filter is that it needs less time to achieve high processing gain due to coherent detection [30]. Another significant disadvantage of the matched filter is that it would require a dedicated sensing receiver for all primary user signal types.

In the CR scenario, however, the use of the matched filter can be severely limited since the information of the PU signal is hardly available at the CRs. The use of this approach is still possible if we have partial information of the PU signal such as pilot symbols or preambles, which can be used for coherent detection [7]. For instance, to detect the presence of a digital television (DTV) signal, we may detect its pilot tone by passing the DTV signal through a delay-and-multiply circuit. If the squared magnitude of the output signal is larger than a threshold, the presence of the DTV signal can be detected.

2) Energy Detection: If prior knowledge of the PU signal is unknown, the energy detection method is optimal for detecting any zero-mean constellation signals [30]. In the energy detection approach, the radio-frequency (RF) energy in the channel or the received signal strength indicator is measured to determine whether the channel is idle or not. First, the input signal is filtered with a band-pass filter to select the bandwidth of interest. The output signal is then squared and integrated over the observation interval. Lastlly, the output of the integrator is compared to a predetermined threshold to infer the presence or not of the PU signal. When the spectral is analyzed in the digital domain, fast Fourier transform (FFT) based methods are used. Specifically, the received signal $x(t)$, sampled in a time window, is first passed through an FFT device to get the power spectrum $|X(f)|^2$. The peak of the power spectrum is then located. After windowing the peak of the spectrum, we get $|Y(f)|^2$. The signal energy is then collected in the frequency domain.

Although the energy-detection approach can be implemented without any prior knowledge of the PU signal, it still has some drawbacks. The first problem is that it has poor performance under low SNR conditions. This is because the noise variance is not accurately known at the low SNR, and the noise uncertainty may render the energy detection useless [30]. Another challenging issue is the inability to differentiate the interference from other secondary users sharing the same channel and the PU [31]. Furthermore, the threshold used in energy selection depends on the noise variance, and small noise power estimation errors can result in significant performance loss.

3) Cyclostationary Detection: Cyclostationary detection is more robust to noise uncertainty than an energy detection. If the signal of the PU exhibits strong cyclostationary properties, it can be detected at very low SNR values by exploiting the information (cyclostationary feature) embedded in the received signal. A signal is said to be cyclostationary (in the wide sense) if its autocorrelation is a periodic function of time t with some period [32]. The cyclostationary detection can be performed as follows.

- First, the cyclic autocorrelation function (CAF) of the observed signal $x(t)$ is calculated as $E\{x(t+\tau) x^*(t-\tau)e^{-i2\pi\alpha t}\}$, where $E\{\cdot\}$ denotes the statistical expectation operation and α is called the *cyclic frequency*.
- The spectral correlation function (SCF) $S(f,\alpha)$ is then obtained from the discrete Fourier transformation of the CAF. The SCF is also called cyclic spectrum, which is a two-dimension function in terms of frequency f and cyclic frequency α.
- The detection is completed by searching for the *unique cyclic frequency* corresponding to the peak in the SCF plane.

This detection approach is robust to random noise and interference from other modulated signals because the noise has only a peak of SCF at the zero cyclic frequency and the different modulated signals have different unique cyclic frequencies. In [33], the cyclostationary detection method is employed for the detection of the Advanced Television Systems Committee DTV signals in wireless region-area network systems. Experimental results show superior detection performance even in very low SNR region. In [34], distributed detection is considered for scanning spectrum holes, where each CR employs a generalized likelihood ratio test for detecting primary transmissions with multiple cyclic frequencies.

The above approach can detect the PU signal from other CR users signals over the same frequency band provided that the cyclic features of the PU and the CR signals differ from each other, which is usually the case, because different wireless systems usually employ different signal structures and parameters. By exploiting the distinct cyclostationary characteristics of the PU and the CR signals, a strategy of extracting channel-allocation information is proposed in spectrum pooling systems [35], where the PU is a GSM network and the CR is an OFDM-based WLAN system. However, cyclostationary detection is more complex to implement than the energy detection and requires a prior knowledge of PU signal such as modulation format.

4) Wavelet Detection: Wavelet transform is a multi-resolution analysis mechanism where an input signal is decomposed into different frequency components, and then each component is studied with resolutions matched to its scales. Unlike the Fourier transform, using sines and cosines as basic functions, the wavelet transforms use irregularly shaped wavelets as basic functions and thus offer better tools to represent sharp changes and local features [36]. For signal detection over wide-band channels, the wavelet approach offers advantages in terms of both implementation cost and flexibility in adapting to the dynamic spectrum, as opposed to the conventional use of multiple narrow-band bandpass filters [37]. In order to identify the locations of vacant frequency bands, the entire wide-band is modeled as a train of consecutive frequency subbands where the power spectral characteristic is smooth within each subband but changes abruptly on the border of two neighboring subbands. By employing a wavelet transform of the power spectral density (PSD) of the observed signal $x(t)$, the singularities of the

PSD $S(f)$ can be located and thus the vacant frequency bands can be found. One critical challenge of implementing the wavelet approach in practice is the high sampling rates for characterizing the large bandwidth. In [38], a dual-stage spectrum sensing technique is proposed for wide-band CR systems, in which a wavelet transform-based detection is employed as a coarse sensing stage and a temporal signature detection is used as a fine sensing stage.

5) Covariance Detection: Given that the statistical covariance matrices or autocorrelations of the signal and noise are generally different, covariance-based signal detection methods were proposed in [39]. By observing the fact that off-diagonal elements of the covariance matrix of the received signal are zero when the primary user signal is not present and nonzero when it is present, the authors in [39] developed two detection methods: covariance absolute value detection and covariance Frobenius norm detection. The methods can be used for various signal detection and applications without knowledge of the signal, channel, and noise power. Later, and by applying eigendecomposition of the covariance matrix, the authors further developed other two detection methods, called max-min eigenvalue detection and max-eigenvalue detection in [40] and [41], respectively. The essence of the eigendetection methods lies in the significant difference of the eigenvalue of the received signal covariance matrix when the primary user signal is present or not.

IV. COOPERATIVE SPECTRUM SENSING

A. General Concept

The critical challenging issue in spectrum sensing is the hidden terminal problem, which occurs when the CR is shadowed or in severe multipath fading. Fig. 1 shows that CR 3 is shadowed by a high building over the sensing channel. In this case, the CR cannot sense the presence of the primary user, and thus it is allowed to access the channel while the PU is still in operation. To address this issue, multiple CRs can be designed to collaborate in spectrum sensing [7]. Recent work has shown that cooperative spectrum sensing can greatly increase the probability of detection in fading channels [42]. For an overview of recent advances in cooperative spectrum sensing, readers are referred to [42]–[52]. In general, cooperative spectrum sensing can be performed as described below.

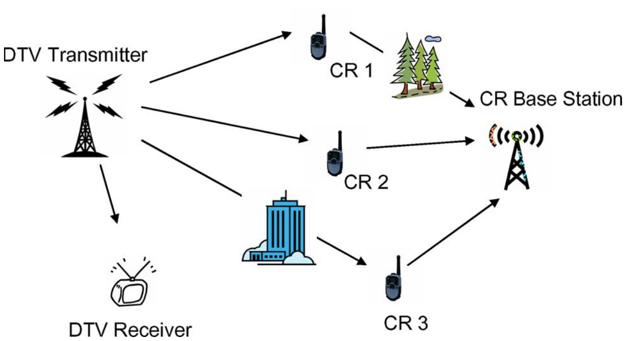

Fig. 1. ***Cooperative spectrum sensing in CR networks. CR 1 is shadowed over the reporting channel and CR 3 is shadowed over the sensing channel.***

Cooperative Spectrum Sensing:

1) Every CR performs its own local spectrum sensing measurements independently and then makes a binary decision on whether the PU is present or not.
2) All of the CRs forward their decisions to a common receiver.
3) The common receiver fuses the CR decisions and makes a final decision to infer the absence or presence of the PU.

1) Decision Fusion Versus Data Fusion: The above cooperative spectrum sensing approach can be seen as a DF protocol for cooperative networks, where each cooperative partner makes a binary decision based on the local observation and then forwards one bit of the decision to the common receiver. At the common receiver, all 1-bit decisions are fused together according to an OR logic. We shall refer to this approach as *decision fusion*. An alternative form of cooperative spectrum sensing can be performed as follows. Instead of transmitting the 1-bit decision to the common receiver in step 2) of the above algorithm, each CR can just send its observation value directly to the common receiver [51]. This alternative approach can then be seen as an AF protocol for cooperative networks. We shall refer to this approach as *data fusion*. Obviously, the 1-bit decision needs a low-bandwidth control channel.

2) Sensing Diversity Gain: It can be seen that cooperative spectrum sensing will go through two successive channels: 1) sensing channel (from the PU to CRs) and 2) reporting channel (from the CRs to the common receiver). The merit of cooperative spectrum sensing primarily lies in the achievable space diversity brought by the sensing channels, namely, *sensing diversity gain*, provided by the multiple CRs. Even though one CR may fail to detect the signal of the PU, there are still many chances for other CRs to detect it. With the increase of the number of cooperative CRs, the probability of missed detection for all the users will be extremely small. Another merit of cooperative spectrum sensing is the mutual benefit brought forward by communicating with each other to improve the sensing performance [48]. When one CR is far away from the primary user, the received signal may be too weak to be detected. However, by employing a CR that is located nearby the PU as a relay, the signal of the PU can be detected reliably by the far user.

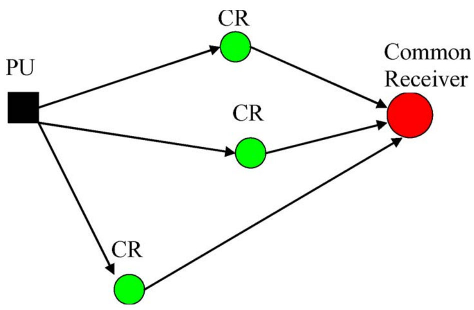

Fig. 2. ***Spectrum sensing structure in a cognitive radio network.***

B. Performance Analysis

1) Local Spectrum Sensing: The essence of spectrum sensing is a binary hypothesis-testing problem

$$\begin{aligned} H_0 &: \quad \text{Primary user is absent} \\ H_1 &: \quad \text{Primary user is in operation.} \end{aligned}$$

The key metrics of the spectrum sensing are the probabilities of correct detection given by $\text{Prob}\{\text{Decision}=H_1|H_1\}$ and $\text{Prob}\{\text{Decision}=H_0|H_0\}$, the false alarm probability given by $\text{Prob}\{\text{Decision}=H_1|H_0\}$, and the missed detection probability given by $\text{Prob}\{\text{Decision}=H_0|H_1\}$.

We consider a CR network composed of K CRs (secondary users) and a common receiver, as shown in Fig. 2. The common receiver manages the CR network and all associated K CRs. We assume that each CR performs local spectrum sensing independently. In order to see how the energy detector works, we only consider the ith CR in the following. The local spectrum sensing problem is to decide between the following two hypotheses:

$$x_i(t) = \begin{cases} n_i(t), & H_0 \\ h_i s(t) + n_i(t), & H_1 \end{cases} \tag{1}$$

where $x_i(t)$ is the observed signal at the ith CR, $s(t)$ is the signal coming from the primary transmitter, $n_i(t)$ is the additive white Gaussian noise, and h_i is the complex channel gain of the sensing channel between the PU and the ith CR. We assume that the sensing channel is time-invariant during the sensing process.

The energy detection is performed by measuring the energy of the received signal $x_i(t)$ in a fixed bandwidth W over an observation time window T. The energy collected in the frequency domain is denoted by E_i, which serves as a decision statistic with the following distribution [53]–[55]:

$$E_i \sim \begin{cases} \chi^2_{2u}, & H_0 \\ \chi^2_{2u}(2\gamma_i), & H_1 \end{cases} \tag{2}$$

where χ^2_{2u} denotes a central chi-square distribution with $2u$ degrees of freedom and $\chi^2_{2u}(2\gamma_i)$ denotes a noncentral chi-square distribution with u degrees of freedom and a noncentrality parameter $2\gamma_i$, respectively. The instantaneous SNR of the received signal at the ith CR is γ_i, and $u = TW$ is the time–bandwidth product. By comparing the energy E_i with a threshold ζ_i, the detection of PU signal is made. Therefore, the probability of false alarm is given by $P_f^{(i)} = \text{Prob}\{E_i > \zeta_i | H_0\}$ and the probability of detection is given by $P_d^{(i)} = \text{Prob}\{E_i > \zeta_i | H_1\}$. Over Rayleigh fading channels, the average probability of false alarm, the average probability of detection, and the average probability of missed detection are given by [55], respectively

$$P_f^{(i)} = \frac{\Gamma\left(u, \frac{\zeta_i}{2}\right)}{\Gamma(u)} \tag{3}$$

$$\begin{aligned} P_d^{(i)} &= e^{-\frac{\zeta_i}{2}} \sum_{p=0}^{u-2} \frac{1}{p!}\left(\frac{\zeta_i}{2}\right)^p + \left(\frac{1+\bar{\gamma}_i}{\bar{\gamma}_i}\right)^{u-1} \\ &\quad \times \left[e^{-\frac{\zeta_i}{2(1+\bar{\gamma}_i)}} - e^{-\frac{\zeta_i}{2}} \sum_{p=0}^{u-2} \frac{1}{p!}\left(\frac{\zeta_i \bar{\gamma}_i}{2(1+\bar{\gamma}_i)}\right)^p \right] \end{aligned} \tag{4}$$

and

$$P_m^{(i)} = 1 - P_d^{(i)} \tag{5}$$

where $\bar{\gamma}_i$ denotes the average SNR at the ith CR, $\Gamma(a,x)$ is the incomplete gamma function given by $\Gamma(a,x) = \int_x^\infty t^{a-1}e^{-t}dt$, and $\Gamma(a)$ is the gamma function.

In Fig. 3, the complementary receiver operating characteristic (ROC) curves (probability of missed detection

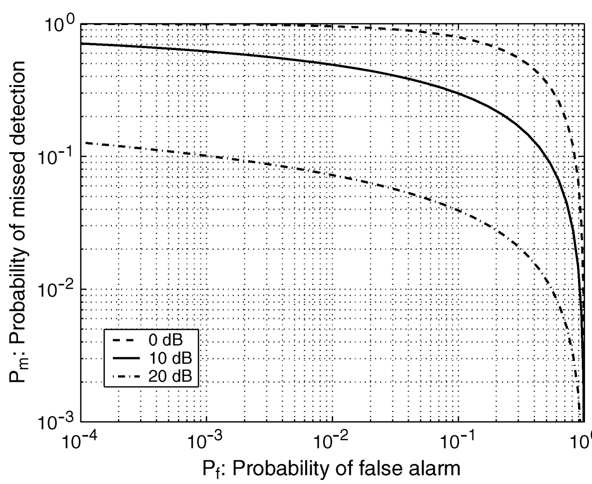

Fig. 3. ***Spectrum sensing performance over Rayleigh fading channels with SNR $\bar{\gamma} = 0, 10, 20$ dB for one cognitive radio.***

versus probability of false alarm) of the energy detection in one CR are plotted for a variety of SNR values according to (3) and (5). In the plotting, we use $u = 5$ and SNR of 0, 10, and 20 dB, respectively. A close observation of Fig. 3 shows that the energy detection performance of one CR gets worse when the SNR decreases. This will be the case when the CR experiences heavy shadowing or fading. In such a scenario, cooperative spectrum sensing can be applied with the help of multiple CRs [42], [47].

2) Cooperative Spectrum Sensing Based on Decision Fusion: In cooperative spectrum sensing, all CRs identify the availability of the licensed spectrum independently. Each cooperative partner makes a binary decision based on its local observation and then forwards one bit of the decision to the common receiver. Let $D_i \in \{0,1\}$ denote the local spectrum sensing result of the ith CR. Specifically, $\{0\}$ indicates that the CR infers the absence of the PU in the observed band. In contrast, $\{1\}$ infers the operating of the PU. At the common receiver, all 1-bit decisions are fused together according to the following logic rule:

$$Z = \sum_{i=1}^{K} D_i \begin{cases} \geq n, & \mathcal{H}_1 \\ < n, & \mathcal{H}_0 \end{cases} \tag{6}$$

where $\mathcal{H}_1$ and $\mathcal{H}_0$ denote the inferences drawn by the common receiver that the PU signal is transmitted or not transmitted, respectively. Equation (6) demonstrates that the common receiver infers the PU signal being transmitted, i.e., $\mathcal{H}_1$, when there exists *at least n out of K CRs inferring* H_1. Otherwise, the common receiver decides the PU signal not being transmitted, i.e., $\mathcal{H}_0$. It can be seen that the OR rule corresponds to the case of $n = 1$ and the AND rule corresponds to the case of $n = K$. For the OR rule, the common receiver infers the presence of the PU signal when there exists at least one CR that has the local decision H_1. It can be seen that the OR rule is very conservative for the CRs to access the licensed band. As such, the chance of causing interference to the PU is minimized. Fig. 4 shows the cooperative spectrum sensing performance with different fusion rules. It can be seen that the OR rule is the best among the fusion rules. In [44], it was also found that for many cases of practical interest, the OR rule gives better performance than other rules. Therefore, we shall consider the OR rule in the sequel.

The false alarm probability of cooperative spectrum sensing based on the OR rule is given by

$$Q_f = 1 - \prod_{i=1}^{K}\left(1 - P_f^{(i)}\right) \tag{7}$$

where $P_f^{(i)}$ denotes the false alarm probability of the ith CR in its local spectrum sensing. The missed detection

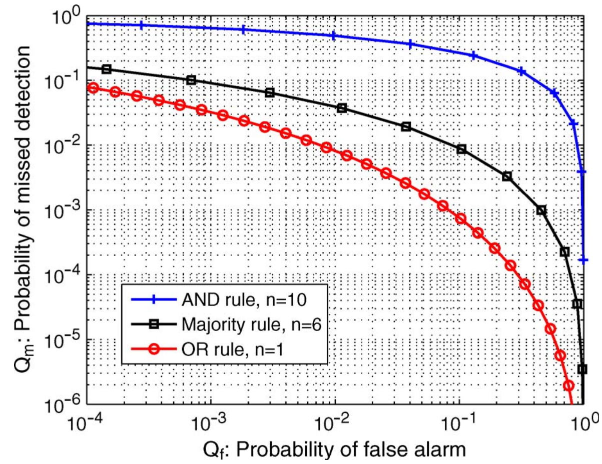

Fig. 4. ***Cooperative spectrum sensing performance with various fusion rules ($n = 1, 6, 10$) over Rayleigh fading channels with SNR $\bar{\gamma} = 10$ dB for ten secondary users (CRs).***

probability of cooperative spectrum sensing is given by

$$Q_m = \prod_{i=1}^{K} P_m^{(i)} \tag{8}$$

where $P_m^{(i)}$ denotes the missed detection probability of the ith CR in its local spectrum sensing.

Assume that every CR achieves identical P_f and P_m in the local spectrum sensing (i.e., $P_f = P_f^{(i)}$ and $P_m = P_m^{(i)}$, $\forall i = 1, 2, \ldots, K$). The false alarm probability and the missed detection probability of cooperative spectrum sensing are then given by

$$Q_f = 1 - (1 - P_f)^K \tag{9}$$

$$Q_m = (P_m)^K. \tag{10}$$

Note that the detection probability of the cooperative spectrum sensing is $Q_d = 1 - Q_m$.

Fig. 5 lists the performance results of cooperative spectrum sensing for different numbers of CRs over Rayleigh fading channels with an SNR $\bar{\gamma} = 10$ dB. It is seen that the probability of missed detection is greatly reduced when the number of cooperative CRs increases for a given probability of false alarm. We shall refer to K as the *sensing diversity order* of cooperative spectrum sensing, since it characterizes the error exponent of Q_m in (10).

C. Limitation of Cooperative Spectrum Sensing

In practice, the reporting channels between the CRs and the common receiver will also experience fading and shadowing (such as CR 1 in Fig. 1). This will typically

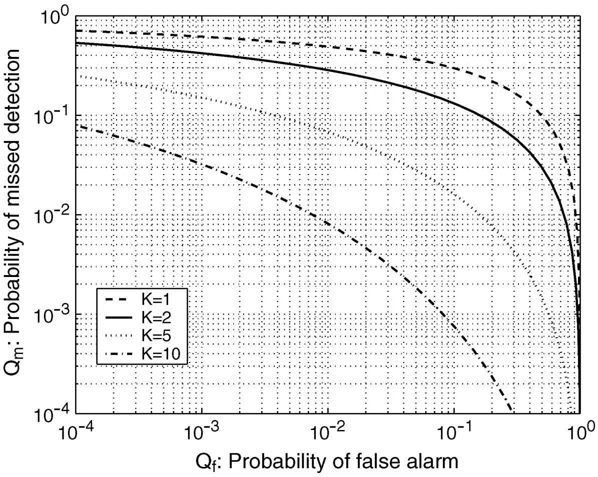

Fig. 5. ***Cooperative spectrum sensing performance over Rayleigh fading channels with SNR $\bar{\gamma} = 10$ dB for different numbers of secondary users (CRs), K $= 1, 2, 5, 10$.***

deteriorate the transmission reliability of the sensing results reported from the CRs to the common receiver. For example, when one CR reports a sensing result $\{1\}$ (denoting the presence of the PU) to the common receiver through a realistic fading channel, the common receiver will likely detect it to be the opposite result $\{0\}$ (denoting the absence of the PU) because of the disturbance from the random complex channel coefficient and random noise. Eventually, the performance of cooperative spectrum sensing will be degraded by the imperfect reporting channels.

Let $P_e^{(i)}$ denote the error probability of signal transmission over the reporting channels between the ith CR and the common receiver. We shall refer to $P_e^{(i)}$ as the probability of reporting errors. Then, the cooperative spectrum sensing performance can be given by [56]

$$Q_f = 1 - \prod_{i=1}^{K}\left[\left(1-P_f^{(i)}\right)\left(1-P_e^{(i)}\right) + P_f^{(i)}P_e^{(i)}\right] \tag{11}$$

$$Q_m = \prod_{i=1}^{K}\left[P_m^{(i)}\left(1-P_e^{(i)}\right) + \left(1-P_m^{(i)}\right)P_e^{(i)}\right] \tag{12}$$

where we recall that $P_f^{(i)}$ and $P_m^{(i)}$ are the false alarm probability and missed detection probability of the local spectrum sensing of the ith CR, respectively.

Suppose that every CR has an identical local spectrum sensing performance and experiences identical but independent fading reporting channels. It follows that $P_e^{(i)} = P_e$, $\forall i = 1, 2, \ldots, K$. As a result, the false alarm probability is lower bounded by $\bar{Q}_f$, as shown in (13)

$$Q_f \geq \bar{Q}_f = 1 - (1 - P_e)^K. \tag{13}$$

For a very small P_e, the bound (13) reduces to $Q_f \geq KP_e$. Equation (13) can be easily derived from (11) by noting that Q_f linearly increases with P_f and $Q_f \geq \min Q_f = \lim_{P_f \to 0} Q_f$.

Next, we would like to evaluate the performance of cooperative spectrum sensing with various system parameters, as described below:

- sensing channels with Rayleigh fading and average SNR: $\bar{\gamma} = 5, 10, 20$ dB.
- $P_e = 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}$.

Fig. 6 shows the analytical complementary ROC curves under different average SNRs for two CRs with $P_e = 0.001$. It can be seen that Q_f is limited by a lower bound and that the bound does not depend on the channel SNR. This is consistent with (13), which shows that the bound depends on K and P_e only. A careful observation of Fig. 6 also indicates that the bound of Q_f is around 0.002. This can be confirmed by putting $K = 2$ and $P_e = 0.001$ into the approximation of $\bar{Q}_f$ in (13).

D. Practical Considerations

1) Tradeoff Between Sensing Duration and Performance: Spectrum sensing is significant in CRs in avoiding a collision with the licensed user and improving the licensed spectrum utilization efficiency. The former is characterized by the parameter P_d, i.e., the probability of detection; and the latter is measured by the parameter P_f, i.e., the probability of false alarm. The sensing duration T is no doubt a key parameter to determine the sensing performance. A longer sensing duration T can produce a better sensing performance but result in longer waiting time for cognitive users to access the channel. An extremely long sensing duration cannot be tolerated by an agile radio. From the perspective of the cognitive users, a lower false alarm probability implies that there will be more chances

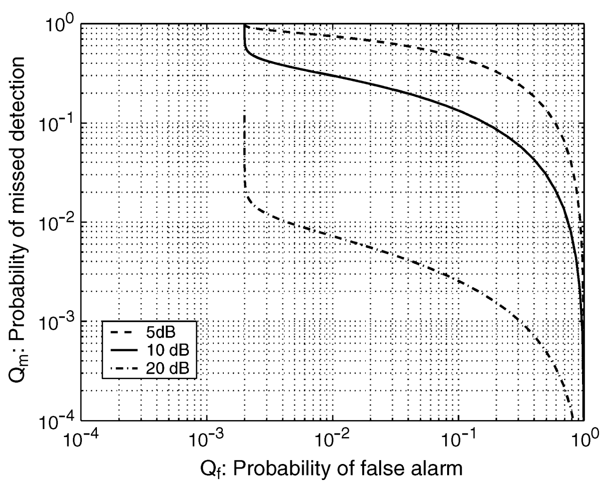

Fig. 6. ***Performance results (Q_m versus Q_f) of cooperative spectrum sensing for two cooperative CRs and different average SNR $\bar{\gamma} = 5, 10, 20$ dB in sensing channels. The reporting error rate is 0.001.***

for the licensed channel to be reused. Assuming that the protection of the primary user is of the first priority in CR networks, the optimal sensing duration was determined in [57] by maximizing the throughput of the cognitive users. Specifically, in [57], the authors assumed a fixed frame duration F in which the sensing duration is T and the remaining duration $F - T$ is used for data transmission. The CRs can access the licensed channels and start data transmission in two scenarios. First, when the primary user is not present and the cognitive users make a correct detection (with probability $\text{Prob}(H_0) \cdot (1 - P_f)$), the throughput of the CRs is C_0. Secondly, when the primary user is present and cognitive users make a missed detection (with probability $\text{Prob}(H_1) \cdot P_m$), the throughput of the CRs is C_1. The average throughput of the cognitive users is then $[C_0 \text{Prob}(H_0)(1 - P_f) + C_1 \text{Prob}(H_1) P_m](F - T/F)$. For a target detection probability, an optimal value of sensing time can be found by maximizing the cognitive users throughput.

2) Tradeoff Between Cooperation and Sensing: In a CR network with a large number of CRs, cooperative spectrum sensing may become impractical because in a time slot only one CR should send its local decision to the common receiver so as to separate decisions easily at the receiver end. Hence, it may make the whole sensing time intolerantly long. Obviously the fewer CRs involved in cooperative spectrum sensing, the shorter the sensing duration. However, a small number of CRs in cooperative spectrum sensing results in a small *sensing diversity order*. This problem can be addressed by allowing the CRs to send the decisions concurrently. But this may complicate the receiver design when we try to identify the decisions from different CRs. Another potential solution is to send the decisions on orthogonal frequency bands, but this requires a large portion of the available bandwidth. In [58], we proposed an efficient sensing algorithm that utilizes the least required number of CRs for a target error probability. By doing so, we can guarantee a target quality-of-service while using the least amount of cooperation among the CRs.

V. ROBUST COOPERATIVE SPECTRUM SENSING

The use of multiple CRs to perform cooperative spectrum sensing can clearly improve the detection probability, but the performance may be limited in realistic fading channels. To alleviate this performance degradation, we propose several robust cooperative spectrum sensing techniques in this section.

A. Technique Exploiting Cooperative Diversity

Consider the case when the ith CR of K CRs shall need to report the decision $D_i \in \{H_0, H_1\}$ to the common receiver. The decision can be represented by a binary hypothesis testing problem [binary phase-shift keying (BPSK) signaling] $H_0 = -1$ and $H_1 = 1$. All K decisions from the CRs are assumed to arrive at the common receiver according to a time-division multiple-access (TDMA) protocol so that the common receiver can gather the K decisions without interference. For instance, the transmission of two CRs can be described as

$$\begin{pmatrix} D_1 & \\ & D_2 \end{pmatrix} \rightarrow \text{Space} \downarrow \text{Time}$$

where the decision D_i $(i = 1, 2)$ will go through a flat fading channel from CR i to the common receiver. After a hard decision, the decoded signal at the common receiver is either 1 or -1. Note that each symbol is decoded independently. Thus, the reception performance of multiple CRs in TDMA is the same as that of one CR. The symbol error rate (SER) of BPSK over Rayleigh fading channels is [59]

$$Q_e^{\text{TDMA}} = \frac{1}{2}(1 - \mu) \tag{14}$$

where $\mu = \sqrt{\bar{\eta}/1 + \bar{\eta}}$, with $\bar{\eta}$ being the average SNR of the reporting channel.

Multiple antennas at the transmitter and receiver have been regarded over the last decade as one major breakthrough. They can not only greatly increase the channel capacity of the so-called multiple-input multiple-output (MIMO) systems but also provide a high spatial diversity gain to combat channel fading [60]. In order to achieve high transmit diversity, space–time (ST) coding was proposed by spreading codewords across different transmit antennas and time slots [61]. In CR networks, implementing multiple antennas at each CR is not practical due to the increasing cost and hardware complexity. Another recently proposed solution for achieving spatial diversity without requiring multiple antennas at any terminal or node is cooperative diversity [5]. It is based on grouping several nodes (each with only one antenna) together into a cluster to form a virtual antenna array. Motivated by the concept of cooperative diversity, we will describe a ST-coded cooperative spectrum sensing [56] in the following.

We shall first consider a simple example of two CRs and then discuss the case of more than two CRs later. Assume that the local decisions are denoted by D_1 and D_2 for CR 1 and CR 2, respectively. Then, the two CRs are coordinated to form a transmit cluster in which ST block coding (STBC) can be applied. Consider 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 interuser channels of a virtual antenna array are noisy and might also be subject to fading. In order to implement distributed ST coding, we allow that the two CRs exchange their information of the local decision. The information exchange can be performed through a similar protocol to the one used in wireless LAN by sending receive-to-send and clear-to-send frames. 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 common receiver. Otherwise, the CRs will transmit their own decisions to the common receiver using the TDMA protocol. In sum, the decisions are reported to the common receiver by employing either direct transmission using TDMA or transmit diversity via ST coding, based on the quality of the interuser channel.

Denote the error rate of BPSK using ST block coding as Q_e^{STBC}; then [62]

$$Q_e^{\mathrm{STBC}} = \frac{1}{2}\left[1 - \mu \sum_{m=0}^{N_t-1} \binom{2m}{m} \left(\frac{1-\mu^2}{4}\right)^m\right] \tag{15}$$

where N_t is the number of cooperative antennas or partners and $\mu = \sqrt{\bar{\eta}/N_t/1+\bar{\eta}/N_t}$. Let ϵ denote the error rate of the transmission over the interuser channels between CR 1 and CR 2. Then, $\alpha = (1-\epsilon)^2$ is the probability of the two CRs' both correctly decoding the received signal coming from each other. Hence, the reporting error rate (per bit) of the proposed user cooperation is given by

$$P_e = \alpha Q_e^{\mathrm{STBC}} + (1-\alpha) Q_e^{\mathrm{TDMA}}. \tag{16}$$

For a good interuser channel, α approaches one and we simply have $P_e \approx Q_e^{\mathrm{STBC}}$. It means that the two CRs can always correctly decode the received signals due to the good interuser 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 greatly reduced. On the other hand, for a poor interuser channel—for instance, when $\epsilon = 0.3$, which corresponds to $\alpha \approx 0.5$—P_e will be dominated by the term $(1-\alpha)Q_e^{\mathrm{TDMA}}$ in (16). 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 common receiver or in an ad hoc fashion through negotiations among neighboring nodes without centralized control [63]. For different clusters, TDMA is used in the process of reporting. That is, each cluster will be assigned a time slot that is different from other clusters to report the decisions. Thus, the common receiver will receive signals from one cluster only in the given time slot without interference from other clusters.

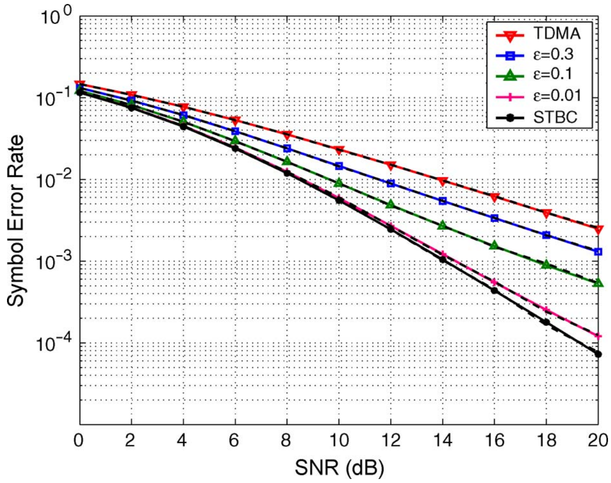

Fig. 7. *Reporting error rate performance for various interuser channel qualities, $\epsilon = 0.01, 0.1, 0.3$. The TDMA and STBC performance, corresponding to $\epsilon = 1$ and 0, respectively, are also given.*

Fig. 7 shows the reporting error rate performance of the proposed transmit diversity technique for various interuser channel qualities, $\epsilon = 0, 0.01, 0.1, 0.3$, and 1. In particular, the cases of $\epsilon = 1$ and 0 correspond to TDMA and STBC, respectively. The case of $\epsilon = 0.3$ corresponds to a very poor interuser channel. Simulation and analytical results are shown as solid curves and dashed curves, respectively. It can be seen that the error-rate performance is improved when ϵ decreases. Even for the very bad interuser channel when $\epsilon = 0.3$, there is still a 3 dB coding gain. This corroborates our analysis given above. Considering that the interuser channel is usually good enough as the CRs are closely located, we can conclude that the proposed transmit diversity technique can achieve a performance that is as good as STBC.

Fig. 8 shows the performance comparison of cooperative spectrum sensing with two CRs for various interuser channel qualities, $\epsilon = 0, 0.02, 0.2$, 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 $\bar{Q}_f$ that is 0.002, whereas it is 0.02 for TDMA. For the case of $\epsilon = 0.02$, the performance is almost as good as STBC.

An OFDM-based overlay system was recently investigated and shown as a promising approach for enhancing spectral efficiency [64]. For OFDM-based CRs, a few subchannels are selected to transmit the individual CR local decisions to the common receiver. To avoid the interference generated by other CRs, each subchannel is exclusively assigned to one CR, and different CRs are only allowed to transmit through orthogonal subchannels. As a result, it follows that the transmission from the CRs to the common receiver can be considered as OFDMA protocol. For example, assuming that FDMA is used, then

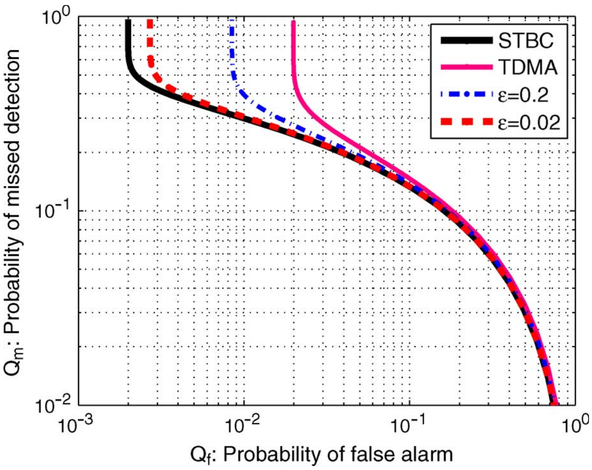

Fig. 8. ***Performance comparison (Q_m versus Q_f) of cooperative spectrum sensing using transmit diversity technique for different interuser channel qualities $\epsilon = 0.02$ and 0.2. TDMA and STBC, which correspond to the case of $\epsilon = 1$ and 0, respectively, are also given. The sensing channels have average SNR $\bar{\gamma} = 10$ dB and reporting channels have average SNR $\bar{\eta} = 14$ dB.***

the system for two CRs can be described by the following matrix [56]:

$$\begin{pmatrix} D_1 & \\ & D_2 \end{pmatrix} \rightarrow \text{Space} \downarrow \text{Subchannel.}$$

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

Recently, it was shown that SF coding [65], [66] can achieve not only space diversity but also frequency diversity by spreading codewords over multiple transmit antennas and OFDM subchannels. In this paper, we can consider the distributed CRs as a virtual antenna array and assume that the CRs can exchange their decisions through a predefined protocol. Instead of transmitting one symbol over one subchannel only for a CR, we can employ SF coding over several OFDM subchannels [56]. For instance, the SF coding for two CRs can be described by the following matrix:

$$\frac{1}{\sqrt{2}}\begin{pmatrix} D_1 & D_2 \\ -D_2 & D_1 \end{pmatrix} \rightarrow \text{Space} \downarrow \text{Subchannel.}$$

The above matrix indicates that the CR decisions will be transmitted from two subchannels simultaneously at each CR. As a result, a frequency diversity gain of two can be achieved over frequency-selective fading channels. Consequently, it can be concluded that by exploiting cooperative diversity among closely located CRs, we can reduce the probability of reporting errors, which will in turn enhance cooperative spectrum sensing performance. It should be emphasized, however, that the proposed technique may not be optimal, though it can significantly improve the performance of cooperative spectrum sensing.

B. Technique Exploiting Multiuser Diversity

Multiuser diversity is a form of selection diversity in which only the best out of all links is chosen based on the highest SNR value as the physical transmission link over which data transmission will occur. Considering that in CR networks the SNRs of the reporting channels are varied for different CRs due to their different distances to the common receiver and the independent fading channels, multiuser diversity can be exploited in cooperative spectrum sensing [67]. Fig. 9 shows a CR network with a two-layer hierarchy in implementing the multiuser diversity technique. In the first layer, all CRs are configured into few clusters according to some distributed clustering method. Then, a cluster head is chosen in each cluster according to the highest SNR of the reporting channels. Once every CR in the same cluster completes the local spectrum sensing, the sensing results will be reported to the cluster head, which will then make a preliminary cooperative decision according to an OR logic rule. In the second layer, only the cluster heads are required to report to the common receiver with their preliminary cooperative decisions; based on these decisions, the common receiver will make a final decision according to an OR logic rule. The advantages of this two-level decision hierarchy are twofold [67]. First, only the user with the highest SNR is chosen as the cluster head in charge of reporting the decisions to the common receiver. By doing so, it produces a selection diversity gain to combat the fading channels. Secondly, the total amount of sensing bits reported to the

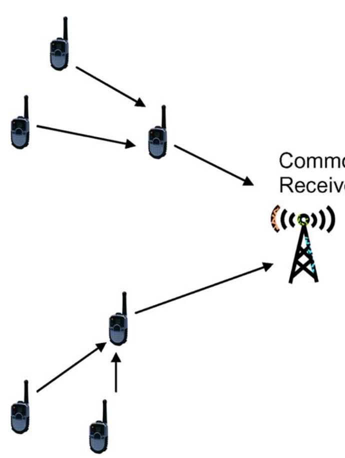

Fig. 9. ***Multiuser diversity technique for cooperative spectrum sensing. Cognitive radios are separated into a few clusters, and only the cluster head (with the highest SNR) participates in the reporting process.***

common receiver can be greatly reduced since most of the work load has been shared by the cluster heads, thereby facilitating a low-bandwidth control channel.

C. Censoring-Before-Cooperation (Whom to Cooperate With)

For a CR network with a large number of CRs, the total number of sensing bits transmitted to the common receiver tends to be very large. This will require a high demand in terms of control channel bandwidth and also result in a long sensing time. Note that since the local decision $D \in \{0,1\}$ is obtained by comparing the local observation with a predesigned threshold ζ, the observation values in the vicinity of the detection threshold are not reliable enough due to the noise disturbance. To exclude the ambiguous detection region around the threshold, a censored decision approach can be used in cooperative spectrum sensing [68]. By carefully setting the ambiguous detection region as the interval $[\zeta_1, \zeta_2]$, only the CRs having the observation values out of this region are required to report to the common receiver. It has been shown in [68] that by using the proposed censored decision approach, the average transmitted sensing bits will be greatly reduced without much affecting the sensing performance. This is because unreliable decisions are censored and excluded from the final decision.

VI. COOPERATIVE SPECTRUM SHARING

CR has the ability to dynamically adapt to the local spectrum environment. Due to the dispersed geographic locations of the secondary devices in a CR network, each CR may experience diverse spectrum conditions such as the activities of different PUs. In Fig. 10, such a CR network with various scenarios is depicted. As we can see, CR 1 is within the transmission range of PU 1 (i.e., the cognitive radio can sense the signal transmitted from the PU 1), while CR 2 is located in the transmission range of PU 2. Since the two PUs may operate independently over a wide-band spectrum, it is most likely that some portions of the spectrum may not be utilized by the primary systems over some time. As such, CRs 1 and 2 can detect various spectrum holes of PUs 1 and 2, respectively. For instance, in a given period, the available frequency bands for CR 1 are f_1 and f_2, while for CR 2 they are f_2 and f_3. Note that the number of available channels and channel identities vary from one CR to another within the network. This in turn results in a wealth of spectrum opportunities that the CR network can dynamically exploit to support continuous transmission, regardless of whether one of the PUs reuses some of the channels or not. In order to realize this seamless transmission within the CR network and take full advantage of the spectrum opportunity, we will next introduce a new concept of a cognitive relay network. A cognitive STF coding technique will then be proposed to exploit the maximum spectrum opportunities within the cognitive relay network.

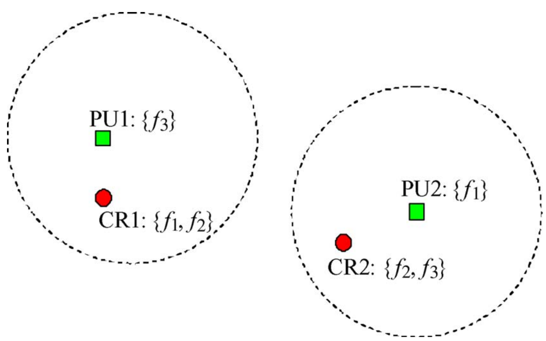

Fig. 10. *Example of cognitive wireless network. CR 1 is within transmission range of PU 1 and CR 2 is in the range of PU 2. The two PUs are in operation independently.*

A. Cognitive Relay Network

We consider a cognitive wireless relay network consisting of a source node that intends to communicate with a destination node aided by a total number of K relay nodes. The relay nodes are CRs and dispersed over a large geographic area. In the proximity of the CR network, several PUs are assumed to be operating over a wide-band spectrum. We assume that each cognitive relay node is within the transmission range of one PU node. It is also assumed that more than one CR node can share the radio spectrum within one PU operating range when the PU is inactive. Furthermore, we shall assume that each PU operates in a wide-band channel consisting of a number of nonoverlapping frequency bands $f_1, f_2, \ldots, f_N$, where N denotes the total number of frequency bands in the bandwidth of PUs. We suppose that when one PU is in operation, it may occupy the whole or part of the wide-band, i.e., all or some of the frequency bands. This is the case for the current OFDMA-based communication infrastructure where some of the OFDM subcarriers are allocated to different users.

Each cognitive relay first gets the spectrum map of its local channel environment by spectrum sensing. Let $\mathbf{b}_i = (b_{i,1}, b_{i,2}, \cdots b_{i,N})$ denote the spectrum indicator of the ith cognitive relay. The entries $b_{i,n}$, $n = 1, 2, \ldots, N$, denote the availability for the frequency bands $f_1, f_2, \ldots, f_N$, respectively. $b_{i,n} \in \{0,1\}$, where 1 indicates that frequency band f_n is available for cognitive relay i and 0 indicates that band f_n is utilized by the PU and that cognitive relay i is not allowed to access this frequency band. Clearly, the spectrum environment of the whole cognitive relay network can be characterized by the following matrix:

$$\mathbf{B} = \begin{pmatrix} b_{1,1} & b_{1,2} & \cdots & b_{1,N} \\ b_{2,1} & b_{2,2} & \cdots & b_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ b_{K,1} & b_{K,2} & \cdots & b_{K,N} \end{pmatrix}$$
$$\downarrow \text{relay(space)} \rightarrow \text{band(frequency)}. \quad (17)$$

The matrix $\mathbf{B}$ is a binary matrix in which each entry is either zero or one. The total number of ones in $\mathbf{B}$ indicates the amount of "spectrum opportunities" and represents a degree of freedom in the cognitive relay network. This can also represent the diversity gain due to space and frequency. Compared to the conventional relay network, such as the OFDM-based relay network where every relay has the same number of available frequency bands, the number of available bands varies from one relay to another in cognitive relay networks. In other words, the matrix $\mathbf{B}$ is a binary matrix for a cognitive relay network but an all-ones matrix for conventional relay networks.

One of the benefits of the cognitive relay network is that seamless transmission can be realized. Without cognitive relay, the source node (cognitive user) will send data to the destination node directly when the source–destination channel is not utilized by the PUs. If the PU returns over to the channel, the source should stop its transmission immediately so as not to cause interference to the primary system. Aided by a large number of cognitive relays, the transmission in the cognitive relay network does not necessarily stop even when some PUs are operating again. This is because there is always at least one available band in the cognitive relays that can be utilized as a relay channel to continue data transmission. If we define $q_{i,n}$ as the "access opportunity" (i.e., the probability of channel availability for a cognitive user) of band n in cognitive node i, then the access opportunity of the whole cognitive relay network is

$$Q = 1 - \prod_{i=1}^{K}\prod_{n=1}^{N}(1 - q_{i,n}).$$

The above result is based on the assumption that the access opportunity of each channel is independent of others. If we further assume that the access opportunity is equal to q for every channel of all the relay nodes, then we can obtain

$$Q = 1 - (1 - q)^{NK}.$$

It is evident that Q is almost equal to one when N or K is large. Thus, the network access opportunity is greatly improved by utilizing a large number of cognitive relays while supporting seamless data transmission.

In [69], a similar cognitive wireless relay network was investigated where the source node communicates with the destination node via intermediate nodes operating in orthogonal frequency bands. The spectrum map of the cognitive relay network in [69] can be denoted by a diagonal matrix $\mathbf{B}$ in (17) with binary diagonal entries $b_{i,i} \in \{0, 1\}$. Moreover, only one CR within the transmission range of a PU is chosen as a potential relay node in [69]. In contrast, here we allow every CR to be chosen as a potential relay no matter which PU range it is located in. Furthermore, we assume that every available band is utilized as a relay channel without the constraint of orthogonality. By doing so, we can achieve the maximum spectrum opportunity of the cognitive relay network. In the following, we propose a simple cooperative transmission scheme to achieve the full benefit of the spectrum opportunity.

The cognitive relay network operation can be described in two phases. In the first phase, the source node broadcasts the data information to all intermediate nodes. In the second phase, depending on whether the AF or DF cooperative protocol is used, the received message will be relayed to the destination node via activated intermediate nodes (i.e., cognitive relay). For the AF protocol, the received signal at each cognitive relay is first amplified in power and then retransmitted through all available frequency bands simultaneously. If there are no available channels for one intermediate node, the node will not be chosen as a cognitive relay and will remain silent in the second phase. For the DF protocol, an intermediate node is activated as a cognitive relay only if it can both decode the message from the source and acquire the available channel(s) from its local spectrum environment. The cognitive relays in both protocols will collaborate in order to relay the message in an orthogonal fashion. This can be done, for instance, by taking turns to transmit, i.e., only one cognitive relay is allowed to communicate to the destination in one time slot of the second phase.

Now let $Z_{i,n}$ denote the received signal at the destination on band n. It is then given by

$$Z_{i,n} = h_{R_{i,n},D}\tilde{Y}_{i,n} + N_{i,n}, \quad \forall i, n \in \{i, n | b_{i,n} = 1\}$$

where $h_{R_{i,n},D}$ is the nth channel between cognitive relay i and the destination, $\tilde{Y}_{i,n}$ is the transmit signal from the relay i on the nth channel, and $N_{i,n}$ denotes the complex Gaussian noise with zero mean and variance N_0. For the DF protocol, the signal $\tilde{Y}_{i,n}$ is just the source message. Assuming perfect channel knowledge at the destination, then all the received copies of the message are combined according to $\sum_{\forall i,n\in\{i,n|b_{i,n}=1\}} h^*_{R_{i,n},D} Z_{i,n}$. The postprocessing SNR ϱ is then given by

$$\varrho = \sum_{\forall i,n\in\{i,n|b_{i,n}=1\}} \left|h_{R_{i,n},D}\right|^2 \rho$$

where $\rho = E_s/N_0$. Obviously, the maximum spectrum opportunities are exploited and a full diversity gain is achieved, but at the cost of a very low symbol rate. Assuming that there are M out of K intermediate cognitive nodes selected as cognitive relays, then the symbol rate of the above transmission scheme is $1/M{+}1$. This is because the source message is relayed to the destination via one cognitive relay in one time slot.

B. Cognitive Space–Time–Frequency Coding

In order to fully exploit the spectrum opportunities in cognitive relay networks while supporting high-rate cooperative transmission, we shall propose a cognitive STF coding technique.

In the first phase of cooperative transmission, the source will broadcast to all intermediate nodes a block of N_s information symbols in N_s symbol periods. In the second phase, the cognitive relay will decode the received signal and then reencode the message according to a given coding structure. Afterwards, the coded signal will be forwarded to the destination. Note that all cognitive relays should transmit signals over all available channels simultaneously. Then, the received signal block at the destination on the nth band is given by

$$\mathbf{Z}_n = \sum_{i=1}^{K} b_{i,n}\left(\mathbf{c}_{i,n} h_{R_{i,n},D} + \mathbf{N}_{i,n}\right) \tag{18}$$

where $\mathbf{c}_{i,n}$ is the coded signal block sent from band n of cognitive relay i and $\mathbf{N}_{i,n}$ is the noise vector with zero-mean complex Gaussian random variable entries. We rewrite (18) into the following expression:

$$\mathbf{Z}_n = \mathbf{C}_n \mathbf{H}_n + \mathbf{N}_n \tag{19}$$

where

$$\mathbf{C}_n = [b_{1,n}\mathbf{c}_{1,n} \quad b_{2,n}\mathbf{c}_{2,n} \quad \cdots \quad b_{K,n}\mathbf{c}_{K,n}] \tag{20}$$

and

$$\mathbf{H}_n = \left[h_{R_{1,n},D} \quad h_{R_{2,n},D} \quad \cdots \quad h_{R_{K,n},D}\right]^T.$$

By combining the received signals over all channels, we get

$$\mathbf{Z} = \mathbf{CH} + \mathbf{N}$$

where $\mathbf{Z} = [\mathbf{Z}_1^T\ \mathbf{Z}_2^T\ \cdots\ \mathbf{Z}_N^T]^T$, $\mathbf{H} = [\mathbf{H}_1^T\ \mathbf{H}_2^T\ \cdots\ \mathbf{H}_N^T]^T$, $\mathbf{N} = [\mathbf{N}_1^T\ \mathbf{N}_2^T\ \cdots\ \mathbf{N}_N^T]^T$ and $\mathbf{C} = \mathrm{diag}(\mathbf{C}_1\ \mathbf{C}_2\ \cdots\ \mathbf{C}_N)$. Because $\mathbf{C}$ comprises the coded symbols across the space (relay), time, and frequency (bands), we shall refer to it as a *cognitive STF code*. In contrast to the existing STF code, the cognitive STF code has a flexible code structure, which is attributed to the dynamic spectrum environment across the cognitive relays.

From the diversity analysis in [70], it is known that the diversity gain depends on the minimum rank of the matrices $\mathbf{C} - \hat{\mathbf{C}}$ for any pair of distinct codewords $\mathbf{C}$ and $\hat{\mathbf{C}}$. It is evident that $\mathrm{rank}(\mathbf{C}) = \sum_{n=1}^{N} \mathbf{C}_n$ because $\mathbf{C}$ is a block diagonal matrix. Then, a full diversity code should be able to maximize the minimum rank of all matrices $\mathbf{C}_n - \hat{\mathbf{C}}_n$, $n = 1, 2, \ldots, N$.

By considering the special structure of $\mathbf{C}_n$ in (20), we intend to design a code

$$\mathbf{D}_n = [\mathbf{c}_{1,n} \quad \mathbf{c}_{2,n} \quad \cdots \quad \mathbf{c}_{K,n}]. \tag{21}$$

This is because $\mathbf{D}_n$ is a special case of $\mathbf{C}_n$ when all $b_{i,n} = 1$, $i = 1, \ldots, K$. Thus, if $\mathbf{D}_n$ achieves full rank, then $\mathbf{C}_n$ must also have full rank.

Denote $\mathbf{D} = \mathrm{diag}(\mathbf{D}_1\ \mathbf{D}_2\ \cdots\ \mathbf{D}_N)$; then the cognitive STF code design of $\mathbf{C}$ is equivalent to the design of the full-diversity STF code matrix $\mathbf{D}$. One simple design is as follows:

$$\mathbf{D} = \mathbf{I}_N \otimes \mathbf{A}_O \tag{22}$$

where $\mathbf{A}_O$ is the conventional orthogonal STBC matrix of size $L \times K$ with $\mathbf{A}_O^H \mathbf{A}_O = \mathbf{I}_K$. Clearly, the matrix $\mathbf{D}$ has full rank. As a result, $\mathbf{C}$ will also have full rank because $\mathbf{C}$ is actually a submatrix of $\mathbf{D}$ after deleting some columns.

The code design in (22) shows that each cognitive relay just picks up a unique column of the orthogonal STBC matrix and then maps the column vector on other bands of the same cognitive relay. As such, the full spectrum opportunities can be exploited. Meanwhile, the rate of the cognitive STF coded relay network is $N_s/N_s + L$. This is because in the second phase of cooperative transmission, L symbol periods are occupied to convey the columns of the orthogonal STBC matrix from all cognitive relay nodes and bands to the destination. This is also true regardless of the number of cognitive relay nodes M. It is further noted that the rate of the orthogonal STBC $\mathbf{A}_O$ is $R_O = N_s/L$. Immediately, we get the rate of the cognitive STF code as

$$R_{\mathrm{CSTF}} = \frac{R_O}{R_O + 1}.$$

It can be seen that the cognitive STF code results in a significant increase in the data rate regardless of the number of cognitive relays.

VII. CONCLUSION

Cognitive radio is a novel technology that can potentially improve the utilization efficiency of the radio spectrum. Cooperative communications can play a key role in the development of CR networks. In this paper, we considered the application of such communications approach to cooperative spectrum sensing and cooperative spectrum sharing. The conventional spectrum sensing methods were first presented, and their advantages and disadvantages were discussed. Cooperative spectrum sensing was then considered and shown to be a powerful method for dealing with the hidden terminal problem. However, under realistic scenarios, where the reporting channels are subject to fading and/or shadowing, the performance of cooperative spectrum sensing can be severely limited. To address this and other cooperative spectrum sensing challenges, various potential solutions were presented. We have also shown that dynamic spectrum can be fully utilized through a number of cognitive relay nodes. The so-called cognitive wireless relay network can support seamless data service for cognitive users while causing zero interference to primary systems. ■

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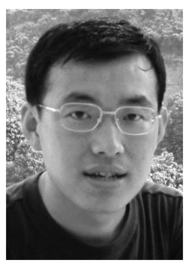

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