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Cooperative Spectrum Sensing and Spectrum Sharing in Cognitive Radio: A Review

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Abstract — **Cognitive radio is a transforming and revolutionary technology that represents a paradigm shift in the design of wireless systems, as it allows agile and efficient utilization of the radio spectrum by offering the ability of radio sensing, self-adaptation, and dynamic spectrum sharing. In this paper the use of cooperative spectrum sensing in cognitive radio systems to enhance the reliability of detecting primary users is discussed and also cooperative communications for spectrum sharing in a cognitive wireless relay network is investigated. To exploit the maximum spectrum opportunity, a cognitive space-time-frequency coding technique is presented that can opportunistically adjust its coding structure by adapting itself to the dynamic spectrum environment.**

Keywords — **cognitive radio, cooperative communication, spectrum sensing, spectrum sharing, cognitive relay network, cognitive space-time-frequency coding.**

I. Introduction To Cognitive Radio and Cooperative communication

With the explosive growth of communication applications, the spectrum has become more congested. Even if the spectrum is allocated to particular users, this does not guarantee that it is being used most efficiently at all times. This is the reason for allowing unlicensed users to utilize licensed bands assuming that it would not cause any interference. Such a paradigm is called cognitive radio, which was originated by Mitola [1]. Cognitive radio arises to be a tempting solution to spectral crowding problem by introducing the opportunistic usage of frequency bands that are not heavily occupied by licensed users [2]. One of the important components of cognitive radio concept is its ability to measure, sense, learn, and be aware of the parameters related to the radio channel characteristics, availability of spectrum and power, user requirements and applications, and other operating restrictions [1]. In cognitive radio terminology, primary users (PUs) may be defined as the users who have higher priority on the usage of a particular part of the spectrum. On the other hand, secondary users, which have lower priority, exploit this spectrum so that they do not cause interference to primary users. Therefore secondary users need to have cognitive radio capabilities, such as sensing the spectrum reliably to check whether it is being used by primary users and to change radio parameters to exploit the unused part of the spectrum [3].

A CR description is found in Jondral’s paper [4], 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 [5]:

- 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).

Direct point-to-point or point-to-multipoint (e.g., cellular) topologies were used in traditional wireless networks. In comparison 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 information is sent out not only by the user but also by the collaborating users [6]. Cooperative communications and cooperative networking is a new communication paradigm that promises significant capacity and multiplexing gain increase in wireless networks. In order to combat the detrimental effects of severe fading it also realizes a new form of space diversity.

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

II. Cooperative Spectrum Sensing

A. General Concept

In Cognitive radio, Primary users are referred as the users who have higher priority or legacy rights on the usage of a part of the spectrum. Spectrum sensing is a key element in Cognitive radio 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 part of the spectrum is to detect the Primary users that are receiving data within the range of a CR. 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].

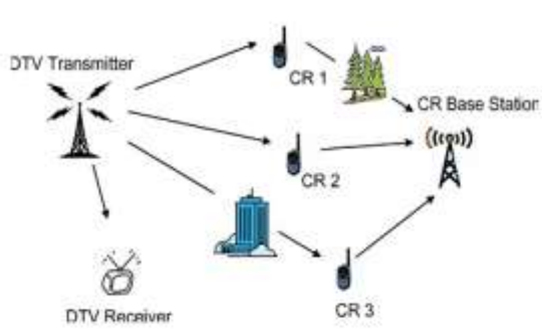

Fig. 1 Cooperative spectrum sensing in CR networks. CR1 is shadowed over the reporting channel and CR3 is shadowed over the sensing channel.

In general, cooperative spectrum sensing can be performed as described below.

1) Every Cognitive radio performs its own local spectrum sensing measurements independently and then makes a binary decision on whether the PU is present or not.

2) All the CRs then forward their decisions to a common receiver.

3) The common receiver fuses all the CR decisions and makes a final decision to infer the absence or presence of the PU.

B. Performance Analysis

1) Local Spectrum Sensing: Spectrum sensing uses a binary hypothesis-testing problem

H0: Primary user is absent.

H1: Primary user is in operation.

The key metrics of the spectrum sensing are the probabilities of correct detection given by Prob {Decision=H1|H1} and Prob {Decision=H0|H0}, the false alarm probability given by Prob {Decision=H1|H0}, and the missed detection probability given by Prob {Decision=H0|H1}.

Also consider a CR network composed of K CRs (secondary users) and a common receiver, as shown in Fig. 2[8].

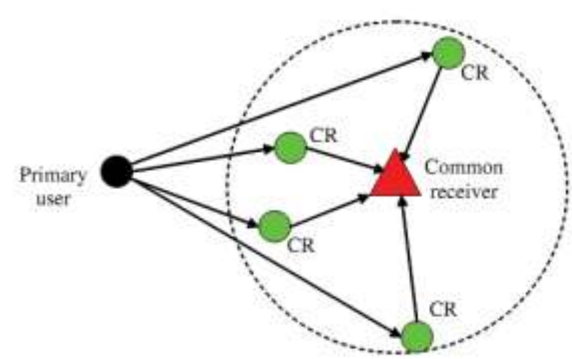

Fig. 2 Spectrum sensing structure in a cognitive radio network.

Common receiver manages the CR network and all the associated K CRs. Each CR performs local spectrum sensing independently. In order to see how the energy detector works, only consider the ith CR in the following. The local spectrum sensing problem is to decide between the following two hypotheses:

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

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. 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 [9], respectively

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

$$P_d^{(i)} = e^{\frac{-\zeta_i}{2}} \sum_{P=0}^{u-2} \frac{1}{P!}\left(\frac{\zeta_i}{2}\right)^P + \left(\frac{1+\gamma_i}{\gamma_i}\right)^{u-1}\left[e^{\frac{-\zeta_i}{2(1+\gamma_i)}} - e^{\frac{-\zeta_i}{2}} \sum_{P=0}^{u-2} \frac{1}{P!}\left(\frac{\zeta_i \gamma_i}{2(1+\gamma_i)}\right)^P\right] \quad (3)$$

$$P_m^{(i)} = 1 - P_d^{(i)} \quad (4)$$

where γ_i denotes the average SNR at the ith CR, ζ_i is the threshold, $\Gamma(a,x)$ is the incomplete gamma function given by

$$\Gamma(a, x) = \int_x^{\infty} t^{a-1} e^{-t} dt \quad (5)$$

and $\Gamma(a)$ is a gamma function.

In Fig. 3[9], the complementary receiver operating characteristic (ROC) curves (probability of missed detection versus probability of false alarm) of the energy detection in one CR are plotted for a variety of SNR values according to (2) and (4).

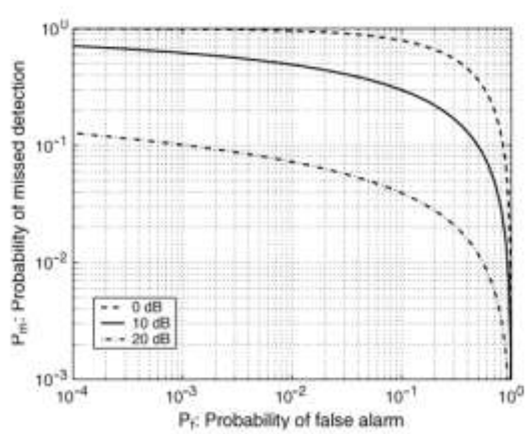

Fig. 3 Spectrum sensing performance over Rayleigh fading channels with SNR 0, 10, 20 dB for one cognitive radio.

2) Cooperative Spectrum Sensing Based on Decision Fusion: In cooperative spectrum sensing, all CRs identify the availability of the licensed spectrum independently. Each CR makes a binary decision based on its local observation and then forwards one bit of the decision to the common receiver. Let D_i belongs to {0, 1} denote the local spectrum sensing result of the ith CR. Specifically, {0} 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:

$$Z = \sum_{i=1}^{K} D_i \begin{cases} \geq n, & H_1 \\ < n, & H_0 \end{cases} \quad (6)$$

where H_1 and H_0 denote the inferences drawn by the common receiver that the PU signal is transmitted or not transmitted, respectively. Fig. 4[10] 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.

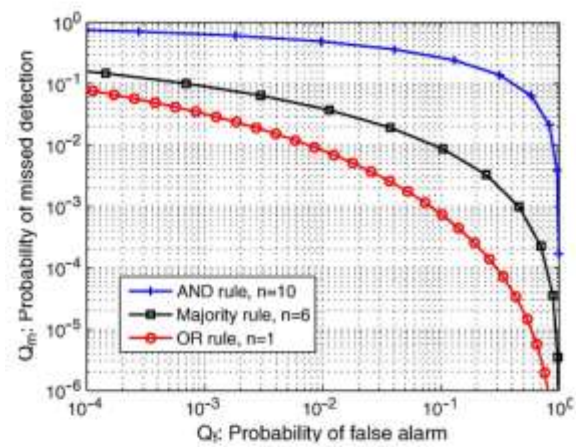

Fig. 4 Cooperative spectrum sensing performance with various fusion rules (n =1, 6, 10) over Rayleigh fading channels with SNR =10 dB for ten secondary users (CRs).

III. Cooperative Spectrum Sharing

Cognitive radio 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. 5[10], such a CR network with various scenarios is depicted. It can be seen that CR1 is within the transmission range of PU1 (i.e., the cognitive radio can sense the signal transmitted from the PU1), while CR2 is located in the transmission range of PU2.

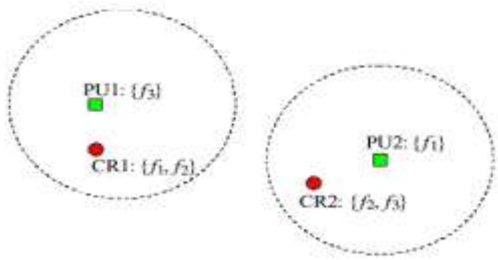

Fig. 5 Example of cognitive wireless network. CR1 is within transmission range o f PU 1 and CR2 is in the range of PU 2. The two PUs are in operation independently.

Since both the 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, at a point of time, the available frequency bands for CR1 are f1 and f2, while for CR2 they are f2 and f3, and 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.

A. *Cognitive Relay Network*

A cognitive wireless relay network consisting of a source node is considered that communicates with the 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 Primary users are assumed to be operating over a wide-band spectrum. Each cognitive relay node is within the transmission range of one PU node, and more than one CR node can share the radio spectrum within one PU operating range when the PU is inactive. Also each PU operates in a wide-band channel consisting of a number of non overlapping frequency bands $f_1,f_2,.\ ,\ f_N$, where N denotes the total number of frequency bands in the bandwidth of PUs. 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.

The current OFDMA-based communication infrastructure has such a case where some of the OFDM sub carriers are allocated to different users. Each cognitive relay first gets the spectrum map of its local channel environment by spectrum sensing. Let $b_i=(b_{i,1},b_{i,2}\ldots b_{i,N})$ denote the spectrum indicator of the ith cognitive relay. The entries $b_{i,n}$, n =1,2, ... N , denote the availability for the frequency bands f1,f2,... fN , respectively, where $b_{i,n}$ belongs to{0,1}, where 1 indicates that frequency band fn is available for cognitive relay i and 0 indicates that band fn 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:

$$\mathbf{B} = \begin{pmatrix} b_{1,1} & b_{1,2} & \cdots & b_{1,N} \\ b_{2,1} & b_{2,2} & \cdots & b_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ b_{K,1} & b_{K,2} & \cdots & b_{K,N} \end{pmatrix}$$

$$\downarrow \text{relay(space)} \rightarrow \text{band(frequency)}.$$

The matrix B is a binary matrix in which each entry is either zero or one. Total number of ones in B indicates the amount of B "spectrum opportunities" and represents a degree of freedom in the cognitive relay network. 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. The transmission in the cognitive relay network does not necessarily stop even when some Primary users 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.

Two phases of the cognitive relay network operation can be described. In the first phase, the source node broadcasts the 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.

B. Cognitive space-time-frequency coding

In order to fully exploit the spectrum opportunities in cognitive relay networks while supporting high-rate cooperative transmission, proposed here a cognitive STF (state time frequency) coding technique.

In the first phase of cooperative transmission, the source will broadcast to all intermediate nodes, a block of N_s in formation symbols in N_s symbol periods. In the second phase, the cognitive relay will decode the received signal and then re encode 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

$$Z_n = \sum_{i=1}^{K} b_{i,n}\left(c_{i,n} h_{R_{i,n},D} + N_{i,n}\right) \qquad (7)$$

where $c_{i,n}$ is the coded signal block sent from band n of cognitive relay i and $N_{i,n}$ is the noise vector with zero-mean complex Gaussian random variable entries. We rewrite into the following expression:

$$Z_n = C_n H_n + N_n \qquad (8).$$

By using proper code design it can be shown 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 A_0 is $R_0=N_s/L$. Immediately, getting the rate of the cognitive STF code as

$$R_{CSTF} = \frac{R_0}{R_0 + 1} \qquad (9).$$

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.

IV. CONCLUSIONS

Spectrum is a very valuable resource in wireless communication systems. Cognitive radio, which is one of the efforts in utilization of the available spectrum more efficiently through opportunistic spectrum usage, has become an exciting and promising concept. Cooperative communications can play a key role in the development of CR networks. In this paper, Cooperative spectrum sensing method was 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. It is also shown in the paper that dynamic spectrum can be fully utilized through a number of cognitive relay nodes. Cognitive wireless relay network can support data services while causing zero interference to primary systems.

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