Cooperative Communications for Cognitive Radio Networks†

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***Abstract*— Cognitive Radio is observed as a novel approach, which could cope with the spectral limitations. This approach is designed to detect whether a particular segment of the radio spectrum is currently in use and to jump into the temporarily-unused spectrum rapidly without interfering with the transmissions of other users. However, there are some challenges such as the protection of the licensed users from the opportunistic usage of the unlicensed radios. In this paper, we discuss the techniques used to deal with the issues related to spectrum sensing and interference avoidance for cognitive radio systems. An extensive analysis on cooperative communications in both centralized and decentralized networks is discussed. We also propose new methodologies to protect the operation of incumbent, licensed radio services. Our analysis suggest that collaboration may improve the usage and the spectrum sharing while causing no interference to the primary system.**

I. Introduction

The explosive growth in wireless services over the past several years illustrates the huge and growing demand of the business community, consumers and the government for spectrum-based communications. With the growth of communication applications, the spectrum becomes more congested. Even though the Federal Communications Commission (FCC) has expanded some unlicensed spectral bands, the present system assigns different frequency bands to different users or service providers and licenses are required to operate within those bands. Thus, even if spectrum may be allocated to specific users, this does not necessarily ensure it is being used most efficiently at all times. It turns out that most of the radio frequency spectrum may be inefficiently utilized. This was the reason for allowing non-legitimate users to utilize licensed bands assuming that it would not cause any interference. Such a paradigm is called cognitive radio. The concept of the cognitive radio was originated by Mitola [1], and is the 'next step up' for software defined radios that are emerging today. By detecting particular spectrum holes and jumping into them rapidly, the cognitive radio can improve the spectrum utilization significantly. To guarantee a high spectrum efficiency while avoiding the interference to the licensed users, the cognitive radio should be able to adapt spectrum conditions flexibly.

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Hence, some important abilities should be provided by the cognitive radio which include spectrum sensing, dynamic frequency selection and transmit power control [2]. To make the cognitive radio systems practical, several cognitive networks must be able to coexist. However, the coexistence of multiple cognitive users generates interference to each others, leading to the hidden terminal problem. This problem occurs usually when the cognitive radio is shadowed, in severe fading or with high path loss while a primary user is in vicinity. In order to deal with the hidden problem in cognitive networks, cognitive users can cooperate to sense the spectrum as well as share the spectrum without causing harmful interference to the primary user.

Cooperative communication has been known recently as a way to overcome the limitation of wireless systems. In some recent works, the cognitive radios are allowed to cooperate for sensing the spectrum, so that the hidden terminal issues are addressed [3].

In this paper, we study the spectrum sharing methods where multiple systems coexist and interfere with each other. The paper is devoted to the discussion about cooperative users in cognitive radio systems. We will discuss cooperation in centralized networks and decentralized networks separately. The centralized network is a network whose size is fixed by the coverage area of the access point or base station. The decentralized network has a size that can be scaled up more flexibly by allowing intermediate nodes in the transmission path as a relay. Also, the de-centralized manner of cognitive radio broadens the scope of its applications. Cooperative decentralized systems are usually modeled as cooperative ad-hoc networks [4]. With cooperation, systems can support more users because of the improved spectrum-management strategy. An extensive analysis on cooperation in both networks is discussed in this paper. We also propose new cooperative schemes to deal with the coexistence issue of the cognitive network while limiting the interference to the incumbent user.

The rest of the paper is organized as follows. In section II, the cooperation is analyzed in decentralized networks. In Section III, cooperation will be analyzed, for both sensing and interference mitigation, in centralized networks. A collaboration between power control and spectrum sensing is described in Section IV. In Section V, a scheduling scheme for multiple input/multiple output (MIMO) broadcast cognitive channels is

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treated. Finally, conclusions are drawn in Section VI.

II. Cooperation in decentralized cognitive Networks

In [5], a game theoretic framework to analyze the behavior of cognitive radios for distributed adaptive channel allocation was described. The authors considered the assumption that radios can measure the local interference temperature on different frequencies and can adjust it by optimizing the information transmission rate. Targeting at a bit error rate (BER) or an equivalent signal-to-interference ratio (SIR) requirement, the channel allocation problem is modeled to a potential game which converges to a deterministic Nash equilibrium channel allocation point. A No-regret learning implementation is proposed with cooperation on the potential game. Performance is similar but with a higher variability across users. Cooperation based spectrum sharing etiquette improves the overall network performance at the expense of an increased overhead required for information exchange. With the game theory framework, the problem is described by a normal form game Γ where it takes three parameters, (1) players: set of cognitive radio users K, (2) strategies: choice of transmitting channel associated with user k, $\{S_k\}_{k\in K}$ and (3) preferences: quality of the channels which is determined by the cognitive radios by measurements on different radio frequencies, $\{U_k\}_{k\in K}$. Since the performance of the adaptation algorithm significantly depends on the choice of the utility function, it is carefully chosen such that the problem is modeled as an exact potential game and converge to a Nash equilibrium when the best response adaptive strategy is adapted. A distributed scheduler is proposed. At the beginning of each time slot, each user flips a coin with probability p_a of success. If successful, the user make a new decision based on the current values for the utility functions on each channel. Otherwise, the user takes no new action.

As game theory has been commonly applied to decentralized cognitive radio networks and game theory can not provide any conclusion if one of its requirement is not hold. Research effort has been put to find the existence of solution. In [6], three fundamental assumptions are ruled out to be the sufficient conditions for the existence of cooperative solutions to a class of N-Person Games. The assumptions are as follows.

A) Each strategy set is assumed to be a close bounded convex set in a finite-dimensional Euclidean space.
B) The utility function is continuous.
C) The utility functions are quasi-concave.

It has been shown that in N-Person game, satisfying A), B) and C), there will be at least one joint strategy choice $s_1,\ s_2,\dots,\ s_K$, which is in equilibrium in the sense that no coalition has an alternative strategy which guarantees higher utility levels for all of its members, independently of the strategies of the complementary coalition.

In [7], game theory is proposed to solve the fairness issue in cognitive radio, not only taking care of the interference avoidance problem in decentralized network. There are N transmit and receive pairs in the network whereas each transmitting nodes is allowed to have different transmit power constraint. The interference cause is influenced by the power constraints and associated channel characteristics of the user nodes. Modeling the problem into a potential game, each user picks their own strategy following the best response dynamics at each stage. Utilization functions are chosen in a way that the global utility can be maximized by only trying to maximize their own utilities. Finally, following the best response dynamics, the system converge to equilibrium which is predicted by maximizing the utilization functions. However, the implementation of this algorithm requires feedback from the receive nodes. More efficient feedback mechanism need to be investigated.

Although a lot of people considered the problem using game theory, the authors in [8] introduced a development to an ad-hoc cognitive radio that can realize a frequency sharing system under existing communication systems using a multi-hop small power communication. An ad-hoc cognitive radio concept was proposed, in which the transceiver with small power transmission and the multi-hop communication are used for expanding that service area by using software defined radio (SDR) terminal. Each node reconfigures the surrounding radio environment by itself so that interference area can be avoided by controlling the relay operation in each node. Each terminal is in active awareness that each of them recognizes the surrounding frequency status by itself and decides whether the frequency band can be used for cognitive radio or not. However, active receiver cannot be recognized because the receiver does not transmit the signals during the communication. In order to deal with interference avoidance, multi-hop communication with small power transmission of each node is applied using MAC protocol (carrier sensing on all frequency bands). To reduce interference, multi-hop communication can not be equipped with routing. The interference area can be bypassed by recognizing the surrounding radio environment using carrier sense in each node. Cooperative diversity method is applied by regarding one antenna of each node as one of the diversity branches.

III. Cooperation in Centralized cognitive networks

In this section, we discuss how cooperation could cope with the current dilemmas in spectrum sensing and interference mitigation in cognitive radio networks. The network studied here is infrastructure based where there has to be a base station or access point providing connection to a backbone connection, as typically found in Internet access networks. For this type of networks, the central station of the existing communication system broadcasts the frequency resource information for the secondary users, which are responsible for sensing spectrum utilization information in their neighborhood and feedback the utilization information to the base system through the uplink transmission. In downlink transmission, the base station, using the spectrum feedback side-information, decides which user accesses to the channel.

A. Spectrum sensing

In this section, we will give a survey on cooperative spectrum sensing for cognitive radio networks. A review of some well-know spectrum sensing techniques are presented and the principle of cooperative spectrum sensing is introduced. In order to avoid the harmful interference to the primary system, the cognitive radio needs to sense the availability of the spectrum. The goal of spectrum sensing is to decide between the following two hypotheses:

$$\begin{aligned} H_0 &: \text{Primary user is absent;} \\ H_1 &: \text{Primary user is present.} \end{aligned} \tag{1}$$

1) Energy detection: In the absence of much knowledge concerning the signal, it has been proved to be appropriate to use an energy detector to determine the presence of a signal. The energy detector measures the energy in the input wave over a specific time interval. In particular, in order to avoid the harmful interference to primaries, the wireless device measures radio frequency energy in the channel or the received signal strength indicator (RSSI) to determine whether the channel is idle or not. However, this technique has a problem that wireless devices can only sense the presence of a primary if and only if the energy detected is above a certain threshold. One can not arbitrarily lower the threshold as this would result in non-detection because of the presence of noise. In addition, using the energy approach the spectrum agile radio device will not be able to distinguish between other secondary users with whom it can share the medium, and primary users that require vacation of the channel.

2) Feature detection: In the feature detection approach, which has been used in the military to detect the presence of weak signals, the wireless device uses cyclostationary signal processing to detect the presence of primaries. The spectral analysis of stationary random signals has been widely studied. Many random signals encountered in the field of wireless communications are more appropriately modeled as cyclostationary because of underlying periodicities due to various operations such as sampling, scanning and modulation. However, detection is compromised when a user experiences shadowing or fading effects. In such cases, user can not distinguish between an unused band and a deep fade.

3) Collaborative spectrum sensing: Collaborative spectrum sensing has been proposed and has proved that cooperation between the users affected by such effects improved sensing performance significantly. When the cognitive radio is suffering from shadowing by a high building over the sensing channel, it definitely can not sense the presence of the primary user appropriately due to the low received SNR. Therefore, the cognitive radio access the channel in the presence of the primary user. To address this issue, multiple cognitive radios 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 [9]. Cooperative spectrum sensing is performed as the following. Firstly, every cognitive radio performs local spectrum measurements independently and then makes a binary decision. Then, all the cognitive users forward their binary decisions to a common receiver. Later on, the common receiver combines those binary decisions and makes a final decision to infer the absence or presence of the primary user in the observed frequency band. At the common receiver, all 1-bit decisions are fused together according to an "OR" logic. This cooperative sensing algorithm is referred to as decision fusion.

Another option to address the shadowing problem during the sensing phase is to exploit the relay diversity [10]. The base station sense the SNR of the received signal to check whether this cognitive radio is reliable enough before counting it into the cooperative decision. If the SNR of the received signal from the kth cognitive radio is lower than a predesigned threshold, then it will be labeled as an unreliable one. Under the supervision of the base station, the unreliable cognitive radio can relay its local spectrum sensing result to other cognitive radios which have good channel conditions. With the relay technique, cooperative spectrum sensing achieves the full cooperation among cognitive radios by avoiding transmission of local sensing results over bad reporting channels.

In order to reduce the reporting error probability, we may also take advantage of multiuser diversity in cooperative spectrum sensing. By taking advantage of the independent fading channels, multiuser diversity can be exploited in cooperative spectrum sensing in [10]. First, all cognitive radios are clustered into a few groups. Then, a cluster head is chosen in each cluster according to the highest SNR of the reporting channels. Once every cognitive radio in the same cluster finishes the local spectrum sensing, the sensing results will be reported to the cluster head which will make a preliminary cooperative decision according to an "OR" logic rule. Second, only cluster heads are required to report to the common receiver with their preliminary cooperative decisions and based on these decisions, the common receiver will make a final decision.

B. Interference avoidance

In cognitive systems, the cognitive users have to be designed to efficiently use and share the spectrum and at the same time without causing harmful interference to the licensed users. In fact, one of the most challenging problems of cognitive radio is the interference. It results when a cognitive radio accesses to some licensed bands on the spectrum and fails to notice the presence of licensed user. To address this problem, the cognitive radio should be able to coexist with the primary user without creating harmful interference. We discuss here several techniques have been used in the literature to solve this problem. Specifically, we study a spectrum sharing problem where multiple cognitive radios coexist and interfere with each other; this problem is analyzed in a cooperative setting where collaboration is needed to achieve a common goal. The scenario of a coexistence between a primary network and a secondary network is illustrated in Fig. 1. In the literature, orthogonal frequency division multiplexing (OFDM) modulation has been considered [11] as a candidate for cognitive radio to

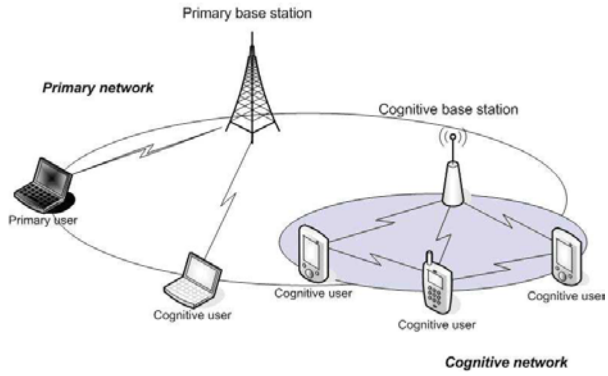

Fig. 1. Spectrum sharing: primary and cognitive networks.

avoid interference by nulling a certain set of subcarriers where the second users are working in the spectrum.

In [12] exploits the fact that cognitive radios is able to listen to the surrounding wireless channel, makes decisions and encodes using a variety of schemes. In a fraction of the transmission time, the cognitive radio listens to, and obtains the message transmitted by the other sender. It could then use this message knowledge of the interference it will counter, to intelligently mitigate the interference. The use of collaboration between the users to get information between each others is made in a theoretic angle.

Attractive techniques for power control rule have been used to allow cognitive radio to not interfere to the licensed users. [13] studied a spectrum sharing problem in an unlicensed band where multiple systems coexist and interfere with each other. An analysis for a cooperative setting where all the systems collaborate to achieve a common goal is considered and then a non cooperative situation, where the systems act in a selfish and rational way is analyzed. In the cooperative situation, the authors model the situation in which M systems, each formed by a single transmitter-receiver, coexist in the same area. [14] explores the idea of using cognitive radio to reuse locally unused spectrum for their own transmissions. Using received SNR as a proxy for distance, it has been shown that a cognitive radio can vary its transmit power while maintaining a guarantee of service to primary users. A power control rule which allows secondary users to aggressively increase their transmit powers while still guaranteeing an acceptable level of aggregate interference at the primary receivers.

IV. Power allocation and spectrum sensing

In this section, a framework on power allocation based on spectrum sensing side information is presented. A power control approach in cognitive radio systems based on spectrum sensing side information is implemented to utilize the spectrum efficiently by allowing the cognitive radio to co-exist with the primary system. The distance between the primary transmitter and the cognitive radio is determined based on spectrum sensing side information. Then, the transmit power of the cognitive radio is controlled based on the distance in order to guarantee a quality of service (QoS) requirement of the primary receiver [15]. In order to avoid the harmful interference to the primary system, a cognitive radio senses the availability of the spectrum sensing, based on the conditions in (1). The average probability of false alarm, detection and missing of energy detection over Rayleigh fading channels can be given by, respectively,

$$P_f = \mathbf{E}\left[\mathrm{Prob}\{H_1|H_0\}\right], \tag{2}$$

$$P_d = \mathbf{E}\left[\mathrm{Prob}\{H_1|H_1\}\right] \tag{3}$$

and

$$P_m = \mathbf{E}\left[\mathrm{Prob}\{H_0|H_1\}\right] = 1 - P_d, \tag{4}$$

The transmit power of the cognitive radio that guarantees a good QoS for the primary receiver is determined from the following steps for power control

Step 1: Calculate P_m based on the following estimation:

$$\hat{P}_m = 1 - \frac{1}{L}\sum_{i=1}^{L} I(Y_i), \tag{5}$$

where

$$I(Y_i) = \begin{cases} 1, & \text{if } Y_i > \lambda \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

for $i = 1, \cdots, L$. Y_i denotes the energy collected by the cognitive radio in time slot i and L is the total number of time slots.

Step 2: Derive the distance d from $P_m = f(d)$, which can be easily derived based on the SINR and the expression of P_m.

Step 3: Calculate $\max\{Q_c\}$, the maximum value of cognitive transmitted power, based on the condition of decodability SINR $\geq \gamma_d$, where γ_d is the threshold of decodability.

For further details about the above steps, one can refer to [15]. The relation between $\max\{Q_c\}$ and P_m based on the proposed scheme is illustrated in Fig. 2. By calculating P_m, the maximum transmit power $\max\{Q_c\}$ can be determined to guarantee the quality of service for the licensed user in the presence of cognitive radio.

V. Scheduling in MIMO broadcast cognitive channels

Scheduling schemes have been extensively studied in the framework of cellular networks. They are defined as algorithms for distributing resources in a wireless network that take advantage of certain requirement of the system. So, we can define the scheduling as a kind of cooperation of the base station that helps users to be selected for transmission or reception.

In this section, we consider the downlink of a single cognitive radio network, where the cognitive base station transmits signals to a large number of secondary users using an adaptive antennas; and a primary user receives its desired

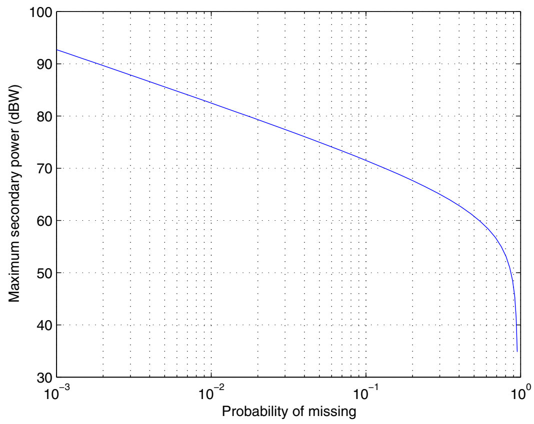

Fig. 2. $\max\{Q_c\}$ versus P_m.

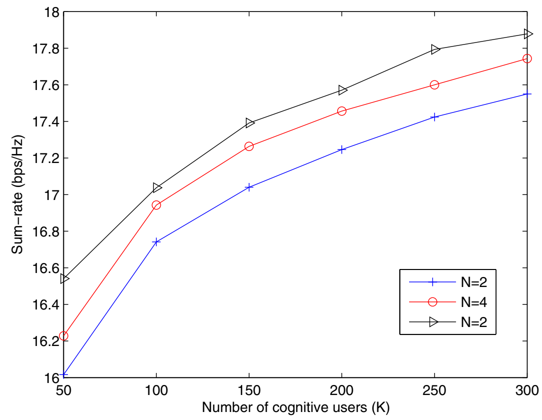

Fig. 3. Sum-rate versus Number of users with different number of antennas at the receiver.

signal from a primary transmitter and interference from the cognitive base station. In particular, we investigate the case of a large number of cognitive users, where user selection is needed. We propose a low-complexity algorithm, which we refer to as $\{\delta_p, \delta_c\}$-orthogonal user selection, for selecting a set of users to improve the system performance. The algorithm combined with zero-forcing beamforming is able to achieve high system throughput, significant interference limitation, as well as complexity reduction.

Let $\Delta(\mathbf{h}_i, \mathbf{h}_j) \triangleq \frac{|\mathbf{h}_i \mathbf{h}_j^{\mathcal{H}}|}{\|\mathbf{h}_i\|\|\mathbf{h}_j\|}$, then, user i and j are δ-orthogonal if and only if

$$\Delta(\mathbf{h}_i, \mathbf{h}_j) \leq \delta. \tag{7}$$

Firstly, a cognitive user k is selected when the δ_p-orthogonality condition is satisfied. Then, the selected users are sorted based on their channel magnitudes in order to guarantee that the scheduled users have relatively large channel gains. In the second step, if the number of users in the set S of the selected users satisfies $|S| < M$, where M is the number of antennas at the cognitive base station, the algorithm proceeds to the selection part. Otherwise, the algorithm is stopped. In second part, the users are selected if they satisfy the δ_c-orthogonality condition. Finally, the set of the selected cognitive users in S become δ_c-orthogonal to one another and δ_p-orthogonal to the primary user, with relatively large channel gains. δ_p and δ_c are thresholds set by the cognitive base station.

The proposed algorithm can be deployed to the MIMO broadcast channels where the users are deployed by N antennas. The algorithm is always able to achieve high system throughput. Fig. 3 shows the advantage of the proposed algorithm when we use multiple antennas at the cognitive users.

VI. Conclusion

In this paper, we have discussed the concept of cooperation in cognitive radio systems. To limit the interference to the primary user, we have discussed techniques to solve the problems related to sensing and interference mitigation to the primary systems. We analyzed the use of cooperation in both centralized and decentralized networks. We then proposed some schemes for protecting the incumbent users from the harmful interference by controlling the transmit power of the cognitive transmitter and dynamically allocating the cognitive users to the available channels using scheduling schemes.

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