Spectrum Sharing in Cognitive Radio Networks

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***Abstract*— The limited available spectrum and the inefficiency in the spectrum usage necessitate a new communication paradigm to exploit the existing wireless spectrum opportunistically. This new networking paradigm is referred to as cognitive radio(CR) networks. In CR networks, one of the main challenges in open spectrum usage is the spectrum sharing. In this paper, we delve into the specific challenges for spectrum sharing in CR networks, overview the existing solutions and discuss open research areas.**

I. INTRODUCTION

In CR networks, one of the main challenges in open spectrum usage is the spectrum sharing. Spectrum sharing can be regarded to be similar to generic medium access control (MAC) problems in existing systems. However, as we will investigate in this paper, substantially different challenges exist for spectrum sharing in CR networks. The coexistence with licensed users and the wide range of available spectrum are two of the main reasons for these unique challenges. In this paper, we delve into the specific challenges for spectrum sharing in CR networks, overview the existing solutions and discuss open research areas.

In order to provide a directory for different challenges during spectrum sharing, we first enumerate the steps in spectrum sharing in CR networks. The challenges and the solutions proposed for these steps will then be explained in detail. The spectrum sharing process consists of five major steps.

1. *Spectrum sensing*: An CR user can only allocate a portion of the spectrum if that portion is not used by an unlicensed user. Accordingly, when an CR node aims to transmit packets, it first needs to be aware of the spectrum usage around its vicinity.
2. *Spectrum allocation*: Based on the spectrum availability, the node can then allocate a channel. This allocation not only depends on spectrum availability, but it is also determined based on internal (and possibly external) policies. Hence, the design of a spectrum allocation policy to improve the performance of a node is an important research topic.
3. *Spectrum access*: In this step, another major problem of spectrum sharing comes into picture. Since there may be multiple CR nodes trying to access the spectrum, this access should also be coordinated in order to prevent multiple users colliding in overlapping portions of the spectrum.
4. *Transmitter-receiver handshake*: Once a portion of the spectrum is determined for communication. the receiver of this communication should also be indicated about the selected spectrum. Hence, a transmitter-receiver handshake protocol is essential for efficient communication in CR networks. Note that the term handshake by no means restricts this protocol between the transmitter and the receiver. A third party such as a centralized station can also be involved.
5. *Spectrum mobility*: CR nodes are regarded as ‘‘visitors’’ to the spectrum they allocate. Hence, if the specific portion of the spectrum in use is required by a licensed user, the communication needs to be continued in another vacant portion. As a result, spectrum mobility is also important for successful communication between CR nodes.

The existing work in spectrum sharing in CR networks aims to provide solutions for each step explained above. The existing solutions constitute a rich literature for spectrum sharing in CR networks.

This paper is organized as follows. In Section II, we classify the spectrum sharing techniques and describe the fundamental results about these techniques in CR networks. These work provide insight about how a spectrum sharing protocol can be designed. Accordingly, in Sections III and IV, we overview the solutions for spectrum sharing among multiple coexisting CR networks (inter-network spectrum sharing), and inside an CR network (intra-network spectrum sharing), respectively. in Section V, the open research issues for spectrum sharing in CR networks are discussed. Finally, conclusions are drawn in section VI.

II. OVERVIEW OF SPECTRUM SHARING TECHNIQUES

The existing solutions for spectrum sharing in CR networks can be mainly classified in three aspects: i.e., according to their aspects: i.e., according to their architecture assumption, spectrum allocation behavior, and spectrum access technique. In this section, we describe these three classifications and present the fundamental results that analyze these classifications.

The analysis of CR spectrum sharing techniques has been investigated through two major theoretical approaches. While some work uses optimization techniques to find the optimal strategies for spectrum sharing, game theoretical analysis has also been used in this area.

The first classification for spectrum sharing techniques in CR networks is based on the architecture, which can be described as follows:

- *Centralized spectrum sharing*: In these solutions, a centralized entity controls the spectrum allocation and access procedures [1]. With aid to these procedures, generally, a distributed sensing procedure is proposed such that each entity in the CR network forward their measurements about the spectrum allocation to the central entity and this entity constructs a spectrum allocation map.
- *Distributed spectrum sharing*: Distributed solutions are mainly proposed for cases where the construction of an infrastructure is not preferable [2]. Accordingly, each node is responsible for the spectrum allocation and access is based on local (or possibly global) policies.

The second classification for spectrum sharing techniques in CR networks is based on the access behavior. More specifically, the spectrum access can be cooperative or non-cooperative as explained below:

- *Cooperative spectrum sharing*: Cooperative (or collaborative) solutions consider the effect of the node's communication on other nodes [1]. In other words, the interference measurements of each node are shared among other nodes. Furthermore, the spectrum allocation algorithms also consider this information. While all the centralized solutions can be regarded as cooperative, there also exist distributed cooperative solutions.
- *Non-cooperative spectrum sharing:* Contrary to the cooperative solutions, non-cooperative (or non-collaborative, selfish) solutions consider only the node at hand [3]. These solutions are also referred to as selfish. While non-cooperative solutions may result in reduced spectrum utilization, the minimal communication requirements among other nodes introduce a tradeoff for practical solutions.

These two solutions have generally been compared through their spectrum utilization, fairness, and throughput. The utilization and fairness in spectrum access has been investigated in [4], where the spectrum allocation problem is modeled as a graph coloring problem and both centralized and distributed approaches are investigated. Using this model, an optimization framework is developed. In this framework, secondary users allocate channels according to the interference that will be caused by the transmission. Both cooperative and non-cooperative approaches are considered such that cooperative approaches also consider the effect of the channel allocation on the potential neighbors. The simulation results show that cooperative approaches outperform non-cooperative approaches as well as closely approximating the global optimum. Moreover, the comparison of centralized and distributed solutions reveals that distributed solution closely follows the centralized solution. However, such an assumption may not always be valid in CR networks.

Game theory has also been exploited for performance evaluation of CR spectrum access schemes. Especially, the comparison between cooperative and non-cooperative approaches has been presented in [5] through game theoretical analysis. In [5], game theory is exploited to analyze the behavior of the cognitive radio for distributed adaptive channel allocation. It is assumed that users deploy CDMA and determine the operating channel and the coding rate by keeping transmission power constant. It is shown that the cooperative case can be modeled as an exact potential game, which converges to a pure strategy Nash equilibrium solution. However, this framework has been shown not to be applicable for non-cooperative spectrum sharing and a learning algorithm has been proposed. The evaluations reveal that Nash equilibrium point for cooperative users is reached quickly and results in a certain degree of fairness as well as improved throughput. On the other hand, the learning algorithm for non-cooperative users converge to a mixed strategy allocation. Moreover, the fairness is degraded when non-cooperative approach is used. While this approach results in slightly worse performance, the information exchange required by selfish users is significantly low.

Finally, the third classification for spectrum sharing in CR networks is based on the access technology as explained below:

- *Overlay spectrum sharing*: Overlay spectrum sharing(Figure 1.b) refers to the spectrum access technique used. More specifically, a node accesses the network using a portion of the spectrum that has not been used by licensed users [1,2,6]. As a result, interference to the primary system is minimized.

Underlay spectrum sharing: Underlay spectrum sharing (Figure 1.a) exploits the spread spectrum techniques developed for cellular networks [6]. Once a spectrum allocation map has been acquired, an CR node begins transmission such that its transmit power at a certain portion of the spectrum is regarded as noise by the licensed users. This technique requires sophisticated spread spectrum techniques and can utilize increased bandwidth compared to overlay techniques.

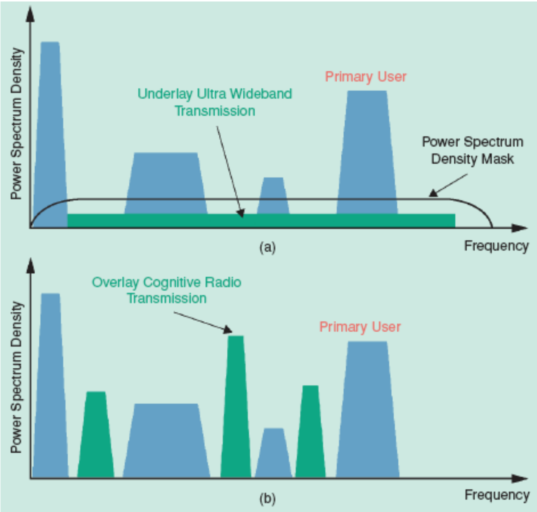

Figure 1. (a) Underlay and (b) Overlay approach for sharing spectrum with primary users.

The effects of underlay and overlay approaches in a cooperative setting are investigated in [7], where non-cooperative users are analyzed using a game theoretical framework. Using this framework, it is shown that frequency division multiplexing is optimal when interference among users is high. As a result, the overlay approach becomes more efficient than underlay when interference among users is high. The lack of cooperation among users, however, necessitates an overlay approach. The comparative evaluations show that the performance loss due to the lack of cooperation is small, and vanishes with increasing SNR. However, in this framework, the cost and inaccuracies of information exchange between users are not considered.

Another comparison of underlay and overlay approaches is provided in [8]. The comparison is based on the influence of the secondary system on the primary system in terms of outage probabilityand and three spectrum sharing techniques have been considered. The first technique (spreading based underlay) requires secondary users to spread their transmit power over the full spectrum such as CDMA or Ultra Wide Band (UWB). The second technique (interference avoidance overlay) requires nodes to choose a frequency band to transmit such that the interference at a primary user is minimized. Also an hybrid technique (spreading based underlay with interference avoidance) is investigated where a node spreads its transmission over the entire spectrum and also null or notch frequencies where a primary user is transmitting. Consequently, first, the interference statistics for each technique are determined for outage probability analysis. Then, the outage probability for each technique is derived assuming no system knowledge, perfect system knowledge, and limited system knowledge. Similar to other existing work, when perfect system knowledge is assumed, the overlay scheme outperforms the underlay scheme in terms of outage probability. However, when interference avoidance is incorporated into spectrum sharing, the underlay scheme with interference avoidance guarantees smaller outage probability than the pure interference avoidance. In a more realistic case, when limited system knowledge is considered, the importance of the hybrid technique is exacerbated. The overlay schemes result in poor performance due imperfections at spectrum sensing. More specifically, a node can transmit at a channel where a primary user is transmitting. However, when underlay with interference avoidance is used, the interference caused to the primary user is minimized. Another important result is that a higher number of secondary users can be accommodated by the hybrid scheme than the pure interference avoidance scheme. The theoretical work on spectrum access in CR networks reveals important tradeoffs for the design of spectrum access protocols. As expected, it has been shown that cooperative settings result in higher utilization of the spectrum as well as fairness. However, this advantage may not be so high considering the cost of cooperation due to frequent information exchange among users. On the other hand, the spectrum access technique, i.e., whether it is overlay or underlay, affects the performance in each setting. While an overlay technique focuses on the holes in the spectrum, dynamic spreading techniques are required for underlay techniques for interference free operation between primary and secondary systems. Considering the tradeoff between system complexity and performance, hybrid techniques may be considered for the spectrum technique. In the following two sections, we explain the existing spectrum sharing techniques that are combinations of the three classifications we have discussed in this section.

III. INTER-NETWORK SPECTRUM SHARING

CR networks are envisioned to provide opportunistic access to the licensed spectrum using unlicensed users. This setting enables multiple systems being deployed in overlapping locations and spectrum. Hence, spectrum sharing among these systems is an important research topic in CR networks. Up to date, inter-network spectrum sharing has been regulated via static frequency assignment among different systems or centralized allocations between different access points of a system in cellular networks. In ad-hoc networks, only the interference issues in the ISM band has been investigated focusing mostly on the coexistence of WLAN and Bluetooth networks. Consequently, intra-network spectrum sharing in CR networks poses unique challenges that have not been considered before in wireless communication systems. In this section, we overview the recent work in this research area.

Centralized inter-network spectrum sharing

As a first step for the coexistence of open spectrum systems, in [9], the common spectrum coordination channel (CSCC) etiquette protocol is proposed for coexistence of IEEE 802.11b and 802.16a networks. In this scheme, each node is assumed to be equipped with a cognitive radio and a low bit-rate, narrow-band control radio. The coexistence is maintained through the coordination of these nodes with each other by broadcasting CSCC messages. Each user determines the channel it can use for data transmission such that interference is avoided. In case channel selection is not sufficient to avoid interference, power adaptation is also deployed. The evaluations reveal that when there is vacant spectrum to use frequency adaptation, CSCC etiquette protocol improves throughput by 35–160% via both frequency and power adaptation. Another interesting result is that when nodes are clustered around IEEE 802.11b access points, which is a realistic assumption, the throughput improvement of CSCC protocol increases.

Distributed inter-network spectrum sharing

A distributed spectrum sharing scheme for Wireless Internet Service Provides (WISPs) that share the same spectrum is proposed in [10], where a distributed QoS based dynamic channel reservation (D-QDCR) scheme is used. The basic concept behind D-QDCR is that a base station (BSs) of a WISP competes with its interferer BSs according to the QoS requirements of its users to allocate a portion of the spectrum. Similar to the CSCC protocol [9], the control and data channels are separated. The basic unit for channel allocation in D-QDCR is called Q-frames. When a BS allocates a Q-frame, it uses the control and data channels allocated to it for coordination and data communication between the users. The competition between BSs are performed according to the priority of each BS depending on a BSs data volume and QoS requirement. Moreover, various competition policies are proposed based on the type of traffic a user demands. Although thorough evaluations are not provided in [10], the D-QDCR scheme serves an important contribution for inter-network spectrum sharing.

The inter-network spectrum sharing solutions so far provide a broader view of the spectrum sharing solution including certain operator policies for the determination of the spectrum allocation. A major problem for the existing solutions in the CR network architecture is the requirement for a common control channel. We detail the potential problems and open research issues in this aspect in Section V.

IV. INTRA-NETWORK SPECTRUM SHARING

A significant amount of work on spectrum sharing focuses on intra-network spectrum sharing, where the users of an CR network try to access the available spectrum without causing interference to the primary users. In this section, we overview the existing work and the proposed solutions in this area while providing a classification of existing protocols in terms of the classification provided in Section II.

Cooperative intra-network spectrum sharing

A cooperative local bargaining (LB) scheme is proposed in [2] to provide both spectrum utilization and fairness. The local bargaining framework is formulated based on the framework in [4]. Local bargaining is performed by constructing local groups according to a poverty line that ensures a minimum spectrum allocation to each user and hence focuses on fairness of users. The evaluations reveal that local bargaining can closely approximate centralized graph coloring approach at a reduced complexity. Moreover, localized operation via grouping provides an efficient operation between a fully distributed and a centralized scheme.

So far, we have presented distributed solutions where a fixed infrastructure is not assumed. In [11], dynamic spectrum access protocol (DSAP), which is a centralized solution for spectrum sharing in CR networks, is presented. The dynamic spectrum access protocol (DSAP) proposed in this work enables a central entity to lease spectrum to users in a limited geographical region. DSAP consists of clients, DSAP server, and relays that relay information between server and clients that are not in the direct range of the server. Moreover, clients inform the server their channel conditions so that a global view of the network can be constructed at the server. By exploiting cooperative and distributed sensing, DSAP servers construct a *RadioMap*. This map is used for channel assignments which are leased to clients for a limited amount of time.

An reinforcement learning based spectrum sharing scheme proposed in [13], where by using reinforcement-based learning, CR users will assess the success level of a particular action and they always choose the spectrum with the highest weight to communicate, and the weights of the resource for these users will be modified based on the assessment of the degree of success. The concept of ‘weight’ in this work is a number assigned to a resource, and the number reflects the importance of the resource to a certain CR user. In other words, CR users are learning from the interaction between themselves and the environment.

Initially, all CR users have equal access to the entire available spectrum pool. After each activation, the weight of the successfully used spectrum for a user is increased by a certain weighting factor. When the attempt fails, the weight is reduced. The action policy of CR users is updated according to the reward function feedback, therefore the reward function of reinforcement learning is also the system objective function in this work. The linear reward equation $w_t = f_1 w_{t-1} + f_2$ is used as the reward function to determine the weights of the resource. where f_1 and f_2 are weighting factors that have different values depending on the localized judgment of current system states and the environment. w_{t-1} is the weight of a channel at time $t-1$, and w_t is the weight at time t according to previous weight w_{t-1} and the updated feedback from system. The values of weighting factors are shown in TABLE I. Based on the degree of success, either a reward or a punishment is assigned to the weight of the used spectrum. The reward value of 1 is used in all of the three schemes in TABLE I. The main difference between these schemes is the values assigned to punishment factors. In the first scheme, the absolute values of the reward value and the punishment value are equal. In other words the weight is increased or decreased by the same step size. This scheme is also named the 'mild punishment scheme' in [13].

TABLE I. WEIGHTING FACTOR VALUES

SCHEMES	f_1		f_2	
	Reward	Punishment	Reward	Punishment
Mild Punishment Scheme	1	1	1	-1
Harsh Punishment Scheme	1	0	1	0
Discounted Scheme	1	0.5	1	0

In the second scheme, if the attempt for communication fails, the weight is directly reduced to zero. Therefore it is called the 'harsh punishment scheme'. Practically, the second scheme is a low complexity learning scheme where the CR users remember the last successful spectrum and keep using it at new activation until the request for that resource is declined. Then the user picks up a channel randomly and keeps using it as long as the quality of communication in that channel is above the requirement. Weights are reduced by a certain percentage in the third scheme, and a percentage of 50% is used to reduce the weight of an unsuccessful channel. it can refer to the scheme as the 'discounted scheme'.

Non-cooperative intra-network spectrum Sharing

An opportunistic spectrummanagement scheme is proposed in [12], where users allocate channels based on their observations of interference patterns and neighbors. In the device centric spectrum management scheme (DCSM), the communication overhead is minimized by providing five different system rules for spectrum allocation. As a result, users allocate channels according to these rules based on their observations instead of collaborating with other users. In case more than one node chooses the same channel in close proximity, random access techniques are used to resolve the contention. The comparative analysis of this scheme with the cooperative schemes show that rule-based spectrum access results in slightly worse performance. However, the communication overhead is reduced significantly.

A spectrum sharing protocol for ad-hoc CR networks, (AS-MAC), is proposed in [3]. AS-MAC exploits the RTS-CTS exchange and Network Allocation Vector (NAV) concepts of the IEEE 802.11 MAC protocol in an open spectrum setting. Moreover, a common control channel is used such that transmitter receiver handshake is initiated through this channel. In this work, the CR network is assumed to coexist with a GSM network. Each node first listens to the broadcast channel of the GSM network as well as the control channel of the CR network, and each node then constructs its NAV and selects channels accordingly.

V. SPECTRUM SHARING CHALLENGES

In the previous sections, the theoretical findings and solutions for spectrum sharing in CR networks are investigated. Although there already exists a vast amount of research in spectrum sharing, there are still many open research issues for the realization of efficient and seamless open spectrum operation. In the following, we detail the challenges for spectrum sharing in CR networks along with some possible solutions.

Common control channel (CCC)

Many spectrum sharing solutions, either centralized or distributed, assume a CCC for spectrum sharing [1,3]. It is clear that a CCC facilitates many spectrum sharing functionalities such as transmitter receiver handshake, communication with a central entity [1], or sensing information exchange. However, due to the fact that CR network users are regarded as visitors to the spectrum they allocate, when a primary user chooses a channel, this channel has to be vacated without interfering. This is also true for the CCC. As a result, implementation of a fixed CCC is infeasible in CR networks. On the other hand when CCC is not used, the transmitter receiver handshake becomes a challenge.

Dynamic radio range

Radio range changes with operating frequency due to attenuation variation. In many solutions, a fixed range is assumed to be independent of the operating spectrum [2]. However, in CR networks, where a large portion of the wireless spectrum is considered, the neighbors of a node may change as the operating frequency changes. This effects the interference profile as well as routing decisions. Moreover, due to this property, the choice of a control channel needs to be carefully decided. It would be much efficient to select control channels in the lower portions of the spectrum where the transmission range will be higher and to select data channels in the higher portions of the spectrum where a localized operation can be utilized with minimized interference. So far, there exists no work addressing this important challenge in CR networks and we advocate operation frequency aware spectrum sharing techniques due the direct interdependency between interference and radio range.

VI. CONCLUSIONS

CR networks are being developed to solve current wireless network problems resulting from the limited available spectrum and the inefficiency in the spectrum usage by exploiting the existing wireless spectrum opportunistically. CR networks, equipped with the intrinsic capabilities of the cognitive radio, will provide an ultimate spectrum-aware communication paradigm in wireless communications. In this paper, specific challenges for spectrum sharing in CR networks are presented and overview the existing solutions and discuss open research areas. we classify the spectrum sharing techniques and describe the fundamental results about these techniques in CR networks.. Accordingly, we overview the solutions for spectrum sharing among multiple coexisting CR networks (inter-network spectrum sharing), and inside an CR network (intra-network spectrum sharing), respectively. Finally, the open research issues for spectrum sharing in CR networks are discussed.

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