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Cognitive Radio Networks Spectrum Sharing Techniques

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Abstract—*As the complexities of wireless technologies increase, novel multidisciplinary approaches for the spectrum sharing/management are required with inputs from the technology, economics and regulations. Recently, the cognitive radio technology comes into action to handle the spectrum scarcity problem. To identify the available spectrum resource, decision on the optimal sensing and transmission time with proper coordination among the users for spectrum access are the important characteristics of spectrum sharing methods. In this paper, technically overviewed the state-of-the-art of the various spectrum sharing techniques and discussed their potential issues with emerging applications of the communication system, especially to enhance the spectral efficiency.*

The potential advantages, limiting factors, and characteristic features of the existing cognitive radio spectrum sharing domains are thoroughly discussed and an overview of the spectrum sharing is provided as it ensures the channel access without the interference/collision to the licensed users in the spectrum.

Keywords*: Cognitive radio, Dynamic spectrum access, Opportunistic spectrum access, Wireless communication, Spectrum sharing, Spectrum sensing.*

1. INTRODUCTION

Recently, the spectral resource demand has been greatly increased due to the emerging wireless services and products in the market. However, the frequency allocation charts reveal that almost all the frequency bands have already been assigned and the traditional static spectrum allocation strategies cause temporal and geographical holes [1] of the spectrum usage in the licensed bands. However, it might be possible that at certain time or space, some of the spectrum allocated to a certain service is unutilized and because of the fixed spectrum allocation scheme, the other user/service provider cannot use this unutilized spectrum.

Therefore, the spectrum is not scarce but the inefficient utilization of the allocated spectrum leads to the spectrum scarcity problem. The limitations of fixed spectrum allocation based scheme have been discussed in detail in [2]. To overcome the aforementioned limitations of the fixed spectrum allocation scheme, the concept of dynamic spectrum access (DSA) [3] and opportunistic spectrum access (OSA) [4] have been introduced, which defines a set of techniques and models to support the dynamic management of the spectrum for wireless communications systems. Therefore, the cognitive radio evolved as a technique to improve the overall spectrum usage by exploiting the spectrum opportunities in both the licensed and unlicensed bands. It starts with the sensing of radio frequency (RF) medium—radios are able to exploit information about the wireless environment to be aware of local and temporal spectrum usage.

The opportunistic users may dynamically select the best available channels, and adapt their transmission parameters to avoid harmful interference between the contending cognitive users. Therefore, the cognitive radio is a promising wireless communication technology geared to solve the spectrum scarcity problem by opportunisticallyidentifying the unused portions of the spectrum. It observes, learns, optimizes and intelligently adapts to achieve optimal frequency band usage and establish communication, while ensuring that the licensed or primary users of the spectrum are not affected [2].

The driving force behind the cognitive radio technology is the new spectrum licensing methods initiated by the federal communication commission (FCC), which is more flexible to allow the unlicensed (or secondary/cognitive) users to access the spectrum as long as the licensed (primary) users are not interfered by the unlicensed users [5].

According to the communication theorists view, the cognitive radio is primarily concern with the dynamic spectrum sharing, while the networking/information technology researchers interpret cognitive radio as a device capable of cross-layer optimization, the computer scientists picture it as a device capable of learning and adapting with assumed capabilities, while the hardware/ radio frequency community often views it as an evolutionary step from Software Defined Radio (SDR) [5–9].

There are various applications proposed for the deployment of cognitive radio network in coexisting/ shared basis because of their highly underutilized spectrum such as television, microwave point-to-point links and land mobile radio. The cognitive radio based communication standard IEEE 802.22 WRANs (Wireless Regional Area Networks) is discussed in [10] which allows the coexistence of television users and cognitive radio users for wireless internet access. The cognitive radio users can use the television band for Internet applications in rural areas when it is unused and is advantageous to have broadband internet access over these television white spaces, otherwise separate broadband network deployment could be difficult and costly in rural areas. This technology can also be applied for e-health services [11], intelligent transportation system such as VANET (vehicular ad-hoc network) [12], emergency [13] and military services [14]. Zhao and Sadler [3] have described the basic aspects of the DSA with regulatory issues and Akyildiz et al. [15] have provided the brief overview of cognitive radio technology and its functioning. Further, the authors in [16] have overviewed the different spectrum sensing techniques and spectrum sharing domain has been briefly explored. In this paper, technically overviewed the state-of-the-art of various spectrum sharing/management techniques in detail and discussed their potential issues with emerging applications of the communication system, especially to enhance the spectral efficiency and fairness among the users. The sharing techniques which are employed by cognitive users or network are: (1) power control method, (2) game theory, (3) multiple antennas, and (4) medium access control (MAC) protocol. In particular, Sect. 2 describes the spectrum sharing model in cognitive radio network. Further, in Sect. 3 different domains of spectrum sharing are described. Section 4 shows the related work done by researchers in the direction of throughput/capacity enhancement of the cognitive radio system and Sect. 5 concludes the paper and explores the future scope.

2. COGNITIVE RADIO NETWORK ARCHITECTURE

The architecture of cognitive radio network is an important aspect for sharing the licensed spectrum with multiple cognitive users. There are mainly two types of cognitive radio network architecture which is described as follows [2].

A. Centralized cognitive radio network

In the centralized cognitive radio network, the control of spectrum allocation and access to a particular regime of the spectrum by cognitive users is performed by a central controller, for example, a base station [16, 17]. In addition to this, all the cognitive user's communication are followed through this central controller and the spectrum access decisions like duration of spectrum allocation and transmit power by the cognitive user is controlled through the central base station. However, the information collection and exchange to and from the central controller and the cognitive users incur a considerable overhead [2].

B. Distributed cognitive radio network

In the distributed cognitive radio network, the cognitive users communicate with each other directly that is in a peer-to-peer manner without requiring any base station or central controller [2, 16]. However, the cognitive user can make a decision on spectrum access independently and autonomously. In the multi-hop communication, the cognitive users sometimes may be assumed as relay stations [2].

3. SPECTRUM ALLOCATION BEHAVIOR

A. Cooperative spectrum sharing

In the cooperative sharing scheme [18], all the cognitive users cooperate with each other either through a centralized base station or through a common control channel in the centralized or distributed cognitive radio networks.

The cooperation between cognitive users is performed to share the spectrum with maximum efficiency by exchanging the sensing information with each other and thus the cooperative spectrum sensing [19] reduces the sensing time while improving the spectrum sensing accuracy, incurs good degree of fairness, higher complexity, and overhead with an increase in the energy consumption [20].

B. Non-cooperative spectrum sharing

In comparison to the cooperative spectrum sharing, in this spectrum sharing method the cognitive users do not exchange any kind of information with each other. However, this method of sharing is advantageous for less number of cognitive user's network and provides less communication overhead, but in the multiuser network it causes severe degradation of spectrum efficiency because of the selfish nature of each cognitive user.

4. SPECTRUM ACCESS TECHNIQUES

A. Spectrum interweave/opportunistic spectrum access(OSA)

At a particular time, frequency or space, if the spectrum is not utilized by the primary user, it can be opportunistically accessed by the cognitive users with the help of spectrum interweave access method [21, 22] as shown in Fig. 1(a). Therefore, in order to access the regime of spectrum using the spectrum interweave technique, the cognitive user has to perform spectrum sensing to detect the activity of a primary user in that regime. If a spectrum hole that is inactive primary user is detected, the cognitive users may access that unutilized spectrum as is shown from Fig. 1(a).

B. Spectrum underlay

In the spectrum underlay access method, the cognitive users transmit concurrently with primary user as shown in Fig. 1(b). However, the transmit power of cognitive user should be limited so that the interference caused by the cognitive users to the primary users remain below the interference temperature limit [21]. The interference temperature is defined as the interference limit set at primary user's receiver up to which it can tolerate interference without affecting their operation.

C. Spectrum overlay

In the spectrum overlay mode of spectrum access method, the concurrent primary and cognitive user's transmission are allowed as shown in Fig. 1(c). However, the interference at secondary and primary receiver is mitigated by the advanced pre-coding and interference cancellation techniques as discussed in [23–25].

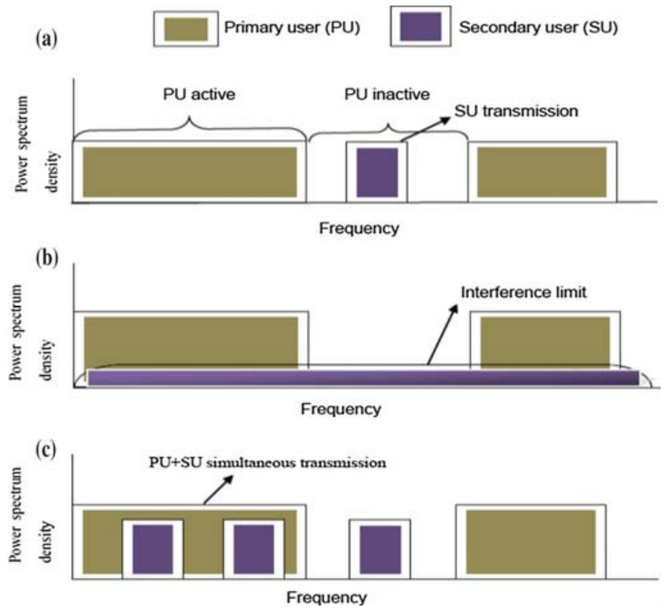

Fig. 1: The spectrum access techniques a spectrum interweaves, b spectrum underlay and, c spectrum overlay approach.

5. DIFFERENT DOMAINS OF SPECTRUM SHARING

A. Power control

The cognitive radios must follow the rules/restrictions to access the spectrum [2] and the management of protocol as well as a reliable and scalable mechanism, which allow a cognitive user to follow the rules, is required. However, in case, the protocols are violated then proactive and reactive techniques of power control is used to avoid this misbehavior.

A proactive technique includes the rule (for example, maximum power limit) and an enforcement mechanism (power allocation), however this proactive technique is applied before the cognitive radio users start misbehaving that is before violating the spectrum access rules. On the other hand, a reactive technique is required to punish the misbehaving cognitive radio. Since the cognitive users coexist with the primary users in an operating spectrum, mere consideration of transmission power limits on a channel may not be sufficient [26]. Further, the adaptation in transmission power and rate according to fading conditions is discussed in [27, 28].

Kang [29], have determined the optimal power allocation to cognitive users under Rayleigh fading environment with the assumption of channel state information (CSI) availability at cognitive users and have computed the ergodic and outage capacities closed-form expressions. Moreover, one important parameter, namely, the interference transmission ratio (ITR) which is the ratio of primary to secondary channel gain, has been defined based on which the cognitive user get the priority to transmit over other cognitive user.

The NOMA is an efficient scheme of spectrum sharing in cognitive radio because it avoids the competition among the cognitive users of getting the specific channels out of all the available channels and there is need of only power control according to the environment. The base station or central coordinator, controls the power allocation to different users, however for distributed environment NOMA concept is still open for research.

B. Game theory

The game theory in cognitive radio network is developed basically for the spectrum sharing through trading and fairness rules and main objective is to fulfill the cognitive network demand while maximizing revenue of the primary network. Therefore, employing the game theory could effectively guarantee the fairness and rationality or the spectrum management among the cognitive network [30].

Further, in [30], the authors have also proposed the OODA (orient-observe-decide and act) method to share the primary network's spectrum among multiple heterogeneous cognitive networks with different QoS requirements and this method take into account the behavior modeling of the cognitive users.

C. Multiple antennas

The concept of multiple antennas has also been exploited as a potential method for the spectrum sharing in the cognitive radio communication system due to the throughput enhancement and interference cancellation. A system model for the cognitive radio network, where multiple antennas are implemented at cognitive user transmitter is presented [31], which provides the significant enhancement in the channel capacity as compared to the single antenna at the cognitive user transmitter. In addition to this, it is also able to transmit on the same spectrum which the primary user is currently using due to the multiple antennas beam-forming.

Moreover, the multiple antennas are used to allocate the transmit dimensions in space and hence provide the cognitive transmitter in a cognitive radio network more degrees of freedom in space in addition to the time and frequency to balance between maximizing its own transmit rate and minimizing the interference powers at the primary receivers. Furthermore, in [32, 33], the authors have discussed about the characteristic function and its application in computation of the channel capacity under the fading environment. In [34], the moment generating function (MGF) and characteristic function (CF) is used to compute the error rate as well as channel capacity. The fading channel capacity using the MGF approach in multiple antennas scenario with different correlation coefficient in the fading environments has been formulated in [35].

D. Medium access control (MAC) protocol

Traditionally, in the spectrum sharing, the users get access to the channel through medium access control (MAC) protocol. The main difference in MAC protocol of traditional wireless communication and cognitive radio system is that the multiple channels have to be shared by the multiple cognitive users instead of the single channel sharing by the multiple users in conventional MAC protocols. In addition to this, the cognitive users have to differentiate between the primary user and cognitive user transmission, therefore it has to decide whether to stop transmission to protect the primary user or to retransmit in case of interference with other cognitive user.

All these parameters of MAC layer are the part of MAC protocol and are responsible for the spectrum sensing and spectrum access decisions [36]. The major objectives of cognitive MAC protocol designs are:

1. To optimize the spectrum sensing and spectrum access decision,
2. To control the multiuser access in the multichannel network, and
3. To allocate the radio spectrum and schedule traffic transmission.

E. Throughput/capacity of cognitive radio

In general, the channel capacity is used as a basic tool for the performance analysis and design of new and more efficient techniques to improve the spectral efficiency of wireless communication systems. In the frame structure of cognitive radio user, longer sensing time accurately detect the presence of primary users and improves the sensing performance. However, for a fixed frame size (T), the longer sensing time (s) shorten the allowable data transmission time (T _ s) of the cognitive users as is clear from the below mentioned throughput equation of the cognitive user and the sensing-throughput tradeoff problem occurred [37]. This method can be adapted for the cognitive radio user by employing the cognitive user to spatially share the spectrum with primary user. In [38], the fading scenario and their effect on the rate and power selection for the cognitive radio user are illustrated. The throughput of cognitive radio users has been computed by considering the interference, transmit power and qualityof-service constraints, which reveals the significant improvement in the sensing reliability and throughput of the cognitive user.

6. CONCLUSION AND FUTURE DIRECTIONS

With the increasing importance of wireless communications, an adaptive and efficient utilization of the spectrum resources are required. The traditional technology-specific spectrum allocations are unable to accommodate the increasing demand uncertainty that characterizes the wireless communication today. The technology specific spectrum allocation will, therefore, inevitably lead to suboptimal spectrum allocations. In this paper, finally presented an overview of the state-of-the-art of spectrum sharing/management in the cognitive radio communication system, which provides significantly high bandwidth to the mobile users via the heterogeneous wireless architecture and dynamic spectrum access techniques.

Due to the fluctuating nature of available spectrum and diverse quality- of-service requirements for various applications, it imposes several challenges. The main challenges and future research directions have been presented, when emphasizing on the close-coupling of MAC protocol design with the other layers of protocol stack. The algorithm and protocol for self-configuring cognitive radio, centralized/distributed cognitive radio network and for radio resource management is an emerging research area. The MAC protocol design should have some sleep and wake kind of procedure without service degradation of cognitive network. Since the user's terminal have limited battery life and the cognitive radio users sensing will also consume energy in addition to its data transmission therefore, the cognitive radio spectrum sharing techniques should enhance the performance with minimum energy consumption. Moreover, 5G communication using the cognitive radio has been recently proposed to performed on some higher frequencies e.g. on 28 GHz and 60 GHz [140], however it is challenging task to have a un-interruptive communication at such high frequency due to small coverage area and interference. Therefore, the practical implementation of cognitive radio in 5G is an open research area for researchers/scientists.

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