Wireless Pers Commun (2011) 59:525–535
DOI 10.1007/s11277-011-0243-5

Cognitive Radio Concept and Challenges in Dynamic Spectrum Access for the Future Generation Wireless Communication Systems

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Published online: 26 February 2011

Abstract Recently, the Dynamic Spectrum Access (DSA) techniques are proposed to solve the problem of spectrum scarcity and help to use the limited spectrum resource as effectively as possible. The current ongoing spectrum reform opens up the possibilities to exploit the DSA techniques. This paper aims to provide a critical review on the various ongoing efforts towards the use of DSA concept for the frequency management of future wireless communications systems, especially from the Cognitive Radio (CR) perspective. The CR aims for an efficient and dynamic access to the spectrum, and provides a new method of spectrum management. This paper also highlights the various challenges associated with CR in order to realize the concept of DSA.

Keywords Cognitive Radio · Dynamic spectrum usage · Spectrum sensing · Spectrum management challenges

1 Introduction

Presently, the most frequency bands are already assigned to different licensed users for specific services and applications. The available spectrum is becoming increasingly scarce over certain bands, yet it is found to be significantly underutilized [1]. Recently, the DSA techniques are proposed to solve the problem of spectrum scarcity and help to reuse the assigned frequency spectrum and to use the limited spectrum resource as effectively as possible. In fact DSA is considered to be a promising solution to the problem of overcrowded spectrum. The DSA also aims for spectrum sharing to help to overcome the lack of available spectrum for new communications services [2]. The mechanism of DSA requires a flexible approach not only for spectrum sharing but also for technology and service neutrality [3]. It also supports the heterogeneous technologies in the wireless environment. A DSA mechanism may be agile or flexible. It is possible for an agile device to operate over many frequency bands whereas a

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flexible device can operate over many different transmission standards. The DSA is defined in draft standard of IEEE 1900.1 as “a technique by which a radio system dynamically adapts to select operating spectrum to use available (in local time-frequency space) spectrum holes with limited spectrum use right”. Once DSA technique becomes widespread we can expect a reduced entry costs for new service providers to speed up product and business lifecycles [2].

The current ongoing spectrum reform opens up the possibilities to exploit the DSA access. The present spectrum authorities must find an appropriate way to deal with such flexibility to create a space for technological innovations. In fact the DSA based spectrum management policy has to face major changes to reflect future radio spectrum needs and technological advances [4].

This paper aims to provide a critical review on the ongoing efforts towards the use of DSA concept for the frequency management of future wireless communications systems, especially from the Cognitive Radio (CR) perspective.

2 The Cognitive Radio Concept

In fact DSA is being considered as the prime candidate for the first practical application of the CR technology. The CR is deemed to be a breakthrough technology and is expected to deeply impact the way radio spectrum will be accessed, shared and managed in future. It is an important innovation for the future communication systems and is likely to be a part of the new wireless standards [5]. The CR aims for an efficient dynamic access to the spectrum, and provides a new method of spectrum management.

The CR devices use the real time knowledge of its wireless environment to dynamically adapt its own behavior in order to enhance the spectrum utility. The real time knowledge of the wireless environment indicates the situational awareness which includes various aspects such as information about the channel conditions, availability of resources and the intended applications. That is how the CR technology aims for an informed decision making process and also functions without any human intervention. The cognitive capability and the reconfigurability are the two main characteristics of CR devices. The cognitive capability provides a real time interaction with the wireless environment in order to find the transmission opportunities. The reconfigurability means adapting the best transmission band and the most appropriate transmission parameters [6].

The devices using CR may change its transmitter parameters on the fly, based on the interaction with the wireless environment in which it operates. In fact CR facilitates an autonomous mechanism to intelligently adapt the appropriate operational characteristics (frequency, waveform, modulation and power), in response to the changes in the surrounding environment while complying with spectrum policies. For doing so a CR device continuously performs spectrum sensing over a range of frequency bands and dynamically identifies unused spectrum and then operates in this spectrum when it is not already in use.

The CR concept allows the devices to coexist in two different modes. First, the CR devices transmit only on white space, and do not create any interference to the licensed device. Second, a CR device can transmit as long as it creates interference to the licensed device below some acceptable interference threshold. These two kinds of spectrum access can take place both on temporal and spatial domains. In temporal domain the CR monitors the activity of the licensee in a given location and uses the licensed frequency only when it is permissible. In spatial domain it identifies geographical regions where certain licensed bands are unused and access these bands without causing harmful interference to the operation of the licensee

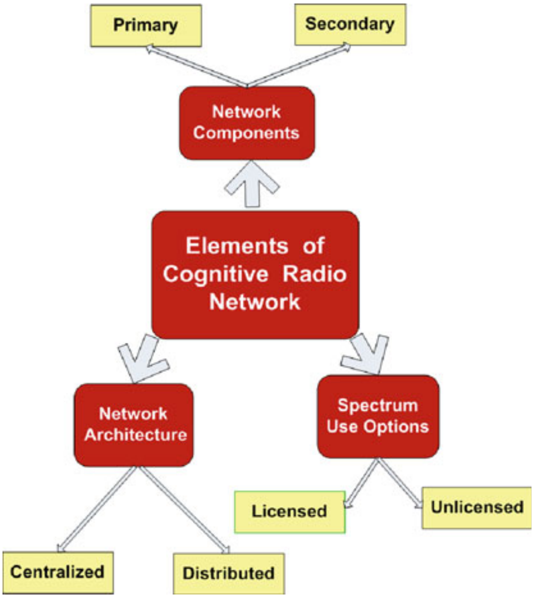

Fig. 1 The elements of a Cognitive Radio network

in that region [7]. In the CR terminology, the licensee is generally referred to as primary and the devices without license but a permission to use the spectrum of the licensee is known as secondary devices.

The basic idea is that a secondary device must sense the whole range of spectrum in order to find the usable part of the spectrum. Based on this sensing information and the regulatory policies, a CR device identifies spectrum opportunities (in terms of frequency, time, space and code), and do transmit in a manner that avoids/minimize the interference to the primary device in order to ensure coexistence and cooperation. The IEEE 1900.1 defines CR as "a radio in which communications system are aware of their environment and internal state and can make decisions about their radio operating behavior based on that information and predefined objectives [2]". Therefore, a CR is an intelligent wireless system that periodically monitors the radio spectrum, intelligently detects occupancy in the different parts of the spectrum and then opportunistically communicates over spectrum holes with minimal interference to the primary user.

2.1 The Elements of Cognitive Radio Network

In a communication framework, an interaction among a number CR devices will constitute a CR network. In order to understand the CR network environment it is important to know the various elements of the CR network. The various elements of the CR network are shown in the Fig. 1.

Network Components. There can be two types of the network components such as primary and secondary networks. The primary network is composed of the devices that have license to use the spectrum band. These have priority in spectrum access. The secondary network consists of secondary devices. The secondary devices actually use the Cognitive Radio concept and are built with the Cognitive Radio capabilities. These devices have no license for the spectrum use but have permission to access the spectrum of the primary devices with

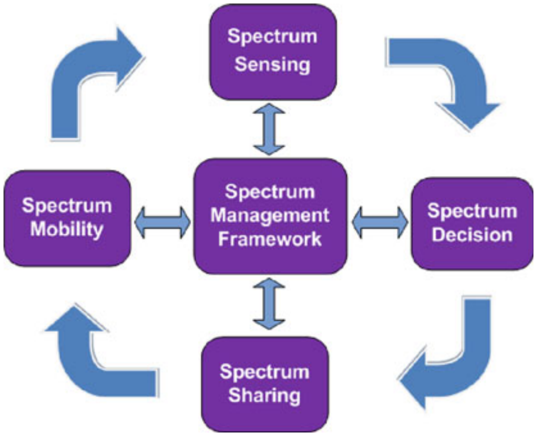

Fig. 2 Spectrum management framework of Cognitive Radio

a restriction on not to affect the performance requirements of the primary devices. The secondary devices should have capabilities to use the spectrum in dynamic manner and hence, an additional functionality to share the licensed spectrum band. It is the also assumed that the primary may remain unaware of the presence of the secondary devices.

Network Architecture. The access to the spectrum in a Cognitive Radio network may have centralized or distributed approach. In the centralized approach, a central entity is responsible for spectrum allocation among the devices for the licensed or the unlicensed part of the spectrum. In case of the distributed approach the Cognitive Radio devices make their own decision to access the spectrum.

Spectrum Use Options. It is discussed that the primary devices have license but the secondary devices do not have license to use the spectrum. In this regards the use of spectrum for the primary is limited within the licensed band only, whereas secondary may use both the licensed and the unlicensed bands. The secondary can use the licensed band of the primary with restrictions for not creating any performance degradation for the primary. Secondary can also use the unlicensed band where they have to interact with other secondary devices with equal access opportunities. In this situation the secondary devices have to follow the regulatory policies and the etiquettes to access the spectrum.

2.2 Spectrum Management Framework

The CR network exploits the dynamic spectrum environment, requiring awareness about the changing conditions over the spectrum bands. Such spectrum aware operation leads to the cognitive cycle consisting of various spectrum management functions. In fact the Cognitive Radio network needs to determine which portions of the spectrum are available or use.

It selects the best available spectrum band for transmission and vacates it when a licensed user is found with an intension to use this band [8]. Based on these prime activities the CR network performs the following four functionalities; Spectrum Sensing, Spectrum Decision, Spectrum Sharing and Spectrum Mobility. The spectrum management framework of CR network is shown in Fig. 2.

Spectrum Sensing. A Cognitive Radio based device is not allowed to allocate spectrum wherever it desires but only on those portions of the spectrum where it does not interfere significantly with the primary. This is a very important requirement to ensure coexistence with the primary, and to fulfill the spectrum sharing requirements. The continuous sensing of the wireless environment is mandatory for the secondary devices to fulfill such functions. The secondary must capture the required information about the occupancy of the spectrum bands and act accordingly.

Spectrum Decision. The availability of certain spectrum band may be known based on the sensing information. The allocation of the spectrum band does not depend only on the availability but also takes into account the regulatory policies. The decision to allocate the spectrum is taken based on these facts.

Spectrum Sharing. In order to make the final allocation a spectrum band may need to be shared with the other secondary or the primary devices. A proper mechanism is required to coordinate the spectrum sharing.

Spectrum Mobility. In fact the Cognitive Radio devices are considered as the visitors to the spectrum. The secondary device may use any band of the spectrum, but if it is required by the primary at any specific time or location, the secondary devices have to vacate this band and move to another band of the spectrum. Even if the secondary device may aim to maintain the communication as far as possible.

3 The Cognitive Radio Challenges

The Cognitive Radio technology offers many potential benefits such as improving spectrum utilization, introducing innovative resource management schemes, generating new revenues, facilitating optimized services and making high bandwidth available to the users. These advantages can be realized by meeting the challenges associated with each of the spectrum management functionalities. In fact the development of the Cognitive Radio concept is still in the conceptual stage due to the multitude of open research challenges in these functional areas. Considerable research need to be performed in order to reach the full promise of Cognitive Radio [9].

The CR network impose challenges mainly due to the fluctuating nature of the available spectrum band, the need of coexistence and cooperation with the primary devices and the diverse QoS requirements of various applications. The critical design challenges of CR networks are the following:

Interference Minimization. The CR network aims to minimize the interference to the primary devices. When using the overlay mechanism for the spectrum access, the secondary aims to avoid interference to primary on certain spectrum bands. While using underlay mechanism, it aims to transmit below the acceptable level of interference. In both the conditions it becomes important to make an interference estimation of the wireless environment on continuous basis. This is considered to be a critical design challenge. Appropriate schemes must be investigated to find the suitable approaches.

QoS Guarantee. The CR device uses the spectrum in an opportunistic manner and therefore, the quantity of used spectrum fluctuates over the spectrum bands. This makes difficult to guarantee the specific Quality of Service (QoS) requirement of users. This is a challenging task and suitable schemes must be investigated for this.

Seamless Communications. The communication in the CR network may be disrupted due to spectrum mobility and also due to lack of spectrum availability. Therefore, providing seamless communication becomes challenging in the Cognitive Radio environment.

3.1 Spectrum Sensing

Spectrum sensing is an important function for realization of the CR functionalities. It helps the secondary devices to identify the spectrum opportunities. Sensing is needed to be performed over the wideband in continuous manner. Generally the spectrum sensing aims for the primary transmitter detection, primary receiver detection and the interference level detection.

Primary Transmitter Detection. In this sensing approach the main aim is to detect the presence of the primary transmitter in the vicinity. It helps to identify the spectrum used by the primary transmitter in order for the secondary to avoid transmission on those spectrum bands. In fact the secondary looks for the weak signals from the primary to make transmission decision. To ensure coexistence the primary transmission detection becomes important for the secondary. It needs no information exchange between the primary and the secondary. Sometimes a single secondary device cannot detect the presence of the primary due to the multipath and the shadowing effects, resulting into hidden node problem. In such case a cooperative detection among the secondary devices becomes important. The cooperative detection is supposed to be more accurate since it helps to avoid the uncertainty in single user detection. However, it may adversely affect the resource utilization. There are following three prevalent mechanisms to perform primary transmitter detection.

Matched Filter Detection. When the secondary user has a-priory knowledge of the channel characteristics of the primary user, then the matched filter detection is considered to be the optimal detection strategy.

Energy Detection. When a secondary device does not have sufficient knowledge about the primary channel characteristics, then the energy detection method is considered to be an optimal detection strategy. The performance of the energy detector is affected by the uncertainty exhibited in the noise power distribution.

Feature Detection. Generally the modulated signals are characterized by its features such as periodicity or cyclostationarity. These features can be identified to detect the primary transmission. The main advantage of the feature detection is its robustness to uncertainty in noise power distribution, however, it is computationally complex and needs long observation time to make a detection decision.

Primary Receiver Detection. Another mechanism to identify the spectrum hole is to detect the primary users' received spectrum in the CR network. This is the uplink spectrum used for the primary devices.

Interference Level Estimation. One of the most important tasks for the secondary devices is to estimate the level of interference over the spectrum bands. When using the overlay mechanism, the secondary devices aim to avoid the interference by transmitting only on the unused spectrum bands. In case of underlay mechanism it may transmit over the same spectrum band of the primary, with some transmission power restrictions. In both of these circumstances, the interference level estimation becomes very important requirement to accomplish the spectrum management functionalities in the Cognitive Radio system.

Spectrum Sensing Challenges. There exist several open research challenges in the spectrum sensing functionality. Some of the challenges associated with spectrum sensing are the following:

- Sensing to make an estimation of the Interference level in the Cognitive Radio network.
- Spectrum sensing in multi user environment.
- Investigation of Spectrum efficient sensing mechanisms.

3.2 Spectrum Decision

The CR network needs to decide the most suitable one among the available spectrum bands, based on the applications, QoS guarantee and the policy requirements. The spectrum decision also takes into account the presence of other secondary devices in the CR network. This decision on spectrum selection is related to the channel characteristics and is usually performed in two steps. First, each spectrum band is characterized using sensing information and second, the most appropriate band is chosen. The channel may be characterized using the information related to the path loss, transmitter power, link error and link delays. The primary activity cycle has significant impact on the spectrum decision. The primary activity cycle indicates how often the primary appears over the spectrum. Because of the primary activity cycle the secondary cannot ensure that a particular spectrum band will always remain available to it, hence multiple non contiguous bands must be used as far as possible.

Spectrum Decision Challenges. The spectrum decision is a complex functionality which involves various challenges, such as:

Finding a Suitable Spectrum Decision Model This is very important task for the secondary to take right decision for selection of the spectrum band for transmission in dynamic wireless environment. The Signal to Noise Ratio (SNR) alone may not be sufficient criteria to select the spectrum band. An appropriate model needs to be developed to enable the spectrum decision.

Cooperation to Assist Spectrum Decision In a CR network sometimes cooperation may be required to assist the spectrum decision and to reconfigure the transmission parameters accordingly. It is challenging to design such scheme for cooperative information exchange in CR environment.

Spectrum Decision over Heterogeneous Network The CR device may need to coexist in heterogeneous wireless environment. The heterogeneous wireless environment will consist of multitude of devices and applications over the different frequency bands. A secondary device may be designed to use the spectrum from such numerous services. In such scenario the spectrum decision should be supported with suitable algorithms. Designing such algorithm is not a trivial task.

3.3 Spectrum Sharing

The Cognitive Radio network aims for spectrum sharing, which can be based either on the concept of coexistence or coordination. The secondary devices need to coexist in an heterogeneous wireless environment and use and share the spectrum in the licensed band with primary and in the unlicensed band with other secondary devices. A suitable mechanism must be established for the spectrum sharing functionalities. The spectrum sharing concept in the Cognitive Radio can be viewed in various domains as illustrated in Fig. 3.

Based on Network Architecture. The spectrum sharing schemes may be different in centralized or distributed network architecture. In centralized architecture, the spectrum allocation and the sharing process is controlled by a central entity. The parameters of the spectrum measurement are forwarded to this central entity to enable to take decision. The central entity may lease the spectrum to the users in a specific geographical region for a specific amount of time and the competitions among the users are also controlled by this entity. In the distributed architecture the spectrum allocation and the sharing decisions are taken by the individual devices in decentralized manner. The spectrum sharing mechanisms are required to developed for both the scenarios.

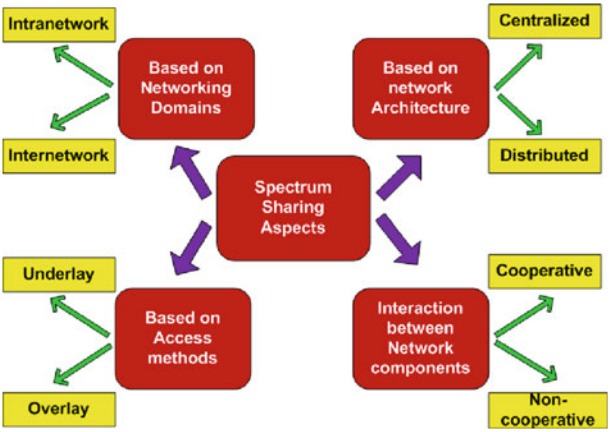

Fig. 3 Spectrum sharing domains

Interaction Between Network Components. The other basis for developing spectrum sharing schemes may account for the extend of mutual interaction and the behavior of the devices in the CR network. The cooperative and non cooperative spectrum sharing schemes may be designed. In cooperative scheme the devices exchange limited information within themselves to influence the decision making process for spectrum sharing. The devices may form a cluster to simplify the share the interference information locally. This localized operation may provide a balance between the fully centralized and the fully distributed schemes. In non cooperative scheme no collaboration is assumed to exits among the devices and hence there is no information exchange. Each device has to base its decision only from its own sources of information. The cooperative scheme generally outperforms the non cooperative scheme in terms of accuracy, fairness and throughput performance. However, it results in high amount of spectrum overhead due to information exchange.

Based on Access Methods. The spectrum sharing can be performed using overlay and/or underlay access methods. In overlay method the secondary devices looks for an opportunity to find the white space in primary transmission in order to adapt its own transmission. The white space is where the primary makes no transmission at the moment. In this method the secondary creates no interference to the primary on that spectrum band. This is also considered to be an opportunistic spectrum allocation. In underlay method, a tolerable interference limit is agreed for the primary. The secondary transmission is not limited to the white space only. The secondary may transmit over the spectrum used by the primary also but under the constraint that the tolerable interference threshold is not surpassed. The underlay method may result in higher bandwidth utilization compared to the overlay method, with a slight increase in the complexity. Wherever suitable the hybrid method can also be used for spectrum sharing in CR networks.

Based on Networking Domains. The terms intra-network and inter-network spectrum sharing are used to indicate whether the spectrum sharing is performed within a particular CR network or among a number of CR interworks. The intra-network sharing aims for spectrum allocation between the entities of a particular Cognitive Radio network without causing interference to the primary devices. The inter-network spectrum sharing enables sharing within multiple systems and networks and may include the concerned operators' policies as well.

Spectrum Sharing Challenges. There are many open research issues associated with the spectrum sharing mechanisms such as:

Designing a Common Control Channel. An information exchange is required in the CR network for cooperative scheme. A common control channel can facilitate the information exchange. Even though the amount of information may be limited, but this is helpful in decision making. Designing a channel common to all the users is not a trivial task because of the variations in wireless channels, different topologies of the users' locations and various applications. This is an open research challenge.

Location Information. One important requirement for the spectrum sharing assumption is that the secondary should know the location of the primary device as well as the other secondary devices in order to compute the transmit powers and the interference scenarios. The frequency of operation and the range are inter-dependent. Any variation in frequency may dynamically vary the range, making the interference computation difficult. The spectrum sharing mechanism should also account for this phenomenon.

Designing a Spectrum Sharing Uni. The spectrum sharing may be performed using a specific size of the spectrum band. Designing the smallest unit of the spectrum band for sharing needs careful investigation

3.4 Spectrum Mobility

The secondary device transmits over a spectrum band after the spectrum decision. However, it may not continuously use this spectrum band due to the primary activity cycle. The appearance of primary may necessitate the secondary to vacate this spectrum. In such circumstances, secondary needs to switch over to the other spectrum band. Each time a CR network changes its spectrum, the network protocol may require modifications to the operational parameters. This spectrum mobility gives a new kind of hand off in the CR network, called spectrum handoff [5]. The information on duration between such hand-offs is an important consideration for designing mobility management schemes.

Spectrum Mobility Challenges. The secondary may change spectrum use over time in CR network. The spectrum use may also change, as the secondary changes its location in space domain. It becomes extremely challenging ensure specific QoS guarantee and even to ensure the continuity of the communication. A continuous allocation of spectrum to secondary is a major challenge in spectrum mobility function.

4 Conclusions

A critical review on various aspects of DSA and CR has been presented in this paper. The current notion of DSA and its effectiveness in managing the spectrum for the future communication system has been discussed. The DSA is considered to be the prime candidate for the first practical application of the CR technology. The CR has been considered to be an important innovation and is expected to be a breakthrough technology which will deeply impact the way radio spectrum will be accessed, shared and managed in future. It aims for an efficient dynamic access to the spectrum, and provides a new method of spectrum management. The various elements of CR network has been highlighted, which helps to exploit the dynamic spectrum environment. The cognitive framework, consisting of various spectrum management functions such as spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility, have been illustrated. In fact the development of the CR is still in the conceptual stage. The multitude of open research challenges is associated with CR. This paper also highlights the various challenges associated with CR in order to realize its full potential.

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