A Survey of Cognitive Radio Management Functions

Ola Ashour Mohammed
Department of Electrical, Computer and Software Engineering, UOIT
Oshawa, Canada
ola.ashoor@gmail.com

Khalil El-Khatib, Miguel Vargas Martin
Faculty of Business and Information Technology, UOIT
Oshawa, Canada
{khalil.el-khatib, miguel.vargasmartin}@uoit.ca

***Abstract*— Due to the fast growth in wireless communication services, the need for radio spectrum increased. However, most of the suitable radio spectrum has already been allocated using long term licenses. A considerable part of the allocated spectrum is underutilized over time and space. Cognitive Radio (CR) technology has arisen to solve the spectrum scarcity problem by allowing cognitive radio devices to opportunistically make use of the unused frequency bands in the allocated spectrum, which are termed white spaces or spectrum holes. Four CR functions have to be performed to allow CR devices to efficiently utilize the available spectrum holes without interfering with licensed devices already operating in the allocated spectrum. This paper presents a survey of the CR technology, its architecture and operation, a detailed description of the four CR functions, and the techniques and processes used in each function.**

Keywords-Cognitive Radio; Spectrum holes; Spectrum decision; Spectrum Sharing; Spectrum Mobility.

I. INTRODUCTION

The radio spectrum is a natural resource managed by governments, which have assigned fixed portions of this spectrum to various operators using long term licenses. With the trend of using wireless devices continue to increase, spectrum usage increases on a daily bases, and it is becoming certain that there is a real need for more spectrum bands to facilitate the implementation of new wireless services. However, it is hard to find free bands, as most of the suitable spectrum bands have already been assigned.

Recent measurements [1] showed that a considerable part of the allocated radio spectrum is underutilized due to temporal and geographic disparities in how the allocated spectrum is used. The unused frequency bands in time or space are usually termed spectrum holes or white spaces. One way to make efficient use of these spectrum holes is to use Dynamic Spectrum Access (DSA) techniques, which enable secondary (unlicensed) users to make use of the spectrum when primary (licensed) users are not using it.

Primary Users (PUs) have rights to access a certain part of the available spectrum and hence have a higher priority in accessing the spectrum. On the other hand, Secondary Users (SUs) can utilize the spectrum under the condition of not interfering with PUs. Thus, SUs need devices that have the ability to determine whether the spectrum is being utilized at a specific location and at a certain time [2].

Cognitive Radio (CR) is an important enabling technology for DSA which helps SUs make efficient use of the radio spectrum. CR is a wireless communication technology based on Software Defined Radio (SDR), where each device is capable of determining its location, sensing its environment and learning about its radio resources [3]. The device can dynamically adjust its operational parameters, such as transmission frequency and power, to opportunistically utilize the empty frequency bands without disturbing PUs [2], [4]. A CR device has two main characteristics which are cognitive capability and re-configurability [2], [4]. The cognitive capability allows the device to sense the medium and determine the available spectrum bands. Re-configurability enables the CR device to adjust its operating frequency, modulation technique and transmission power without the need for hardware modification.

After the transition from analog TV to digital TV transmissions, large amounts of frequencies in Very High Frequency (VHF) and Ultra High Frequency (UHF) bands have been freed up. These unused frequency portions on the TV broadcasting (UHF and VHF bands) are referred to as TV White Spaces (TVWS). Frequencies in the TV broadcast bands benefit from high bandwidth, long transmission ranges and better building penetration.

A White Space Device (WSD) is a device that can make use of the available white spaces when not being used by incumbent transmitters (TV transmitters or Wireless microphones). This device should not interfere with any of the PUs operating on that band.

This paper will provide an overview on CR architectures, its operation in both licensed and unlicensed bands, and a detailed description of the CR functions. A classification for each cognitive radio function will be also discussed. The rest of the paper is organized as follows: Section II provides a background of the regulation for utilizing white spaces and the countries that started making use of the available white spaces. The architecture of the cognitive radio network is then discussed in Section III. Section IV illustrates the operation of a CR device in the licensed and unlicensed bands. In Section V, CR spectrum management functions are presented and then a detailed description of the techniques used in each function is discussed in Sections VI, VII, VIII and IX. A conclusion is presented in Section X.

II. BACKGROUND

While the USA was not the first country to switch to digital TV, they did become leaders in making the decision to utilize white spaces. The Federal Communications Commission (FCC) allowed unlicensed radio transmitters to operate in the unused frequency portions of the broadcast television spectrum [5]. These unlicensed radio transmitters (secondary devices) have to make sure that they will not interfere with licensed users [6]. The FCC ruling stated that secondary devices must both consult a database which, given a certain a certain location, would be able to provide a list of the available channels at that location, and must also perform a real-time spectrum sensing every minute to ensure that no licensed devices such as wireless microphones exist.

On September 23, 2010 a Memorandum Opinion and Order was released by the FCC [7], in which the final rules for utilizing white spaces for unlicensed wireless devices was determined. The mandatory requirement for using spectrum sensing was eliminated, paving the way for geo-location based channel allocation. Spectrum sensing had been removed from FCC rules due to many reasons: 1) it is time-consuming, 2) it increases development cost, and 3) it inappropriately protect other unlicensed devices, which should not be protected from interference, as it cannot differentiate between licensed and unlicensed devices.

In early 2011, the FCC released an order [9] conditionally designating nine TV white space database operators, including for example, Google, Motorola, and HP. Microsoft was later added to the list of approved operators. The FCC stated that a trial period of 45 days is required for all database operators before being able to announce the public availability of each database. FCC stated also that, using multiple database operators will create a healthy competitive basis between the operators Spectrum Bridge's database was the first trial that began on the 19th of September, 2011.

The second country to make a decision was the UK, when Ofcom published a document on September 2011, which expressed their intention to support commercial utilization of white spaces [10]. In that document, Ofcom mentioned that their approach is based on using geo-location databases rather than alternative approaches like sensing or beacons. Ofcom also explained the UK's preference for a harmonized approach to WSDs across Europe, as it believes that this harmonized European approach would deliver greatest benefits for citizens and consumers. Ofcom said that it will continue the development of new business opportunities while waiting European-wide regulatory decisions.

III. Cognitive Radio Network Architecture

Cognitive Radio Networks (CRNs) or secondary networks do not have licenses to access the spectrum and can be referred to as un-licensed networks. CRNs can be classified based on their architecture [8], [11] as infrastructure-based or ad hoc networks. An example of infrastructure-based network is shown in Fig. 1 [8]. These networks have secondary Base Stations (BSs) or secondary Access Points (APs) that can coordinate the communication between secondary devices in their coverage areas. The secondary APs can be connected together through a wired network (Core network) to allow communication between SUs in different coverage areas.

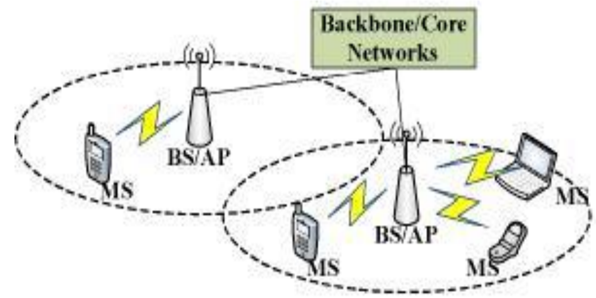

Fig. 1. Infrastructure-based CRN [8].

Ad hoc or distributed CRNs do not require an infrastructure. SUs or CR users can directly communicate with each other using certain communication protocol (Wi-Fi or Bluetooth) or they can utilize the available spectrum bands for their communications as shown in Fig. 2 [8].

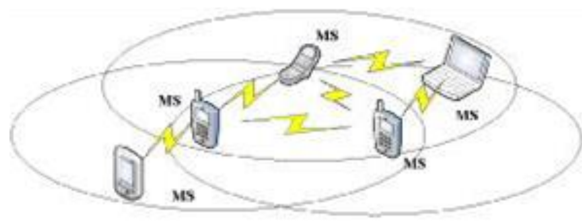

Fig. 2. Ad hoc CRN [8].

CRNs either infrastructure-based or ad hoc networks usually work inside the transmission range of primary networks as shown in Fig. 3 [12]. Primary networks or licensed networks refer to already existing infrastructure-based wireless networks like mobile networks that are allocated certain frequency bands for their operation. The infrastructure of these primary networks consists of base-stations that can control the activities of PUs.

A CR device always has to determine the available white spaces in its location, to avoid interfering with users operating in the licensed band. In infrastructure-based CRNs, CR devices have two different ways to determine the a-vailable spectrum holes. The CR devices can sense the medium and send the sensed information to the base station, which performs the spectrum decision, spectrum sharing and spectrum mobility functions. The other way of determining the available spectrum holes is through the base station itself, which can obtain a list of the available spectrum holes by contacting a database of incumbents. This approach will be covered in detail in Section VI-B.

In ad hoc CRNs, each device should have a cognitive ability, which allows the device to sense the medium and determine the available white spaces in its location. CR devices can cooperate in determining the available spectrum holes by sharing the sensed information with each other (cooperative sensing). A CR device may also get a list of the

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available spectrum holes in its location by connecting to a database of incumbents.

IV. USAGE PRIORITY IN LIENSED BAND

A CR user can operate in licensed and unlicensed band as well [2]. In licensed band operation, the priority is for PUs operations. SUs can use the spectrum when not being used by PUs. SUs have to vacate the channel whenever a PU appears and move to another available channel. In unlicensed band operation, all users have equal opportunity for spectrum access (no priorities).

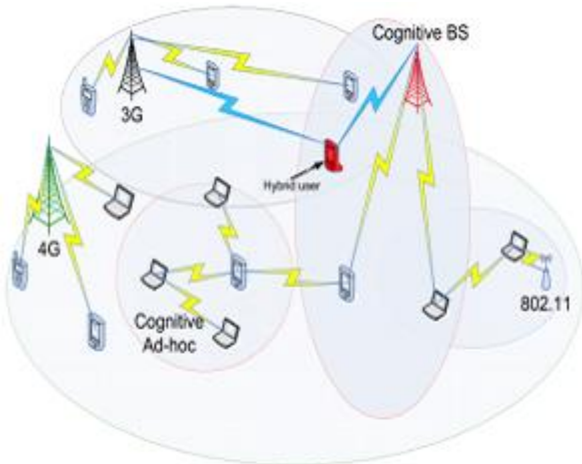

Fig. 3. CRNs operate inside the coverage area of primary networks [12].

V. COGNITIVE RADIO SPECTRUM MANAGEMENT FUNCTIONS

A CR device has to perform four basic functions to be able to manage the available spectrum holes in its location [2], [12]. These functions, illustrated in Fig. 4, are: White Space Determination, Spectrum Decision, Spectrum Sharing, and Spectrum mobility.

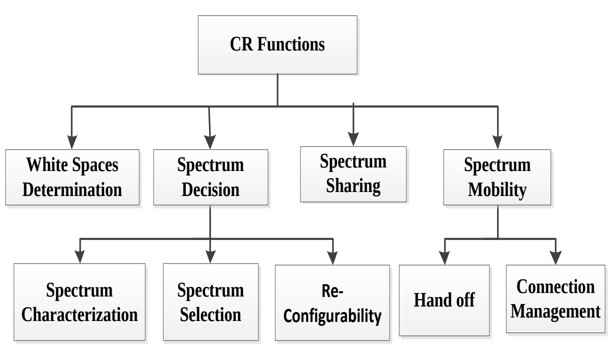

Fig. 4. Cognitive Radio Functions.

The main function of a CR device is to determine the available white spaces at a certain place and at a specific time. After determining the available spectrum holes, the spectrum decision is performed by selecting the best channel for the operation of a CR. Channel selection is usually done based on specific criteria, which could be the policy, Quality of Service (QoS) or avoiding interference to other CR devices. As the spectrum is shared among multiple SUs, Spectrum sharing is required to coordinate how SUs can coexist and access the same spectrum without interfering or colliding with each other. In Spectrum mobility, a CR device has to vacate the channel and move to another available channel if a PU appears on that channel.

VI. DETERMINING AVAILABLE SPECTRUM HOLES

The basic function of any CR device is to be able to determine the available spectrum holes which vary in time and space. A CR device should have the capability to determine its location as the available spectrum differs from one place to another. Also, the device has to repeat the calculation periodically as the available spectrum varies with time. Fig. 5 shows a hierarchal description for the approaches used in determining the available spectrum holes.

A. Spectrum Sensing

Spectrum sensing allows a CR user to periodically sense the spectrum and determine its availability for use by SUs. There are two main categories of spectrum sensing techniques [2], namely, Primary transmitter detection and Primary receiver detection (Fig. 5).

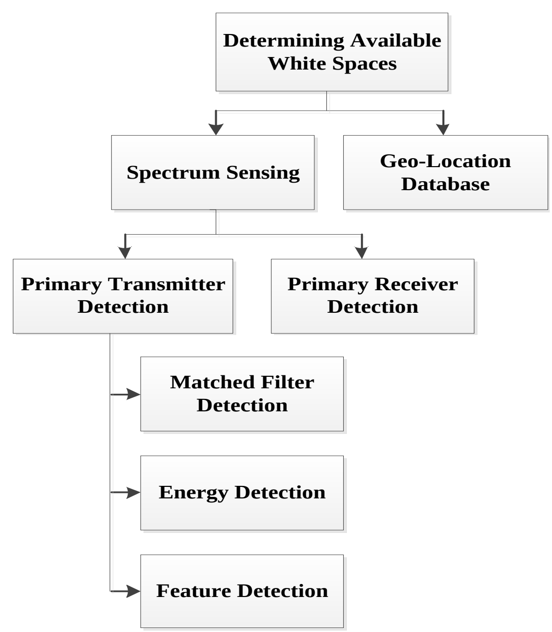

Fig. 5. Methods used for white spaces determination.

In the case of primary transmitter detection, the medium is considered available if the CR device cannot hear the signal sent from any primary transmitter. Three methods [2], [4], [13] can be used for primary transmitter detection. These methods are matched filter detection, energy detection, and feature detection.

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The matched filter detection is the optimal detection in the presence of stationary Gaussian noise. This method maximizes the received Signal to Noise Ratio (SNR), but it requires prior information about the characteristics of the PU's signal. The matched filter operates by correlating the pattern that needs to be detected (known information about the signal) with the received signal. If the magnitude of the resulting signal is above a certain threshold; the medium is considered busy otherwise the medium is free. The matched filter is a fast detection technique, but it requires previous knowledge about the signal to be detected.

In the energy detection, no prior information about the primary transmitter signal is required. In this technique, a CR device measures the energy in a certain frequency band if it is above a predefined threshold; the medium is considered busy. If the measured value is below the threshold the medium is considered free and can be used by SUs. One of the concerns of using energy detection is that it just detects the presence or absence of a signal, but it cannot differentiate whether the detected signal is from a primary transmitter or from a secondary transmitter. Another concern is adjusting the threshold value of the detector as this value is affected by the noise level.

The feature detection, also called cyclostationary detection, depends on detecting the cyclostationary (built-in periodicity) feature of the modulated signal for detecting the presence of a signal. This kind of detector is better than energy detector as it is more robust against the uncertainty in noise power, but requires more observation time and is computationally complex.

A main problem in the primary transmitter detection is the hidden node problem. Where, a CR user may be shadowed from detecting the signal of a primary transmitter, due to the presence of an object that block the transmitter signal, as shown in Fig. 6 [2]. The hidden node problem can be solved by using cooperative spectrum sensing or cooperative detection, which allows the CR devices to share the sensed information with each other. This results in a higher detection capability, but comes with the cost of additional overhead

The primary receiver detection technique is the most efficient technique in determining spectrum holes. In this technique, the CR user needs to detect primary receivers in its communication range and avoid interfering with them. Primary receivers detecting is not an easy process. Usually, primary receivers, such as televisions or cellular phones, are passive, which makes it hard for the CR devices to detect them or determine their location. One way to allow a CR device to detect a primary receiver [14] is by utilizing the leakage power of the Local Oscillator (LO), which is emitted by the RF front end of the primary receivers. This method is currently feasible only in TV receiver detection.

Interference temperature is a model introduced by the FCC [15] to accurately measure and limit the amount of interference at the receiver. Interference temperature dictates the cumulative amount of interference from all the undesired RF energy sources that exist at a receiver at any point of time. Interference temperature provides a higher protection for the receiver against harmful interference. A CR user can use the channel while it does not surpass the limit on interference temperature.

B. Geo-Location Database

In the Geo-location database approach, a CR device does not use spectrum sensing to determine the free spectrum;

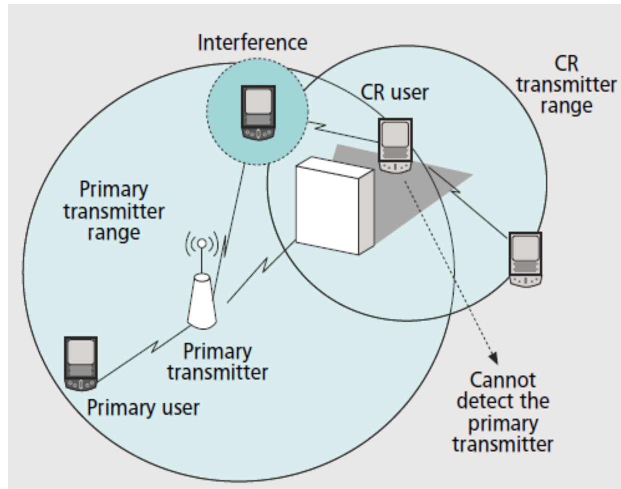

Fig. 6. Shadowing uncertainty [2].

instead it depends on an up-to-data database of incumbents. The database stores information about all primary transmitters and their locations. It also stores terrain information. The data base uses the information it has to calculate available whitespaces at the CR user`s location. According to FCC regulation [6], a CR device should have the capability to determine its location, and a way to connect to the internet to be able to access the database. The process of determining the available whitespaces is done as follows. First, the CR device provides identifying information to register with the database. Then the CR device calculates its location and send it to the database, which uses some propagation models to calculate the available white spaces at the user`s location. After that, the database will send a list of the available white spaces to the user. The database may also inform the device with the maximum allowable transmit power for its operation. In this case, the device can use its adaptable power control to ensure that the transmitting power does not exceed the maximum allowed value. Using a database to calculate spectrum holes overcomes the problem of false alarm that can happen with spectrum sensing and thus provides more efficient use of the spectrum.

Microsoft presented an approach for a geo-location database called “SenseLess: A Database Driven White Spaces Network” [16]. The SenseLess architecture consisted of a logically centralized entity called SenseLess Service. Base stations and CR devices are connected to this central entity which is responsible for determining the available white spaces for any given location. Two components mainly constitute the SenseLess service, the back-end store and the SenseLess engine. The back-end store consisted of a terrain server and a database of incumbents, such as TV transmitters (their location, antenna height, transmission power) and wireless microphones. The database is also used to cache the computed white spaces for different locations. The terrain server store high resolution terrain elevation data which can be obtained from one of the publicly available terrain maps. Sophisticated signal propagation modeling is used by the SenseLess engine to compute the available white spaces at any given location. Results showed that the Longley-Rice (L-R) with terrain propagation model [17] gave accurate results when determining the available white spaces for any given location.

In [18], a White Space Database (WSDB) was used to control the transmit power levels of the White Space Devices (WSDs). WSDs use one of the geo-location capabilities to determine their location and send it to the database. The WSDB sends a list of the available channels to the WSD to ensure that the device will not cause interference to primary incumbents. The database will also inform the device with the transmit power level that it should not exceed. The sum of all WSDs transmit powers should be kept below a certain level to avoid making interference to PUs. Considering these limitations an optimization problem was formulated to control the transmit power while maximizing the total throughput of the system uplink. Solution to the optimization problem becomes the same like the water-filling algorithm problem. Simulation results showed that in the case of using co-channel, increasing the number of users cause the spectrum efficiency to increase. While in case of adjacent channel the spectrum efficiency decrease by increasing the number of users.

VII. SPECTRUM DECISION

Spectrum decision is the capability of a CR device to choose the most appropriate channel for its operation. Channel selection should satisfy Quality of Service (QoS) requirements of SUs and at the same time ensures that they do not cause interference to PUs. Spectrum decision consists of three functions, which are spectrum characterization, spectrum selection and CR re-configurability [19], [11].

The first step after determining the available spectrum holes is to characterize them based on PUs activities and conditions of the radio environment. As the CR user opportunistically utilizes the channel; channel availability can't be guaranteed during the whole period of its transmission because a PU may appear at any time. Modeling PUs activities can be used to predict future usage of the spectrum based on the historical information of previous spectrum usage. The condition of the radio environment is another factor that is used to characterize the channel based on interference, the number of users utilizing the same channel, and the strength of the received signal. Once the channel characterization is done, a channel that satisfies QoS requirements of the SU is selected. The last step is to adjust the transceiver parameters of the CR device to be able to communicate on the selected spectrum band.

VIII. SPECTRUM SHARING

Spectrum sharing is the most challenging function among CR functions. It addresses the problem of coordinating the transmission of CR devices to allow them to coexist and share the medium without causing interference to each other. Spectrum sharing can be categorized according to architecture, scope, spectrum allocation behavior, spectrum sharing models and spectrum access techniques [2], as shown in Fig. 7.

The spectrum sharing architecture can be centralized or distributed. In centralized spectrum sharing, a central unit is responsible for allocating the spectrum and controlling access to it. In distributed spectrum sharing, spectrum allocation and access is done by each node according to a certain policy specified by the node itself.

The spectrum allocation behaviour can be cooperative or non-cooperative spectrum sharing. In the cooperative spectrum sharing, the CR devices cooperate together to avoid interference with each other. Each CR device adjusts its transmission power taking into account other devices transmission. In the non-cooperative spectrum sharing, each CR device behaves in a selfish manner. A CR device will transmit without considering if its transmission will affect other devices transmission. Thus, in the non-cooperative case there will be high interference between CR devices, which in turn will reduce the spectrum utilization.

The spectrum access techniques can be classified as overlay spectrum sharing and underlay spectrum sharing. In the overlay spectrum sharing, SUs can opportunistically make use of the spectrum when not being used by PUs to avoid causing interference to PUs. In the underlay spectrum sharing, SUs can transmit at the same time with PUs as long as their transmission is below the noise floor of PUs. In this case, SUs use spread spectrum techniques and can only transmit over short range.

The spectrum sharing scope in infrastructure-based CRNs, can be classified to intra-cell spectrum sharing and inter-cell spectrum sharing [20]. The intra-cell spectrum sharing is related to spectrum sharing between CR users in the same cell. The inter-cell spectrum sharing is related to spectrum sharing between different cells.

The two spectrum sharing models are exclusive allocation model and common use model [20]. In the exclusive

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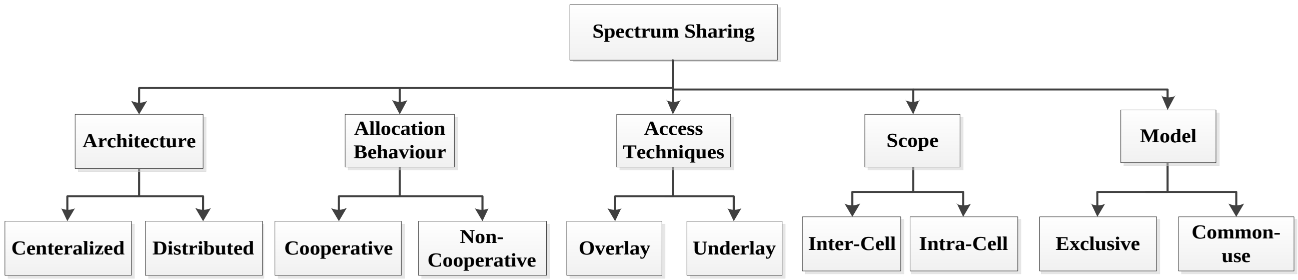

Fig. 7. Spectrum Sharing Categorization.

allocation model, each CR user is allocated a different channel to mitigate the interference between CR users. This model is optimum in maximizing the capacity of the network, but it provides unfair resource allocation in networks that have limited spectrum availability. Although the focus of this approach is on spectrum allocation, power allocation has to be considered to avoid interfering with PUs.

In the common use model, several CR users can simultaneously use the same channel by adjusting their transmission power to minimize interference. This model is preferred in networks with limited spectrum holes; as it can provide fairness in the allocation of the available spectrum. However, the achieved capacity is lower than that of the exclusive model.

Several research papers have been proposed to address the spectrum sharing problem in CRNs. The main differences between papers addressing spectrum sharing techniques are in the model they used for spectrum sharing and the objective of the network.

In [21], a combined power/channel allocation method was applied in a WiFi-like spectrum sharing scenario in TV white spaces. Three types of Secondary Users (SUs) were defined which are protected, interfered and out of range SUs. The network goal was to increase the number of supported SUs while reducing the interference secondary devices cause to each other. They used the NBS to allocate transmit power for Secondary Access Points (SAPs). SAPs cooperate by exchanging the information through relaying nodes. These relaying nodes are the interfered SUs that can hear from more than one SAP. SAPs compete on their transmission powers to maximize the number of supported SUs. SAPs have to decrease their power until there is no overlapping between their coverage areas. Two stage of cooperation were made. In the first stage, only neighboring SAPs cooperate and compete for power control, while in the second stage, all the next hop neighboring SAPs can cooperate. When the SAPs are highly overlapped, the algorithm can switch to channel allocation instead of power allocation to enhance the network performance. The switch is done if the number of interfered secondary users was above a certain number. Simulation results showed that the number of iteration required to reach optimality is decreased by SAPs cooperation. The number of supported users increased while the average SAP throughput decreased.

A downlink channel assignment and power control for an infrastructure-based cognitive radio network was implemented in [22]. The opportunistic spectrum access problem was formulated as a non-cooperative game in which the game players are the base stations. Each base station bargain to increase the number of supported CRs. Channel allocation was done by the base stations, which randomly assign channels to users. A distributed power allocation is then applied using the Iterative Water Filling algorithm. Results showed that the pure non cooperative game might have multiple Nash equilibrium points [23] that are undesirable and may lead to non-convergence. To obtain better results, the Nash bargaining solution was applied in which the cooperation of base stations was required. Simulation results showed that a unique optimal solution was achieved by using the Nash bargaining solution.

IX. Spectrum Mobility

Spectrum mobility is the process of performing a seamless transition from one channel to another available channel. After a CR user selects the channel and starts transmitting on a certain frequency band, a PU may appear on the same channel; in this case the CR user has to move to another empty channel and vacate this channel to PU to avoid causing interference to the PU. The SU may also change its channel to access another spectrum hole with better QoS. Spectrum mobility consists of two processes [24], spectrum handoff and connection management.

In the spectrum handoff process, the SU transmission is transferred from its current channel to another empty channel. Three events can trigger the spectrum handoff process. The first event is the arrival of a PU in a channel occupied by a SU. The second is the spatial movement of SUs to a place where their coverage overlap with PUs already utilizing the channel. The third is the degradation of the link quality.

The spectrum handoff process consists of two phases, evaluation phase and link maintenance phase. In the evaluation phase, the SU keep monitoring the environment to determine if an event that trigger spectrum handoff occurred, then the SU moves to the next phase (Link maintenance). In the Link maintenance phase, the SU pauses its transmission on the current channel and continues the transmission on another available channel.

Connection management process is used to compensate for the unavoidable handoff delay, which happens when the SU transmission is transferred from a channel to another, by adjusting the parameters of the protocol stack according to the existing situation.

X. CONCLUSION

In this paper, we have presented a comprehensive overview of the CRN architecture and operation in licensed and unlicensed bands. The paper focused on the four CR spectrum management functions, white space determination, spectrum decision, spectrum sharing, and spectrum mobility. The white spaces can be calculated using either spectrum sensing or geo-location database. Most of the papers in the literature use spectrum sensing to calculate white spaces. However, the geo-location database approach is more accurate and efficient. Also, it overcomes spectrum sensing problems such as false alarms. The decision to select one of the white spaces depends on characterizing all the available white spaces based on the PUs activities and the conditions of the radio environment. The CR device transceiver is then adjusted to operate on the selected band. Sharing the spectrum is a very interesting and challenging function throughout the CR functions. Spectrum sharing is concerned with the way that enables all the CRNs to coexist and share the same spectrum without interfering with PUs or with each other. The spectrum sharing function was comprehensively covered according to different aspects, architecture, scope, allocation behavior, sharing models, and access techniques. The spectrum mobility was used to avoid interfering with PUs by transferring CR users to another available channel if a PU appears on that channel.

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