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THE KEY FUNCTIONS FOR COGNITIVE RADIOS IN NEXT GENERATION NETWORKS: A SURVEY

Suhail Ahmad, Computer Science & Engineering Department, University of Kashmir, Srinagar (J & K), India, *sa_mir@in.com*;
Ajaz Hussain Mir, E & C Engineering Department, National Institute of Technology, Srinagar (J & K), India, *ahmir@rediffmail.com*

Abstract

The limited available spectrum and the fixed spectrum allocation by governmental agencies results in inefficient use of it. This fixed allocation and inefficient usage necessitate a new communication paradigm which is referred as Next Generation (xG) Network Technology. This new networking paradigm also termed as cognitive radio (CR) technology as well as Dynamic Spectrum Access is envisaged to solve the problem of limited spectrum availability by opportunistic spectrum access. CR networks, equipped with the intrinsic capabilities of the cognitive radio, will provide an ultimate spectrum aware communication paradigm in wireless communication. The scope of this work is to give an overview of the important function for CRs in xG networks which include spectrum sensing, spectrum management, spectrum mobility and spectrum sharing. The current research challenges and the novelties in terms of functionality are explained in detail.

Keywords: ***Cognitive radio, Spectrum Sharing, Spectrum Sensing, Spectrum Sharing, Spectrum Mobility***

1. Introduction

Cognitive radio (CR) is a promising technology geared to solve the spectrum scarcity resulted from fixed spectrum assignment policy. In the fixed spectrum assignment policy the spectrum is regulated by the government agencies and is assigned to license holders on a long term basis for large geographical regions. This fixed assignment policy results in sporadic usage of spectrum as shown in fig. 1, where the signal strength distribution over a large portion of the wireless spectrum is shown. The spectrum usage is concentrated on certain portions of the spectrum while a large amount of spectrum remains under-utilized [1].

In order to address critical spectrum scarcity problem and the inefficient usage of spectrum, the FCC has recently approved the use of unlicensed devices in licensed bands. As a result, dynamic spectrum access (DSA) techniques are proposed to solve these current spectrum inefficiency problems. This new area of research foresees the development of cognitive radio (CR) networks to further improve spectrum efficiency. The basic idea of cognitive radio networks is that the unlicensed devices (also referred as secondary users (SU) or CR users) need to vacate the licensed band when the primary user (PU or licensed device) is detected.

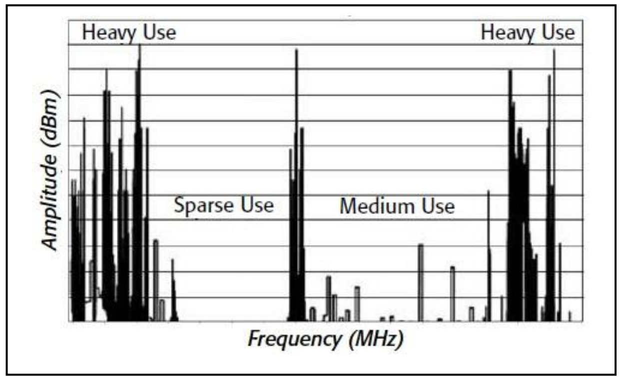

Figure1. Spectrum utilization

The key enabling technology of xG networks is cognitive radio. Cognitive radio techniques enables user to use or share the spectrum in an opportunistic manner. CR enabled devices can use Dynamic spectrum access to operate in best available channel. The formal definition of the term cognitive radio is as follows [2]:

"A cognitive radio is a radio that can change its transmitter parameters based on its interaction with the environment in which it operates. This interaction may involve active negotiation or communications with other spectrum users and/or passive sensing and decision making within the radio. The majority of cognitive radios will probably be SDRs, but neither having software nor being field reprogrammable are requirements of a cognitive radio."

According to this definition, two important characteristics of cognitive radio can be defined as follows [3, 4]:

- *Cognitive capability:* It refers to the ability of the radio technology to capture or sense the information from its radio environment. This capability cannot be realized simply by monitoring the power in some frequency bands but by using sophisticated techniques like autonomous learning and action decision are required in order to capture the temporal and spatial variation in the radio environment and avoid interference to other users. From this capability, the portions of the spectrum that are unused at a specific time or location can be identified. As a result, the best spectrum and appropriate operating parameters can be selected. The tasks which are very vital for operating in open spectrum formulate a cycle as shown in fig. 2, which is often referred as cognitive cycle [3, 4, 5].

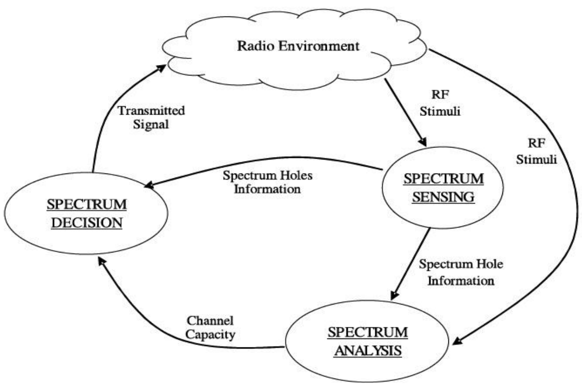

Figure 2. Cognitive cycle

The three main steps of the cognitive cycle are spectrum sensing, spectrum analysis and spectrum decision. These will be discussed in sections 2, 3 and 4.

• *Re-configurability:* Re-configurability enables the radio to be dynamically programmed according to the environment. More specifically, the cognitive radio can be programmed to transmit and receive on a variety of frequencies and to use different transmission access technologies supported by its hardware design [6]. Several reconfigurable parameters that can be incorporated into the cognitive radio to achieve re-configurability are:

• *Operating frequency:* A cognitive radio is capable of changing the operating frequency while the communication is going on. This change is based on the information sensed from the radio environment, then the most suitable operating frequency can be determined and the communication is dynamically performed on this appropriate operating frequency.

• *Transmission power:* Another key reconfigurable parameter is transmission power which can be configured within the power constraints. This enables dynamic transmission power configuration within the permissible power limit.

• *Modulation:* A cognitive radio should reconfigure the modulation scheme adaptive to the user requirements and channel conditions. For example, in the case of loss-sensitive applications, the error rate is more important than the data rate. Thus, the modulation scheme that enables the high reliability should be selected. Conversely, the delay sensitive applications focus on the data rate, which necessitate modulation schemes with high spectral efficiency bit error rate.

• *Communication technology:* A cognitive radio can also be used to provide interoperability among different communication systems.

The transmission parameters of a cognitive radio can be reconfigured while the transmission is going on not only at the beginning of a transmission. According to the spectrum characteristics, these parameters can be reconfigured such that the cognitive radio is switched to a different spectrum band, the transmitter and receiver parameters are reconfigured and the appropriate communication protocol parameters and modulation schemes are used.

The ultimate objective of cognitive radio is to obtain the best available spectrum through cognitive capability and to adjust transmission parameters using re-configurability. More specifically, the cognitive radio technology will enable the users to determine (a) which portions of the spectrum is available and detect the presence of primary users when the secondary user operates in the licensed band (Spectrum Sensing), (b) select the best available channel (Spectrum Management), (c) coordinate access with others users (Spectrum Sharing), and (d) vacate the channel when a licensed user is detected (Spectrum mobility).Once the aforementioned objectives are met, the next challenge is to make the network protocols adaptive to the available spectrum. Hence, new functionalities are required in an xG network to support this adaptivity. In brief, the critical functions for cognitive radio technology in xG networks can be summarized as:

- *Spectrum Sensing:* is the functionality enabling cognitive radios to be aware of spectrum usage and to detect spectrum opportunities
- *Spectrum Management:* Capturing the best available spectrum to meet the user communication requirements.
- *Spectrum Mobility:* Maintaining seamless transmission, a cognitive radio vacates its channel and reconstructs a transmission link on a different channel.
- *Spectrum sharing:* Provides the capability to maintain the QoS for CR users without causing interference to the primary users by coordinating the multiple accesses of CR users as well as allocating communication resources adaptively to the changes of radio environment.

This paper presents the critical functions required and current research challenges of the CR networks. In section 2, a brief overview of spectrum sensing techniques and challenges are discussed. In section 3-5, we explain the existing work and challenges in spectrum management, spectrum mobility and spectrum sharing, respectively. However, the complete analysis of spectrum sharing is taken as the future work in this area. Finally, conclusion is given in section 6.

2. Spectrum Sensing

Spectrum sensing a key function in CR networks is used to determine the vacant spectrum opportunities and to avoid interference with the PUs. In brief, CR monitors spectrum bands, captures information, and tries to detect spectrum holes. Cognitive radios have to account for situations where there can be presence of PUs and SUs occupying the same channel space like in licensed band scenarios or when there are no primaries and every cognitive radio contends with other cognitive and non-cognitive radio for spectrum in the unlicensed band. The two main approaches for spectrum sensing techniques for CR networks are primary receiver detection and primary transmitter detection [7]. The primary receiver is based on determining the PUs that are receiving data within the communication range of a CR user. However, it is difficult for a cognitive radio to have a direct measurement of a channel between a receiver and a transmitter. The primary transmitter detection aims at finding the weak signal from a primary transmitter through the local observations of CR users. Thus, the most recent work focuses on primary transmitter detection based on local observations of CR users.

In general, spectrum sensing techniques can be classified as transmitter detection, cooperative detection and interference-based detection [7] as shown in Fig. 3.

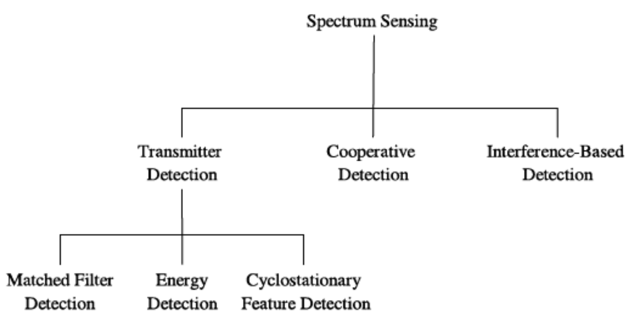

Figure 3. Spectrum Sensing Techniques

2.1 Transmitter Detection

In transmitter detection, the CR user should distinguish between used and unused spectrum bands, i.e. CR users should have the capability to detect their own signal from a PU transmitter. Transmitter detection focuses on the detection of the weak signal from a primary transmitter through the local observations of xG users. The transmitter detection can be expressed by the following hypothesis [8]:

$$x(t) = \begin{cases} n(t) & H_0, \\ hs(t) + n(t) & H_1, \end{cases}$$

where x(t) is received signal received by the CR user, s(t) is the transmitted signal of the PU, n(t) is the AWGN and h is the amplitude gain of the channel. H_0 is a null hypothesis, which states that there is no licensed user signal in a certain spectrum band. H_1 is an alternative hypothesis, which indicates that there exists some licensed user signal. Three schemes are generally used for transmitter detection in spectrum sensing [9]: matched filter detection, energy detection and feature detection.

2.1.1 Matched Filter Detection

The matched filter is a linear optimal filter used for coherent signal detection to maximize the signal-to-noise ratio (SNR) in the presence of additive stochastic noise. It is obtained by correlating a known original PU signal s(t) with a received signal r(t) where T is the symbol duration of PU signals, as shown in fig. 4 [10]. Then the output of the filter is sampled at the synchronized timing. If the sampled value Y is greater than the threshold λ, the spectrum is determined to be occupied by the PU transmission otherwise spectrum is free.

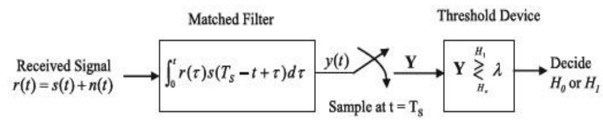

Figure 4. Matched Filter Detection

This detection method is referred an optimal detector in stationary Gaussian noise. However, the matched filter requires not only a priori knowledge of the characteristics of the PU signal but also the synchronization between the PU transmitter and the CR user. If this information is not accurate, then the matched filter performs poorly. Also, CR users need to have different multiple matched filters dedicated to each type of the PU signal, which increases the implementation cost and complexity. For more practical implementation, a pilot signal of PU systems is used for the matched filter detection in [11].

2.1.2 Energy Detection

It is a non coherent detection optimal method to detect the unknown signal if the noise power is known. Due to its simplicity and no requirement on a priori knowledge of primary user signal, energy detection is the most popular sensing technique [11, 12, 13]. In this method, CR users sense the presence/absence of the PUs based on the energy of the received signals. As shown in Fig. 5, the measured signal r(t) is squared and integrated over the observation interval T. Finally, the output of the integrator is compared with a threshold λ to decide if a PU is present or not [14].

r (t)= s (t) + n (t)

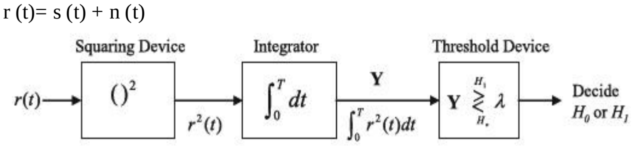

Figure 5. Energy Detection

Energy detection method is also referred as Blind signal detector because it ignores the structure of the signal. It estimates the presence of the signal by comparing the energy received with a known threshold λ derived from the statistics of the noise. Analytically, it can be expressed again by the same hypothetical model as:

$$x(t) = \begin{cases} n(t) & H_0, \\ hs(t) + n(t) & H_1, \end{cases}$$

Where x (t) is the sample to be analyzed at each instant t and n (t) is the noise of variance σ^2. Let x (t) be a sequence of received samples t $\in$ {1, 2….N} at the signal detector, then a decision rule can be stated as,

H_0 if $\varepsilon < \lambda$

H_1 if $\varepsilon > \lambda$; Where $\varepsilon = E\,|y(t)|^2$ the estimated energy of the received signal and λ is chosen to be the threshold.

Energy detector is easy to implement but it has several shortcomings. It requires $O(1/SNR^2)$ samples for a given detection probability [9,15]. Thus, in case of energy detection if CR users need to detect weak PU signals (SNR: -10 dB to -40 dB), the energy detection takes longer detection time compared to that of matched filter detection. Also, since the energy detection depends only on the SNR of the received signal, its performance is susceptible to uncertainty in noise power. If the noise power is uncertain, the energy detector will not be able to detect the signal reliably as the SNR is less than a certain threshold, referred as SNR wall [16]. Also, the energy detector can only determine the presence of the signal but cannot differentiate signal types. Thus, the energy detector is prone to the false detection triggered by the unintended CR signals.

2.1.3 Feature Detection

In feature detection the presence of primary user is detected by extracting their specific features such as pilot signals, symbol rate, cyclic prefixes, spreading codes or modulation types from local observation. These features introduce built-in periodicity in the modulated signals, which can be detected by analyzing a spectral correlation function as shown in Fig. 6. The feature detection leveraging this periodicity is also called cyclostationary detection. Here, the spectrum correlation of the received signal r(t) is averaged over the interval T, and compared with the test statistic to determine the presence of PU signals, similar to energy detection [9].

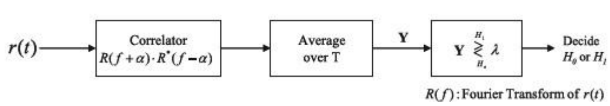

Figure 6. Feature Detection

The distinguishing feature of this method of sensing is its robustness to the uncertainty in noise power. Also, it can distinguish the signals from different networks. This method allows the CR user to perform sensing operations independently of those of its neighbors without synchronization. Although feature detection is most effective but it is computationally complex and requires significantly long sensing time [17].

In [18], the enhanced feature detection scheme combining cyclic spectral analysis with pattern recognition based on neural networks is proposed. The distinct features of the received signal are extracted using cyclic spectral analysis and represented by both spectral coherent function and spectral correlation density function. The neural network, then, classifies signals into different modulation types. In [19], it is shown that the feature detection enables the detection of the presence of the Gaussian minimum shift keying (GMSK) modulated GSM signal (PU signal) in the channel under severe interference from the orthogonal frequency division multiplexing (OFDM) based wireless LAN signal (CR signal) by exploiting different cyclic signatures of both signals.

A covariance-based detection scheme based on the autocorrelations or statistical covariance of the received signal is proposed in [20]. The statistical covariance matrices or autocorrelations of signal and noise are generally different. The statistical covariance matrix of noise is determined by the receiving filter. Based on this characteristic, it differentiates the presence of PU users and noise. The method can be used for various signal detection applications without knowledge of the signal, the channel and noise power.

The comparison of different transmitter detection techniques for spectrum sensing and the spectrum opportunities is shown in fig. 7. It is clear from the figure that matched filter based detection is complex to implement in CRs, but has highest accuracy. Similarly, the energy based detection is least complex to implement in CR system and least accurate compared to other approaches. And other approaches are in between of these two [21].

2.2 Cooperative Detection

Cooperative detection refers to spectrum sensing techniques where information from multiple CR users is used for primary user detection. In next Generation networks, each CR user needs to determine spectrum availability by itself depending only on its local observations. However the observation range of the CR user is small and typically less than its transmission range. Thus, even though CR users find the unused spectrum portion, their transmission may cause interference at the primary receivers inside their transmission range, which is referred receiver uncertainty problem [7]. Also, if the CR user receives a weak signal with a low signal-to-noise ratio (SNR) due to multi-path fading, or it is located in a shadowing area, it cannot detect the signal of the PUs. Thus, in CR networks, spectrum sensing necessitates an efficient cooperation scheme in order to prevent interference to PUs outside the observation range of each CR user [7, 22].

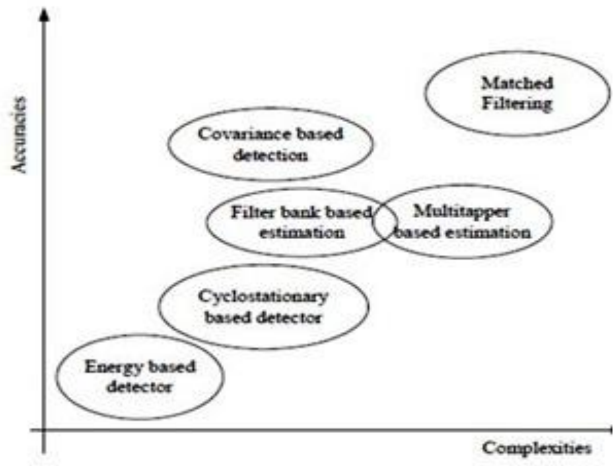

Figure 7. Sensing accuracy and complexity of various sensing methods

For cooperation, when a CR user detects the PU activities, it should notify its observations promptly to its neighbors to evacuate the busy spectrum. For this, a reliable control channel is needed for discovering neighbors of a CR user as well as exchanging sensing information. In addition to this, asynchronous sensing and transmission schedules make it difficult to exchange sensing information between neighbors. Thus, robust neighbor discovery and reliable information exchange are critical issues in implementing cooperative sensing in CR Networks.

In [23], a scheme for wireless mesh networks is proposed, where the mesh router and the mesh clients supported by it form a cluster. Here, the mesh clients send their individual sensing results to the mesh router, which are then combined to get the final sensing result. In [24], a notification protocol based on in-band signaling is proposed to disseminate the evacuation information among all CR users and thus evacuate the licensed spectrum reliably. This protocol uses the spreading code for its transmission, leading to tolerance in interference from both primary and other CR transmissions. Furthermore, due to its flooding-based routing scheme, it requires little prior information on the network topology and density.

In [25], an optimal cooperative sensing strategy is proposed, where the final decision is based on a linear combination of the local test statistics from individual CR users. The combining weight for each user's signal indicates its contribution to the cooperative decision making. For example, if a CR user receives a higher-SNR signal and frequently makes its local decision consistent with the real hypothesis, then its test statistic has a larger weighting coefficient. In case of CR users in a deep fading channel, smaller weights are used to reduce their negative influence on the final decision.

Cooperative detection is theoretically more accurate since the uncertainty in a single user's detection can be minimized through collaboration [26]. Moreover, shadowing effects and multipath fading can be mitigated so that the detection probability is improved in a heavily shadowed environment. While cooperative approaches provide more accurate sensing performance, they cause adverse effects on resource-constrained networks due to the overhead traffic required for dissemination of sensing information.

2.3 Interference based detection

The basic idea behind the interference based detection is to set up an upper interference limit for given frequency band in specific geographic location such that the CR users are not allowed to cause harmful interference while using the specific band in specific area. Typically, CR user transmitters control their interference by regulating their transmission power (their out of band emissions) based on their locations with respect to primary users. This method basically concentrates on measuring interference at the receiver.

This new method for measuring interference, referred to as interference temperature model shown in Fig. 8 has been introduced by the FCC [27]. The model shows the signal of a radio station designed to operate in a range at which the received power approaches the level of the noise floor. As additional interfering signals appear, the noise floor increases at various points within the service area, as indicated by the peaks above the original noise floor. The interference temperature model accounts for the cumulative RF energy from multiple transmissions and sets a maximum cap on their aggregate level. As long as xG users do not exceed this limit by their transmissions, they can use this spectrum band. In [28], a direct receiver detection method is presented, where the local oscillator (LO) leakage power emitted by the RF front-end of the primary receiver is exploited for the detection of primary receivers. In order to detect the LO leakage power, low-cost sensor nodes are mounted close to the primary receivers. The sensor nodes detect the leakage LO power to determine the channel used by the primary receiver and this information is used by the unlicensed users to determine the vacant spectrum.

However, there exist some limitations in measuring the interference temperature. In [29], the interference is defined as the expected fraction of primary users with service disrupted by the CR operations. This method considers factors such as the type of unlicensed signal modulation, power control, antennas, ability to detect active licensed channels, and activity levels of the licensed and unlicensed users. However, this model describes the interference disrupted by a single CR user and does not consider the effect of multiple CR users. In addition, if CR users are unaware of the location of the nearby primary users, the actual interference cannot be measured using this method.

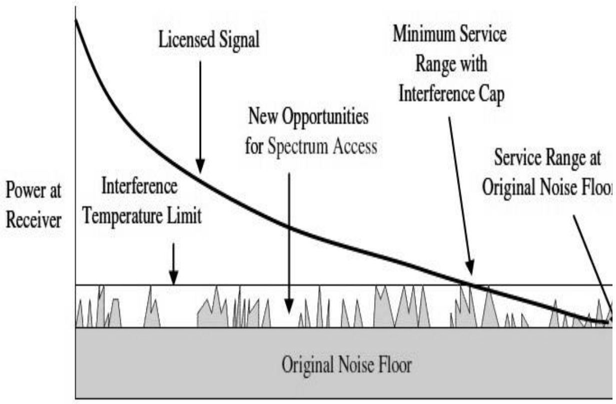

Figure 8. Interference temperature model

2.4 Research challenges in spectrum sensing

There are various research challenges that need to be addressed inorder to formulate the best spectrum sensing function and some of them are as follows:

Detection Capability: The main requirement of CR networks is the detection of the primary users in a very short time. OFDM based CR networks are known to be excellent fit for the physical architecture of xG networks [30, 31]. Since in OFDM based xG networks multicarrier sensing can be exploited which reduces the sensing time. In [30] power based sensing algorithm is used to detect the presence of primary users. The overall detection time is reduced by collecting information from each carrier but it increases the design complexity. Hence, efficient sensing algorithms need to be developed such that the complexity can be reduced within a given detection error probability.

Optimization of cooperative sensing: Cooperative sensing involves sharing of sensing information among the CR users. This improves the accuracy of sensing at the cost of increased network traffic. It also results in higher latency in collecting and this information and due to channel contention and packet re-transmission. Hence, efficient cooperative techniques are required for correct and efficient sensing.

Effect of Multi-user networks: The CR users work in multi-user networks wherein multiple CR users and PUs operate. Also there may be other CR users contenting for the same spectrum band. However current interference models do not consider the effect of multiple CR users [29]. The Multi-user environment imposes more challenges to the CR user to sense the PUs and to estimate the actual interference. So, sensing techniques should be developed which will consider this multi-user environment.

Interference temperature measurement: A CR user is aware of its transmission power level and its precise location with the help of a positioning system. With this ability, however, its transmission could cause significant interference at a neighboring nodes receiving on the same frequency. However, currently, there exists no practical way for a cognitive radio to estimate the interference temperature at nearby primary receivers as these are usually passive devices, a CR user cannot be aware of the precise locations of primary receivers. Hence, if the CR users cannot measure the effect of their transmission on all possible receivers, a useful interference temperature measurement may not be feasible and we cannot formulate an efficient temperature model.

3. Spectrum Management

The main aim of Cognitive radio technology is to improve the usage of scarce electromagnetic spectrum resource by operating in unused spectrum bands that may be spread over wide frequency range including both licensed and unlicensed bands. As these unused licensed and unlicensed bands may be spread over a wide range, the CR networks should decide on the best spectrum band to meet the QoS requirements over all available spectrum bands. To achieve this new spectrum management functions are required for CR networks. These functions can be classified as spectrum sensing, spectrum analysis, and spectrum decision. While spectrum sensing has been discussed in previous section, which is primarily a PHY layer issue, spectrum analysis and spectrum decision are closely related to the upper layers. In this section, spectrum analysis and spectrum decision are investigated.

3.1 Spectrum analysis

In CR networks, the available spectrum holes show different characteristics which vary over time. Since the CR users are equipped with the cognitive radio based physical layer, it is important to understand the characteristics of different spectrum bands. Spectrum analysis enables the characterization of different spectrum bands, which can be exploited to get the spectrum band appropriate to the user requirements. In order to describe the dynamic nature of CR networks, each spectrum hole should be characterized considering the primary user activity and the spectrum band information such as operating frequency and bandwidth. Hence, it is essential to define parameters such as interference level, channel error rate, path-loss, link layer delay, and holding time that can represent the quality of a particular spectrum band.

Since spectrum being the shared resource and some spectrum bands can be crowded compared to others. Hence the spectrum in use determines the interference characteristics of the channel. The path loss factor is associated with the frequency. It increases with the increase in frequency and as a result, if transmission power is kept constant, than the transmission range reduces with the increase in frequency. Now, if transmission power is increased to compensate the path loss, this results in higher interference to other users. Another important factor being the holding time refers to the expected time duration that the CR user can occupy a licensed band before getting interrupted. The longer holding time results in better quality. Frequent spectrum handoff can decrease the holding time, so previous statistical patterns of handoff should be considered while designing the CR networks with large expected holding time.

Channel capacity can be derived from the above mentioned parameters. The related work [28, 30] on spectrum analysis only focuses on spectrum capacity estimation. However, besides the capacity, other factors such as link error rate, delay, and holding time also have significant influence on the quality of services. Moreover, the capacity is closely related to both interference level and path loss. However, a complete analysis and modeling of spectrum in CR networks is yet to be developed.

3.2 Spectrum decision

Based on the characteristics of spectrum bands, appropriate operating spectrum band should be selected for the current transmission considering the QoS requirements and the spectrum characteristics. Hence, the spectrum management function must be aware of user QoS requirements. Based on the user requirements, acceptable error rate, delay bound, the transmission mode, the data rate and the bandwidth of the transmission can be determined. Then, according to the decision rule, the set of appropriate spectrum bands can be chosen from these parameters. Five spectrum decision rules are presented in [32], which are focused on fairness and communication cost. However, this method assumes that all channels have similar throughput capacity. An opportunistic frequency channel skipping protocol is proposed in [33], for the search of better quality channel, where this channel decision is based on SNR. In order to consider the primary user activity, the number of spectrum handoff, which happens in a certain spectrum band, is used for spectrum decision [34]. Thus the main functionalities required for spectrum decision are:

- *Spectrum characterization:* Based on the observation of radio environment and PU activity, the CR users determine not only the characteristics of each available spectrum but also its PU activity model.
- *Spectrum selection:* The CR user finds the best spectrum band for each hop on the determined end-to-end route so as to satisfy end-to-end QoS requirements.
- *Reconfiguration:* Besides route and spectrum selection, spectrum decision involves reconfiguration of CR users. The CR users reconfigure communication protocol as well as communication hardware and RF front-end according to the radio environment and user QoS requirements. The adaptive protocols are developed in [35] to determine the transmission power as well as the best combination of modulation and error correction code for a new spectrum band by considering changes in the propagation loss.

3.3 Spectrum management challenges

The various challenges that the researchers need to address in defining optimum spectrum management function are as follows:

Multiple spectrum bands: In CR networks, multiple spectrum bands can be simultaneously used for the transmission. Also, the CR networks do not require the selected multiple bands to be contiguous. Thus, a CR user can send packets over non-contiguous spectrum bands. This multi-spectrum transmission shows less quality degradation during the spectrum handoff compared to the conventional transmission on single spectrum band [36]. A spectrum management framework should support multiple spectrum decision capabilities but to determine the number of spectrum bands and how to select the set of appropriate bands are still open research issues in CR networks.

Joint spectrum decision and reconfiguration framework: Once the available spectrum bands are characterized, the most appropriate spectrum band should be selected by considering the QoS requirements (delay, jitter, average session time, acceptable loss rate, etc) and the spectrum characteristics. However, according to the reconfigurable transmission parameters such as modulation type, error control scheme, and communication protocol, these spectrum characteristics change significantly. Sometimes, with only reconfiguration, CR users can maintain the quality of the current session. Thus there is a need for a joint spectrum decision and reconfiguration framework so as to find the optimal combination of the spectrum band and parameter configuration according to applications with diverse QoS requirements.

Decision model: A simple decision model based on Signal to noise ratio is not enough to characterize the spectrum band in CR networks. Besides the SNR, many spectrum characterization parameters would affect the quality. Thus, how to combine these spectrum characterization parameters for the spectrum decision model is still an open issue.

4. Spectrum Mobility

CR users are generally regarded as visitors to the licensed spectrum. Hence, if the specific portion of the spectrum in use is required by a PU, the communication needs to be continued in another vacant portion of the spectrum. This notion is called spectrum mobility. Spectrum mobility gives rise to a new type of handoff in CR networks, the so-called spectrum handoff, in which, the users transfer their connections to an unused spectrum band. In CR networks, spectrum handoff occurs:

- when PU is detected,
- with a current spectrum band cannot provide the QoS requirements,
- the CR user loses its connection due to the mobility of users involved in an on-going communication.

The main functionalities required for spectrum mobility in CR networks are spectrum handoff and connection management. These are discussed in following sub-sections.

4.1 Spectrum handoff

Spectrum mobility gives rise to a new type of handoff in CR networks, referred as spectrum handoff. Spectrum handoff can be implemented based on two different strategies: reactive and proactive. In reactive spectrum handoff, CR users perform spectrum switching after detecting link failure due to spectrum mobility. This method requires immediate spectrum switching without any preparation time, resulting in significant quality degradation in on-going transmissions. On the other hand, in proactive spectrum handoff CR users predict future activity in the current link and determine a new spectrum while maintaining the current transmission, and then perform spectrum switching before the link failure happens. Since proactive spectrum handoff can maintain current transmissions while searching a new spectrum band, the spectrum switching is faster but requires more complex algorithms for these concurrent operations. Depending on the events that trigger the spectrum mobility, different handoff strategies are needed.

Spectrum handoff delay is an important factor in determining the performance of spectrum mobility. This delay is dependent on the following operations in CR networks: First, the different layers of the protocol stack must adapt to the channel parameters of the operating frequency. Also we need to consider the spectrum and route recovery time and the actual switching time determined by the RF front-end reconfiguration. Furthermore, to find the new spectrum and route, CR users need to perform out-of band sensing and neighbor discovery. Furthermore, for more efficient spectrum discovery in out-of-band sensing, IEEE 802.22 adopts the backup channel lists which are selected and maintained so as to provide the highest probability of finding an available spectrum band within the shortest time [37]. Algorithm for updating the backup channel lists is proposed in [38] to support fast and reliable opportunity discovery with the cooperation of neighbor users.

To overcome the effect of delay on the on-going transmission, connection management needs to coordinate the spectrum switching by collaborating with upper-layer protocols, which will be explained in the following subsection.

4.2 Connection Management

When the current operational frequency becomes busy in the middle of a communication by a CR user, then applications running in this node have to be transferred to another available frequency band. However, the selection of new operational frequency may take time. An important requirement of connection management protocols is the information about the duration of a spectrum handoff. Once the latency information is available, the CR user can predict the influence of the temporary disconnection on each protocol layer, and accordingly preserve the ongoing communications with only minimum performance degradation through the reconfiguration of each protocol layer and an error control scheme.

4.3 Spectrum mobility research challenges

This subsection discusses the open research issues for efficient spectrum mobility in CR networks.

Spectrum mobility in time domain: CR networks adapt to the wireless spectrum based on available bands of the spectrum. Since these available channels change over time, enabling QoS in this environment is challenging. The physical radio should move through the spectrum to meet the QoS requirements.

Spectrum mobility in space: The available bands also change as a user moves from one place to another. Hence, continuous allocation of spectrum is a major challenge in such networks.

Switching delay management: The spectrum switching delay is associated not only with hardware, such as an RF front-end, but also to algorithm development for spectrums sensing, spectrum decision, link layer, and routing. Thus, it is desirable to design spectrum mobility in a cross-layer approach to reduce the operational overhead among each functionalities and to achieve a faster switching time. Also, the estimation of accurate latency in spectrum handoff is essential for reliable connection management.

Flexible spectrum handoff framework: As stated previously, there are two different spectrum handoff strategies: reactive and proactive, which show different influence on the communication performance. Furthermore, spectrum handoff should be performed while adapting to the type of applications and network environment. In case of a delay-sensitive application, CR users can use a proactive switching, instead of a reactive switching. In this method, through the prediction of PU activities, CR users switch the spectrum before PUs appear, which helps to reduce the spectrum switching time significantly. On the other hand, energy constrained devices such as sensors need reactive spectrum switching. Thus, we need to develop a flexible spectrum handoff framework to exploit different switching strategies.

5. Spectrum Sharing

Spectrum sharing provides the capability to maintain the QoS of CR users without causing interference to the PUs by coordinating the multiple access of CR users as well as allocating communication resources adaptively to the changes of radio environment. Thus, spectrum sharing is performed in the middle of a communication session and within the spectrum band, and includes many functionalities of a medium access control (MAC) protocol and resource allocation in classical ad hoc networks. However, the unique characteristics of cognitive radios such as the coexistence of CR users with PUs and the wide range of available spectrum incur substantially different challenges for spectrum sharing in CR Networks. Spectrum sharing techniques are generally focused on two types of solutions, i.e., spectrum sharing inside a CR network (intra-network spectrum sharing), and among multiple coexisting CR networks (inter-network spectrum sharing) [7].

The spectrum sharing techniques can be classified into three categories [7]:

Architecture based: includes centralized and distributed spectrum sharing approaches.

Spectrum allocation behavior: includes cooperative and non-cooperative spectrum sharing approaches.

Spectrum access technique: includes overlay and underlay approaches.

The analysis of CR spectrum sharing technique has been investigated by various researchers which include [32, 39-44]. .

6. Conclusion

Cognitive radio networks are envisaged as a promising technology for future wireless networks. It aims to solve the problem of spectrum scarcity by making efficient and opportunistic use of spectrum bands reserved for the use of licensed users. The basic feature of CR technology is that CR devices are able to sense the operating environment and adapt to real-time changes. This enables CR devices to find the available non-utilized spectrum bands and access them, while not interfering with licensed transmissions. Spectrum sensing, spectrum management, spectrum mobility and spectrum sharing are key mechanisms that ensure the efficient operation of both cognitive and primary networks. The objective is to assign spectrum bands to cognitive users in order to avoid interfering with licensed users and maximize their performance.

In this paper a brief overview of the key functions required in cognitive radio networks is presented. We analyze the spectrum sensing techniques, the different approaches used for sensing and the various aspects of spectrum management and spectrum mobility that are used to solve the spectrum assignment problem. In addition to it, we have also discussed several open issues and challenges that need to investigated fully by the research community and can be the basis for future work in this area.

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Biographies

Suhail Ahmad Mir received the B.E degree in Computer Science & Engineering from the University of Kashmir, India, in 2008 and the M. Tech degree in Communication and Information Technology from National Institute of Technology, Srinagar, India, in 2011. He has been working as Assistant Professor in Department of Computer Science and Engineering, University of Kashmir since 2012. His research interests include Network Security, Wireless Networks, CR Networks, MPLS and Computer Networks.

Ajaz Hussain Mir is Professor and Head of Electronics and Communication Department, National Institute of Technology, Srinagar, India. He received the PhD and M. Tech degree from IIT-Delhi. His current research interests include Network Security, Wireless Communication, Computer Networks and Image Processing.