2.1 Introduction

Cognitive radio, from the name it can denote that this device can understand or know if the radio channel is free or not. It meansto use the spectrum resources when it's not allocated by owner user (free) to sufficient utilization.

What is Cognition? According to the Encyclopedia of Computer, three-point computational view of cognition is listed

- Mental states and processes intervene between input stimuli and output responses.
- The mental states and processes are described by algorithms.
- The mental states and processes lend themselves to scientific investigations.

The Federal Communications Commission (FCC) defines the Cognitive radio as a radio that can change its transmitter parameters based on interaction with the environment in which it operates. Figure 2.1 show the simple idea of cognitive radio network.

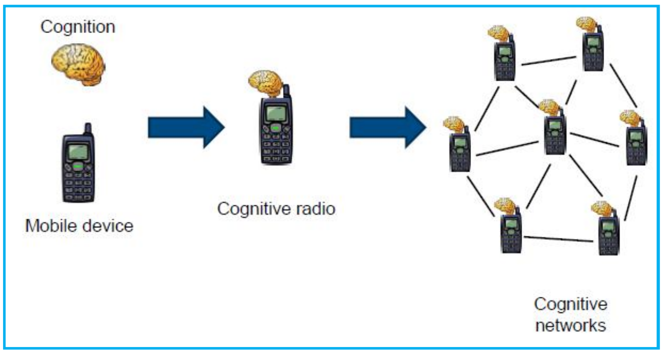

Figure (2.1):Cognition, Cognitive radio and Cognitive networks

2.2 Related Work

First of all Cognitive radio was proposed in 1999[1], by J.Mitola and G. Q. Maguire as a promising technology to fully exploit the under-utilized spectrum.And in 2000[7]J.Mitola also discussed An Integrated Agent Architecture for Software Defined Radio in cognitive radio.

The cognitive radio then faced several challenges such as; multipath fading, shadowing and hidden node problem where a few sensing methods were proposed. In 2005[17] A. Sahai et al proposed the energy detection method as a spectrum sensing technique.

In 2007[18], the matched filtering detection technique was proposed by H.S.Chen et al. The cyclostationary detection method was then introduced by N.Han et al in 2006.

Next in 2007[9], H. Arslanwrite a book in cognitive radio this book is aimed to discuss the cognitive radio, software defined radio (SDR), and adaptive radio concepts from several aspects. In 2007 also Y. Zeng, Y.-C. Liangpresented new spectrum sensing technique in cognitive radio [19].

Then in 2008[20], Leonardo.cardoso et altalk about a new spectrum sensing technique based on random matrix theory and shown its performance in comparison to the cooperative energy detector scheme for both a known and unknown noise variance.Remarkably, the new technique is quite robust and does not require the knowledge of the signal or noise statistics.

After that Ian F. Akyildiz et al In this paper, the state of-the-art survey of cooperative sensing is provided to address the issues of cooperation method, cooperative gain, and cooperation overhead. Specifically, the cooperation method is analyzed by the fundamental components called the elements of cooperative sensing, including cooperation models, sensing techniques, hypothesis testing, data fusion, control channel and reporting, user selection, and knowledge base in March 2011[3].

Finally, in the last few years, researchers have focused on the spectrum sensing techniques. In 2013[21], K.Seshu Kumar et al published a paper deals with a new scheme of sensing based on the eigenvalues concept. It contains signals of covariance matrix received by the secondary users. In this method we are suggested two algorithms of sensing, one algorithm established by the maximum to minimum eigenvalue ratio. Other algorithm focused on average to minimum eigenvalue ratio. In 2013[2], Tulika Mehta et al In this paper spectrumsensing techniques are reviewed. Finally, in 2014 [22] L. Safatly et al developed a new CR transceiver.

2.3Cognitive Radio Technology

The key enabling technologies of CR networks are the cognitive radio techniques that provide the capability to share the spectrum in an opportunistic manner. Formally, a CR is defined as a radio that can change its transmitter parameters based on interaction with its environment.From this definition, two main characteristics of cognitive radio can be defined;

• Cognitive Capability: Through real-time interaction with the radio environment, the portions of the spectrum that are unused at a specific time or location can be identified. As shown in Figure 2.2, CR enables the usage of temporally unused spectrum, referred to as spectrum hole or white space. Consequently, the best spectrum can be selected, shared with other users, and exploited without interference with the licensed user.

• Cognitive Re-configurability: A CR can be programmed to transmit and receive on a variety of frequencies, and use different access technologies supported by its hardware design. Through this capability, the best spectrum band and the most appropriate operating parameters can be selected and reconfigured.

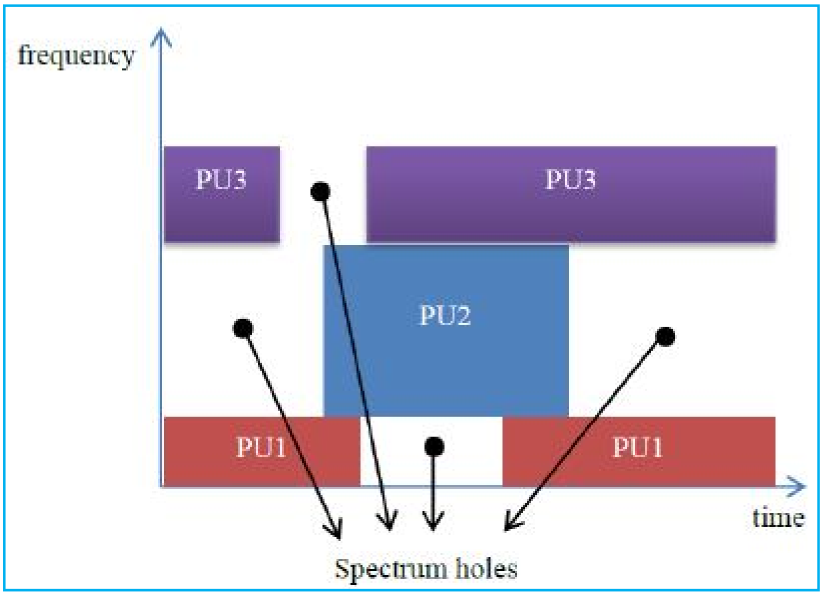

Figure (2.2):Cognitive Radio Spectrum Holes.

More specifically, the cognitive radio technology will enable the users to:

1- Spectrum Sensing:determine which portions of the spectrum are available and detect the presence of licensed users when a user operates in a licensed band.
2- Spectrum Management:selects the best available channel.
3- Spectrum Mobility: vacate the channel when a licensed user is detected.
4- Spectrum Sharing: coordinate access to this channel with other users.

2.3.1Spectrum Sensing

An important requirement of the cognitive radio network is to sense the spectrum holes. Cognitive radio is designed to be aware of and sensitive to the changes in its surrounding. The spectrum sensing function enables the cognitive radio to adapt to its environment by detecting spectrum holes.
The most efficient way to detect spectrum holes is to detect the primary users that are receiving data within the communication range of a cognitive radio user. In reality, however, it is difficult for a cognitive radio to have a direct measurement of a channel between a primary receiver and a transmitter. The spectrum sensing techniques can be classified as transmitter detection, cooperative detection, and interference-based detection [5].

2.3.2 Spectrum Management

In cognitive radio networks, the unused spectrum bands will be spread over wide frequency range including both unlicensed and licensed bands. These unused spectrum bands detected through spectrum sensing show different characteristics according to not only the time varying radio environment but also the spectrum band information such as the operating frequency and the bandwidth [6].

Since cognitive radio networks should decide on the best spectrum band to meet the QoS requirements over all available spectrum bands, new spectrum management functions are required for cognitive radio networks, considering the dynamic spectrum characteristics. These functions are classified as spectrum sensing, spectrum analysis, and spectrum decision. Spectrum sensing is primarily a PHY layer issue, spectrum analysis and spectrum decision is closely related to the upper layers [7].

1- Spectrum Analysis

In cognitive radio networks, the available spectrum holes show different characteristics which vary over time. Since the cognitive radio 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 cognitive radio networks, each spectrum hole should be characterized considering not only the time-varying radio environment but also 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 as follows:

- **Interference Level**: Some spectrum bands are more crowded compared to others. Hence, the spectrum band in use determines the interference characteristics of the channel. From the amount of the interference at the primary receiver, the permissible power of cognitive radio user can be derived, which is used for the estimation of the channel capacity.
- **Channel error rate**: Depending on the modulation scheme and the interference level of the spectrum band, the error rate of the channel changes.
- **Path loss**: The path loss increases as the operating frequency increases. Therefore, if the transmission power of a cognitive radio user

remains the same, then its transmission range decreases at higher frequencies. Similarly, if transmission power is increased to compensate for the increased path loss, then this results in higher interference for other users.

- **Link layer delay**: To address different path loss, wireless link error, and interference, different types of link layer protocols are required at different spectrum bands. This results in different link layer packet transmission delay.
- **Holding time**: The activities of primary users can affect the channel quality in cognitive radio networks. Holding time refers to the expected time duration that the cognitive radio user can occupy a licensed band before getting interrupted [6]. Obviously, the longer the holding time, the better the quality would be. Since frequent spectrum handoff can decrease the holding time, previous statistical patterns of handoff should be considered while designing cognitive radio networks with large expected holding time.

Channel capacity, which can be derived from the parameters explained, is the most important factor for spectrum characterization. Usually signal to noise ratio (SNR) at the receiver has been used for the capacity estimation. However, since SNR considers only local observations of cognitive radio users, it is not enough to avoid interference at the primary users. Thus, spectrum characterization is focused on the capacity estimation based on the interference at the licensed receivers. The interference temperature limit indicates an upper bound or cap on the potential RF energy that could be introduced into the band. Consequently, using the amount of permissible interference, the maximum permissible transmission power of a cognitive radio user can be determined.

2- Spectrum Decision

Once all available spectrum bands are characterized, appropriate operating spectrum band should be selected for the current transmission considering the QoS requirements and the spectrum characteristics. Thus, the spectrum management function must be aware of user QoS requirements [4].

Based on the user requirements, the data rate, acceptable error rate, delay bound, the transmission mode, and the bandwidth of the transmission can be determined. Then, according to the decision rule, the set of appropriate spectrum bands can be chosen. 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.

2.3.3 Spectrum Mobility

Cognitive radio networks target to use the spectrum in a dynamic manner by allowing the radio terminals, known as the cognitive radio to operate in the best available frequency band. This enables ‘‘Get the Best Available Channel’’ concept for communication purposes. A cognitive radio has to capture the best available spectrum. Spectrum mobility is defined as the process when a cognitive radio user changes its frequency of operation as shown in figure (2.3).

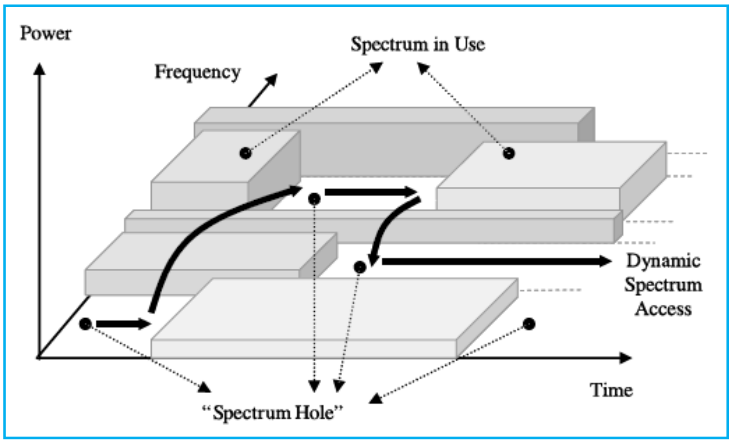

Figure (2.3): Spectrum Mobility.

- **Spectrum Handoff**

In cognitive radio networks, spectrum mobility arises when current channel conditions become worse or a primary user appears. Spectrum mobility gives rise to a new type of handoff in cognitive radio networks called spectrum handoff. The protocols for different layers of the network stack adapt to the channel parameters of the operating frequency [9].

As pointed out earlier, a cognitive radio can adapt to the frequency of operation. Therefore, each time a cognitive radio user changes its frequency of operation, the network protocols are going to shift from one mode of operation to another. The purpose of spectrum mobility management in cognitive radio networks is to make sure that such transitions are made smoothly and as soon as possible such that the applications running on a cognitive radio user perceive minimum performance degradation during a spectrum handoff. It is essential for the mobility management protocols to learn in advance about the duration of a spectrum handoff. This information should be provided by the sensing algorithm. Once the mobility management protocols learn about this latency, their job is to make sure that the ongoing communications of a cognitive radio user undergo only minimum performance degradation. Consequently, multi-layer mobility management protocols are required to accomplish the spectrum mobility functionalities. These protocols support mobility management adaptive to different types of applications. For example, a TCP connection can be put to a wait state until the spectrum handoff is over. Moreover, since the TCP parameters will change after a spectrum handoff, it is essential to learn the new parameters and ensure that the transition from the old parameters to new parameters is carried out rapidly. For a data communication e.g., FTP, the mobility management protocols should implement mechanisms to store the packets that are transmitted during a spectrum handoff, whereas for a real-time application there is no need to store the packets as the stored packets, if delivered later, will be stale packets and cannot be used by the corresponding application [8].

2.3.4 Spectrum Sharing

In cognitive radio networks, one of the main challenges in open spectrum usage is the spectrum sharing. Spectrum sharing can be regarded to be similar to generic medium access control (MAC) problems in existing systems. Substantially different challenges exist for spectrum sharing in cognitive radio networks. The coexistence with licensed users and the wide range of available spectrum are two of the main reasons for these unique challenges [9].

In order to provide a directory for different challenges during spectrum sharing, the spectrum sharing process consists of the following five major steps;

1. **Spectrum Sensing**: A cognitive radio user can only allocate a portion of the spectrum if that portion is not used by an unlicensed user. The solutions and the challenges for this problem, i.e., spectrum sensing, are described. Accordingly, when a node aims to transmit packets, it first needs to be aware of the spectrum usage around its vicinity.
2. **Spectrum Allocation**: Based on the spectrum availability, the node can then allocate a channel. This allocation not only depends on spectrum availability, but it is also determined based on internal (and possibly external) policies.
3. **Spectrum Access**: In this step, another major problem of spectrum sharing comes into picture. Since there may be multiple cognitive radio nodes trying to access the spectrum, this access should also be coordinated in order to prevent multiple users colliding in overlapping portions of the spectrum.
4. **Transmitter-Receiver Handshake**: Once a portion of the spectrum is determined for communication, the receiver of this communication should also be indicated about the selected spectrum. Hence, a transmitter-receiver handshake protocol is essential for efficient communication in cognitive radio networks. The term handshake by no means restricts this protocol between the transmitter and the receiver. A third party such as a centralized station can also be involved.
5. **Spectrum Mobility:** cognitive radio nodes are regarded as visitors to the spectrum they allocate. Hence, if the specific portion of the spectrum in use is required by a licensed user, the communication needs to be continued in another vacant portion. As a result, spectrum mobility is also important for successful communication between cognitive radio nodes [10].

In order to provide these capabilities, CR requires novel radio frequency (RF) transceiver architecture.

2.4Cognitive Radio NetworksArchitecture

This is a clear description of the primary system, cognitive radio system and network architecture.

2.4.1 Primary System and Cognitive Radio System

The components of the cognitive radio network architecture, as shown in Figure (2.4), can be classified in two groups as the primary network and the cognitive network. Primary network is referred to as the legacy network that has an exclusive right to a certain spectrum band.On the contrary, cognitive network does not have a license to operate in the desired band.

The basic elements of the primary and unlicensed networks are defined as follows:

- Primary User: Primary user has a license to operate in a certain spectrum band. This access can be only controlled by its base-station and should not be affected by the operations of any other unauthorized user.
- Primary Base-Station: Primary base-station is a fixed infrastructure network component which has a spectrum license. In principle, the primary base-station does not have any cognitive radio capability for sharing spectrum with cognitive radio users. However, primary base-

station may be required to have both legacy and cognitive radio protocols for the primary network access of cognitive radio users.

- Cognitive Radio User:Cognitive radio user has no spectrum license. Hence, the spectrum access is allowed only in an opportunistic manner. Capabilities of the cognitive radio user include spectrum sensing, spectrum decision, spectrum handoff and cognitive radio MAC/routing/transport protocols. The cognitive radio user is assumed to have the capabilities to communicate with not only the base-station but also other cognitive radio users.
- Cognitive Radio Base-Station: Cognitive radio base-station is a fixed infrastructure component with cognitive radio capabilities. Cognitive radio base-station provides single hop connection to cognitive radio users without spectrum access license [15].

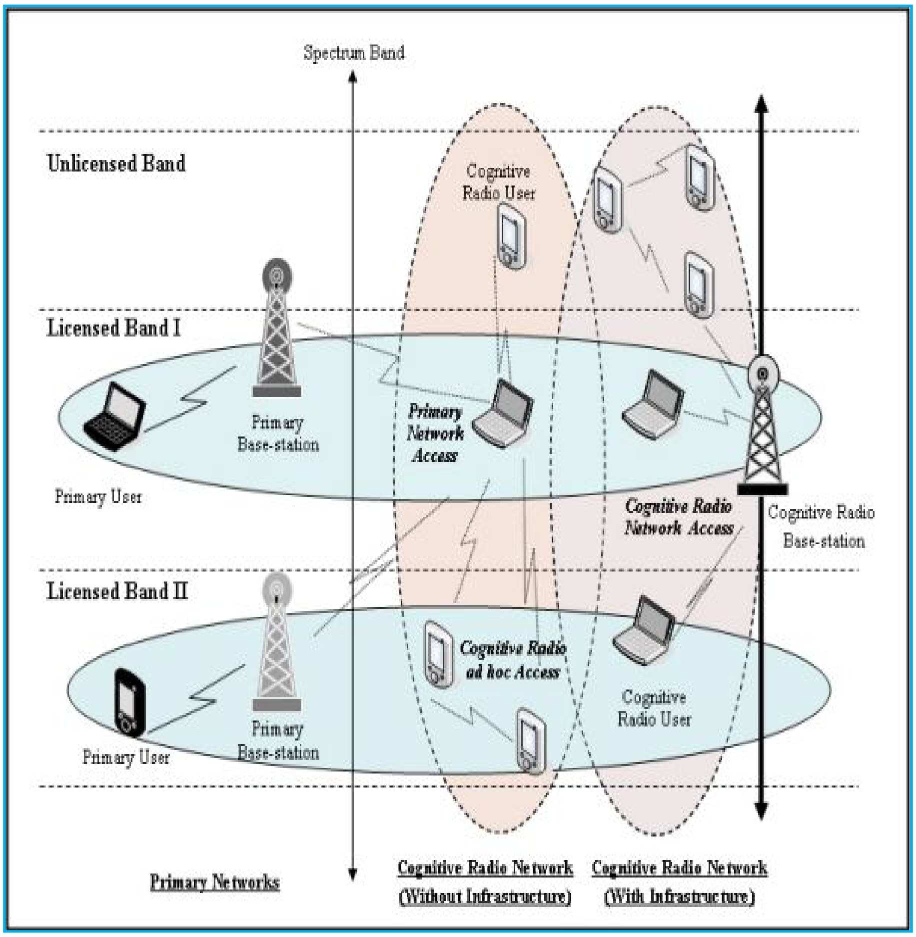

Figure (2.4): Cognitive radio network components.

2.4.2 Network Architecture

The cognitive radio network can be deployed in network-centric, distributed, ad hoc, and mesh architectures, and serve the needs of both licensed and unlicensed applications.

The basic components of CRNs are mobile station (MS), base station/access point (BSs/APs) and backbone/core networks. These three basic components compose three kinds of network architectures in the CRNs: Infrastructure, Ad-hoc and Mesh architectures, which are introduced as follows.

1. Infrastructure Architecture

In the Infrastructure architecture, a MS can only access a BS/AP in the one-hop manner. MSs under the transmission range of the same BS/AP shall communicate with each other through the BS/AP. Communications between different cells are routed through backbone/core networks. The BS/AP may be able to execute one or multiple communication standards/protocols to fulfill different demands from MSs. A cognitive radio terminal can also access different kinds of communication systems through their BS or AP.

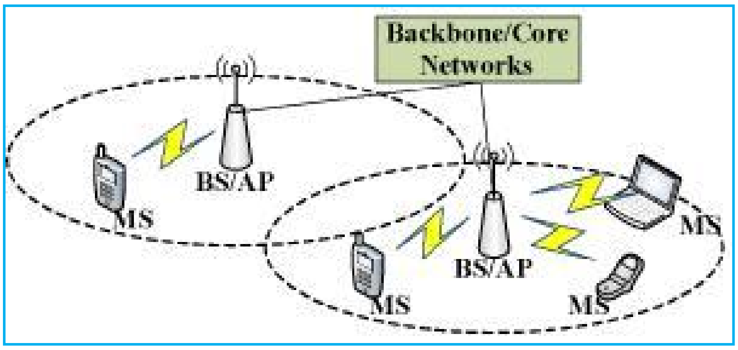

Figure (2.5): infrastructure architecture.

2. Ad-hoc Architecture

There is no infrastructure support (or defined) in ad-hoc architecture. If an MS recognizes that there are some other MS nearby and are connectable through certain communication standards/protocols, they can set up a link and thus form an ad hoc network. Note that links between nodes may be set up by different communication technology. Two cognitive radio terminals can either communicate with each other by using existing communication protocols (e.g. WiFi, Bluetooth) or dynamically using spectrum holes.

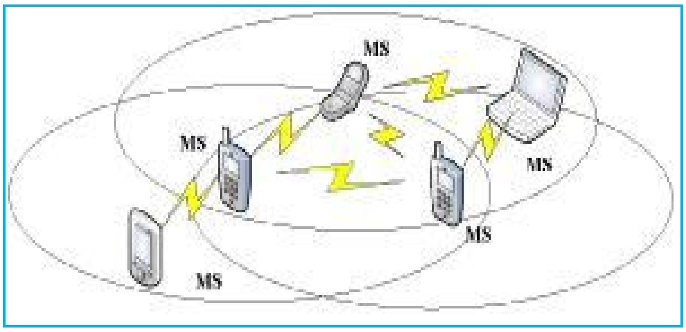

Figure (2.6): Ad-hoc Architecture

3. Mesh Architecture

This architecture is a combination of Infrastructure and Ad Hoc architectures by enabling the wireless connections between BSs/APs, which is similar to the Hybrid Wireless Mesh Networks. BSs/APs work as wireless routers and form wireless backbones. MSs can either access the BSs/APs directly or use other MSs as multi-hop relay nodes. Some BSs/APs may connect to the wired backbone/core networks and function as gateways. Since BSs/APs can be deployed without necessarily connecting to wire backbone or core networks, it is more flexible and less costly in planning the locations of BSs/APs. For BSs/APs having cognitive radio capabilities, they may use spectrum holes to communicate each other [16].

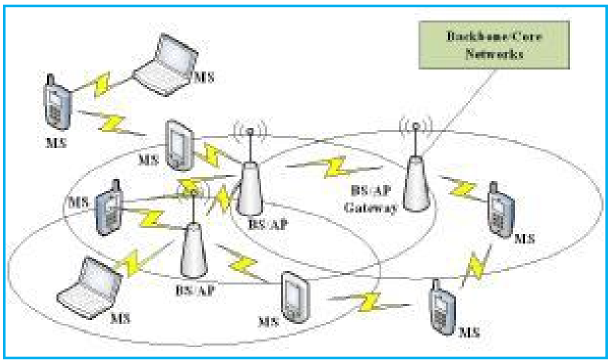

Figure (2.7):Mesh architecture.

2.5 Limitation in Cognitive Radio

A spectrum hole is a band of frequencies assigned to a primary user, but at a particular time and specific geographic location, the band is not being utilized by that user. Spectrum utilization can be improved significantly by making it possible for a secondary user (who is not being serviced) to access a spectrum hole unoccupied by the primary user at the right location and the time.

The most important challenge is to share the licensed spectrum without interfering with the transmission of other licensed users. The cognitive radio enables the usage of temporally unused spectrum, which is referred to as spectrum hole or white space. If this band is further used by a licensed user, the cognitive radio moves to another spectrum hole or stays in the same band, altering its transmission power level or modulation scheme to avoid interference.

Unlicensed users can temporarily borrow spectrum from licensed holders as long as no undue interference is seen by the primary user. Devices that borrow spectrum on a temporary basis without generating harmful interference are commonly referred to as cognitive radio. Basic cognitive radio techniques, such as dynamic frequency selection (DFS) and transmit power control (TPC), already exist in many unlicensed devices.

Before beginning the operations, cognitive radios will obtain an estimate of the power spectral density (PSD) of the radio spectrum to determine which frequencies are used and which frequencies are unused. In order to accurately measure the spectrum, a highly sensitive radio will be required to measure signals at their cell edge. Consider the example of digital TV which lies at the cell edges; the received signal will be just barely above the sensitivity of the receiver. For a cognitive radio to be able to detect this signal, it needs to have a radio that is considerably more sensitive.

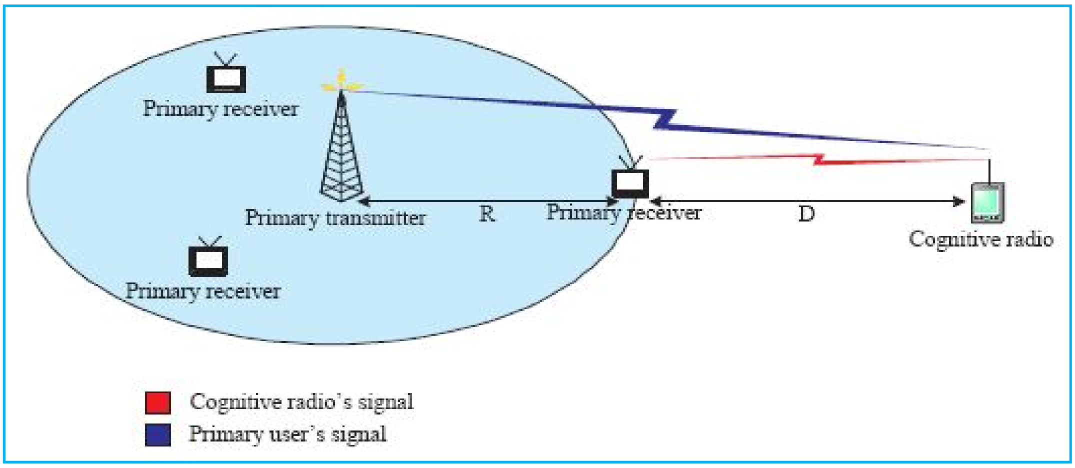

Figure (2.8): Hidden Node Problem

If the cognitive radio is not capable of detecting the digital TV signal, then it will incorrectly determine that the spectrum is unused; thereby leading to potential interference if this radio spectrum is used, i.e., the signal transmitted by the cognitive radio will interfere with the signal the digital TV. This situation is often referred to as Hidden Node Problem as shown in Figure (2.8).

Besidehidden node problem there is shadowing problem effect where an individual sensing node may beblocked by an obstacle, therefore may not be able tosee the Primary User (PU), as shown in Figure (2.9).

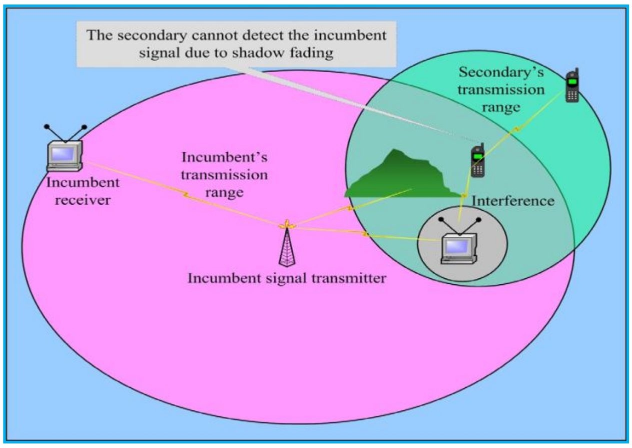

Figure (2.9):The hidden Node Problem Caused by Shadow Fading.

Furthermore there is multipath fading problem where the signals from the PU that travel different paths may or may not add coherently at the receiver, as shown in Figure (2.10). As a result, small changes in locationrelative to the wavelength of PU impact the Quality of Detection.

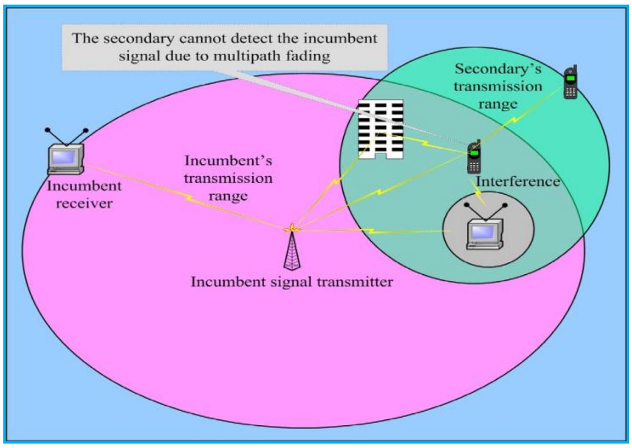

Figure (2.10):The hidden Node Problem Caused by Multipath Fading.

Further, when the spectrum is occupied, the cognitive radio will also be able to estimate the interference temperature that the primary user can tolerate, i.e. the transmit power level that a cognitive device can utilize without raising the noise floor of the primary user's device beyond a specified amount. In many cases, this specified amount is on the order of 0.5 dB to 1.0 dB, but will depend heavily on the link margin available at the primary user's receiver. The interference temperature can be determined with at least two pieces of information: an estimate of the signalbandwidth used by the primary userand the distance between the cognitive radio and the victim device. The signal bandwidth can be used to determine the noise floor for the victim device, while the distance can be used to determine the received signal strength seen by the victim device as a function of transmit power used at the cognitive radio. Assuming that the noise floor at the victim receiver is allowed to rise by a pre-specified amount, it is easy to calculate the maximum allowed transmit power for the cognitive radio [10].