A DISSERTAION ON

SPECTRUM SENSING IN COGNITIVE RADIO BY STATISTICAL MATCHED WAVELET METHOD

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DECLARATION

I hereby declare that all the information in these documents has been obtained and presented in accordance with academic rules and ethical conduct. It is being submitted for the degree of Master of Technology in Microwave and Optical Communication Engineering at Delhi Technological University. It has not been submitted before for any degree or examination in any other university.

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Abstract

Cognitive radio draw lots of research attentions in recent years for its efficient spectrum utilization. In cognitive radio networks, the first cognitive task preceding any form of dynamic spectrum management is the spectrum sensing and identification of spectrum holes in wireless environment. Spectrum Sensing is an important functionality of Cognitive Radio (CR). Accuracy and speed of estimation are the key indicators to select the appropriate spectrum sensing technique. Wideband spectrum sensing has been introduced due to the higher bandwidth demand and increasing spectrum scarcity since it provides better chance of detecting spectrum opportunity. In this project, the application of wavelet transform used for wideband spectrum opportunity detection in CRs is documented. Conventional spectrum estimation techniques which are based on Short Time Fourier Transform (STFT) suffer from familiar problems such as low frequency resolution, variance and high side lobes/leakages. In this project we used statistical method wavelet algorithm to find the spectrum holes. This is the latest technology to sense the spectrum in the cognitive radio network.

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CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Nowadays users are getting engaged in the services of a number of available wireless access systems. With the development of a host of new and ever expanding wireless applications and services, spectrum resources are facing huge demands. A number of new systems are capable of using the 850-5800 MHz band which is suitable for broadband wireless access systems and for cellular communications as well as the frequency bands such as the very high frequency (VHF) and ultra-high frequency (UHF) bands. It's very likely that in next ten years, the majority of frequency bands used for mobile communication systems will be entirely engaged and new solutions will become compulsory. So to overcome this problem use of "Cognitive Radio" technology is one possible solution which is a radio or system that uses the best wireless channels in its vicinity and is fully aware of its functioning situation and can regulate its radio operating parameters autonomously according to collaborating wireless and wired networks. Cognitive radios are also defined as "a *software defined radio with a cognitive engine brain*"[1]

As Most of the primary spectrum is already assigned, so it becomes very difficult to find spectrum for either new services or expanding existing services. At Presently government policies do not allow the access of licensed spectrum by unlicensed users, constraining them instead to use several heavily populated, interference-prone frequency bands. The national Institute of Information and Communications Technology (NICT), in order to realize this technology, established a project to develop enabling technologies for cognitive radio under the supervision of Ministry of Internal Affairs and Communications (MIC) in 2005. As a delegate result, software defined cognitive radio (SDCR) equipment has been developed which consists of a hardware platform (HWP) and a software platform (SWP). The HWP consists of a signal processing unit (SPU) which consists of Field-Programmable

Gate Array (FPGA) and Central Processing Unit (CPU) boards, multi-band antenna support from the UHF (400 MHz) band to the 5 GHz band and a multiband RF unit (RFU) also supporting the UHF-5GHz band[1]. The SWP on the other hand, consists of numerous managers which control the spectrum sensing and reconfiguration and/or sensing for communication systems. The prototype model developed for cognitive radio is united by software and hardware platforms. It senses the signal level over the 400MHz-6GHz bands, identifies the structure of prototype by the means of software packages and also checks the connectivity.

1.2 BACKGROUND & THESIS MOTIVATION

Most of radio systems bands nowadays are using a specific spectrum access system function in a particular frequency and are not responsive of their radio spectrum atmosphere. An investigation on spectrum utilization indicates that the entire spectrum is not being used in space (geographic location) or time. Therefore a radio is required which can identify and sense its local radio spectrum situation, identify temporarily vacant spectrum and make use of it, has the potential to present higher bandwidth services, enhance spectrum capability and minimize the need for centralized spectrum organization. This might be achieved through a radio which can formulate autonomous decisions regarding how it accesses spectrum. Cognitive radio is considered as a goal towards which a software-defined radio platform should evolve: a fully reconfigurable wireless transceiver which automatically ***adapts*** its *communication parameters* to network and user demands [1]. Cognitive radios have the potential to jump in and out of unused spectrum gaps to enlarge spectrum competence and make available wideband services. In some locations and/or at some times of the day, 70 percent of the allocated spectrum might be unused. The FCC has recently suggested that significantly greater spectral efficiency might be realized by deploying wireless devices which can coexist with the licensed users.

Fig1.1 shows the status of the spectrum band. Blue bar shows the spectrum usage status and red line are indicating the portion of the band which are not in use and spectrum is just wasting.

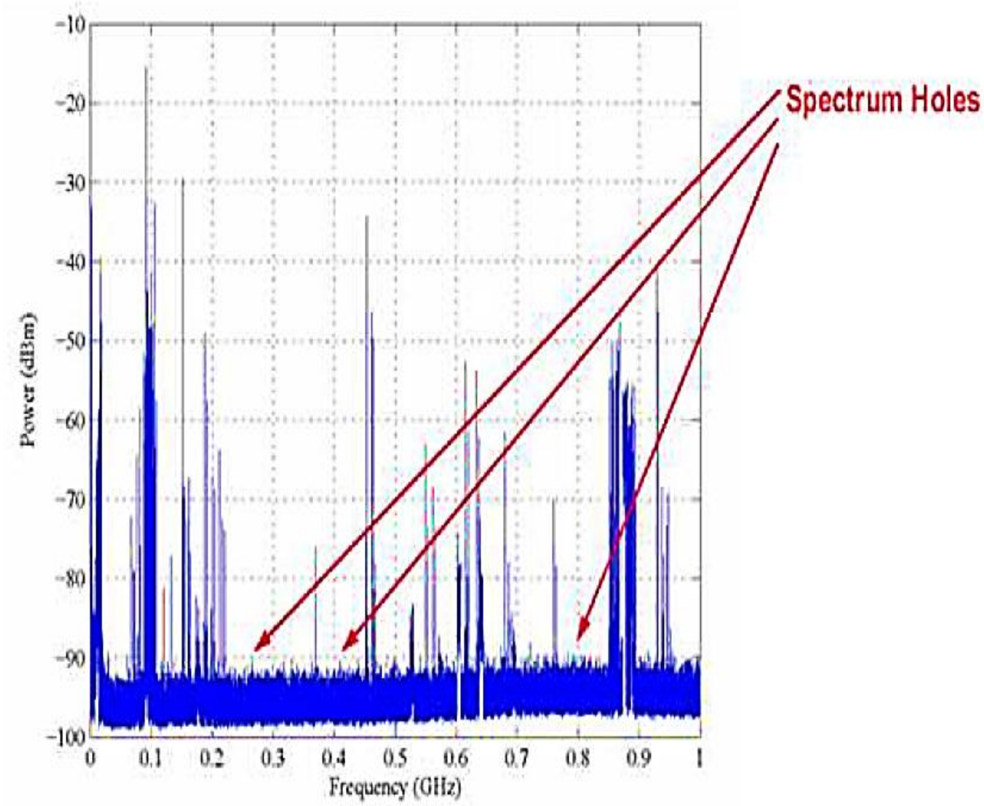

Fig 1.1 Power distribution with respect to frequency [1]

1.3 PROBLEM STATEMENT

Cognitive radio technology is aware of its frequency atmosphere. They can advance the spectral competence by sensing the environment and in order to provide the quality of service to the primary user it fills the discovered gaps of unused licensed spectrum with their own transmissions. Precise spectrum awareness is the main concern for the cognitive radio system (secondary user). In this regard adaptive transmission is proposed in unused spectral bands without causing interference to the primary user. In order to carry out this the transmissions of licensed users have to be detected without failure and the main goal for adaptive transmission is the detection of vacant frequency bands. A scheme is proposed to formulate a cognitive radio that is intelligent enough to detect vacant frequency bands professionally, to get maximum throughput without causing any detrimental harm to the primary user's quality of service.

1.4 OBJECTIVE

The main aim of this work is to explain the problem of spectrum sensing, various spectrum sensing methods, such as cyclostationary detection, wavelet based detection, matched filter detection, energy detection. We are mainly focusing on wavelet based spectrum sensing, In which We have to find the spectrum holes in the wideband spectrum with fast spectrum sensing and to overcome the limitation of previous spectrum sensing method.

1.5 THESIS LAYOUT

The thesis report is divided into five chapters, each having ample information for comprehending the concept of this project.

Chapter 1 Discussed the introductory part of cognitive radio and problem statements.

Chapter 2 Gives an overview of cognitive radio technology, software defined radios and its connection with cognitive radio, operations of the cognitive radio system, tasks of cognitive radio and their descriptions and some of the challenges that are expected to appear when using cognitive radios.

Chapter 3 Discuss the spectrum sensing techniques, its types, challenges for spectrum sensing techniques, standards which employ sensing, and statistical matched wavelet method to sense the spectrum.

Chapter 4 Discuss the results of various cases comprising of non-periodic signals and the output with statistically matched wavelet transform.

Chapter 5 conclusion and scope of future work related to spectrum sensing in cognitive radio network.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

There has been a very rapid growth in the field of wireless communication. The most critical consequences for this growth in wireless networks are the ones related to spectrum usage and management as the electromagnetic radio spectrum is the most precious natural resource when there is discussion about wireless networks. The existing policies of spectrum management are based on static spectrum allocation for a specific technology and service controlled by regulation agencies like the Federal Communications Commission (FCC) and the European Telecommunications Standards Institute (ETSI). After the appearance of wireless personal communication technologies it became unreasonable to use these policies and rely on static spectrum allocation due to economic and technical considerations. In order to solve this, Industrial Scientific and Medical (ISM) [1] bands have been provided as a good solution to handle these types of networks. Nevertheless, after a while ISM bands get congested and over-utilized which affects the quality of communication on those bands. So to overcome this problem software defined radio (SDR) followed by cognitive radio (CR) networks based on dynamic spectrum access have been proposed as a promising solution.

2.2 HISTORY OF COGNITIVE RADIO

The term cognitive radio was first introduced by Joseph Mitola [2]. The Cognitive radio is a radio that adapts to the conditions of the environment by analyzing, observing and learning. The cognitive network makes use of these adaptations for future decisions [1]. Cognitive radio is basically used for maximum utilization of the radio bandwidth. The core of the performance optimization is the cognitive process which is shared by the cognitive radio and the cognitive networks. The main part of this process is to learn from the past decisions and make use of it for future decisions. The radio Knowledge Representation

Language (RKRL) is a language which the cognitive radio uses for knowledge. The cognitive radios need variable parameters for the description of the optimization space. These parameters come from the Software Defined Radio (SDR) [1]. The first phone call over a cognitive-radio network was made on Monday, 11 January 2010 in the Centre for Wireless Communications at the University of Oulu using CWC's cognitive-radio network, CRAMNET (Cognitive Radio Assisted Mobile Ad Hoc Network), which was developed by CWC researchers

2.3 WHY COGNITIVE RADIO?

The main aim of any technology is to utilize the needs in the best possible way at a minimum cost. The cognitive network should be able to provide high performance in a better time period than the non-cognitive radio networks, with better Quality of Service (QoS) and higher throughput. The performance of the cognitive radios must be justified and satisfied by its calculated cost with respect to communication. For the implementation of the actual functionality of the network, cognitive radio requires a Software Adaptable Network (SAN) and in the same way for the modification of radio operation e.g. waveform, bandwidth, time, spatiality etc., the cognitive radio depends on a Software Define Radio (SDR) [2].

2.4 HOW IS A COGNITIVE RADIO DIFFERENT FROM OTHER RADIOS?

2.4.1. APPLICATIONS

Table 1 Comparison of cognitive radio with conventional radio and software radio in application point of view

Conventional Radio	**Software Defined Radio**	**Cognitive Radio**
1.Supports a fixed number of Systems	1.Dynamically support multiple variable systems, protocols and interfaces	1.Can create new waveforms on its own

2.Reconfigurability decided at the time of design	2.Interface with diverse systems	2.Can negotiate new interfaces
3. May support multiple services, but chosen at the time of design	3.Provide a wide range of services with variable QoS	3.Adjusts operations to meet the QoS required by the application for the signal environment

2.4.2 SOFTWARE

Table 2 Comparison of cognitive radio with conventional radio and software radio in software point of view

Conventional Radio	**Software Defined Radio**	**Cognitive Radio**
1.Cannot be made as future proof	1.Ideally software radios could be future proof	1.SDR upgrade mechanisms
2. Typically radios are not upgradeable	2.Many different external upgrade mechanisms	2.Internal upgrades & Collaborative upgrades

2.4.3 DESIGN

Table 3 Comparison of cognitive radio with conventional radio and software radio in design point of view

Conventional Radio	**Software Defined Radio**	**Cognitive Radio**
1. Traditional RF design	1.Conventional Radio + Software Architecture	1.SDR+ Intelligence

2.Traditional baseband design	2 .Reconfigurability	+ Awareness
	3.Provisions for easy upgrades	+Learning Observations

From the above tables it is observed that how a cognitive radio is different from other radios in the scenario application, design and software. From this it is observed that cognitive radio is most suitable for upcoming new wireless communications because of its intelligence, awareness, learning observations and up gradation mechanisms.

2.5 THE COGNITIVE RADIO OPERATION

Fig. 2.1 shows the basic cognitive radio tasks, spectrum sensing, spectrum analysis and spectrum decision in the radio environment.

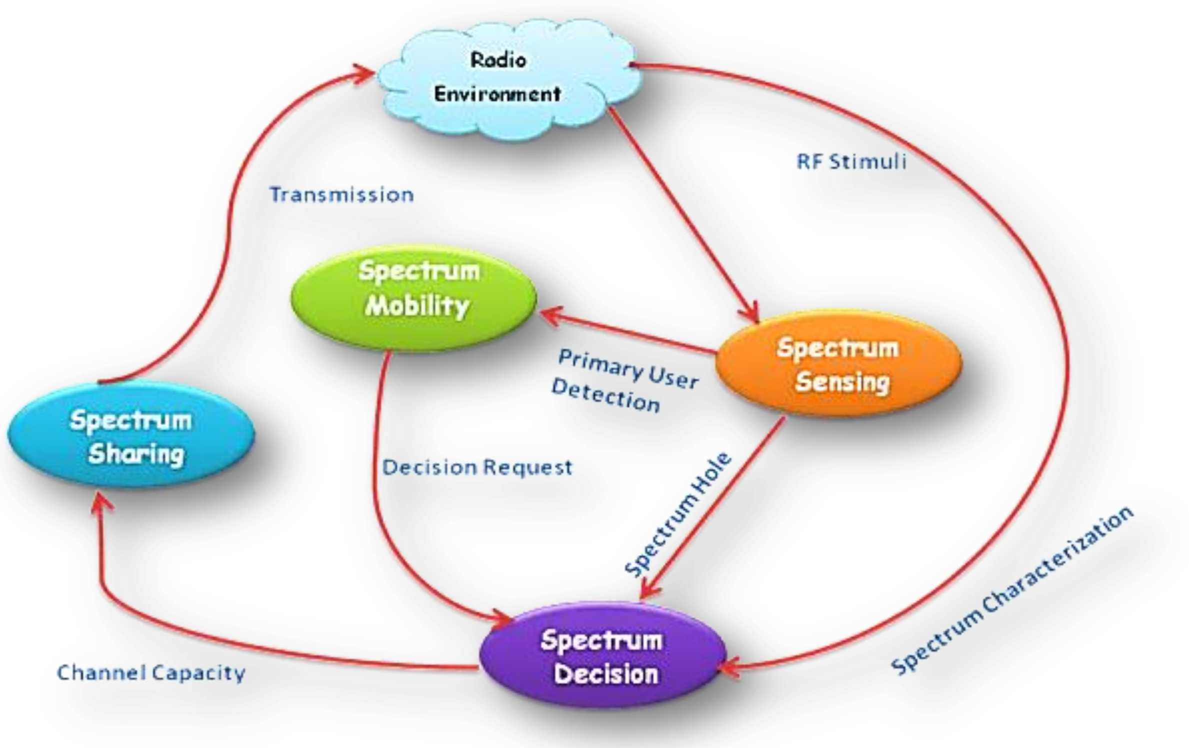

Fig 2.1 Basic Cognition cycle

2.6 SDR AND ITS RELATIONSHIP WITH COGNITIVE RADIO

Previously there was discussion about the adaptability of being the main property of the cognitive radio where frequency, power, modulation and bandwidth can be changed according to the current radio environment. SDR provides variable radio functionality in order to avoid analog circuits and components. The cognitive radio is basically a SDR which already knows the condition, state, position and automatically adjusts its functions according to the desired objectives. The relation between the SDR and the cognitive radio can be demonstrated in Fig 2.2. It is clear from the below diagram that the cognitive radio comprises the SDR. The SDR is developed in software based on Digital Signal Processing with the modifiable Radio Frequency components .Hence, the SDR is a generic radio platform which has the capability to operate in different bandwidths over a large number of frequencies as well as using different modulation schemes and waveform formats[2]. As a result of this, the SDR can support multiple standards such as GSM, WCDMA, WIMAX etc., and multiple access schemes such as TDMA, OFDM and SDMA etc.

2.7 THE COGNITIVE RADIO NETWORK ARCHITECTURE

In a wireless spectrum some part is licensed for different tasks and few bands are still unlicensed. In this section, there is discussion about all the possible scenarios for a better description of the communication protocols. The components of the cognitive radio architecture are illustrated in figure.

2.7.1 PRIMARY NETWORK

The primary networks have special rights to specific bands. The primary network includes the primary user and the primary base-station.

Primary User: Primary users also called licensed users, operate in specific spectrum bands. Only primary base-station controls these operations entirely. These primary users do not require any further enhancements for the coexistence of the primary base-stations and the primary users.

Primary Base-Station: The primary base station has a fixed infrastructure. Primary networks do not have the ability of cognitive radio for sharing the spectrum with cognitive users but it can be requested to have both legacy and cognitive radio protocols for primary network access of cognitive radio users.

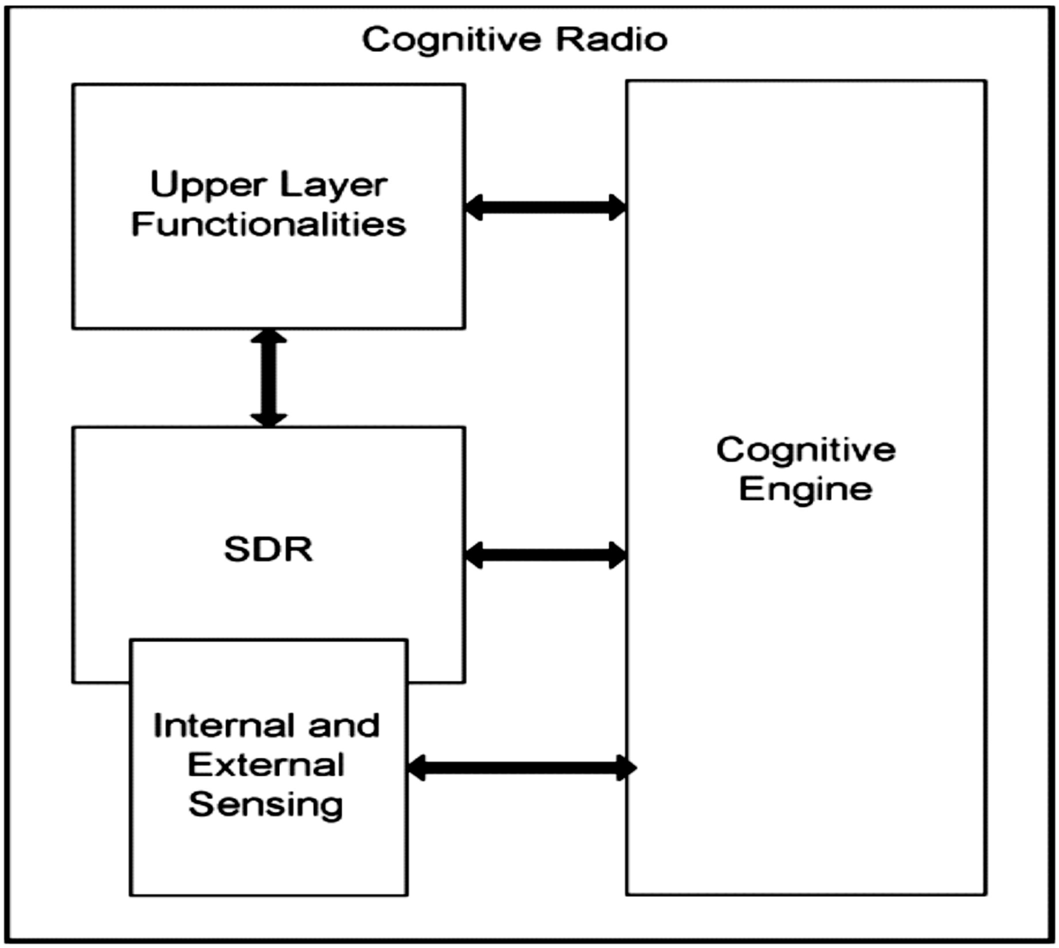

Fig 2.2: Illustration of the relationship between the SDR and the cognitive radio

2.7.2 COGNITIVE RADIO NETWORK

Cognitive radio networks do not have the permission to operate in the required band. The CR networks can be deployed both with infrastructure and without infrastructure networks as illustrated in fig 2.3. The components of the network are as follows:

Cognitive Radio user: The CR user (the unlicensed user) has no spectrum license, so extra functionalities are needed for sharing the spectrum band.

2.8 COGNITIVE RADIO BASE-STATION

The CR base-station (the unlicensed base station) has a fixed infrastructure component with CR abilities. Cognitive Radio can access to different networks by providing the single hop network connection to CR user [2]. Single hop connection is used to reduce the propagation delay; it has now become essential to have single hop network connection which connects the user terminals. The CR network architecture in Fig. 2.3 shows different types of networks and primary network access with infrastructure based CR network and without infrastructure based CR network (adhoc network). The CR networks operate both in licensed and unlicensed bands (mixed spectrum environment). There are three access types as mentioned below:

CR network access: The CR users can access both the CR base-station i.e the licensed bands as well as the unlicensed spectrum bands.

CR ad hoc access: The CR users communicate with different CR users through the ad hoc connection on licensed and unlicensed bands.
In Fig 2.3 it is clear that there are two main groups, the primary networks and the cognitive radio networks (the next generation networks).

Primary network access: The licensed bands are means for the CR users through which they can access the primary base-station.

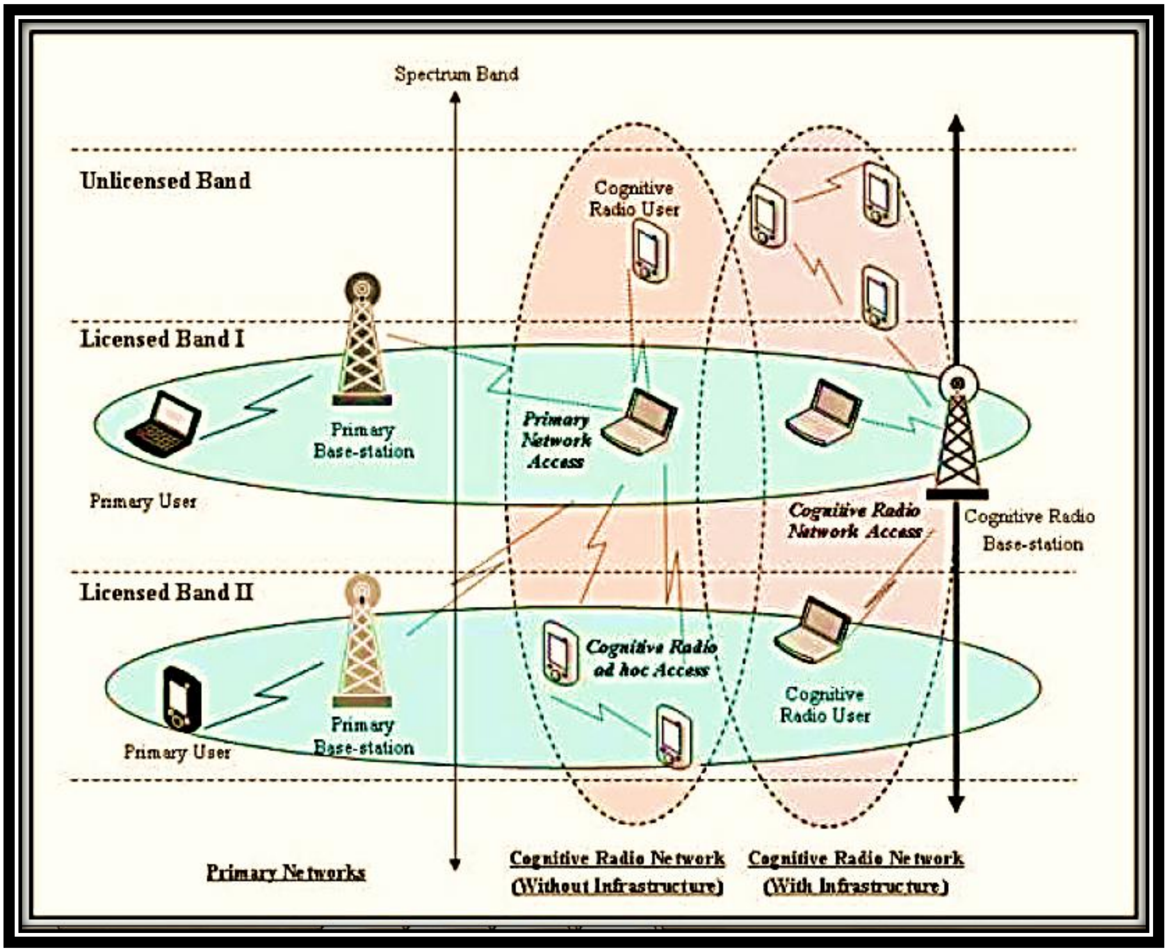

Figure: 2.3 Cognitive radio Architecture

2.9 SPECTRUM SENSING

Due to an increasing demand of high data rates, static frequency cannot fulfill the demand of these high data rates. As a result of this, new methods for exploiting the spectrum are introduced. In cognitive radio, exploiting the unused spectrum is a new way to access the spectrum. Spectrum sensing is measuring the interference temperature over the spectrum to find the unused channels [3]. In this way efficient use of spectrum is utilized. Spectrum sensing is also involved in determining the type of the signal like carrier frequency, the modulation scheme, the waveform etc. [3].

2.10 SPECTRUM HOLE

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 utilized by that user. Primary users are those who hold the licensed channels or primary bands. As said above radio scene analysis includes two functionality. These two stages are performed periodically. The interference temperature is suggested to be estimated for the whole targeted frequency ranges. Then depending on the current interference and the interference temperature on the previous iterations all channels can be classified into three types of spectrum holes.

- **White spectrum holes, which are fully not used**.
- **Gray spectrum holes, which are partially used**.
- **Black spectrum holes, which are fully used**.

After the sensing operation is completed, the users are allowed to access freely the white holes and partially use the gray holes in such a way that does not disturb the primary user. But they will not use the black holes, because the black holes are assumed to be fully used and any extra use will interfere with the ongoing communication in them. In general, there are two sensing modes, reactive sensing and proactive sensing, depending on the way to initiate the sensing. These two modes are defined as under.

2.11 METHODS

The mostly used spectrum sensing techniques are given as [3],

- **Matched Filtering**
- **Waveform-Based Sensing**
- **Cyclostationary Based Sensing**
- **Energy Detector Based Sensing**
- **Radio Identification**
- **Other Sensing Methods**

The methods will be discussed in detail.

2.12 CHALLENGES

There are some challenges which needs to be solved for efficient spectrum sensing which are gives as[3],

- **Hardware Requirements**
- **The Hidden Primary User Problem**
- **Spread Spectrum Primary Users**
- **Sensing Time**
- **Other Challenges**

These challenges will be discussed in detail

2.13 SPECTRUM MANAGEMENT

The goal is to find the best available spectrum to fulfill the needs of the communication. In cognitive radio networks the licensed, unlicensed and unused spectrum bands are spread over a large number of frequencies. These unused spectrum bands show different properties according to the time varying radio environment. The Cognitive radio has to decide the best available spectrum band such that it fulfills the QoS requirements [3].

2.14 SPECTRUM ANALYSIS

Spectrum analysis discovers the different functionalities of the spectrum bands to make productive use of the spectrum band according to the requirements. Each spectrum hole (Band of frequencies assigned to the primary user but at a specific time and geographic location, these bands is not fully utilized by that user [2].) should be defined according to the time varying environment and the information of the band like frequency and bandwidth. Parameters such as interference, holding time, path loss, link layer delay, wireless link errors etc. are defined to represent the quality of the spectrum band.

Interference: The interference of the channel can be determined from the spectrum band being used. The permissible power of a CR user can be calculated from the amount of interference which is used for the calculation of the channel capacity.

Holding time: Holding time is an expected time from which the CR users occupy the licensed band before its interruption. For better quality holding time should be as long as possible.

Path loss: The path loss increases with increase in operating frequency. If the cognitive users have the constant transmission power then at higher frequencies their transmission range decreases. In order to compensate the increased path loss the transmission power is increased which yields in higher interference to the other users.

Wireless link errors: This error rate of the channel changes according to the change in modulation scheme and interference level of the spectrum band.

Link layer delay: Different link layer protocols are required to address path loss, interference and wireless link errors.

2.15 SPECTRUM DECISION

A spectrum band should be selected for the transmission according to the QoS requirements when the analysis of all the spectrum bands is completed. The decision rules are focused on the cost of communication and fairness [4].

2.16 SPECTRUM MANAGEMENT CHALLENGES

Challenges for the spectrum management are listed below; a lot of research is still needed for these issues.

- How to integrate all the parameters of the spectrum for the spectrum decision.
- Multiple spectrum bands used for simultaneous transmission.
- Spectrum decision and reconfiguration is needed in a cooperative framework.
- Spectrum decision over heterogeneous spectrum bands.

For the decision of the best spectrum band over the heterogeneous environment, the CR network supports the spectrum decision operation both for licensed and unlicensed bands under different characteristics.

2.17 SPECTRUM MOBILITY

In cognitive radio networks, spectrum mobility occurs when the frequency of operation changes. For better transition of the spectrum, spectrum mobility maintains all the requirements of the communication. Spectrum mobility has a vital role while designing cognitive protocols [4]. Two main factors affect the spectrum mobility. The first one is the delay incurred during the spectrum handoff. This delay affects the communication at different layers. The cognitive radio performs a new type of handoff which we call a spectrum handoff when the primary user appears,.

2.17.1 SPECTRUM HANDOFF

The cognitive radio has the ability to adapt to the frequency operation. Due to this the network protocol changes its mode of operation from one mode to another. The main goal of mobility management is that these transitions are completed without any disturbance and in a time efficient manner. The mobility management should have an awareness of the duration of the spectrum handoff from the sensing algorithm. When the mobility management learns about the latency, its job is to confirm that the communication of the CR user should undergo on minimum performance degradation [4], [1]. In the same way, multi-layer (supports mobility management for different types of application) documents are needed for accomplishing the functionalities of spectrum mobility. The interaction between spectrum management and spectrum mobility can be illustrated as in Fig 2.4. The spectrum sensing and spectrum sharing are keen to enhance the spectrum efficiency. The spectrum management functionalities cooperate with communication layers. The spectrum management needs QoS information, sensing, scheduling, transport and routing for the decision of the appropriate spectrum band. From Fig. 2.4, link layer information and sensing delay information are required for the estimation of spectrum handoff latency. The transport layer and application layer should know the latency, for the route recovery by using the spectrum handoff. Due to this, spectrum handoff is very important in the communication layers.

2.17.2 SPECTRUM MOBILITY CHALLENGES

The below are some open research challenges for efficient spectrum mobility in cognitive networks [6].

• Spectrum mobility in time domain. The available channels change with respect to time, so to it is a challenge to maintain QoS in this environment. The physical radio goes through the spectrum to fulfill the QoS requirements.

• Spectrum mobility in space. As user changes its position from one place to another, the available bands also changes. To assign a spectrum is a major issue in the CR networks.

• If CR user moves to another place, the available spectrum bands also changes and due to this spectrum handoff takes place. So Integrate inter cell handoff scheme is required spectrum handoff scheme. The spectrum handoff in different networks is referred as vertical handoff which takes place in the CR networks.

• At a particular instance, many frequency bands are available for a CR user. So algorithms are required for the selection of best available spectrum.

• When the operational frequency becomes busy in the communication by a CR user then the node applications have to move to other available frequency bands.

• Designing a new mobility management to reduce the loss and the delay in a handoff.

2.18 SPECTRUM SHARING

Spectrum sharing is the major challenge which open spectrum usage faces. Spectrum sharing is related to medium access control (MAC) problems in the current system; however, there are different challenges for the spectrum sharing in cognitive radio. Spectrum sharing consists of five steps which are,

Spectrum sensing: The CR can allot a specific part of the spectrum if it is not used by the licensed user. When a CR wants to transmit data, it will first sense its surrounding spectrum usage.

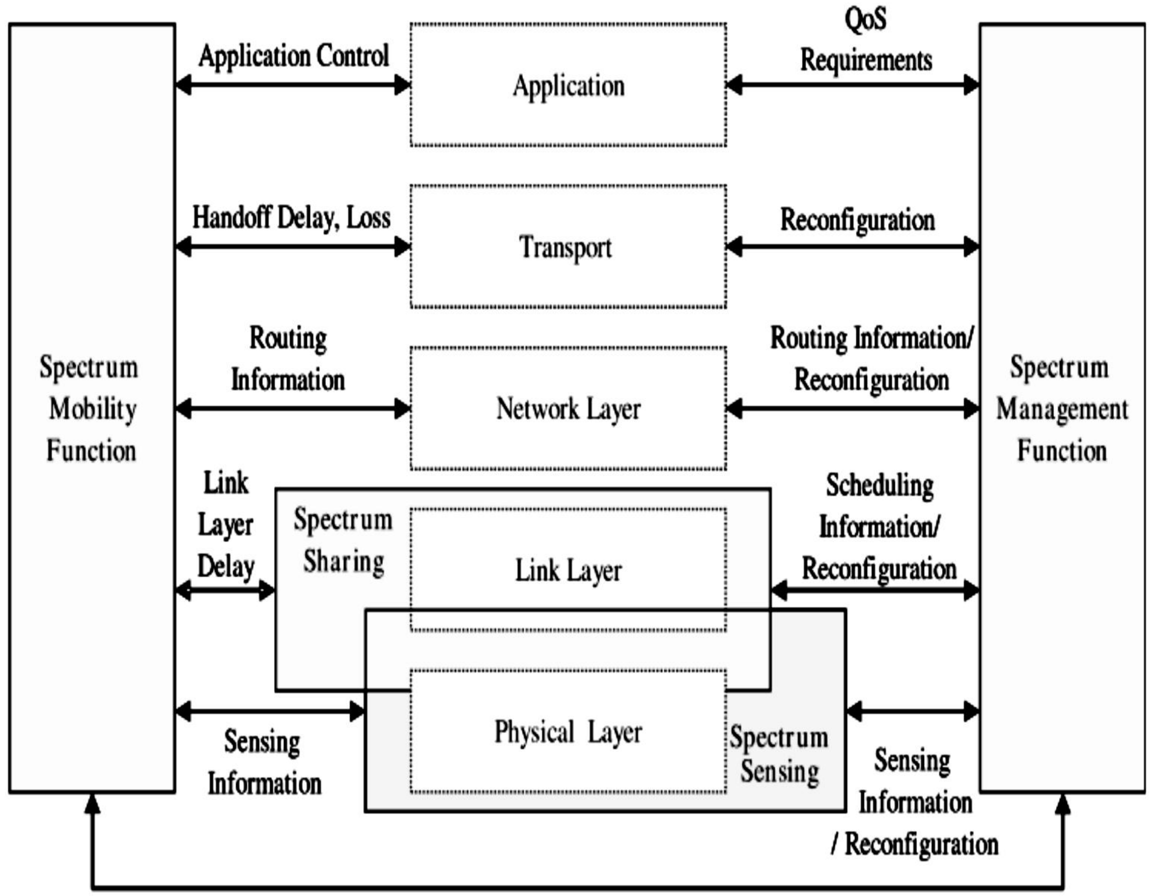

Fig 2.4 Handoff decision and network communication

Spectrum allocation: When spectrum is available, a channel is allocated. This allocation depends on the availability of the channel and also internal/external policies.

Spectrum access: When the nodes are trying to access the available spectrum, spectrum access helps to prevent colliding and overlapping of the spectrum.

Transmitter-receiver handshake: The transmitter-receiver handshake is essential for effective communication in cognitive radio, after the determination of the spectrum.

Spectrum mobility: The spectrum mobility is important in the communication between the nodes. If a particular part of the spectrum is required by the licensed user, communication should be continued by utilizing another free part of the spectrum.

2.18.1 CLASSIFICATION OF SPECTRUM SHARING

Spectrum sharing can be classified into three main parts, i.e. architecture, spectrum allocation behavior and spectrum access techniques.

Architecture

- **Centralized**
- **Distributed**

Spectrum Allocation Behavior

- **Cooperative**
- **Non-Cooperative**

Spectrum Access Technique

- **Overlay**
- **Underlay**

Centralized spectrum sharing: In centralized spectrum sharing, spectrum allocation and access procedures are controlled by a centralized entity [7]. Each entity in the CR network forwards the measurements of spectrum allocation to the central entity.

Distributed spectrum sharing: when the construction of an infrastructure is not suitable, then distributed solutions are proposed.

Cooperative spectrum sharing: The interference measurements are distributed among other nodes, the centralized solution is also referred as cooperative.

Non-cooperative spectrum sharing: Non-cooperative solutions only think about the nodes in hand that's why also called selfish solutions. The Non-cooperative solutions are reduced spectrum utilization and minimal communication requirements.

Overlay spectrum sharing: This overlay spectrum sharing is also known as the spectrum access technique. The node accesses the network by using that portion which is not under usage of the licensed user (LU).

Underlay spectrum sharing: The underlay spectrum sharing technique take advantage of the spread spectrum techniques which are specifically developed for cellular networks [8]. The underlay spectrum sharing requires such spread spectrum technique from which it can utilize high bandwidth.

2.18.2 SPECTRUM SHARING CHALLENGES

There are many ongoing research issues in spectrum sharing which should be properly investigated for the efficient use of the spectrum. A few challenging issues in CR along with their possible solutions are [7]:

Common control channel (CCC): In spectrum sharing solutions, when the primary user has selected a channel, this should be vacated without any interference. As a result, implementation is not feasible in fixed CCC CR networks. When we are not using CCC, the handshaking between the transmitter and the receiver becomes a challenge.

Dynamic radio range: In CR networks, huge amount of spectrums are used. Node neighbors change with respect to the variation of the operating frequency. The changing in the neighbor node affects the interference profile and the routing decisions. For minimum interference, control channels will be selected from the lower portion (high transmission range and selection of data channels in the high part of the spectrum.) and data channels will be selected from the higher portion.

Spectrum unit: The channels can be defined as frequency bands with respect to the frequency dimension [6]. Spectrum sharing is a challenge in advanced algorithms with respect to the definition of the channel behaving as a spectrum unit. The properties of the channel are not constant due to the influence of the operating frequency. The cognitive radio spectrum can be designed based on the generic spectrum unit. In a cognitive radio network it is difficult to find a common spectrum for efficient utilization.

CHAPTER 3

SPECTRUM SENSING TECHNIQUES

3.1 INTRODUCTION

Wireless communication technology has made an amazing development in recent years, which gives great benefit to people all over the world. The increasing diversity of applications (web, voice and multimedia), on one hand, demands high level of Quality of service (QoS) which leads to the allocated spectrum being overcrowded, which results in obvious degradation of user satisfaction. The licensed bands dedicated for paging, radio and televisions broadcasting, on the other hand, are wasting the allocated spectrum due to underutilization of the spectrum. Meanwhile, it results in terrific pressure on the finite radio spectrum resource. But wider band and faster rate are still pursed by communication systems and various networks for higher requirement nowadays. An interesting study conducted by FCC pointed out that more than 70% of radio spectrums are underutilized in certain times or geographic locations [9] .and the recent survey of Federal Communications Commission (FCC) depicts that spectrum usage varying between 15% to 85% in the case of the 0–6 GHz band [10]. This survey highlights the problem of spectrum scarceness and led towards the solution of the conflict between spectrum scarceness and spectrum underutilization. Finally FCC was convinced of the opening of licensed bands for unlicensed users also. Secondary users were allowed to access underutilized band in the case when the licensed user is absent and this was the birth of cognitive radio.The IEEE has organized a group called IEEE 802.22 for the development of an air interface for the secondary user to access the TV spectrum (underutilized) by using cognitive radio technology. The basic phenomenon behind the cognitive radio was to allow maximum possible utilization of the spectrum in such a manner that an unlicensed user does not cause any type of degradation of service for the license holders.

3.2 SPECTRUM SENSING

Spectrum sensing is one of the major functionalities in Cognitive Radio (CR), which allows CRs to monitor spectrum band of interest. Fast and accurate spectrum sensing technique is extensively crucial, since it provides sensing information to an intelligent spectrum management process. As a result, more efficient spectrum usage can be achieved. At the same time, existing users can maintain their communications without being interfered. Spectrum sensing should be performed first before permitting the secondary user to access the vacant licensed band as it is a key element in CR communication. Secondary users (SU) are permitted to utilize the licensed band only in the case when they do not create any type of interference for the primary users (PU). The Fig3.2 [3] shows the summary of spectrum sensing concept and all the related issues (spectrum sensing techniques, types of spectrum sensing and challenges etc.

3.3 MULTI-DIMENSIONAL SPECTRUM SENSING

The conventional definition of spectrum opportunity is “a band of frequencies which are not used by the primary user at a particular time and a particular geographic area” [3] and it only exploits three dimensions: frequency, time and space of the spectrum space. Conventional sensing methods usually undercount the three dimensions (frequency, time and space) during spectrum sensing however for good spectrum opportunity there are some other dimensions also which should be explored, for example, the code dimension of the spectrum space which is not explored well. That’s why conventional sensing algorithms do not deal with signals which utilize frequency hopping codes, time or spread spectrum. Hence as a result such types of signals cause a major problem for spectrum sensing. If interpretation is made of the code dimension as part of the spectrum space, then not only this problem can be avoided but also new opportunities for spectrum usage will be created.

In the same way for spectrum opportunity, angle dimension is not exploited as it should be and it is assumed that the transmission of the primary or/and secondary user is made in all the directions. With continuous advancement in multi-antenna technology has it been made possible multiplexing of multiple users into one channel at the same time and same geographic area with the help of beam forming concept.

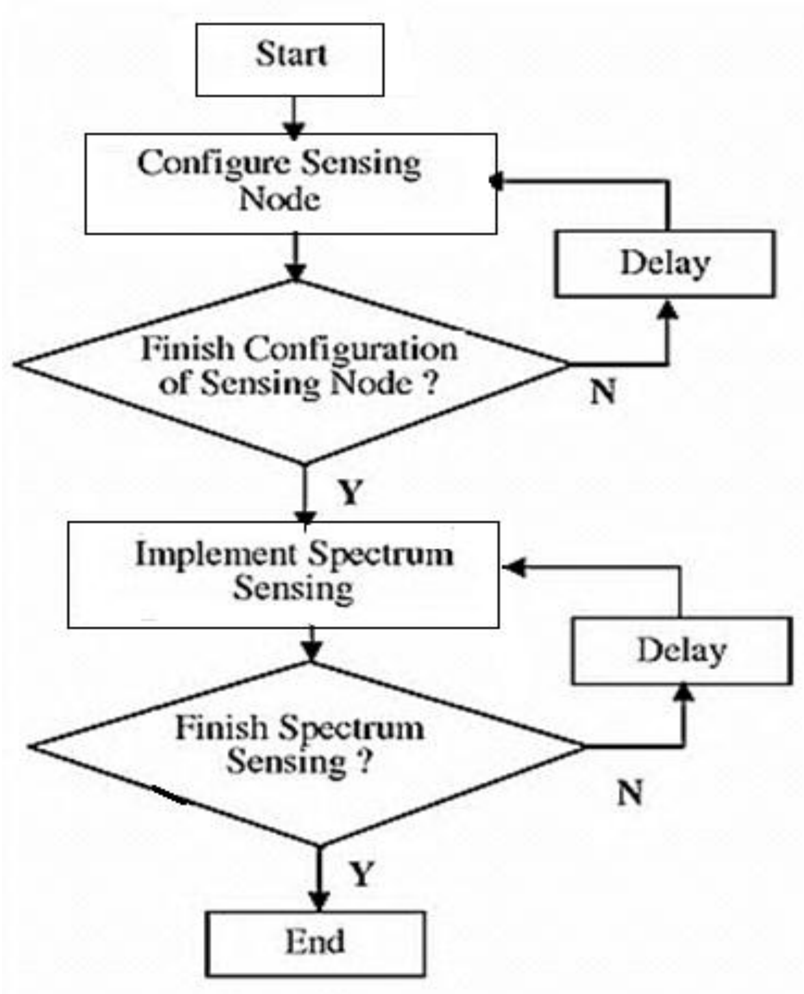

Figure: 3.1 Implementation step for spectrum sensing

In other words, another dimension can be created as an opportunity for spectral space. This angle dimension is different from the geographical space dimension; the angle dimension enables the primary and secondary user space dimension refers to the physical separation of radios in distance. It is of vital to share the same channel and to be in the same geographic area whereas the geographic important to define such an n-dimensional space for spectrum sensing. Spectrum space holes and the procedure of investigating the occupancy in all dimensions of the spectrum

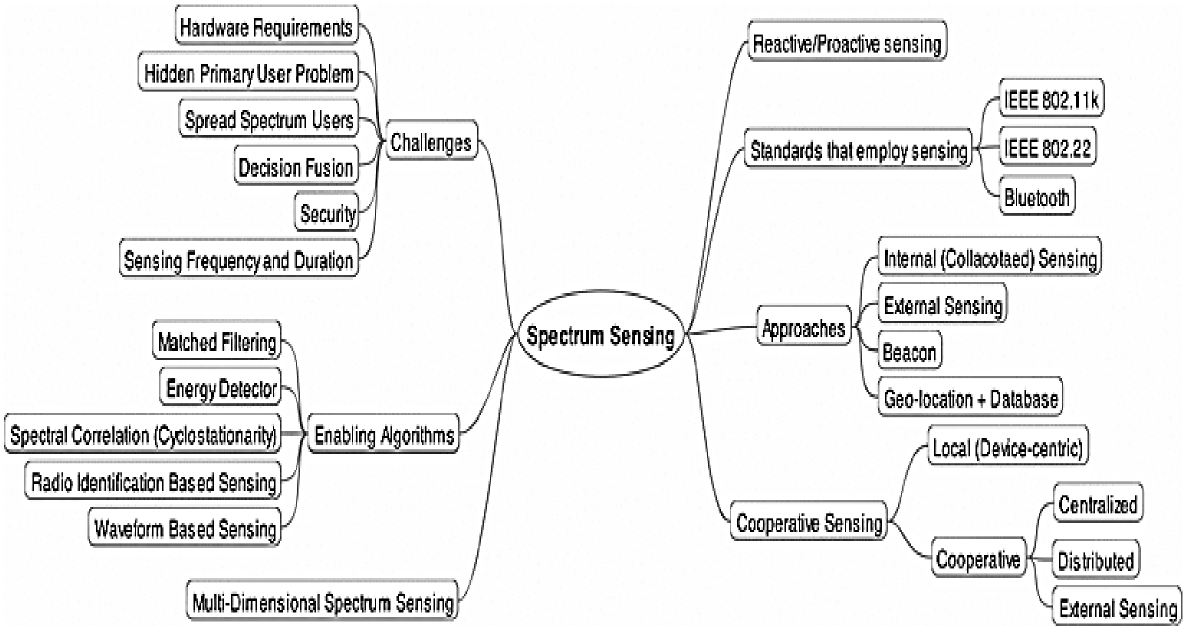

Figure: 3.2 Various Aspects of Spectrum Sensing for CR.[3]

Space should be included in spectrum sensing. For example a particular frequency can be occupied at a certain time and it might be empty also in another time, it makes temporal dimension as important as the frequency dimension. Here is another example of burst transmissions for WLAN [10]. This case is extended to the other dimensions of the spectrum space which are given in Table 3.1.

Table 3.1**:**Multi-Dimensional Spectrum Space and Transmission Opportunities [3]

Dimension	**What needs to be sensed?**	**Comments**
Frequency	Opportunity in the frequency domain	Availability in part of the frequency Spectrum. The available spectrum is divided into narrower chunks of bands. Spectrum opportunity in this dimension means that all the bands are not used simultaneously at the same time, *i.e.*

		some bands might be available for opportunistic usage
Time	Opportunity of a specific band in time	This involves the availability of a specific part of the spectrum in time. In other words, the band is not continuously used. There will be times where it will be available for opportunistic usage.
Geographical Space	Location (latitude, longitude, and elevation) and distance of primary users	The spectrum can be available in some parts of the geographical area while it is occupied in some other parts at a given time. This takes advantage of the propagation loss (path loss) in space. These measurements can be avoided by simply looking at the interference level. No interference means no primary user transmission in a local area. However, one needs to be careful because of the hidden terminal problem
Code	The spreading code, time hopping (TH), or frequency hopping (FH) sequences used by the primary users. Also, the timing information is needed so that secondary users can synchronize their transmissions with respect to primary users. The synchronization estimation can be avoided with long and random code usage. However,	The spectrum over a wideband might be used at a given time through spread spectrum or frequency hopping. This does not mean that there is no availability over this band. Simultaneous transmission without interfering with primary users would be possible in code domain with an orthogonal code with respect to codes that primary users are using. This requires the opportunity in code

	partial interference in this case is unavoidable	domain, *i.e.* not only detecting the usage of the spectrum, but also determining the used codes, and possibly multipath parameters as well.
Angle	Directions of primary users' beam(azimuth and elevation angle) and locations of PU	Along with the knowledge of the location/position or direction of primary users, spectrum opportunities in angle dimension can be created. For example, if a primary user is transmitting in a specific direction, the secondary user can transmit in other directions without creating interference on the primary user.

3.4 CHALLENGES

Before a detailed description of spectrum sensing techniques will be given, spectrum sensing challenges associated with cognitive radio are discussed in this section.

3.4.1 HARDWARE REQUIREMENTS

Analog to digital converters (ADCs) with high speed signal processors, high resolution and with larger dynamic range are required for spectrum sensing for cognitive radio networks [10]. Noise variance estimation techniques have been widely used for optimal receiver designs like channel estimation, soft information generation *etc.*, as well as for channel allocation techniques, and improved handoff power control [3]. As receivers are tuned to receive signals which are transmitted over a desired bandwidth that's why problem of interference is also an easy case in this scenario. Furthermore, receivers are able of processing the narrowband baseband signals with sensibly low complexity and low power processors. In cognitive radio, terminals are essential for processing transmission for any opportunity over a much wider band. Hence, in order to identify any spectrum opportunity, the CR should be in a position to capture and analyze a larger band. Radio frequency (RF) components are imposed on additional requirements by larger operating bandwidths such as antennas and power amplifiers

3.4.2 HIDDEN PRIMARY USER PROBLEM

This hidden primary user problem is like the hidden node dilemma in Carrier Sense Multiple Accessing (CSMA) [11]. Many factors like shadowing or severe multipath fading

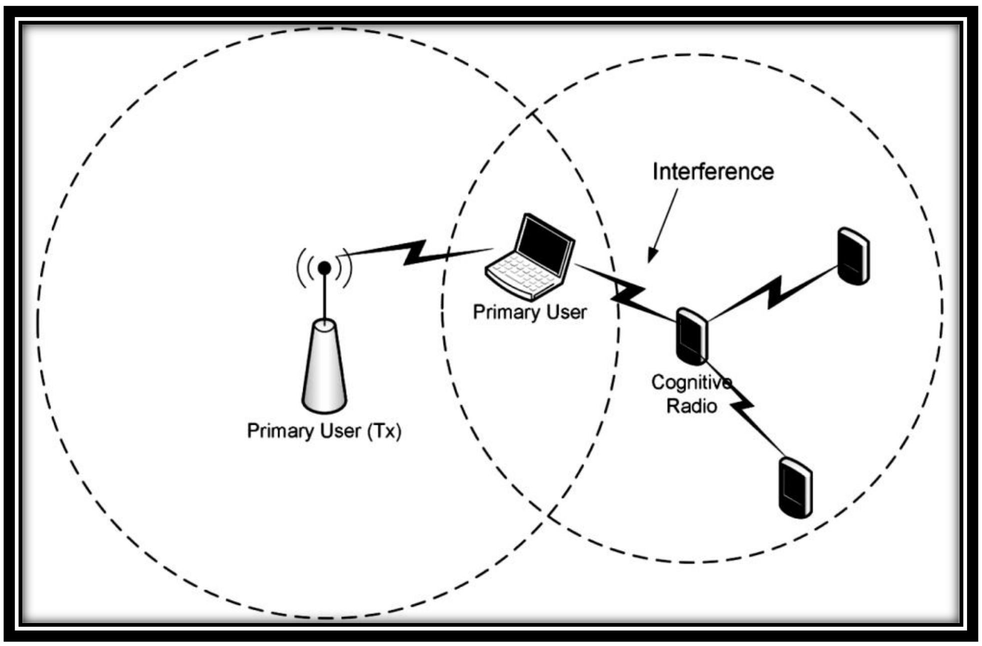

Figure: 3.3 Classification of Hidden Primary User Problem in CR Systems [3].

Which is observed by secondary user during the transmission scanning for the primary user, create this hidden primary user problem. Fig 3.3 illustrates the hidden node problem while the operating ranges for the primary user (PU) and for the cognitive radio device are shown by dashed lines. Here, unwanted interference is generated by cognitive radio devices to the primary user because due to the location of the devices, the primary transmitter's signal could not be detected. To deal with this primary user problem co-operative sensing technique is proposed [11].

3.4.3 DETECTING SPREAD SPECTRUM PRIMARY USERS

Devices which are commercially available have two types of technologies:

- **Fixed Frequency**
- **Spread Spectrum**

Spread spectrum has two further types of technologies:

- **Frequency hopping spread spectrum (FHSS)**
- **Direct sequence spread spectrum (DSSS)**

An example of fixed frequency devices is IEEE 802.11a/g based WLAN and these devices function at a single frequency or channel. FHSS devices adjust their operational frequencies vigorously to multiple narrowband channels. This is called the hopping and is performed according to a sequence which is recognized by the transmitter and the receiver also. DSSS devices resemble the FHSS devices but they utilize a single band in order to spread their energy. Primary users (PUs) which use spread spectrum signaling are hard to identify as the power of the PUs is dispersed over a broad frequency range, while the real information bandwidth is much narrower. A partial solution of this problem is that if you know the hopping pattern and method of perfect synchronization, but it is possible but not easy to develop such an algorithm through which estimation in code dimension is possible.

3.4.4 SECURITY

The cognitive radio air interface can be modified by a malicious user to mimic a primary user. Hence primary users can be misleading during the spectrum sensing process. Such a behavior or attack is called as primary user emulation (PUE) attack. The transmitter position is used to identify an attacker in [12]. A challenging problem is to develop valuable countermeasures when an attack is identified. In order to prevent secondary users masked as primary users, public key encryption based primary user recognition is proposed. An encrypted value (signature) which is generated using a private key is required to transmit with the transmissions of legitimate primary users. This signature is used to validate the primary user but this method is only used with digital modulations. That's why the secondary user should have the capacity for synchronization and demodulation of primary user's signal.

3.5 SPECTRUM SENSING PROBLEM

Spectrum sensing is a key element in cognitive radio communications as it must be performed before allowing unlicensed users to access a vacant licensed band. The essence of spectrum sensing is a binary hypothesis-testing problem

$\boldsymbol{H_0}$: Primary user is absent

$\boldsymbol{H_1}$: Primary user is present

The key metric in spectrum sensing are the probability of correct detection ($\boldsymbol{P_d}$) and two types of error in spectrum sensor, the first error occurs when the channel is vacant ($\boldsymbol{H_0}$) but the spectrum sensor can decide the channel is occupied, the probability of this event is the probability of false alarm(($\boldsymbol{P_d}$**)** , the second error when channel is occupied ($\boldsymbol{H_0}$) the spectrum sensor can decide the channel is unoccupied, the probability of this event is probability of misdetection ($\boldsymbol{P_m}$)[3].

$$P_d = \text{prob}\ \{\ \text{Decision} = {}^{H_1}/_{H_1}\ \}$$

$$P_f = \text{prob}\ \{\ \text{Decision} = {}^{H_1}/_{H_0}\ \}$$

$$P_d = \text{prob}\ \{\ \text{Decision} = {}^{H_0}/_{H_1}\}$$

3.5.1 ENERGY DETECTION

If the previous information of the PU signal is anonymous, then this energy detection method is optimal for detecting any zero-mean constellation signals [3]. In this energy detection approach, in order to determine whether the channel is occupied or not, the received signal strength indicator (RSSI) or radio frequency (RF) energy in the channel is measured. The implementation of this method for spectrum sensing is shown in fig 3.4. Firstly, in order to select the bandwidth of interest; the input signal is filtered by a band pass filter. After getting the square of the output signal, it is integrated over the observation interval. At the end, the output from the integrator is compared to a predetermined threshold value to conclude the presence or not of the PU signal. Specifically, the received signal **X(t)** sampled in a time window are first passed through an FFT device, in order to get the power spectrum ***X(f)***. Then the peak of this power spectrum is located and after windowing the peak of spectrum we obtain ***Y (f).*** Then the signal energy in the frequency domain is collected and the following binary decision is made.

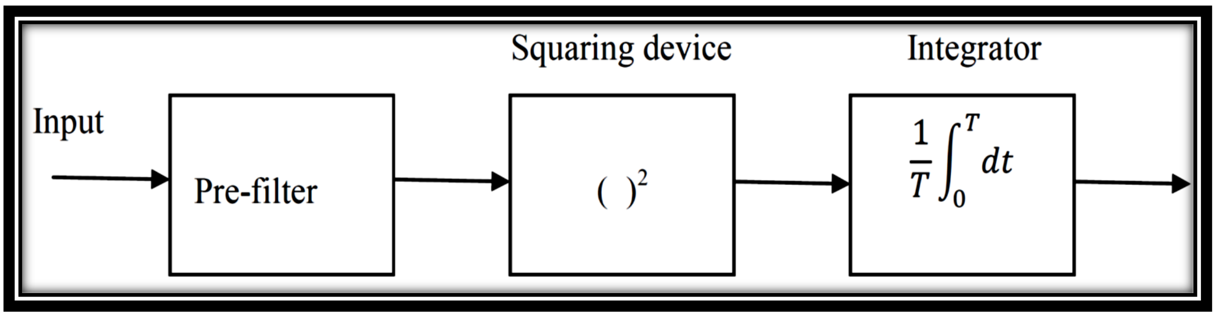

Figure: 3.4 Block diagram of energy detector in time domain

Rather than that this method can be implemented without prior knowledge of PU, it has still some drawbacks also. The first hitch is that it shows poor performance under low SNR conditions because at low SNR noise variance is not accurately known. Another issue is about the ability to differentiate between the other secondary users which are sharing the same channel and the primary user [13]. The threshold selection is also knotty since it is highly vulnerable to the changing background noise and interference level.

The binary hypotheses problem can be formulated by

$$X(N) = W(N)$$

$$X(N) = S(N) + W(N)$$

Where N is the number of samples, N=2TW, T is duration interval ,W is bandwidth, S (N) is the primary user's signal, W (N) is the noise and X (N) is the received signal. The noise is assumed to be additive white Gaussian noise (AWGN) with zero mean and is a random process. The signal to noise ratio is defined as the ratio of signal power to noise power

$$\gamma = \frac{P_S}{N_0}$$

Where P_s and N_0 are the average power of signal and noise

$$\frac{1}{N_0}\sum_{o}^{2TW}|X(N)|^2$$

This energy value has a central or non-central chi-square distribution. The final result is compared with threshold λ and the decision is made, the probability of detection and false alarm can be generally computed.

$$P_f = \frac{\Gamma[N/2, \lambda/2]}{\Gamma[N/2)]}$$

Where Γ (.,.) is the incomplete gamma function and Γ (.) is the complete gamma function

$$P_d = Q_{n/2}(\sqrt{2\gamma}, \sqrt{\lambda})$$

Where $P_d = Q_{n/2}(\sqrt{a}, \sqrt{b})$ is generalized Marcum Q-function .

3.5.2 MATCHED FILTER

A matched filter is the finest detection technique as it maximizes the signal to noise ratio (SNR) of the received signal in the existence of additive Gaussian noise. It is obtained by correlating a known signal with an unknown signal in order to detect the existence of the known signal or template in the unknown signal. It is the same as convolving the unknown signal with a time-reversed version of the template. Radar transmission has common use of a matched filter but its usage in CR is limited because of little available information of

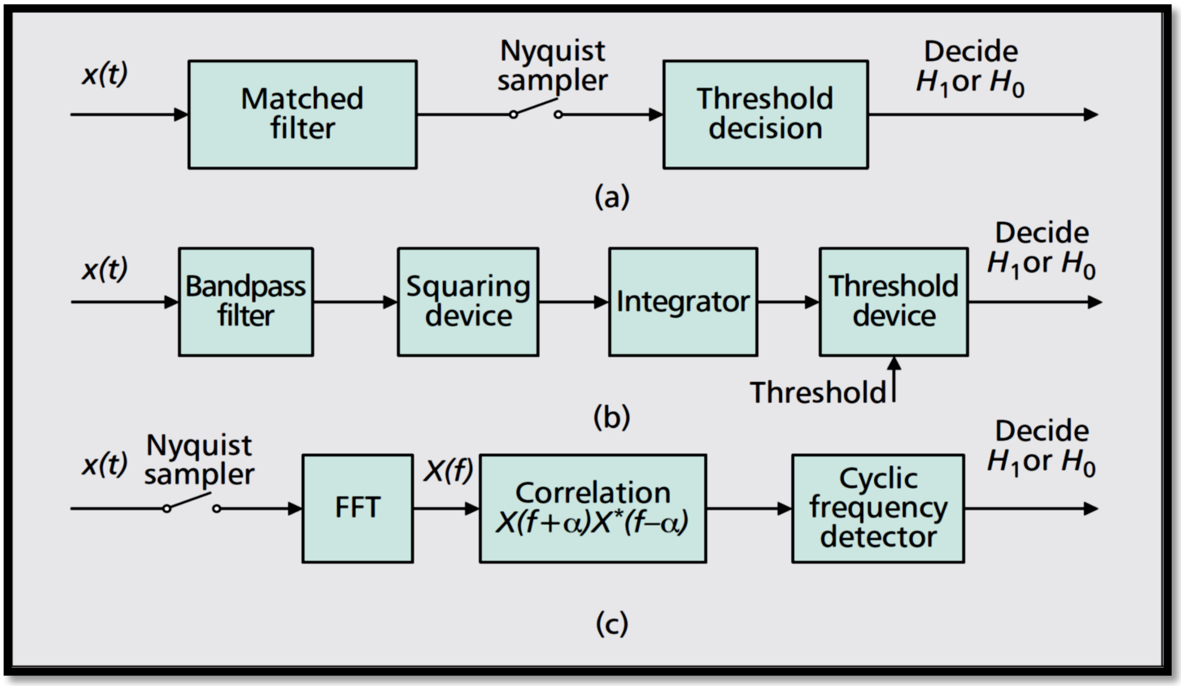

Figure: 3.5 Block diagrams for narrowband spectrum sensing algorithms
(a) Matched filtering, (b) energy detection, (c) cyclostationary feature detection.

Primary user signals in cognitive radio. Its usage is possible for coherent detection if partial information of PU signals is known. For example, in the case of Digital Television, to detect the presence of DTV signals, its pilot tone can be detected by passing the DTV signal through a delay- multiply circuit. Then the square of magnitude of the output signal is taken and if this square is larger than a threshold, the presence of the DTV signals can be detected.

$$T(x) \triangleq \sum_{n=1}^{N} x(N)\, x^{*}(n) \underset{H_1}{\overset{H_0}{\gtrless}} \gamma$$

The test statistic T(x) is normally distributed under both hypotheses

$$T(x) \sim \begin{cases} N(0\,, Np_s\, \sigma_v^2\,) & under\ H_o \\ N(\,Np_s\,, Np_s\, \sigma_v^2) & under\ H_1 \end{cases}$$

The probabilities of false alarm and detection are now given by

$$P_f = Q\left[\frac{\gamma}{\sigma_v\sqrt{Np_s}}\right]$$

$$P_d = Q\left[\frac{\gamma - Np_s}{\sigma_v\sqrt{Np_s}}\right]$$

Where the number of samples are N and σ_v^2 is the noise variance and p_s is the average primary signal power. It is well known that the structure of matched filter is the optimal detector that maximizes the SNR in the presence of additive noise if the transmitted signal, s, is known a priori. However, the matched filter is not suitable for spectrum sensing in very low SNR regions since synchronization is difficult to achieve [14]

3.5.3 CYCLOSTATIONARY DETECTION

Man-made signals are normally not stationary but some of them are cyclostationary, showing periodicity in their statistics. This periodicity can be utilized for the detection of a random signal which has a particular modulation type in a background of noise. Such detection is called cyclostationary detection. The signal of the PU can be detected at very low SNR values if it exhibits strong cyclostationary properties. If the autocorrelation of a signal is a periodic function of time *t* with some period then such a signal is called cyclostationary and this cyclostationary

$$R_x(t + \frac{\tau}{2}, t - \frac{\tau}{2}) = R_x(t + T_0 + \frac{\tau}{2}, t + T_0 - \frac{\tau}{2})$$

For some period $T_0 \neq 0$ where

$$R_x(t + \frac{\tau}{2}, t - \frac{\tau}{2}) = E\{x(t + \frac{\tau}{2}x(t - \frac{\tau}{2})\}$$

Where E[.] is expectation operation. Since R_x is periodic, it can be represented as a Fourier series as

$$R_x(t + \frac{\tau}{2}, t - \frac{\tau}{2}) = \sum_\alpha R_x^\alpha(\tau)\, e^{j2\pi\alpha}$$

Where the sum over α includes all integer multiples of the reciprocal of the fundamental period T_0. The Fourier coefficient $R_x^\alpha(\tau)$ also known as cyclic autocorrelation is given by

$$R_x^{\alpha}(\tau) = \frac{1}{T_0}\int_{-T_0/2}^{T_0/2} R_x(\mathrm{t} + \frac{\tau}{2}, \mathrm{t} - \frac{\tau}{2})\, e^{-j2\pi\alpha}\, \mathrm{dt}$$

Cyclostationary signals exhibit correlation between widely separated spectral components due to spectral redundancy caused by periodicity. The Fourier transform of the cyclic autocorrelation is spectral correlation function and is given by,

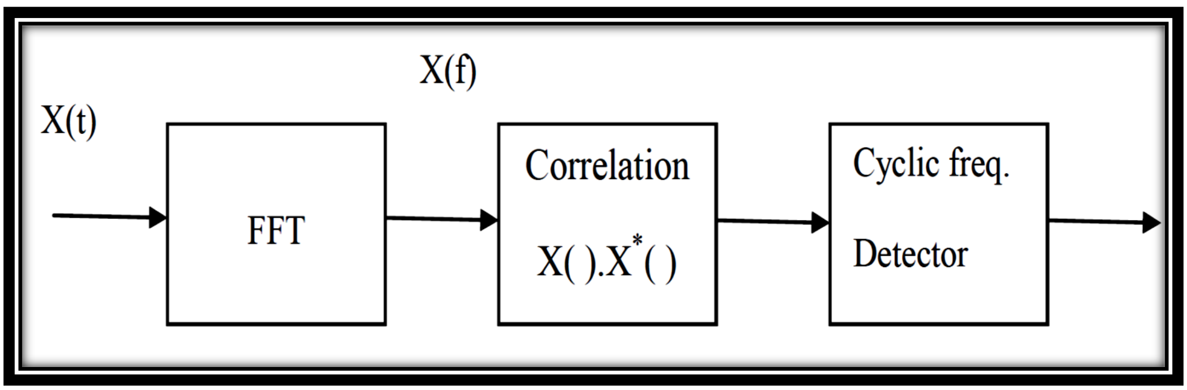

Figure: 3.6 Block diagram of cyclostationary detection

$$S_x^{\alpha}(\tau) = \int_{-\infty}^{\infty} R_x^{\alpha}(\tau)\, e^{-2\pi f\tau}\, d\tau$$

Unlike power spectrum density, which is real-valued one dimensional transform, the spectral correlation function is a two dimensional transform. In general it is complex-valued and the parameter α is called cycle frequency. Power spectral density is a special case of a spectral correlation function for α = 0. Different types of modulated signals (such as BPSK, QPSK, SQPSK) that have identical power spectral density functions can have highly distinct spectral correlation functions. Furthermore, stationary noise and interference exhibit no spectral correlation

Given N samples, the spectral correlation function $S_x^{\alpha}(\tau)$ (SCF) is estimated as [14]

$$s_x^{\alpha}(\mathrm{f}) = \frac{1}{N}\sum_{n=1}^{N} X_L\,(\mathrm{n,k} + \frac{k_\alpha}{2})\, X_\alpha^{*}\,(\mathrm{n,f} - \frac{k_\alpha}{2})$$

$$\text{Where } X_L(n,k) = \frac{1}{\sqrt{L}} \sum_{l=n-\frac{L}{2}}^{n+\frac{L}{2}-1} x(l)\, e^{-\frac{j2\pi kl}{L}}$$

is the L-point discrete Fourier transform (DFT) around the nth sample of the received signal, and $k_\alpha = \alpha L/Fs$ is the index of the frequency bin corresponding to the cyclic frequency α. The SCF of received signal is then correlated with the SCF of the signal (known priori) and then compared to a threshold to detect if the primary signal is present.

3.6 WAVELET BASED SPECTRUM SENSING

For signal detection over wideband channels, the wavelet approach offers advantages in terms of both implementation cost and flexibility in adapting to the dynamic spectrum as opposed to conventional use of multiple narrowband band pass filters (BPF)[15]. Unlike the Fourier transform, using sine's and cosines as basic functions, the wavelet transforms use irregularly shaped wavelets as basic functions and thus offer better tools to represent sharp changes and local features. In order to identify the locations of vacant frequency bands, the entire wide-band is modeled as a train of consecutive frequency sub bands where the power spectral characteristic is smooth within each sub band but changes abruptly on the border of two neighboring sub bands. By employing a wavelet transform of the power spectral density (PSD) of the observed signal x(t), the singularities of the PSD can be located and thus the vacant frequency bands can be found. One critical challenge of implementing the wavelet approach in practice is the high sampling rates for characterizing the large bandwidth.

3.7 STATISTICALLY MATCHED WAVELET

Over the last decade, a lot of work has been conceded out by various researchers to find wavelets matched to signals to provide the best representation for a given signal, but more or less, the issue of finding a matched wavelet has been addressed for deterministic signals. Tewfik et al. [15] also designed a wavelet matched to a signal in the time domain. The best approximation of the given signal f(t) with integer translates of a valid scaling function of finite fixed support N, expanded by a given factor M, at the proper scale J, has been found. Here, the approximation at resolution J depends only on the scaling function and not on the corresponding wavelets. Moreover, instead of minimizing the actual distance between f(t) and , the upper bound of error norm has been minimized. Since the minimization of norm in time domain was complex, minimization was carried out in the frequency domain, assuming that the signal being analyzed is band limited. The optimality was measured with respect to minimization of frequency domain norm of the approximation error. The closed-form expression for the error norm was obtained with this constraint in the frequency domain, but it led to very complex equations that are difficult to solve.

We present a new technique for the detection of power of signal by using statistically matched wavelet. The statistically matched wavelet is designed based on the characteristics of the power quality event using the concept of fractional Brownian motion. The proposed technique is compared with Daubechies wavelet to show its superiority in the detection of power quality events.

3.8 PERFECT RECONSTRUCTION FILTER BANKS

A filter bank is an array of band-pass filters that decomposes the input signal into several components, each one carrying a single frequency sub band of the original signal. It also is desirable to design the filter bank in such a way that sub bands can be recombined to reconstruct the original signal. The first process is called analysis, while the second is called synthesis. The output of decomposition filters is referred to as the sub band coded signal with as many sub bands as there are filters in filter bank[17].

The filter bank serves to isolate different frequency components in a signal. This is useful because for most application some frequencies are more important than others. For example these important frequencies can be coded with a fine resolution. Small differences at these frequencies are significant and a coding scheme that preserves these differences must be used. On the other hand, less important frequencies do not have to be exact. A coarser coding scheme can be used, even though some of the finer details will be lost in the coding.

A 2-channel filter bank splits the frequency spectrum into 2 bands – one containing high frequency information and the other containing low frequency information. A 2 channel filter bank is shown in Fig 3.7

The filters h_1 and g_1 are the decomposition filters and the filters h_2 and g_2 are reconstruction filters

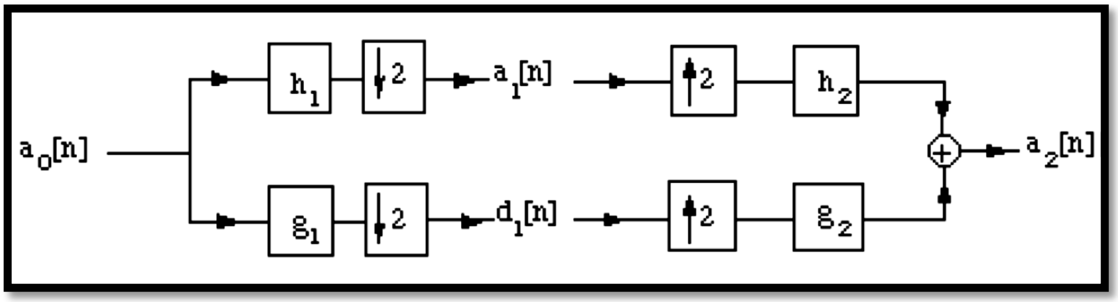

Fig 3.7 Filter bank

A two channel filter bank has the following input-output relation

$$a_1[n] = \sum_m h_1[m-2n]a_0[m]$$

$$d_1[n] = \sum_m g_1[m-2n]a_0[m]$$

In the frequency domain, this implies

$$2^* A_1(2\omega) = (A_0(\omega)H^*(\omega) + A_0(\omega+\pi)H^*(\omega+\pi))$$

$$2^* D_1(2\omega) = A_0(\omega)G^*(\omega) + A_0(\omega+\pi)G^*(\omega+\pi))$$

At the reconstruction end

$$a_2[n] = \sum_m h_2[m-2n]a_1[m] + \sum_m g_2[m-2n]d_1[m]$$

Which implies

$$A_2(\omega) = A_1(2\omega)H_2(\omega) + D_1(2\omega)G_2(\omega)$$

If the signal is perfectly reconstructed (a2=a1) after the decomposition and reconstruction steps, then the filter satisfies the PR property.

$$A_2(\omega) = A_0(\omega)$$

$$A_0(\omega) = 1/2\,(A_0(\omega)H_1^*(\omega) + A_0(\omega+\pi)H_1^*(\omega+\pi))H_2(\omega)$$
$$+ {}^{1}/_{2}\,(A_0(\omega)G_1^*(\omega) + A_0(\omega+\pi)G_1^*(\omega+\pi))G_2(\omega)$$

Equating coefficients of $A_0(\omega)$ and $A_0(\omega+\pi)$ on both sides, we get

$$\begin{bmatrix} H_2(\omega) \\ G_2(\omega) \end{bmatrix} = \frac{2}{\Delta(\omega)} \begin{bmatrix} G_1(\omega+\pi) \\ -H_1(\omega+\pi) \end{bmatrix}$$

Where $\Delta(\omega) = H_1(\omega)G_1(\omega+\pi) - G_1(\omega)H_1(\omega+\pi)$

If we put the constraint that $H_1 = H_2 = H_{cf}$ and $G_1 = G_2 = G_{cf}$, then the filter bank is known as a conjugate mirror filter. For a conjugate mirror filter the equations reduce to

$$|H_{cf}(\omega)|^2 + |H_{cf}(\omega+\pi)|^2 = 2$$

$$|G_{cf}(\omega)|^2 + |G_{cf}(\omega+\pi)|^2 = 2$$

$$H^*_{cf}(\omega)G_{cf}(\omega) + H^*_{cf}(\omega+\pi)G_{cf}(\omega+\pi) = 0$$

After this we will insert the coefficient of the this and we find the best representation of the signal and find the unoccupied spectrum.

3.9 PERFORMANCE ANALYSIS OF SPECTRUM SENSING METHOD

As we can see the difference between the various spectrum sensing techniques in the figure [3]

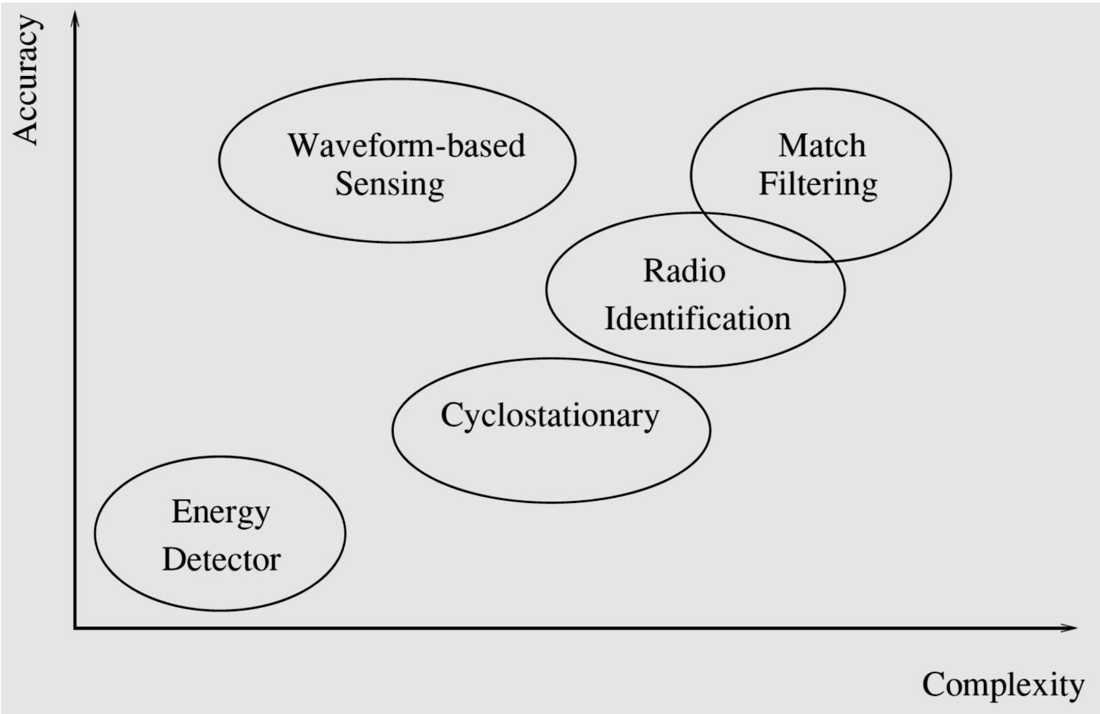

Figure: 3.8 Main sensing methods in terms of their sensing accuracies and Complexities

The energy detection is the most used spectrum sensing method. But the accuracy of the energy detection is very low because of allocation of threshold. In terms of complexity this method is very simple. The match filter based spectrum sensing is very accurate but the main problem of this techniques is that we have all the knowledge of the received signal and the techniques is very complex as compared to energy detection and other. Cyclostationary spectrum sensing is not so accurate and complex also but this is used also due to some advantage of this techniques. And the wavelet technique is explain later.

Table 3.2 performance analysis of spectrum sensing techniques

Spectrum Sensing Approach	**Advantages**	**Disadvantages**
Energy Detection	Does not need any prior Information Low Computational Cost	Cannot work in low SNR Cannot Distinguish Users Sharing the Same Channel
Matched Filter	Optimal Detection Performance Low Computational Cost	Requires a prior knowledge of the Primary User
Cyclostationary	Robust in low SNR Robust to Interference	Detection Requires partial information of the Primary User High Computational Cost
Wavelet Detection	Effective for wideband signal	Does not work for Spread Spectrum Signals High Computational Cost

CHAPTER 4

RESULTS

We proposed the fast spectrum sensing algorithm as a coarse sensing for CR based on the proposed two stage sensing architecture. In this project statistical matched wavelet is used to find the spectrum sensing in cognitive radio network which makes spectrum sensing fast. In cognitive radio there are secondary user can use the spectrum when primary users are not using the spectrum .These are the results given below in which the upper one is the original signal which created. And channel which have some bandwidth. Specifically, there exist 3 licensed (or primary) users that can sense the interested frequency band for CR users. We assume that each primary user's signal is band-pass signal with some bandwidth. In addition, the channel is additive white Gaussian noise (AWGN) channel with zero mean and $\frac{N_0}{2}$ variance

CASE 1: Centre frequencies of 3 primary users' signals as 0.15, 1.15 and 2.4 MHz which are shown in the figure and their magnitude are fixed as 1.1, 0.95 and 1.15 respectively that shown in the figure 4.2 the original signal in the channel first pass through fast fourier transform

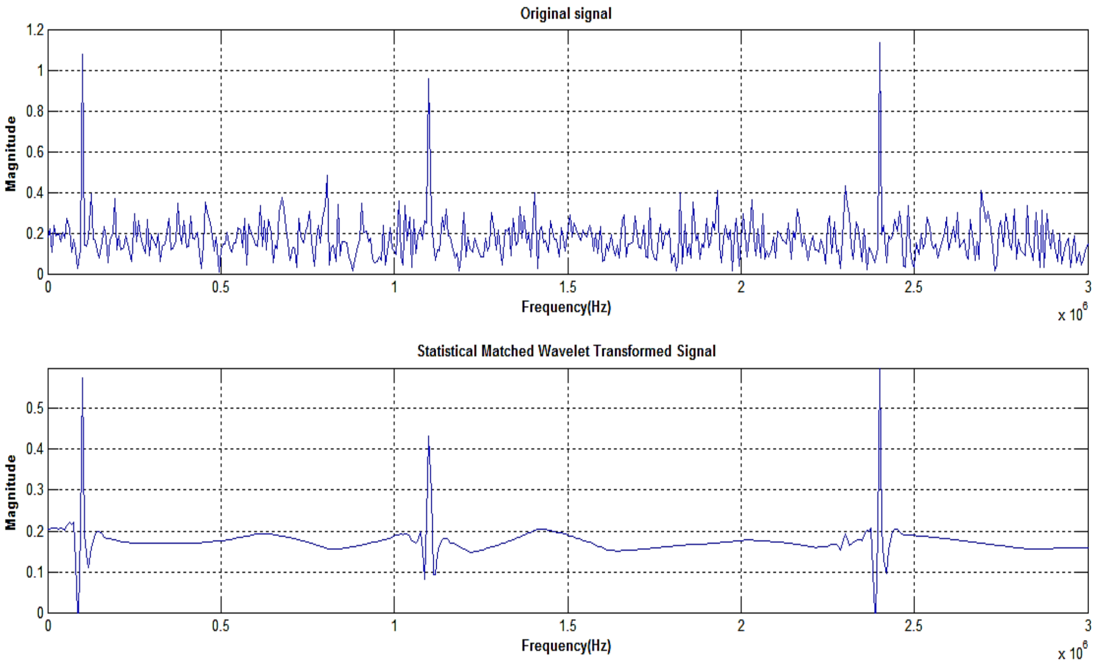

Figure 4.1 Three primary users and statistical matched wavelet transformed signal

CASE 2: Centre frequencies of 4 primary users' signals as 0.2, 1.0, 1.8 and 2.7 MHz which are shown in the figure and their magnitude are fixed as 1.0, 0.95 , 1.18 and 0.9 respectively that shown in the figure 4.2. The original signal in the channel first pass through fast fourier transform. Since centre frequencies that shown in the figure so the magnitude of that frequencies are greater than the others so when pass these signal to statistical matched wavelet so the result shown in the figure 4.2 so by these results we can see easily which part of the spectrum in unused. The statistical matched wavelet transformed the signal in a way, that the wavelet is matched to the original signal in statistical sense

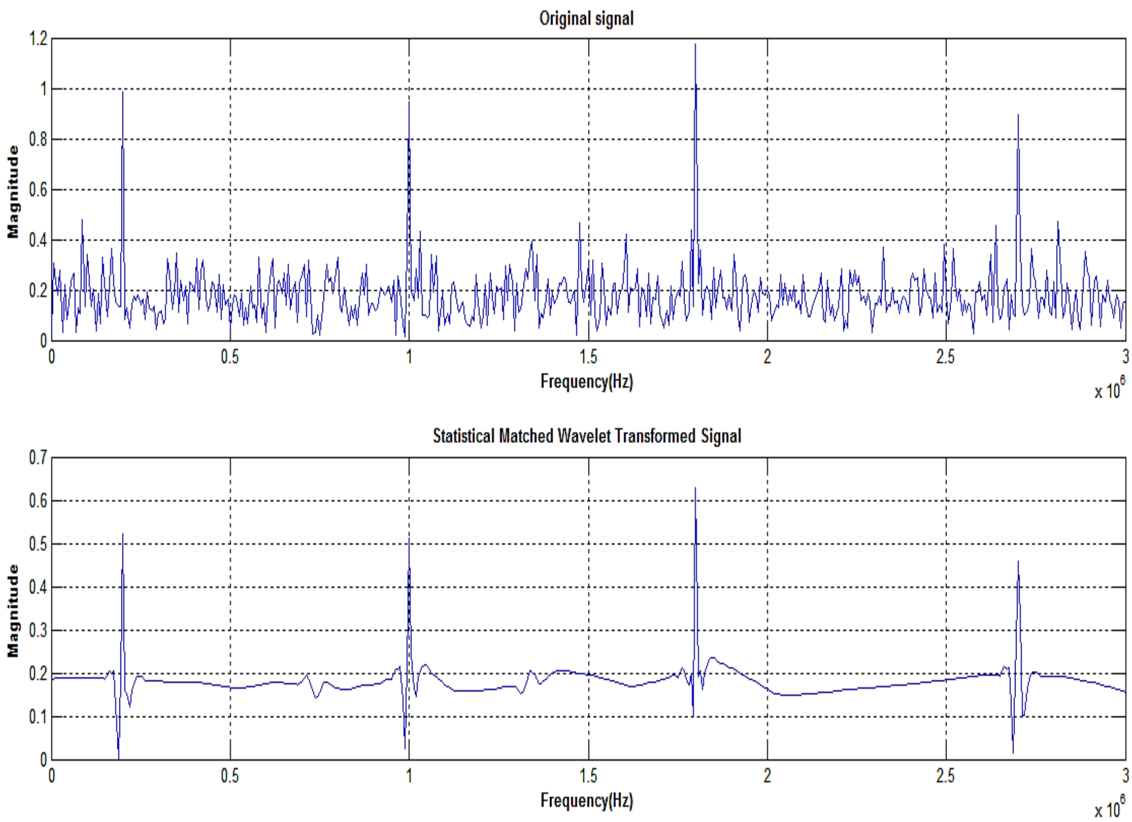

Figure 4.2 Three primary users and statistical matched wavelet transformed signal

CASE 3: The figure 4.3 given below is for the channel in which there are several primary users are using the frequency band. Centre frequencies of these primary users' shown in the figure 4.3 and their signal to noise ratio (SNR) are also fixed as shown. But in this case the number of users are very large and by statistical matched wavelet transformed we can also sense the unused part of spectrum but we have to define the some threshold level in which according to value of SNR so we can say that part of the spectrum is not used. In this case the channel is of 0-1MHz and according to a threshold level on SNR those spectrum have greater than this level so we can detect that part of the spectrum which is unused.

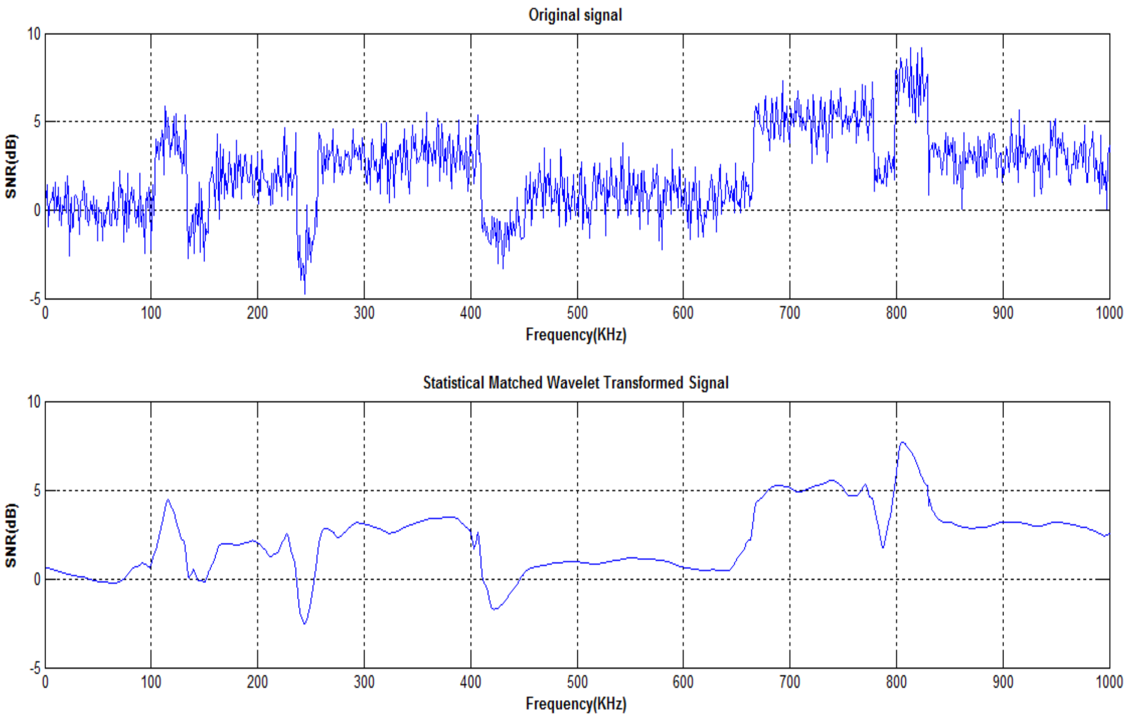

Figure 4.3 Several primary users and statistical matched wavelet transformed signal

CHAPTER 5

CONCLUSION

Spectrum is an incredibly precious reserve in wireless communication systems, and it is an important point of discussion, research and development efforts over the last many decades. CR, which is one of the hard works to employ the available spectrum more ingeniously through opportunistic spectrum usage, has turned into an electrifying and talented concept. The available spectrum opportunities are one of the significant elements of sensing in CR. In this Thesis studies the performance of statistical matched wavelet based spectrum sensing algorithm. Thesis explores various types of spectrum sensing techniques and discusses the performance of spectrum sensing techniques.

The main purpose of the thesis was to study the performance of statistical matched wavelet based spectrum sensing algorithm for spectrum sensing in cognitive radio. First we implemented the statistical matched wavelet transform with the help of MATLAB plate form and simultaneously we generated non periodic signal comprises of more than one frequency which is also incorporated with the additive white Gaussian noise .Each frequency describing a primary users .now with the help of statistical wavelet matched transform it is being statistically matched with the original non periodic signal comprising of noise as well. Now our aim is to reduce the noise and detect or sense the primary users and also find the unoccupied part of the channel which can be utilize by the secondary users. So that the whole channel can be efficiently utilized for communication.

SCOPE FOR FUTURE WORK

The success of the unlicensed band in accommodating a range of wireless devices and services consider opening further bands for unlicensed use. In contrast, the licensed bands are underutilized due to static frequency allocation. Realizing that CR technology has the potential to exploit the inefficiently utilized licensed bands without causing interference to compulsory users. But this technology is not currently in use because of the unsecured communication if certain measure like encryption or the licensing of the secondary users could make the use of this technology popular among the recent communication technique.

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