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**ANALYSIS OF SPECTRUM SENSING TECHNIQUES IN COGNITIVE RADIO FOR SPECTRUM S**

**BY**

SANJAY KUMAR ROY

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A THESIS

SUBMITTED TO THE DEPARTMENT OF ELECTRONICS AND COMPUTER

ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

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**ANALYSIS OF SPECTRUM SENSING TECHNIQUES IN COGNITIVE RADIO FOR SPECTRUM SHARING**

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**Recommendation**

The undersigned certify that they have read and recommended to the Department of Electronics and Computer Engineering for acceptance, a thesis entitled “**Analysis of Spectrum Sensing Techniques in Cognitive radio for Spectrum Sharing**” submitted by Sanjay Kumar Roy in partial fulfillment of the requirement of for the award of the degree of “Master of Science in Information and Communication Engineering”.

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**Abstract**

With the advancement of wireless communications, recent researches by the FCC (Federal Communication Commission) shows that large portion of the available licensed spectrum band lies unused, that is only used by licensed users (primary users). The bandwidth becomes expensive due to a shortage of frequencies. Therefore for efficient utilization of the spectrum band, FCC allowed secondary (unlicensed) users to utilize the licensed band without interfering the primary (licensed) users when it is not in use by primary user named it as Cognitive Radio. Cognitive Radio (CR) defined as:”A radio system employing technology that allows the system: to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained.

This thesis work analyses the performance of the energy detector based on MAP for identifying the status of the primary user. Matlab simulation is used for received signal from Cognitive radio networks and energy detector to find whether the spectrum being used or not by the primary user and later thesis tries to establish relationship between signal to noise ratio and the detection of primary user signal by using maximum a posteriori energy detection method. This thesis work also analyzes the spectrum detection schemes based on dynamic threshold algorithm. Spectrum detection based on fixed threshold are sensitive to noise uncertainty, the energy detection and the matched filter detection are analyzed for the case of noise uncertainty and dynamic threshold algorithm and found that energy detection based on dynamic threshold can improve the antagonism of noise uncertainty; get good performance of detection without increasing the computer complexity and improves the detection performance for the schemes that are sensitive to noise uncertainty.

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**Abbreviations**

A/D: Analog to Digital Converter

BER: Bit Error Rate

BPE: Band Pass Equipment

BWRC: Wireless Research Center Berkley

CR: Cognitive Radio

CRN: Cognitive Radio Network

CRU: Cognitive Radio User

ED: Energy Detector

FCC: Federal Communications Commission

FFT: Fast Fourier Transform

IEEE: Institute of Electrical and Electronics Engineers

ISM: Industrial Scientific and Medicine

MAP: Maximum a Posteriori

MFD: Matched Filter Detector

OSI: Open system interconnection

PDF: Probability Distributive Function

PSD: Power Spectral Density

PU: Primary User

QoS: Quality of Service

RF: Radio Frequency

SDR: Software Defined Radio

SNR: Signal to Noise Ratio

SPTF: Spectrum Policy Task Force

SU: Secondary User

UWB: Ultra Wide Band

WLAN: Wireless Local Area Network

WPAN: Wireless Personal Area Network

WRAN: Wireless Radio Access network

xG: Next Generation

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**Chapter 1**

**Introduction**

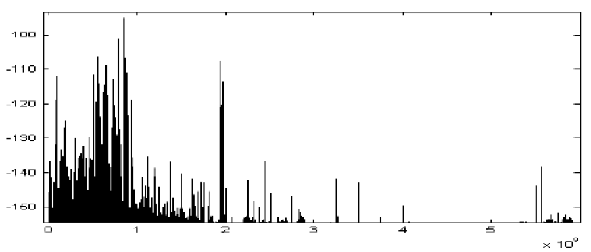
* 1. **Motivation and Background**

Efficient use of the limited natural resources is one of the society’s greatest challenges. Just like petroleum and coal, the natural frequency spectrum is limited and needed to be used more efficiently in order not to use up all. Recent research shows that more than 70% of the available spectrum is not utilized efficiently. The bandwidth becomes expensive due to a shortage of frequencies. Therefore for efficient utilization of spectrum, we need to sniff the spectrum to determine whether it is being used by primary user or not.

It is apparent that current static frequency allocation schemes cannot accommodate the demands of the increasing number of wireless users. Scarcity of electromagnetic spectrum is obvious. Taking this into consideration, the Federal Communications Commission (FCC) published a report prepared by Spectrum Policy Task Force (SPTF)[1] recommends certain rules and regulations for the efficient use of radio spectrum and the ways to improve the existing spectrum usage. In relation to the spectrum utilization this report illustrates that there is significant inefficient spectrum utilization than the actual spectrum scarcity due to the legacy system and the rules imposed by FCC. Most of the allotted channels are not in use most of the time; some are partially occupied while others are heavily used.

In [1] the authors measure the power spectral density (PSD) of the received 6 GHz wide signal. Figure 1.1 shows very low utilization of spectrum from 3-6 GHz. In order to improve spectrum Efficiency dynamic spectrum access technique is imperative.

While the current spectrum allocation leaves no available bandwidth for future wireless systems, actual measurements of the spectrum utilization show that any assigned bands are not being used at every location and time. Table 1.1 shows the spectrum utilization in the frequency range 0…….6GHz measured by BWRC at downtown Berkeley. From the table we can see that for frequency range 2…3GHz and 5…6GHz, the spectrum utilization less than 10%, while for 3…5GHz, it is even worse and is less than 1%.



**Figure 1.1:- Measurement of 0-6 GHz Spectrum Utilization at BWRC [4]**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Frequency**  **(GHz)** | 0-1 | 1-2 | 2-3 | 3-4 | 4-5 | 5-6 |
| **Utilization**  **(%)** | 54.4 | 35.1 | 7.6 | 0.25 | 0.128 | 4.6 |

**Table 1.1:- Frequency Utilization [8]**

Dynamic spectrum access techniques allow the cognitive radio to operate in the best available channel. More specifically the cognitive radio technology will enable the user to determine which portion of the spectrum is available, detect the presence of primary user (spectrum sensing), select the best available channel (spectrum management), coordinates the access to the channel with other users (spectrum sharing) and migrate to some other channel whenever the primary user is detected (spectrum mobility)[8].

The issue of spectrum underutilization in wireless communication can be solved in a better way

using Cognitive radio (CR) technology*.* Cognitive radios are designed in order to provide highly reliable communication for all users of the network, wherever and whenever needed and to facilitate effective utilization of the radio spectrum. Due to the low utilization of the licensed spectrum which is largely, due to inefficient fixed frequency allocations rather than any physical shortage of spectrum. This observation has forced the regulatory bodies to search a method where secondary (unlicensed) systems are allowed to opportunistically utilize the unused primary (licensed) bands commonly referred to as white spaces. Cognitive radio can change its transmitter parameters based on interaction with environment in which it operates. Cognitive radio includes four main functional blocks: spectrum sensing, spectrum management, spectrum sharing and spectrum mobility. Spectrum sensing aims to determine spectrum availability and the presence of the licensed users (also known as primary users). Spectrum management is to predict how long the spectrum holes are likely to remain available for use to the unlicensed users (also called cognitive radio users or secondary users). Spectrum sharing is to distribute the spectrum holes fairly among the secondary users bearing in mind usage cost. Spectrum mobility is to maintain seamless communication requirements during the transition to better spectrum.

Among all other functions, Spectrum sensing is believed as the most crucial task to establish cognitive radio networks. The various spectrum sensing techniques includes primary transmitter detection, cooperative detection and interference detection.

* 1. **Research Challenges**

A major challenge in cognitive radio is that the secondary users need to detect the presence of primary users in a licensed spectrum and quit the frequency band as quickly as possible if the corresponding primary radio emerges in order to avoid interference to primary users. This technique is called spectrum sensing. Spectrum sensing and estimation is the first step to implement Cognitive Radio system. To realize a spectrum sensing cognitive radio, as well as bring benefits at old radio systems, is a fundamental step to make a full CR so spectrum sensing function is an important objective for research world. Spectrum Sensing is not an easy problem to solve. Actually, it can be formulated as a class of optimization problems that arise in CR networks to maximize the spectrum efficiency. A sensing algorithm design should optimize the implementation complexity, the interference measurement, the power absorption, and more [3].

Anyway, it must also tackle others specific problems of the communications systems. Multipath fading would normally be expected to interfere with the signals between the target under detection and CR, so it's difficult to understand if a signal doesn't exist or it's reduced by a bad channel. This problem is called “hidden PU”[9][10] because a SU could transmit in apparent hole of spectrum that on contrary hides a PU signal. Other important feature of CR is the sensing time that may be as fast as possible. Hence, the detection method should be able to recognize the PU within a definite time. Several sources of uncertainty such as channel uncertainty, noise uncertainty, sensing interference limit etc. need to be addressed while solving the issue of spectrum sensing in cognitive radio networks. Finally, we cannot forget that CR network consists of multiple SU and PU, thus interferences between SU can occur so that detection system becomes unreliable. Cooperative sensing is recommended in literature for solving these problems [9][10], but definitive solutions don't exist yet .Actually CR is an open yard so, to uniform the building of CR, a coordinated work is necessary, so the most important challenge is to make a CR standard.

**1.3 Aims and Objectives**

The main aim of this thesis work is to performance analysis of the spectrum detection of primary user based on energy detection and matched filter detection scheme in Cognitive Radio environment. In order to fulfill this aim, it is necessary to have understanding the cognitive radio and the spectrum detection techniques. There are various types of spectrum sensing techniques concept being proposed to be implemented for cognitive radio systems. Studying of those techniques are required. For the spectrum detector performance measurements different metrics are considered such as the Signal to Noise ratio (SNR), Number of samples(N), Noise variance, Signal variance, Probability of False Alarm(PFA) and the Probability of Detection(PD), and Receiver Operating Characteristics (ROC) curves showing the relationship of the Probability of False Alarm(PFA) and the Probability of Detection(PD). With the relationship between SNR and the detections and study of ROC for the Energy detector and the Matched Filter Detector for different condition are obtained. To achieve such aims, following objectives have been set.

1. To perform the literature study of various topics related to the cognitive radio and the spectrum detection techniques in wireless environment
2. To Perform the analysis of Energy detection based on MAP to obtain relationship between SNR and detections for the PU detection
3. To Study and formulate the effect of noise uncertainty and effect of dynamic threshold on the detector (Energy and Matched Filter) performance
4. Perform the simulation to validate the effect of dynamic threshold under noise uncertainty environment for the Energy and Matched filter detector

**1.4 Research Methodology**

In this thesis work, the spectrum sensing techniques has been explored with the aim to use the vacant frequency band of the primary user, which is not utilized at particular time and space. These vacant bands could be used by the secondary users so that the spectrum utilization can be done and cope with the spectrum scarcity problem.

To identify the vacant spectrum of the primary users, it is needed that to detect the status of the primary user which is actually present in our desired band or not. For this we use energy detector based on maximum a posteriori (MAP). In the process of the experiment we encoded the signal in Matlab to simulate the output signal from the integrator with zero mean AWGN. The output of the signal is in Chi-square distribution, but we assume the Chi-square distribution as Gaussian distribution when samples are large. The o/p of integrator consists of the energy values of each samples signal. Then design an energy detector to detect the energy of different samples from the simulated signal we get. Comparing the energy we detected with the threshold, which we mentioned in Section 3.3.1.1, we can determine the presence or the absence of the primary users. We change the SNR to see the relationship between the SNR and the final detections. In the end, comparing the theoretical value and the simulated value to test whether the simulation working normally and the detections we get is reasonable.

In this thesis work, we also present the study of the spectrum detection algorithm based on dynamic threshold. Spectrum detection schemes based on fixed threshold are sensitive to noise uncertainty and the dynamic threshold scheme can improve the antagonism of noise uncertainty, get a good performance of detection while without increasing the computer complexity.

When the information of the primary user signal is known to the CR user, the optimal detector in white Gaussian noise is the matched filter, it maximizes received signal-to-noise ratio. However, the matched filter requires a priori characteristics knowledge of the primary user signal, e.g., modulation type and order, pulse shaping, packet format. If the receiver cannot gather sufficient information about the primary user signal, the optimal detector is an energy detector. However, the performance of the energy detector is susceptible to the uncertainty of noise power. Also, energy detector often generates false alarms triggered by unintended signals because they cannot differentiate signal, noise and interference. The critical technique is how decide the threshold.

The problem of signal detection in AWGN can be formulated as binary hypothesis testing problem with the hypotheses described in chapter 4. The received signals at CR nodes, transmitted signals at primary nodes and white noise samples are taken for testing of hypothesis. We assume that both signals and noise are independent of each other. Noise samples are from a white Gaussian noise process with power spectral density σn2, and its statistics are completely known to the receiver. Given a particular target probability of false alarm probability PFA, probability of miss detection (PMD) and probability of detection (PD = 1- PMD), thesis tries to calculate the samples required N, as a function of the signal to noise ratio (SNR).

To see the effect of noise uncertainty and dynamic threshold, we obtained the relationship of detection performance with both the noise uncertainty and dynamic threshold for both the detectors (matched filter and energy) which is described and simulated in detail in chapter 4 and 5. The noise uncertainty and dynamic threshold on the impact of energy detection and matched filter detection schemes are obtained in the formulation and later they have validated from the simulation. The results and performance analysis have been done and comparison of three conditions that noise power knows completely, existing noise uncertainty and dynamic threshold respectively. Thesis performs all the theoretical and simulation analysis of the dynamic threshold based spectrum sensing algorithm and validated that this has better robustness of anti-noise average power fluctuations for the energy detector.

**1.5 Organization of Report**

Chapter 1 of this thesis includes the motivation and the background of the cognitive radio system in wireless communication environment. It also has the summary of the research challenges to be faced in the present context of the spectrum sensing in cognitive radio. Finally the brief summary of methodology to be used in this thesis to fulfill the objectives has been discussed.

In chapter 2, the literature review of the wireless spectrum, cognitive radio and spectrum sensing in different perspective has been presented.

In chapter 3, the different spectrum sensing techniques and the challenges in the spectrum sensing has been presented. Also, the formulation of the energy detection based on MAP is presented in this chapter

In chapter 4, study and the formulation of the dynamic threshold techniques in cognitive radio system has been presented for the matched filter and energy detector.

In chapter 5, the simulation is performed based on the formulation which is described in chapter 3 and 4. In the first section of chapter 5 the simulations are performed on the basis of formulation which is done in chapter 3 for energy detection based on MAP and in the second section of chapter 5 simulations are performed on the basis of the formulations done for dynamic threshold techniques for spectrum sensing in cognitive radio described in chapter 4. Finally simulations of the performance of the spectrum detection schemes have been analyzed.

In chapter 6, discussion and critical analysis has been presented. The deliverables produced has also been presented.

In chapter 7, the recommendation for further works and improvements has been presented.

**Chapter 2**

**Literature Review**

**2.1 Introduction**

Recently wireless networks have been growing very rapidly. Aiming to meet this huge growth in Wireless technologies and services, recent researchers as well as industry have been working towards new techniques and standardizations.

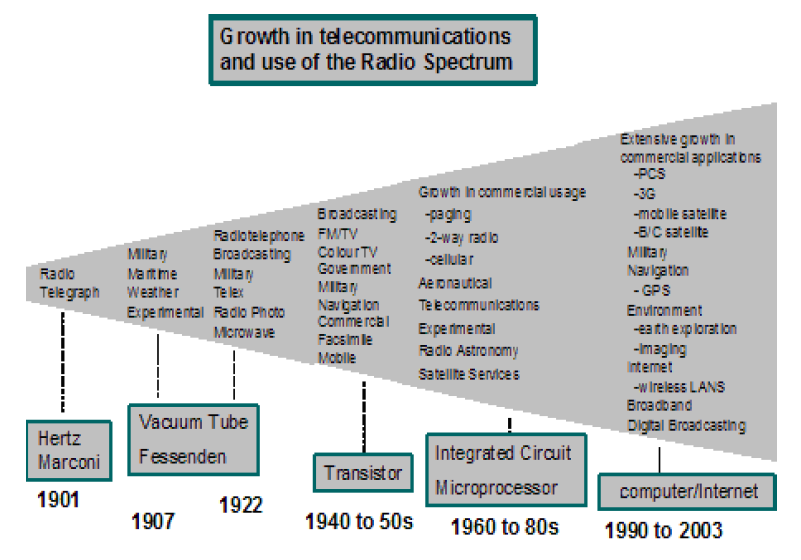
The most critical consequences for this growth in wireless networks are the ones related to spectrum usage and management as the electromagnetic radio spectrum is as the most precious natural resource when there is discussion about wireless networks. The existing policies of spectrum management are based 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 communications technologies it became unreasonable to use these policies and rely on static spectrum allocation due to economical and technical considerations. In order to solve this, Industrial, Scientific and Medical (ISM) [4][5] 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 and to overcome this, software defined radio (SDR) followed by cognitive radio (CR) networks based on dynamic spectrum access have been proposed as a promising solution.

Spectrum access aspects in both traditional radio and cognitive radio and dynamic spectrum access related concepts will be discussed. Some of these concepts and terms are totally new, which they appeared when cognitive radio was suggested as a novel approach to overcome the high growth in wireless communications services and users. On the other hand some of these terms and principles already exist but they got some kinds of new meaning and usage with cognitive radio.

**2.2 The Wireless Spectrum**

**2.2.1 Overview**

There is a rapid growth in the telecommunication sector in the last decade and due to several developments especially in wireless technologies more spectrums is required. Presently, fixed spectrum assignment policy is still in use. Fig.2.1 shows the rapid growth in telecommunication and the corresponding use of radio spectrum.

****

**Figure 2.1:- Rapid Growth in use of the radio spectrum [16]**

Due to the fixed assignment policy, a specific band of spectrum was assigned for different purposes. This removed the interference problem between spectra but also raised the issue of spectrum scarcity. Indeed, spectrum is available but its utilization is not efficient and most of the time the assigned spectrum remains unutilized. Therefore, the assignment and usage of this spectrum is a critical issue

The wireless spectrum is assigned to different operators on request. This assignment is fixed and the operators pay for the use of this spectrum. According to the FCC, the usage of this fixed spectrum is not efficient and results in lot of white spaces also known as spectrum holes. Much worse is that 90% of the time the spectrum remains vacant [23]. Due to the rapid growth in the wireless technology, spectrum usage is becoming a major issue.

**2.2.2 Unlicensed Spectrum:**

Unlicensed or license free spectrum is simply a band that has pre-defined rules for using the spectrum. In unlicensed bands the interference between many devices is minimized with the help of technical rules defined for the band unlike licensed spectrum approach where access is restricted. There are two major advantages of using the unlicensed spectrum. First, there is no requirement to register for using the spectrum and second its deployment is very fast and cost effective. The unlicensed spectrum is shared among users which is indeed useful for wireless systems in which devices can dynamically change its position like notebooks.

Unlicensed spectrum access is openly available but it has strict laws and regulations for utilizing the spectrum. The access to unlicensed spectrum is available for any device but how the device will utilize the spectrum is controlled in a way that other devices should not be affected. The access to the spectrum is allowed only for those devices which can follow the standards of communication while minimizing potential interference. [8]

**2.2.2.1 ISM band**

The ISM radio bands were originally dedicated for the use of Radio Frequency (RF) electromagnetic fields for industrial, scientific and medical research purposes only, not for the field of communications. The different ranges of ISM bands and their available bandwidth for communication is shown in fig.2.2. Since there is no license fee for using ISM bands, devices using these bands are cost effective. Moreover, as there is no requirement of registering the users using these bands, there is no particular restriction on users for their usage and users can use the products anywhere at any place.

**Frequency**

**Bandwidth**

**26 MHz**

**83.5 MHz**

**125 MHz**

**(902-908)MHz**

**(2.4-2.4835)GHz**

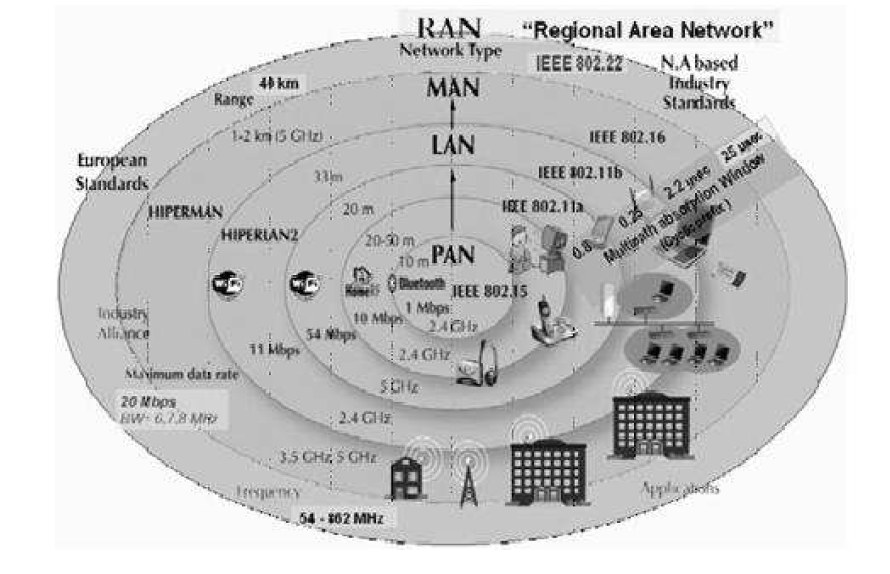
**(5.735-5.864)GHz**

**Figure 2.2:- ISM Bands [8]**

Most of the spectrum for whole WCS is already saturated and now several new wireless technologies tend to use the ISM band since it is easy to exist in the free band rather than assigning a separate portion of the spectrum for new services. Consequently in this band there is a heavy competition for using ISM bands which can also cause interference problems. On the other hand, TV broadcasting bands are used only in broadcasting hours and remains inactive rest of the time and no one can use this band in this inactive time which makes this band underutilized. The ISM band in the of range 2.4 GHz is becoming more and more popular for household devices in the last few years and almost all the commercial areas and buildings are also equipped widely with these devices such as garage door openers, cordless phones, remote controls, Wireless Fidelity (Wi-Fi) hot spots and many short range Bluetooth and Infrared devices.[19]

**2.2.3 Wireless Regional Area Network (IEEE 802.22)**

The Institute of Electrical and Electronics Engineers (IEEE) 802.22 Working Group was started in November 2004 for developing a standard for Wireless Regional Area Network (WRAN) which can also accommodate new technologies like CR. The 802.22 WRAN group is designed to work from the 54 MHz to 862 MHz range which is the Very High Frequency/Ultra High Frequency (VHF/UHF) TV operating bands that has been underutilized in the past. The WRAN target is to provide wireless broadband internet access having a range from 33 km to 100 km. The WRAN aims to utilize the unused TV spectrum by making unlicensed access of the TV spectrum possible. The new 802.22 WRAN system has the capability to sense the spectrum, scan for unused TV spectrum and then use that spectrum for providing broadband services. While doing so, they must make sure that there is no undesirable interference with licensed users. These are all main features for CR. Fig.2.3 shows the WRAN standards and applications.[16]

****

**Figure 2.3:- WRAN [16]**

The IEEE 802.22 WRAN standard is developed with the aim to provide broadband internet services in rural areas with a performance comparable to Digital Subscriber Line (DSL) and cable modems. The UHF/VHF television spectrum is suitable for such a service due to its propagation characteristics and underutilization. Propagation characteristics of UHF/VHF TV signals are basically the same as for FM signals. For example, their transmission is often referred as line of sight (LOS) transmission and their transmitters have to be situated on elevated grounds, they have enough higher frequency and smaller wavelength signal which can pass through the ionosphere instead of being refracted back on earth, etc. So, these TV signals can also be deployed for providing wide area services just like with FM technology. [16]

**2.3 Cognitive Radio**

**2.3.1 Introduction**

In the early days of communication there were fixed radios in which the transmitter parameters were fixed and set up by their operators. The new era of communication includes Software Defined Radio (SDR). A SDR is a radio that includes a transmitter in which the operating parameters including the frequency range, modulation type or maximum radiated or conducted output power can be altered by making a change in software without making any hardware changes [1]. SDR is used to minimize hardware requirements; it gives user a cheaper and reliable solution. But it will not take into account spectrum availability. Cognitive Radio (CR) is newer version of SDR in which all the transmitter parameters change like SDR but it will also change the parameters according to the spectrum availability.

Cognitive radio (CR) is an intelligent wireless communication system that is aware of its surrounding environment, learns from the environment and adapts its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters in real time [13]. The primary objectives of the cognitive radio are to provide highly reliable communications whenever and wherever needed and to utilize the radio spectrum efficiently. The key issues in the cognitive radio are awareness, intelligence, learning, adaptivity, reliability, and efficiency.

The term cognitive radio was first suggested by Mitola. He defines the cognitive radio as a radio driven by a large store of a priori knowledge; searching out by reasoning ways to deliver the service the users want[4]. The cognitive radio is reconfigurable and built on the software-defined radio (SDR).

The aim of the cognitive radio is to use the natural resources efficiently including frequency, time, and transmitted energy. Spectral efficiency is playing an increasingly important role as future wireless communication systems will accommodate more and more users and high performance (e.g. broadband) services. Cognitive radio technologies can be used in lower priority secondary systems that improve spectral efficiency by sensing the environment and then filling the discovered gaps of unused licensed spectrum with their own transmissions [4][13]. Unused frequencies can be thought as a spectrum pool from which frequencies can be allocated to secondary users (SUs), for example, in a hotspot. Spectrum pooling radio is a special case of a cognitive radio. Secondary users can also directly use frequencies discovered to be free without gathering these frequencies into a common pool. In addition, CR techniques can be used internally within a licensed network to improve the efficiency of spectrum use.

The main characteristics that a Cognitive Radio Network (CRN) must comply are:

* **Reconfigurability:** Reconfigurability refers to the ability of radio that allows the cognitive radio to adjust its parameters like link, operating frequency, modulation and transmission power at run time without any modifications in the hardware components. In other words Reconfigurability of CR is SDR. Doing so we dynamically change all the layers of communication. We can use different technologies depending on their spectrum availability with the same hardware.
* **Cognitive Capability:** Cognitive capability refers to the ability of radio to sniff or sense information from its environment and perform real time interaction with it. The cognitive capability can be explained with the help of three characteristics; Spectrum Sensing, Spectrum Analysis and Spectrum Decision. The spectrum sensing performs the task of monitoring and detection of spectrum holes. The spectrum analysis will estimate the characteristic of detected spectrum hole. In the spectrum decision, the appropriate spectrum is selected by determine the parameters like data rate, transmission mode etc.

**2.3.2 Cognitive Radio Tasks**

In [13], a typical cognitive radio operation is represented as a simplification to the cognition cycle. A cognitive cycle by which a cognitive radio interact with environment is described in [4] [5] and can be divided into three, tightly interconnected tasks see in Figure 2.4.which shows the basic cognition cycle which includes the following three tasks.

**(1) Radio-scene analysis, which encompasses the following:**

• Estimation of interference temperature of the radio environment;

• Detection of spectrum holes.

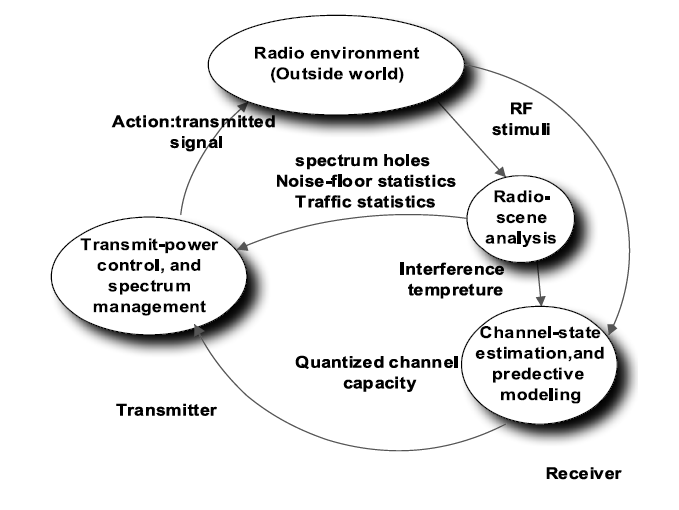
**(2) Channel identification, which encompasses the following:**

• Estimation of channel-state information (CSI)

• Prediction of channel capacity for use by the transmitter.

**(3) Transmit-power control and dynamic spectrum management**

Tasks (1) and (2) are carried out in the receiver, and task (3) is carried out in the transmitter. Through interaction with the RF environment, these three tasks form a cognitive cycle, which is presented in its most basic form in Figure 2.4.



**Figure 2.4:- Basic cognitive cycle [13]**

**2.3.2.1 Radio-scene analysis**

During Radio-scene analysis different radio configurations are probed to estimate interference temperature of the radio environment and detection of spectrum holes. Interference temperature and spectrum holes are defined as under.

**Interference Temperature**

The interference temperature is a measure of the sensed power in a certain frequency band. Thus, by obtaining this measure, two important limits can be identified:

• The maximum level where any signal exceeds threshold level.

• The minimum level where any signal below it can be neglected and thus that certain band can be considered as empty or unused, and can be used by other users.

**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 functionalities. 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.

**Reactive sensing:** The sensing is initiated only when the user has data to send, thus it is called on-demand sensing. If no usable channel is found, the user will wait for a predefined time and then restart sensing again until the user send all data that is available to be send. This technique reduces the sensing overhead. And its disadvantage is that, data is delayed until the sensing is performed with a good accuracy.

**Proactive sensing:** The sensing is done periodically even when the user is not intending to send any data. The time between the sensing iterations is called the sensing period. These sensing periods may differ between channels since each channel has its own unique characteristics. The sensing periods should be optimized separately for each channel to compensate for the unique traffic pattern on that channel. Following are some of the advantages and disadvantages.

Advantage: The delay is decreased since the users will know the holes even before they need them.

Disadvantage: A lot of time and effort is wasted on sensing even when it is not needed, thus increasing the sensing overhead.

**2.3.2.2 Channel-state estimation**

Channel estimation [13] was also proposed to be part of the cognitive radio. This operation aims in analyzing the channel behavior and its effects on the transmitted signal and estimating the impulse response of the channel. By observing the channel impulse response, information is used by the receiver for an equalizer design or the transmitter by transmitting a signal that can absorb those effects.

**2.3.2.3 Distributed transmit-power control**

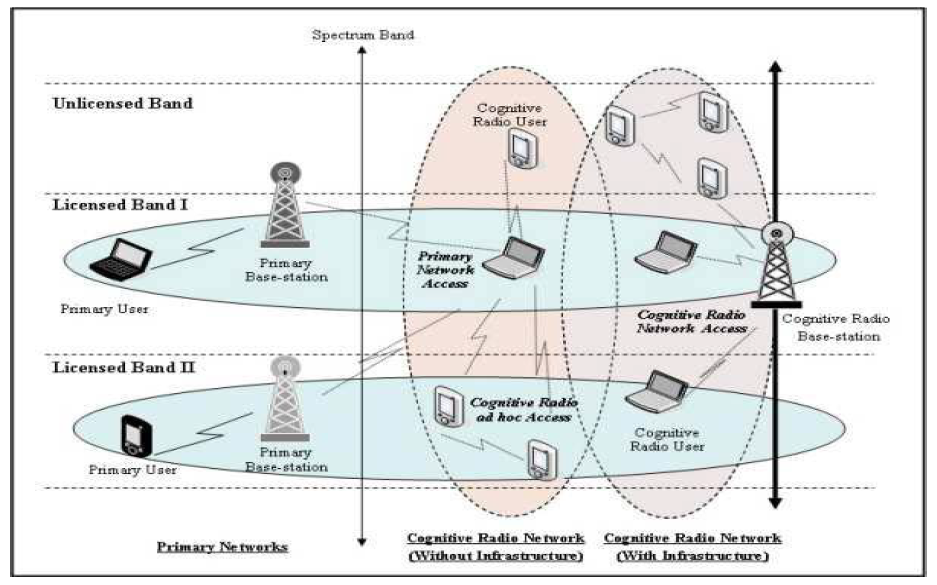
Like the spectrum allocation, this process is done centrally in conventional radios [13]. Thus, in cognitive radio each user should take care of it is own transmission power control and gives some feedbacks related to the signals that it received. As a result, the power control process is done in a distributed manner. In other words, each user must make sure that the signal that it transmits reaches the receiver in a certain level higher by the receiver and low enough to avoid interfering with other users. At the same time each user has to inform other users, which are transmitting to it, about the reception, signal level. The power control operation plays a crucial part in minimizing the interference and in insuring the needed quality of service in many communication systems.

**2.3.2.4 Dynamic Spectrum Management**

As with transmit-power control, dynamic spectrum management [13] (also referred to as dynamic frequency-allocation) is performed in the transmitter. These two tasks are intimately related to each other, and hence have been included inside a single functional module. It performs the role of multiple-access control in basic cognitive cycle as in figure 2.4 simply replace, the primary purpose of spectrum management with an adaptive strategy for the efficient and effective utilization of the RF spectrum. Particularly, the spectrum-management algorithm is designed to do the following. Building on the spectrum holes detected by the radio-scene analyzer and the output of transmit-power controller, select a modulation strategy that adapts to the time-varying conditions of the radio environment, all the time assuring reliable communication across the channel. Communication reliability is assured by choosing the SNR gap large enough as a design parameter.

**2.3.3 Network Architecture for Cognitive Radio Network**

The Network is divided into two parts, the primary network and the cognitive radio network. The general architecture of the cognitive radio network is given in fig.2.5 [8]. The Primary network is deferred to as the legacy network that has the high to use the spectrum. On the other hand, the cognitive radio network does not have the license to operate in desired band. The cognitive radio users can either communicate with each other in multi hop manner or access the base station.



**Figure 2.5:- Cognitive Radio Architecture [8]**

**2.3.3.1 Primary Network**

The primary networks are those which have the license to use the wireless spectrum. Common primary networks include TV broadcasting and cellular companies. [8]

• **The Primary user:** Primary or licensed users are the legal users of the primary network. The operation of primary users is controlled entirely by the primary base station. [1]

• **The Primary Base Station:** The primary base station is a fixed infrastructure network like the Base Station Transceiver (BTS) in the cellular system. The primary base station is unable to manage the sharing of spectrum between the primary and secondary users but it can modify itself upon request. [8]

**2.3.3.2 Cognitive Radio Network**

The cognitive radio network or xG network does not have a license to use the spectrum. Hence, it uses the spectrum when it is vacant. The cognitive radio network is implemented as both a fixed and an ad hoc network. The main parts of the cognitive radio network are as follows [8] :

• **The Cognitive Radio User:** The cognitive users are the secondary users and do not have the license to use the spectrum and they are using the spectrum opportunistically. To access the licensed spectrum they need extra capabilities. [8]

• **The Cognitive Radio Base-Station:** It has a fixed infrastructure and has the next generation capabilities which helps the unlicensed user access the other networks. [8]

**2.3.4 Cognitive Radio and the Physical layer**

Before the invention of cognitive radio, all operating wireless devices were based on the OSI/ISO layering model. CR also uses the OSI/ISO layering model. The most critical issue in the CR is the sensing of free available spectrum and the process of sensing the vacant band is performed on the Physical layer. The critical issue while sensing the unused spectrum is to detect weak signals under noisy conditions. In the process of sensing the unoccupied spectrum, the signal is detected via the RF-front end, and as the received signal is in the analog form, it is converted to the digital form through the Analog to Digital converter (ADC). After the analog to digital conversion, the measurements are made for the detection of the primary user signal. The block diagram of the receiver is shown in fig.5. [23]

RF Front End

A/D

Converter

Signal Measurement

Signal Detection

**Figure 2.6:- Cognitive Radio Receiver**

Channel

Primary User

After detecting the unoccupied spectrum, the CR should adapt a feasible modulation technique to utilize the maximum available capacity. Now coming towards the transmitter side of the CR, the fig.6 shows the major parts of the transmitter used in CR. The critical issue on the transmitter’s side is the generation of a signal that does not create interference with the primary users. [23]

RF Transmitter

D/A

Converer

Signal Generation

Signal Parameters

**Figure 2.7:- Cognitive Radio Transmitter**

Channel

Primary User

**2.4 Spectrum Sensing**

Due to an increasing demand of high data rates, static frequency can’t 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 [4][5]. 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 [4][5]. The ultimate objective of the cognitive radio is to obtain the best available spectrum through Cognitive Capability and Reconfigurability as described above. Since there is already a shortage of spectrum, 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 [15]. 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.



**Figure 2.8:- Spectrum Hole Concept [15]**

Spectrum sensing for cognitive radios is still an ongoing development and the techniques for the primary signal detection are limited in the present literature. One of the most distinguished features of cognitive radio networks will be an ability to switch between radio access technologies, transmitting in different parts of the radio spectrum as idle frequency band slots arise. The dynamic spectrum access which was proposed by Mitola first time is one of the fundamental requirements for transmitters to adapt to varying channel quality, network congestion, and interference and service requirements.

Due to the rapid growth in the field of communication, there is an increasing demand for higher data rates. Static frequency assignment cannot fulfill the requirements of higher data rates. In CR communication, spectrum sensing is performed before an SU starts using the spectrum. By spectrum sensing, the white holes are determined and these holes are used efficiently. There are certain methods for sensing the unused spectrum. Spectrum sensing techniques (Cooperative detection, Transmitter detection and Interference-based detection) are described below.

**2.4.1 Characteristics of Spectrum Sensing**

Spectrum sensing is based on a well-known technique called signal detection. Signal detection can be described as a method for identifying the presence of a signal in a noisy environment. Signal detection has been thoroughly studied for radar proposes since the fifties[9]. Analytically, signal detection can be reduced to a simple identification problem, formalized as a hypothesis test:

H1: x(n) = s(n) + w(n) ……………………………………………………………… (2.1)

H0: x(n) = w(n) ………………………………………………………………….……(2.2)

Where x(n) is the received signal by secondary users, s(n) is the transmitted signal of the primary user, h is the channel coefficient; and w(n) is the additive white Gaussian noise with variance σw2.

H0 and H1 are the sensing states for absence and presence of signal respectively. Another saying: H0 is the null hypothesis which indicates that primary user does not communicate and H1 is the alternative hypothesis that indicates the existence of the primary user. We can define four possible cases for the detected signal:

1. Declaring H1 under H1 hypothesis which leads to Probability of Detection (Pd)

2. Declaring H0 under H1 hypothesis which leads to Probability of Missing (Pm)

3. Declaring H1 under H0 hypothesis which leads to Probability of False Alarm (Pf)

4. Declaring H0 under H0 hypothesis

If H0 is decided under H1 hypothesis, then it leads to probability of missing, Pm that is probability of deciding that there’s no primary signal while primary signal actually exists. Another saying it’s the probability of signal missing. If H1 is decided while H0 is observed then it refers to find the probability of false alarm which indicates to decide primary signal exists while there’s actually no primary user communicating. Thus false alarm error leads to inefficient usage of the spectrum.

Literally, the aim of the signal detector is to achieve correct detection all of the time, but this can never be perfectly achieved in practice because of the statistical nature of the problem. Therefore signal detectors are designed to operate within prescribed minimum error levels. Missed detections are the biggest issue for spectrum sensing, as it means possibly interfering with the primary system. Nevertheless, it is desirable to keep false alarm probability as low as possible, so that the system can exploit all possible transmission opportunities.

**2.4.2 Spectrum Sensing Challenges**

**i. Hidden Node Problem**

The fading effects of the wireless channel plays an especially negative role in the well known ’hidden node’ problem [9], which also refers to hidden primary user. In this problem, the spectrum sensing terminal is deeply faded with respect to the transmitting node while having a good channel to the receiving node. The spectrum sensing node then senses a free medium and initiates its transmission, which produces interference on the primary transmission. Thus, fading here introduces uncertainty regarding the estimation problem. To solve this issue, cooperative sensing has been proposed [8].

**ii. Limited Sensing Ability**

In [9], it’s underlined that cognitive radio has only a basic ’sense of hearing’ to detect the spectrum holes that’s why its ability is limited. That indicates, a cognitive radio has to detect its multidimensional environment with only a single sense. For instance: considering a blind person trying to go across in a busy traffic only use shearing sense just like a cognitive radio does. Many open questions are related to the sensing ability and performance in wide bandwidths. Advanced techniques are needed to overcome this problem and sense very wide bandwidths reliably and rapidly.

**iii .Wideband Sensing**

One of the main concerns in spectrum sensing is how to set the boundaries of spectrum to sense. Instead of very wide band detection, limited spectrum can be used for spectrum sensing. Working in limited spectrum; received signal can be sampled at or above Nyquist rate with current technology. Furthermore; the computational difficulty encountered in wide band detection can be restricted to a reasonable level [9]. Expensive analog front-end required for a very wide spectrum can also be avoided. Taking everything into consideration; regulatory agencies should allocate spectrum bands for different types of cognitive radios depending on the spectrum range that they work [9].

**iv. Spectrum Sensing in Multi-Dimensional Environment**

The environment that cognitive radio based systems work in generally consists of multiple unlicensed users with multiple licensed users [9]. The existence of multiple secondary users causes some challenges in spectrum sensing as interference to other secondary users in the environment that is expected to make it difficult to sense primary users reliably. To overcome the problem, a few aspects of cooperation in spectrum sensing must be considered such as the distributed information (transmitted power, frequency of other users, location), the way to cooperate with other unlicensed users, the need of primary users involving in the cooperation [9].

**v. Sensing Time**

Using cognitive radios; it’s guaranteed that licensed users can use their frequency bands any time and to increase the capacity of the spectrum and avoid interference; spectrum holes must be detected as quickly as possible to accommodate the secondary users. In [9], it’s underlined that spectrum sensing algorithm must be performed within a limited time duration. It also must be taken into account that how often cognitive radio sense the spectrum. It needs to sense very frequently in order not to miss any opportunity.

**2.4.3 Spectrum Sensing Methods**

The mostly used spectrum sensing techniques are given as,

• Matched Filtering

• Cyclostationary Based Sensing

• Energy Detector Based Sensing

• Cooperative Spectrum Sensing

• Other Sensing Methods

Some of these methods will be discussed in detail in chapter 3.

**2.5 Spectrum Management**

The goal is to find the best available spectrum to fulfill the needs of the communication. The licensed, unlicensed and unused spectrum bands are spread over a large number of frequencies in the cognitive radio networks. 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 [5].

**2.5.1 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. To represent the quality of the spectrum band, parameters are defined such as interference, holding time, path loss, link layer delay, wireless link errors etc.

• **Interference:** The interference characteristics of the channel can be determined from the spectrum band in used. The permissible power of a CR user can be calculated, from the amount of interference which is use for the calculation of the channel capacity.

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

• **Path loss:** If the operating frequency increases, the path loss will also be increased. 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 if we increase the transmission power this 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.

**2.6 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.

• **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.

**2.6.1 Classification of spectrum sharing**

Spectrum sharing can be classified into three main parts, i.e. architecture, spectrum allocation behavior and spectrum access techniques which is illustrated in fig2.9 [5].

**Architecture Spectrum Allocation Behavior** S**pectrum Access Techniques**

**Centralized Distributed Cooperative Non Cooperative Overlay Underlay**

**Figure 2.9:- Classification of spectrum sharing in Cognitive radio**

•**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 takeadvantage 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.

**Chapter 3**

**Spectrum Sensing Techniques**

**3.1 Introduction**

The recent continuous and rapid growth of wireless communications and its services has made the problem of spectrum usage ever more critical and demanding. 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. 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.

Spectrum sensing refers to detecting the unused spectrum (spectrum holes) and sharing it without harmful interference with other secondary users. In cognitive radio technology, primary users (can be defined as the users who have the highest priority on the usage of a specific part of the spectrum. Secondary users have lower priority, and should not cause any interference to the primary users when using the channel. Spectrum sensing is still in its early stages of development. A number of various methods are proposed for identifying the presence signal in transmissions. In some another approaches, characteristics of the identified transmission are detected for deciding the signal transmission as well as identifying the type of signal [11]. The well known spectrum sensing techniques used are matched filter detection, energy detection, cyclostationary detection, wavelet detection and covariance detection.

**3.2 Spectrum Sensing Methods for Cognitive Radio**

In CR communication, spectrum sensing is a key element and it should be performed before an unlicensed user (SU) is allowed to access a vacant licensed band. The essence of spectrum sensing is a binary hypothesis-testing dilemma:

H0**:** Primary user is absent

H1**:** Primary user is in operation.

The probability of correct detection PD, probability of false alarm PFA and probability of miss detection PMD are the key metric in spectrum sensing, given respectively as:

PD= Prob{Decision = H1/H1} (3.1)

PFA= Prob{Decision = H0/H0} and (3.2)

PMD= Prob{Decision = H0/H1} (3.3)

There are many signal detection techniques, in order to enhance detection probability, which can be used in spectrum sensing. By spectrum sensing, the white holes are determined and these holes are used efficiently. There are certain methods for sensing the unused spectrum. Spectrum sensing techniques (Cooperative detection, Transmitter detection and Interference-based detection) are shown in fig. 3.1 below. [1]

Spectrum Sensing

Interference Temperature Detection

Cooperative Detection

Trasmitter Detection

Cyclostatinary Feature Detection

Matched Filter Detection

Energy

Detection

**Figure 3.1:- Different Spectrum Sensing Techniques**

**3.3 Transmitter detection**

In this technique, weak signals of the PU transmitter are detected on the basis of local observations of the cognitive user. The transmitter detection method depends on the hypothesis model that is defined as:

x(𝑡) = s(𝑡); H0 …………………………………………………………………. (3.4)

= ℎ(𝑡) + 𝑛(𝑡); H1 …………………………………………………………. (3.5)

Where, x(𝑡) is the signal received by the cognitive user, 𝑠(𝑡) is the signal transmitted by the PU, 𝑛(𝑡) is Additive White Gaussian Noise (AWGN) and h is the channel amplitude gain. H0 is a null hypothesis, which describes the absence of the licensed user in a specific spectrum band. In contrast, H1 is an alternative hypothesis, which describes the presence of some PU signal. Transmitter detection is further divided into three different techniques. They are Energy detection, Matched filter detection and Cyclostationary detection.

**3.3.1 Energy Detection**

The optimal detector would be an energy detector if the receiver is not able to get enough information about the PU signal, for example, the receiver knows about the power of the random Gaussian noise. In the energy detection mechanism, the users of CR use the received primary signal energy to sense whether PUs are present or not. The energy of the received primary signal is measured by squaring and integrating the received signal over the observation interval. To ensure that the PU is present or absent, the output of the integrator is compared with a threshold.

Energy detector is also known as radiometry and it is most common method of spectrum sensing because of its low computational and implementation complexities. Moreover, the cognitive user’s receivers do not need any knowledge of the primary user’s signal. The signal is detected by comparing the output of energy detector with threshold which depends on noise floor [17].

Pre-Filter

Squaring Device

Threshold

i/p

**Figure 3.2:- Block diagram of energy detector in time domain**

o/p

Integrator

The binary hypothesis problem can be formulated by:

X(N) = W(N) H0 (absent)……………………………………………..(3.6)

= S(N) + W(N) H1(Present) …………………………………………… (3.7)

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.

γ = Ps/N0; ………………………………………………………………………. (3.8)

Where, Ps and N0 are the average power of signal and noise.

The decision parameter is as follows:

; ………………………………………………..…………… (3.9)

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 by [18].

Pd = P(Y> λ /H1) = Qm ……………………………………….……. (3.10)

Pf = P(Y> λ /H0) = Г/ Г(m)……………………………………………. (3.11)

Where Y is the SNR, m = TW is the (observation/sensing) time bandwidth product Γ (.) and Γ (.,.) are complete and incomplete gamma functions, Qm() is the generalized Marcum Q-function.

**3.3.1.1 Energy Detection based on MAP**

Energy detector is widely used method in radiometry. Energy detector can be able to implemented as spectrum analyzer, it takes the average frequency bins of a FFT shown below.

FFT

ADC/BPF Filter

Average Freq .Over T

Energy Detector O/P

i/p

Threshold

o/p

**Figure 3.3: Implementation of Energy detector**

The input signal goes into the A/D converter selected by the band pass filter first and we will get the threshold there. After we get the output from the integrator, which is compared with threshold, we will determine the presence of the primary users. The FFT size N and the observation time T will influence the processing gain, if N is increased, it will improve the frequency resolution which is proper to narrowband signal detection. In the other hand, if T is increased the noise power will decreased, thus the SNR will increased [6].

Maximum a Posteriori (MAP) detector is known to be the optimal in Cognitive Radio users starts spectrum sensing to detect the primary users status, the received signal can be expressed as:

r(t) = n(t); H0………………………………………………….……..(3.12)

= s(t) + n(t); H1 ……………………………………………………….(3.13)

Where, H0: ‘No Signal Transmitted’

H1:’ Signal Transmitter’, s(t) is the signal waveform and n(t) is the zero mean AWGN.

Detection probability (Pd) and the false alarm probability (Pf) can be expressed as:

Pd(λ) = Pr(Y>λ/H1);…………………………………………….……….(3.14)

Pf(λ) = Pr(Y> λ /H0);…………………………………………….………(3.15)

Where λ is the decision threshold for MAP detection Pf should be kept as small as possible to avoid the underutilization of transmission opportunities and Pd should be kept as large as possible for the same reason.

In MAP detection, the o/p of the integrator is known as chi-square distribution [14]. If the number of samples is large with CLT theorem, we can assume the chi-square distribution approximated as Gaussian distribution.

Y approximated as: N(nσn2 , 2nσn4) ; H0 ………………………..(3.16)

: N(n(σn2+ σs2 , 2n(σn2+ σs2 ‌)2); H1…………………..………. (3.17)

Where n is the numbr of samples, σn2 is the varaince of noise, σs2 is the variance of the received signal s(t).Minimum sampling rate should be 2W from Nquist sampling theorem, so n can be expressed 2tsW, where ts is observation time and W is bandwidth of spectrum, the false alarm probability(Pf) can be derived in terms of Q-function, expressed as follows[14].

Pf(W,ts) = Q ………………………………………….……………(3.18)

From equation above, we can get false alarm probability varies with the W and observation time ts. We get the threshold λ as follows by solving the equation :

λ = Q-1(Pf) + 2 …………………….................................... (3.19)

**3.3.2 Matched Filter Detection**

The coherent detector also referred to as a matched filter shown in figure 3.4 below. It can improve detection performance if the primary transmitted signal’s is deterministic and known a priori. 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 [11]. 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 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.

Matched Filter

Threshold Decision

X(t)

**Figure 3.4 : Block Diagram of Matched Filter Detector**

Sampling

H0 or

H1

**3.3.3 Cyclostationary feature Detection**

Modulated signals are in general coupled with sine wave carriers, pulse trains, repeating spreading, hopping sequences, or cyclic prefixes, which result in built-in periodicity [12]. Even though the data is stationary random process, these modulated signals are characterized as Cyclostationary, since their statistics, mean and autocorrelation, exhibits periodicity. These features are detected by analyzing a spectral correlation function. The periodicity is provided for signal format so that receiver can use it for parameter estimation like pulse timing, carrier phase etc. This periodicity can be used in the detection of random signals with a particular type of modulation with the noise and other modulated signals. The block diagram for cylostationary feature detector shown in figure 3.5.

Recent research efforts exploit the Cyclostationary feature of signal as method for classification, which has been found to be superior to simple energy detection and match filtering. As discussed, a matched filter as a coherent detector requires prior knowledge about primary user’s wave while as in energy detector as a non coherent detection does not require any sort of prior knowledge about primary user’s waveform. Although energy detector is easy to implement, it is highly susceptible to in band interference and changing noise levels [9] and cannot differentiate between signal power and noise power.

Correlate R(f) R(f-α)

Average Over T

Feature Detector

r(t)

**Figure 3.5:- Block Diagram of Cyclostationary Feature Detector**

Table 3.1 below has the overall summary of advantages and disadvantages of all the spectrum sensing techniques for non cooperative case. By means of time-frequency analysis, maximum interval of a signal and standard variation of the instant frequency are extracted and for recognition of dynamic transmissions by means of these features, neural networks are used. For detection and signal organization, cycle frequencies of the received signal are used.

|  |  |  |
| --- | --- | --- |
| **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  Detection | Optimal Detection Performance  Low Computational Cost | Requires a prior knowledge of  the Primary User |
| Cyclostationary  Detection | Robust in low SNR  Robust to Interference | Requires partial information of  the Primary User  High Computational Cost |

**Table 3.1:- Advantages and Disadvantages of Spectrum Sensing Techniques [11]**

**Chapter 4**

**Spectrum Detection Method based on Dynamic threshold in CR Systems**

**4.1 Introduction**

In this chapter we formulate the problem of signal detection in additive white noise and explain the spectrum detection schemes which include Energy detection and Matched filter detection. Noise uncertainty effects on spectrum detection performance of matched filter,[21][22] new algorithm applying dynamic threshold for anti-noise uncertainty and analyze noise uncertainty effects on energy detection and dynamic threshold in energy detection is also analyzed.

**Problem formulation:**

The problem of signal detection in additive noise can be formulated as a binary hypothesis testing problem with the following hypotheses:

H0: Y(n) = W(n), ………………………………........................(4.1)

H1: Y(n) = X(n)+W(n), Where, n=1,2,3,………………..,N

Where, Y(n), X(n) and W(n) are the received signals at CR nodes, transmitted signals at primary nodes and white noise samples, respectively. We assume that both signals and noise are independent each other. Noise samples W (n) are from a white Gaussian noise process with power spectral density, i.e., W(n): N(0,σn2) and its statistics are completely known to the receiver. Given a particular target probability of false alarm probability PFA, probability of missed detection PMD and probability of detection PD = 1-PMD, our aim is to derive the sample complexities for various possible detectors, i.e., we are interested in calculating the number of samples required N, as a function of the signal-to-noise ratio (SNR).

**Matched filter detection:**

When the information of the primary user signal is known to the CR user, the optimal detector in white Gaussian noise is the matched filter, it maximizes received signal-to-noise ratio. However, the matched filter requires a priori characteristics knowledge of the primary user signal, e.g., modulation type and order, pulse shaping, packet format.

**Energy detection:**

If the receiver cannot gather sufficient information about the primary user signal, the optimal detector is an energy detector. However, the performance of the energy detector is susceptible to the uncertainty of noise power. Also, energy detector often generates false alarms triggered by unintended signals because they cannot differentiate signal, noise and interference. The critical technique is how decide the threshold.

**4.2 Spectrum Detection Schemes**

**4.2.1 Matched Filter Detector (MFD)**

When the signal X(n) is completely known to the receiver, the optimal detector is the matched filter detector or the coherent detector [22]. The decision model is:

> γ ; H1……………………..……………………………(4.2)

< γ;H0

Where T(Y) is the decision variable, γ is the decision threshold and N is the number of samples. If noise variance is completely known, from central limit theorem (CLT) the following approximations can be made:

T(Y/H0) ~ N (0, Pσn2/N)

…………………………………………...………………. (4.3)

T(Y/H1) ~ N (P, Pσn2/N)

Where, P is the average signals power, N is the number of samples and σn2 is the noise variance. Using these approximations, following expressions are made for false alarm probability and detection probability for the matched filter detection technique.

...…………………………………….….. (4.4)

……………………………………………………… (4.5)

On solving the above equations i.e., (4.4) and (4.5) we get,

…………………………………………… (4.6)

Where, SNR (signal to noise ratio) = P/; Where, is the normalized noise power.

**4.2.2 Dynamic Threshold Algorithm for Matched Filter Detector (MFD)**

**4.2.2.1 Noise uncertainty**

In the previous analysis it was assumed that there is no noise variation or uncertainty, if there is uncertainty in the noise model [21] [20]. The distributional variation of noise is in the interval:

Here, r is the noise uncertainty coefficient and is assumed to be greater than one i.e., r>1.

For probability of false alarm chosen maximum value in the above interval and for the probability of detection chosen minimum value. Now the probability equations are modified as [22].

………… ……………………………………………….... (4.7)

……………………………………..…………. (4.8)

On solving and eliminating γ from equation (4.7) and (4.8) we get the following equation:

……………………………………….. (4.9)

**4.2.2.2 Dynamic threshold**

In the previous analysis, it was assumed that there is noise variation or uncertainty, and there is uncertainty in the noise model and represented the noise uncertainty factor r. We introduced the dynamic threshold factor r’. So the distributional of dynamic threshold is in the interval:

Here, r’ is the dynamic threshold factor and is assumed to be greater than one i.e., r’>1.

For probability of false alarm chosen maximum value in the above interval and for the probability of detection chosen minimum value. Now the probability equations are modified as [22].

………………………………………………………..….. (4.10)

……………………………………………….…………… (4.11)

On solving and eliminating γ from equation (4.10) and (4.11) we get the following equation:

……………………….………………. (4.12)

**4.2.2.3 Noise uncertainty and dynamic threshold**

Now considering noise uncertainty and dynamic threshold jointly,

The noise variance is in the interval as follows:

The threshold value is in the interval as follows:

Now the probability relationship can be modified as:

…….………………….. (4.13)

…………………………. (4.14)

Removing the threshold parameter from the equation (4.13) and (4.14) and we finally get the following relationship as shown below:

……………..……………………… (4.15)

**4.2.3 Energy Detector (ED)**

Under the assumption of absolutely no deterministic knowledge about the signal X(n), i.e., we assume that we know only the average power in the signal. In this case the optimal detector is energy detector or radiometer can be represented as [22].

> γ ; H1…………….………………………………………… (4.16)

<γ; H0

Where T(Y) is the decision variable and γ is the decision threshold, N is the number of samples. If the noise variance is completely known, then from the central limit theorem the following approximations can be made [22].

T(Y/H0) ~ N (σn2, Pσn2/N)

………………………………………………. (4.17)

T(Y/H1) ~ N (P+σn2, 2(P+σn2)2/N)

Where, is the average signals power, N is the number of samples and σn2 is the noise variance. Using these approximations, following expressions are made for false alarm probability and detection probability for the energy detection technique.

……………………………….…………. (4.18)

…………………………….……………… (4.19)

On solving the above equations i.e., (4.18) and (4.19) we get,

…………………………. (4.20)

Where, SNR (signal to noise ratio) = P/; Where, is the normalized noise power.  
Q(.) is the standard Gaussian complementary cumulative distribution function and Q-1(.) is the inverse standard Gaussian complementary cumulative distribution function.

**4.2.4 Dynamic Threshold Algorithm for Energy detector (ED)**

**4.2.4.1 Noise uncertainty**

We have discussed and analyzed the case of no noise fluctuation or uncertainty. Now, considering the case with uncertainty in the noise model [20], the distributional uncertainty of noise can be represented as:

Here, r is the noise uncertainty coefficient and is assumed to be greater than one i.e., r>1.

For probability of false alarm chosen maximum value in the above interval and for the probability of detection chosen minimum value. Now the probability equations are modified as [22].

…………………………………… (4.21)

……………………………………. (4.22)

On solving and eliminating γ from equation (4.21) and (4.22) we get the following equation:

……………. (4.23)

**4.2.4.2 Dynamic threshold**

In the previous analysis, it was assumed that there is noise variation or uncertainty for the detection of the primary user signal, and there is uncertainty in the noise model and represented the noise uncertainty factor r. Now we introduced the dynamic threshold factor r’. So the distributional of dynamic threshold is in the interval:

Here, r’ is the dynamic threshold factor and is assumed to be greater than one i.e., r’>1.

For probability of false alarm chosen maximum value in the above interval and for the probability of detection chosen minimum value. Now the probability equations are modified as [22].

…………………………………………………………. (4.24)

…………………………………………………………… (4.25)

On solving and eliminating γ from equation (4.24) and (4.25) we get the following equation:

…………. (4.26)

**4.2.4.3 Noise uncertainty and dynamic threshold**

Now considering noise uncertainty and dynamic threshold jointly,

The noise variance is in the interval as follows:

The threshold value is in the interval as follows:

Now the probability relationship can be modified as:

……………………………... (4.27)

………………………………. (4.28)

Removing the threshold parameter from the equation (4.27) and (4.28) and we finally get the following relationship as shown below:

…………………………….…… (4.29)

**Chapter 5**

**Simulation and Results**

In this chapter we simulate and analyses the formulations which are discussed in previous chapters. Here we take the suitable assumption based on different comprehensive experiments. In the first section of this chapter we discussed about the performance of the energy detector based on MAP. And second section we analyses and simulate to find the result of noise fluctuation and dynamic threshold techniques for the energy detection and matched filter detection techniques and put a comparative study through the simulation results will be discussed in this chapter.

**5.1 Simulation and results for Energy Detector (ED) based on MAP**

* + 1. **Simulation steps**

**Step 1:** The system parameters are set in this step. The parameters are: (i) the operating frequency, ‘f’; (ii) the sampling frequency, ‘Fs’; (iii) bandwidth of spectrum, ‘W’; (iv) the sensing time, ‘ts’; (v)Noise variance, ‘σn2’; (vi)number of samples ‘N’; (vii) signal to noise ratio, ‘SNR’; (viii) channel impulse response, ‘h’.

**Step 2:** Output of the integrator from figure [3.3] of ED is approximated as Gaussian random variable which is generated by using Matlab code.

**Step 3:** Calculating the energy values of different samples from simulated signal we obtain by squaring operation of the received sampled signal i.e., integrator output.

**Step 4:** Calculating the threshold values using equation (3.19) with the knowledge of desired false alarm probability(PFA), noise variance(σn2), signal variance(σs2) bandwidth of spectrum(W) and sensing time(ts).

**Step 5:** Compare the energy values we calculated in step 3 with the threshold we calculated in step 4.

**Step 6:** If the of the calculated energy value is greater than the threshold PU signal is detected and if less than the threshold no PU signal is detected

**Step 7:** Finally we calulate the number of detections based on above steps(1 to 6) for the different SNR values and hence established the relationship between SNR with the detection probability and the false alarm probability and plotted.

**5.1.2 Simulation results**

Here, we set the different parameters to simulate the signal to calculate the number of detections by using the MAP energy detection techniques. Different parameters values are taken approximated to practical values so as to realize the simulation scenario:

**Parameter assumption:**

Signal to Noise Ratio(SNR) = -10dB,

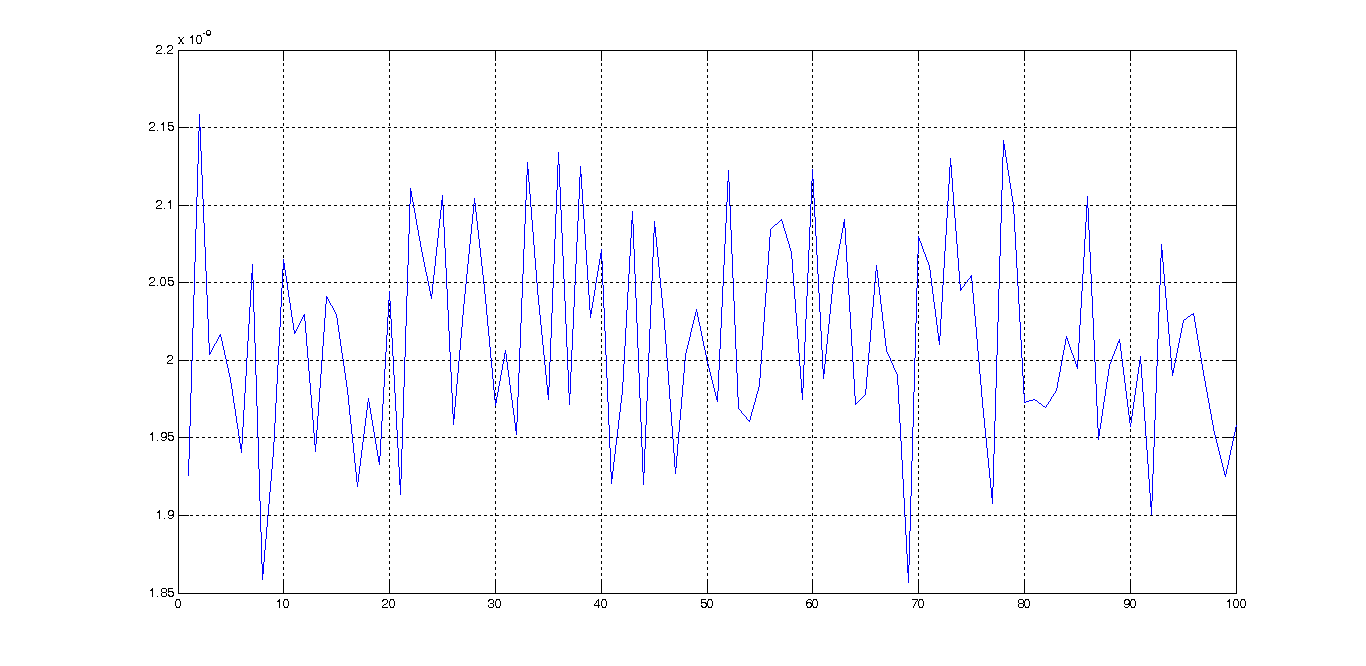
Signal Bandwidth (W) = 50KHz

Sampling Time(ts) = 1ms

and Noise Variance(σn2) = 1e-12.

One of the arbitrary signal input is plotted below whose energy is calculated later to examine the energy and the relationship among the SNR and detection probability. The threshold is calculated Eqn.(3.19) which is justified by the outputs plotted below.

The Energy calculated from the output of the ADC and after squaring speration which is plotted below, we have taken 100 different signals taken N number of samples from each. The x-axis shows the different signals energy at different samples. The simulated energy plotted below.



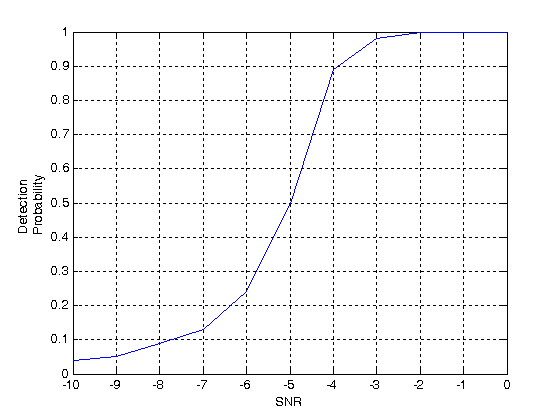
**Figure 5.1:- Output Signal(Energy values) of AWGN Sampled signal**

Now we are going to establish the relationship between the SNR with the Detection Probability and the False alarm probability. As we take the SNR = -10 dB for an example, but we get the result which is totally different with the theoretical result. So we change the SNR from -10 dB to 0 and get the detections and calculated the Detection probability (Pd) and False alarm probability (Pf), which are showed in Table 5.1 below:

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| SNR | -10 | -9 | -8 | -7 | -6 | -5 | -4 | -3 | -2 | -1 | 0 |
| Number of Detections | 4 | 5 | 9 | 13 | 24 | 50 | 89 | 98 | 100 | 100 | 100 |
| Detection Probability(Pd) | 0.04 | 0.05 | 0.09 | 0.13 | 0.24 | 0.5 | 0.89 | 0.98 | 1 | 1 | 1 |
| False Alarm Probability(Pf) | 0.96 | 0.95 | 0.91 | 0.87 | 0.76 | 0.5 | 0.11 | 0.02 | 0 | 0 | 0 |

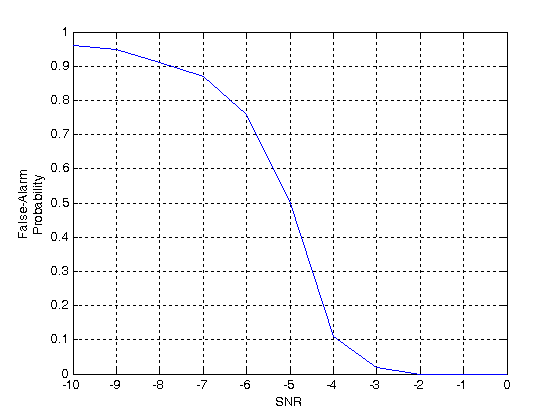
**Table 5.1:- Calculated values showing different SNRs, Detections, Detection Probability and False alarm probability**

As we can see from the fig.5.2, with the increasing of the SNR (from -10 dB to 0) the detections we get also increased and within -6 dB and -4 dB, the increasing slope is the largest. So the SNR influences the detections. It indicates that with the increasing of the SNR, the more spectrums which are occupied we can detect.



**Figure 5.2:- Relationship showing Detection probability by varying SNR**

Fig.5.3 shows the diagram between SNR and the false alarm probability. As we know that the false alarm probability = 0.01, the figure above shows that when SNR is between -2 dB and 0, the false alarm probability is approximately 0, which are the mostly approximate to the theory value = 0.01. Thus when SNR is between -2 dB to 0, the energy detector performs best for this scenario.



**Figure 5.3:- Relationship showing False Alarm probability by varying SNR**

**5.2 Performance Analysis of Matched Filter Detector (MFD) and Energy Detector (ED) based on dynamic threshold**

In this section, we discuss the effect of noise fluctuation or uncertainty on the spectrum detection performance of matched filter detector (MFD) and energy detector (ED). A new algorithm applying based on dynamic threshold for the anti-noise uncertainty effects on both of the detectors i.e., MFD and ED. All the results that obtained from simulation are compared and discussed in the following sections.

**5.2.1 Performance analysis of MFD and ED without noise uncertainty**

**5.2.1.1 Simulation steps:**

**Step 1:** Define the transmitted signal by the PU in RF environment as X (n) and is assumed to be known so that the optimal detector is MFD or coherent detector. And for the ED the transmitted signal X(n) is unknown to the SU receiver, so called the non-coherent or energy detector.

**Step 2:**Assume the average signal power (P), noise variance (σn2), decision variable T(Y), decision threshold (γ), the number of samples (N), and required range of false alarm probability are completely known and there is no noise fluctuation or uncertainty for both the detectors(MFD and ED).

**Step 3:** The expression for the probability of false alarm (PFA), the probability of detection (PD) and the relationship between the number of samples (N) with PFA, PD and SNR is derived for both detectors.

**Step 4:** We obtain the receiver operating characterstics (ROC) curve showing the relationship between PD and PFA, with the use eqn.(4.6) for MFD and eqn.(4.20) for ED and by varying the signal to noise ratio with fixed number of samples (N) and range of false alarm probability

PFA[0, 0.5] taken for both the detectors.

**Step 5:** We also obtain the ROC curve showing the relationship between PD and PFA, with the use eqn.(4.6) and (4.20) by varying the number of samples (N) also called detection duration, with fixed signal to noise ratio (SNR) and range of false alarm probability PFA[0, 0.5] taken for both the detectors.

**5.2.1.2Simulation results**

The performance of the matched filter detector (MFD) at different SNR conditions is analyzed below. For the Simulation different parameters are assumed: The Range of False Alarm PFA[0,0.5], number of samples N=150 and at varying SNR conditions (SNR=-20dB,-15dB,-12dB and -8dB).

****

**Figure 5.4:- ROC of MFD by varying SNR without noise uncertainty**

From the figure 5.4 it is observed that the performance of MFD can be improved by increasing the SNR values. And even for the very low SNR conditions the MFD schemes works good.

The performance of the matched filter detector at different number of samples (N) is analyzed below. For the Simulation different parameters are assumed: The Range of False Alarm PFA[0,0.5], at SNR=-15dB, the different values of N taken are: 100, 150, 200 and 400.

****

**Figure 5.5:- ROC of MFD by Varying N without noise uncertainty**

Figure 5.5 show that the performance of the MFD by varying the number of samples (N) or detection duration. From graph it is observed that the performance of MFD is improved significantly by increasing the number of samples (N) values.

Now, the performance of the energy detection scheme at different SNR conditions is analyzed below. For the Simulation different parameters are assumed: The Range of False Alarm PFA[0,0.5], number of samples N=1500 and at varying SNR conditions (SNR=-15dB,-12dB,-10dB and-8dB).

****

**Figure 5.6:- ROC of ED by Varying SNR without noise uncertainty**

Figure 5.6 shows that the numerical results of (4.20). From graph it is observed that the performance of energy detection scheme is improved gradually by increasing the SNR values.

The performance of the energy detection scheme at different number of samples (N) is analyzed below. For the Simulation different parameters are assumed: The Range of False Alarm PFA[0,0.5] at SNR=-10dB and different values of N taken are: 500, 1000, 2000 and 3000.

****

**Figure 5.7:- ROC of ED by Varying N without noise uncertainty**

Figure 5.7 shows the numerical results of (4.20). From figure it is observed that the performance of energy detection scheme is improved significantly by increasing the number of samples or detection duration, N values. Even for the lower SNR values, as long as N is large enough, without noise uncertainty the detection performance can be improved.

From the above analysis for the energy detection and matched filter detection schemes, the detection duration for energy detector is almost 10 times that of the matched filter detector, so that the matched filter detection scheme is superior to the energy detection scheme in the same detection performance.

**5.2.2 Performance analysis of MFD and ED with noise uncertainty**

**5.2.2.1 Simulation steps**

**Step 1:** Define the transmitted signal by the PU in RF environment as x (n) and is assumed to be known so that the optimal detector is MFD or coherent detector. And for the ED the transmitted signal x(n) is unknown to the SU receiver, so called the non-coherent or energy detector.

**Step 2:**Assume the average signal power (P), noise variance (σn2), decision variable T(Y), decision threshold (γ), the number of samples (N), and required range of false alarm probability are completely known and there is noise fluctuation or uncertainty factor r for both the detectors.

**Step 3:** The expression for the probability of false alarm (PFA), the probability of detection (PD) and the relationship between the number of samples (N) with PFA, PD, SNR and noise uncertainty factor (r) is derived for detectors.

**Step 4:** We obtain the ROC curve showing the relationship between PD and PFA, with the use eqn.(4.9) for MFD and eqn.(4.23) for ED and by varying the the noise uncertainty factor r at particular signal to noise ratio and fixed number of samples (N) and range of false alarm probability PFA[0, 0.5] taken for both detectors.

**5.2.2.2 Simulation results**

The performance of the matched filter detection at different noise uncertainty values is analyzed below. For the Simulation different parameters are assumed: The Range of False Alarm PFA[0,0.5], number of samples N=150, SNR=-15dB. Figure 5.8 shows the response of probability of false alarm on X-axis and probability of detection on Y-axis for different values of uncertainties.

****

**Figure 5.8:-ROC of MFD by varying noise uncertainty values**

From the above figure 5.8, it is observed that as the noise uncertainty value increases the performance is slightly decreases, which shows that the matched filter detection scheme by the noise uncertainty have very less effect to the matched filter detection performance.

Now the performance of the energy detection scheme at different noise uncertainty values is analyzed and described below. For the simulation different parameters are assumed: The range of false alarm PFA[0,0.5], number of samples and the SNR values are taken differently. Figure (5.9) and (5.10) are plotted keeping N=1000 fixed and SNR taken -10dB and -8dB respectively and figure (5.10) and (5.11) are plotted keeping fixed SNR=-8dB and N is varied as 1000 and 500 respectively. The performance curve for ED is plotted below.

****

**Figure 5.9:- ROC curves of energy detection scheme with different noise uncertainty at N=1000 and SNR=-10dB**

****

**Figure 5.10:- ROC curves of energy detection scheme with different noise uncertainty at N=1000 and SNR=-8dB**

****

**Figure 5.11:- ROC curves of energy detection scheme with different noise uncertainty at N=500 and SNR=-8dB**

From the above figures (5.9),(5.10)&(5.11), it is observed that the performance gradually drops as noise factor increasing. Energy detection scheme is very sensitive to the noise uncertainty. Above figure 5.9 shows the that it can’t complete the detection, that is to say, the tiny noise fluctuations will lead to the detection performance of energy detection scheme falling sharply. It means that the cognitive users identify the spectrum to be idle no matter; whether there are primary users are present or absent.

Secondary users are often harmful licensed user when there are primary users present, which occur generally in lower SNR environments. In order to guarantee the good performance, choosing the suitable threshold is very important. Traditional energy detection based on fixed threshold under noise uncertainty has very poor performance. So that the choice of fixed threshold ins no longer valid under noise uncertainty and the threshold should be chosen dynamically based on necessities or different conditions.

**5.2.3 Performance analysis of MFD and ED with dynamic threshold**

**5.2.3.1 Simulation steps**

**Step 1:** Define the transmitted signal by the PU in RF environment as x (n) and is assumed to be known so that the optimal detector is MFD or coherent detector. And for the ED the transmitted signal x(n) is unknown to the SU receiver, so called the non-coherent or energy detector.

**Step 2:**Assume the average signal power (P), noise variance (σn2), decision variable T(Y), decision threshold (γ), the number of samples (N), and required range of false alarm probability are completely known and there is dynamic threshold factor r’ for both detectors.

**Step 3:** The expression for the probability of false alarm (PFA), the probability of detection (PD) and the relationship between the number of samples (N) with PFA, PD, SNR and dynamic threshold factor (r) is derived for both detectors.

**Step 4:** We obtain the ROC curve showing the relationship between PD and PFA, with the use eqn.(4.12) for MFD and eqn.(4.26) for ED and by varying the the dynamic threshold factor r’ at particular signal to noise ratio and fixed number of samples (N) and range of false alarm probability PFA[0, 0.5] taken for both detectors.

**5.2.3.2 Simulation results**

The performance of the matched filter detection at different dynamic threshold values is analyzed below. For the Simulation different parameters are assumed: The Range of False Alarm PFA[0,0.5], number of samples N=150, SNR=-15dB. Figure 5.12 shows the response of probability of false alarm on X-axis and probability of detection on Y-axis for different values of dynamic threshold factors. Dynamic threshold factors are taken such that r’>1, and varied r’ as 1, 1.25, 1.50 and 1.80.

****

**Figure 5.12:- ROC of MFD detection by varying dynamic threshold values**

From figure 5.12 it is observed that with increasing the dynamic threshold the detection performance slightly increases, in other words, matched filter detection scheme issensitive to dynamic threshold factors at lower SNR values.

Now for the performance of energy detection scheme at different dynamic threshold values is analyzed below. For the Simulation different parameters are assumed: The Range of False Alarm PFA[0,0.5], number of samples N=1000, SNR=-10dB. Figure 5.13 shows the response of probability of false alarm on X-axis and probability of detection on Y-axis for different values of dynamic threshold factors. Dynamic threshold factors are taken such that r’>1, and varied r’ as 1, 1.01, 1.02 and 1.03.

****

**Figure 5.13:- ROC curves of energy detection scheme with different dynamic threshold**

From figure 5.13 it is observed that with increasing the dynamic threshold the detection performance slightly increases, in other words, energy detection scheme is also sensitive to dynamic threshold factors at lower SNR values.

**5.2.4 Performance analysis of MFD and ED with noise uncertainty and dynamic threshold**

**5.2.4.1 Simulation steps**

**Step 1:** Define the transmitted signal by the PU in RF environment as x (n) and is assumed to be known so that the optimal detector is MFD or coherent detector. And for the ED the transmitted signal x(n) is unknown to the SU receiver, so called the non-coherent or energy detector.

**Step 2:**Assume the average signal power (P), noise variance (σn2), decision variable T(Y), decision threshold (γ), the number of samples (N), and required range of false alarm probability are completely known and there is noise uncertainty factor r and dynamic threshold factor r’ for both detectors.

**Step 3:** The expression for the probability of false alarm (PFA), the probability of detection (PD) and the relationship between the number of samples (N) with PFA, PD, SNR, noise uncertainty (r) and dynamic threshold factor (r’) is derived for both detectors.

**Step 4:** We obtain the ROC curve showing the relationship between PD and PFA, with the use eqn.(4.15) for MFD and eqn.(4.29) for ED and by varying the the noise uncertainty and dynamic threshold factor r’ at particular signal to noise ratio and fixed number of samples (N) and range of false alarm probability PFA[0, 0.5] taken for both detectors.

**5.2.4.2 Simulation results**

The performance of the matched filter detection by varying dynamic threshold at fixed noise uncertainty parameters is shown in figure 5.14 below. For the Simulation different parameters are assumed: The Range of False Alarm PFA[0,0.5], number of samples N=150, SNR=-15dB, noise uncertainty (r) =1.5 and dynamic threshold (r1) is varied as 1, 1.25, 1.6 and 1.85.

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**Figure 5.14:-ROC of MFD by varying the dynamic threshold with noise uncertainty at N=150 and SNR=-15dB**

From figure 5.14 it is observed that with noise uncertainty the detection performance slightly decreases, and as we increase the dynamic threshold values the performance of the detector is increasing gradually which can be observed from the result. In other words, matched filter detection scheme is sensitive to noise uncertainty at lower SNR values and by considering the dynamic threshold the performance is improved even in the case of noise uncertainty.

The performance of the matched filter detection by varying parameters is shown in figures below. For the Simulation different parameters are assumed: The Range of False Alarm PFA[0,0.5], number of samples N=150, SNR=-15dB, noise uncertainty (r) =1.7 and dynamic threshold (r1) =1.9.

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**Figure 5.15:- The performance of MFD for different cases by changing different parameters**

From above figure 5.15 it is observed that with noise uncertainty the detection performance slightly decreases, in other words, matched filter detection scheme is sensitive to noise uncertainty at lower SNR values. By considering the dynamic threshold the performance is improved even in the case of noise uncertainty.

Now, for the performance of energy detection scheme with noise uncertainty and different dynamic threshold values is analyzed below. For the simulation different parameters are assumed: range of false alarm PFA[0,0.5], number of samples N=1000, SNR=-10dB, r and r’ values are taken as shown in figure 5.16. Figure below shows the response of probability of false alarm on X-axis and probability of detection on Y-axis for different values of dynamic threshold factors with noise uncertainty. Figure 5.17 is drawn by changing the parameter: number of samples N=2000 and figure 5.18 is plotted changing value of SNR to -8dB and other parameters are kept same as of figure 5.16.

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**Figure 5.16:- ROC curves of energy detection scheme with different dynamic threshold having uncertainty noise at N=1000 and SNR=-10dB**

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**Figure 5.17:- ROC curves of energy detection scheme with different dynamic threshold having uncertainty noise at N=2000 and SNR=-10dB**

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**Figure 5.18:- ROC curves of energy detection scheme with different dynamic threshold having uncertainty noise at N=1000 and SNR=-8dB**

In the Figure 5.16, where r = 1.00 denotes that the average noise power keeps constant (without noise uncertainty); r’ =1.00 denotes that the algorithm did not use dynamic threshold (the threshold is fixed); otherwise, it represents cases with noise uncertainty and dynamic threshold. Here we have taken SNR=-10dB, N=1000, PFA is varied from 0 to 0.5. From figure 5.16, it indicates that a tiny fluctuation of average noise power causes a sharp decline in detection performance. The dynamic threshold improves the performance improve significantly as the dynamic threshold factor increasing. If a suitable dynamic threshold factor is selected, the falling proportion of performance caused by noise uncertainty can be omitted and the performance may be more accurate.

Figure 5.17 shows the numerical result of (4.29), probability of false alarm on X-axis and probability of detection on Y-axis for SNR=-10dB, N=2000 and varying the dynamic threshold value.

Figure 5.18 shows the numerical result of (4.29), probability of false alarm on X-axis and probability of detection on Y-axis for SNR=-8dB, N=1000 and varying the dynamic threshold value.

As the detection duration N has been increased largely to N=2000 with the same probability parameters PD and PFA as shown in Figure 5.17. It can be concluded that as long as the dynamic threshold factor is suitable, even if there is noise uncertainty, we can get a better spectrum performance. And also by increasing the SNR value to the -8dB attaining the better detection performance for the same case which can be clearly shown from the above figures.

Now, the performance of the energy detection scheme by varying parameters is shown in figures below. For the simulation different parameters are assumed: The Range of False Alarm PFA[0,0.5], number of samples N=1000, SNR=-10dB, noise uncertainty (r) =1.02 and dynamic threshold (r1) =1.01.

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**Figure 5.19:- The performance of Energy detector by various parameters**

From above figure 5.19, it is observed that with tiny noise uncertainty the detection performance of the energy detector is sharply decreased, in other words, energy detection scheme is very sensitive to noise uncertainty at lower SNR values. By considering the noise uncertainty and proper dynamic threshold the performance is improved even in the case of noise uncertainty which can be shown on the above figure.

**Chapter 6**

**Discussion and Conclusion**

**6.1 Discussion**

The requirements motivates for the development of new ideas and technologies. Due to the rapid growth in wireless technologies spectrum scarcity is a major issue. The utilization of the spectrum is not efficient and most of the times it remains vacant. So these facts motivate for the development of new concept regarding to utilize our precious natural resource called spectrum. Due to our fixed spectrum assignment policy these frequency bands are allocated to particular operators and the spectrum used by them are called the licensed spectrum and those spectrum couldn’t be used by any other operators although the spectrum remains vacant or unutilized. The inability of our system or technology to use such vacant spectrum is really a serious drawback. Also our fixed spectrum assignment policies which have to change to dynamic spectrum access to utilize such bands without any degradation in the quality of service of the licensed users. These are main reasons for the development of the system which really can solve this problem of spectrum scarcity. The system developed to solve those tasks called Cognitive radio system, which is a wireless intelligent radio.

One of the major challenges of the Cognitive radio system is spectrum sensing. Spectrum sensing is the method of identifying the vacant spectrum band (spectrum holes) in the particular licensed frequency band. For this we need to identify the status of the primary user in the wireless environment. In this thesis work, we studied about the performance of energy detector based on MAP to obtain relationship between the signal to noise ratio of the PU and identify the number of detections has been studied in detail with the help of literature reviews and simulation results. In the first section of the simulation, we study and investigated performance analysis of energy detection based on MAP, for this we have taken the 100 samples and calculate the number of detections, false alarm probability, and detection probability. By changing the value of SNR, we obtain the relationship between the SNR and the detections; from the obtained results we see from -2dB to 0, SNR makes the energy detector perform the best. The results are seems to be satisfactory and the energy detector works successfully in the simulation.

In the second section of the simulation, we study and investigated the performance analysis of spectrum detection based on dynamic threshold for primary user detection. For this we use matched filter detector and the energy detector for analysis. The performance metric used for the simulations is receiver operating characteristics (ROC). It is completely specified by the values of probability of false alarm PFA and probability of detection PD. In signal detection theory, ROC is used for measuring the performance as a tradeoff between selectivity and sensitivity. The probability of detection (or true positive) PD is given as a function the probability of false alarm (or false positive) PFA­. In this thesis we explores various types of spectrum sensing techniques and discusses the effect of noise uncertainty, noise uncertainty and dynamic threshold on energy detection and matched filter detection algorithm in detail with the help of literature reviews and simulation results. We set different parameters to obtain the performance analysis of the detectors. The parameters used are signal to noise ratio (SNR), number of samples required (N), probability of detection (PD), Probability of false alarm (PFA), ROC curve, noise variance, threshold, noise uncertainty factor (r) and dynamic threshold factor (r’). From literature reviews, we obtain the relationship between those parameters. And finally we obtain the ROC curve for both detectors (energy and Matched filter) for various cases are discussed in chapter 5. From those results we found that the number of samples (detection time) required for energy detector has been almost 10 times that of the matched filter detector to obtain the same kind of performance. Matched filter is working well for very low SNR regions while the energy detector performance is not as good for the very low SNR regions which we can see in the results. We also see that for noise fluctuation or uncertainty factor has very less effect to the matched filter detector performance while for energy detector tiny noise fluctuation in noise uncertainty leads to the detection performance falling sharply. We also observed that the addition of dynamic threshold in noise uncertainty environment the detection performance have been improved significantly for both the detectors.

These are the cases which we studied and perform the simulations in this thesis work for the performance analysis of spectrum sensing techniques in the cognitive radio environment.

**6.2 Critical Evaluation**

This thesis is prepared as the extraction of the research works. While critically evaluating the research work in this thesis, the practical implementation of this thesis could be used to help and build software that can be used for the spectrum detection techniques based on energy detection and the matched filter detection.

All the simulation results are based on computer based simulations, which are simulated in MATLAB7. For the simulation it has been assumed the channel is additive white Gaussian noise (AWGN) channel. The output signal of integrator assumed to be chi-square distribution and is approximated as Gaussian distribution when sample size is large. These are the statistical data generated by using the Matlab code which obey the Gaussian distribution. The different parameters values are taken approximated to practical values obtained from various experiments and literature study. Hence the simulation results obtained are not accurate and may slightly change from one simulation to next. Also in this thesis, there is scope of improvement in the algorithm used and more efficient programming could be used for the performance analysis.

**6.3 Conclusion**

The main objective of this thesis work is to study and analysis of the spectrum sensing techniques in cognitive radio environment. For this, the literature reviews of the Cognitive radio and spectrum sensing techniques have been performed. Thesis studies the energy detection based on MAP and simulation are performed for the analyses of the performance of energy detector. From the simulation the relationship between the performance metrics like SNR and detection or SNR with the probability of false alarm has been obtained.

This thesis studies the performance of energy detection and matched filter detection sensing algorithm and the effect of noise uncertainty and dynamic threshold on the performance of these detectors by drawing the Receive operating characteristics (ROC) curves showing the relationship between probabilities of false alarm vs. probability of detection for various cases. In cognitive radio systems the energy detector and matched filter detector performance can be improved by increasing the SNR values and also by increasing the number of sample points. And the detection performance is much better even at lower SNR values are obtained from the simulation results graph. The detection performance of both the detectors can be improved by using dynamic threshold based spectrum detection algorithm in cognitive radio systems. Energy detection based on fixed threshold are sensitive to noise uncertainty, a fractional change of average noise power causes decreasing the performance sharply while matched filter is almost not sensitive to noise uncertainty, by using dynamic threshold the performance of both (energy and matched filter) detectors can be improved as compared with the fixed threshold. Hence we concluded that for the case of noise uncertainty and dynamic threshold algorithm and found that energy detection based on dynamic threshold can improve the antagonism of noise uncertainty; get good performance of detection without increasing the computer complexity and improves the detection performance for the schemes that are sensitive to noise uncertainty.

**6.4 Deliverables Produced**

The aims and objectives set for this thesis have been fulfilled with the deliverables in different chapters. For objective 1 set in this thesis, the literature review related to various topics such as wireless spectrums, cognitive radio and spectrum sensing has been performed in the chapter 2. For objective 2 the formulation of the energy detection based on MAP has been done in chapter 3 and later the simulation for performance analysis has been performed in chapter 5. For objective 3 a separate chapter 4 has been dedicated to literature analysis and formulates the dynamic threshold techniques on the detector performance in cognitive radio system. Finally the objective 4 is the major portion of the thesis work which is completely based on the formulation of chapter 4 and performance analysis of the matched filter and the energy detector has been analyzed for different case and finally found that with the dynamic threshold techniques in noise uncertainty environment the detectors gives better results which can be seen with the help of different ROC curves.

**Chapter 7**

**Future Work**

There is lots of scope for the improvements in this thesis work by adding concept and several ideas for future from this thesis work regarding the spectrum sensing techniques in cognitive radio environment. First, simulation models can be improved. Multipath fading effects, shadowing effects could be added and their effects on the performance of the proposed scheme could be investigated. Instead of generating the RF signals and the sampled signals in MATLAB, actual transmitted signals could be collected in the field to performance analysis. The computer simulations of the dynamic threshold based spectrum detection algorithm in cognitive radio improve the detection performance but in practical how acquire the detection threshold and how to improve the detection performance by other sensing methods could be investigated. All the simulation results are computer based simulations and could be verified in real environment on future.

Most of the research on spectrum sensing is mainly focused on reliable sensing to meet the regulatory requirements. One of the important areas for the research is to focus on user level cooperation among cognitive radios and system level cooperation among different cognitive radio networks to overcome the noise level uncertainties. Also research can be done for cross layer communication in which spectrum sensing and higher layer functionalities can help in improving quality of service (QoS) of CRN.

**References**

[1] Federal Communication Commision, “Spectrum Policy Task Force,”Rep. Docket no.02-135

[2] FCC,“FCC-03-322,”Dec.2003.[online] Available:http://harunfoss.fcc.gov/edocspublic

[3] M. Subhedar and G. Birajdar,” Spectrum sensing techniques in Cognitive Radio networks: A Survey”

[4] J.Mitola et al,” Cognitive Radio: Making software Radios more personal,” IEEE Pers. Communications, vol.6, no.4, pp.13-18, 1999

[5] J.Mitola,” Cognitive Radio: A integrated agent architecture for software defined radio,” Doctor of technology, Royal Inst. Technology.

[6] AmitKataria, “Cognitve Radios- Spectrum Sensing Issues”

[7] http://cdsr.net.dynamicweb.dk/Files/Filer/PDF/CSDR\_Whitepaper.pdf

[8] IF. Alkylidiz, W.Y. Lee and M.C. Vuran, "Next generation/dynamic spectrum access/cognitive radio wireless networks: A Survey, "IEEE Transaction on Computer Networks,vol.50,n0.13,pp.2127-2159,May 2006

[9] TevﬁkYucek and Huseyin Arslan, “A Survey of Spectrum Sensing Algorithms for Cognitive Radio Applications”, IEEE Comm. Survey& Tutorials, Vol. 11, No. 1, 2009

[10] Refik Fatih U¨ STOK , “Spectrum Sensing Techniques for Cognitive Radio systems with Multiple Antennas”

[11] A. Sahai, N. Hoven, and R. Tandra, “Some fundamental limits on cognitive radio,” in *Proc. Allerton Conf. on Communications, Control, and Computing* Monticello), Oct.2004.

[12] H. Arslan, “Cognitive Radio, Software Defined Radio, And Adaptive Wireless Systems”, Springer, 2007.

[13] S. Haykin, “Cognitive radio: brain-empowered wireless communications,” *IEEE Journal on Selected Areas in Communications, vol. 23,no. 2, pp. 201–220, Feb. 2005*

[14] W. Y. Lee and I. F. Akyildiz, “Optimal spectrum sensing framework for cognitive radio networks” *IEEE Trans. Wireless Commun.*, vol. 7, pp. 3845-3857, Oct. 2008

[15] Lars Berlemann, George Dimitrakopoulos, Klaus Moessner and Jim Hoffmeyer, ”Cognitive radio and Management of Spectrum and Radio Resources in Reconfigurable Networks”

[16] Ghayoor Abbas Jafri, Ateeq Ur Rehman, Muhammad Tariq Sadiq, “Spectrum Sensing and Management in Cooperative Cognitive Radio”

[17] H.Urkowitz, “Energy detection of unknown deterministic signals,” *Proceedings of the IEEE*, vol. 55, no. 4, pp. 523–531, April 1967.

[18] Mohmmad Hamid, " Dynamic Spectrum Access in Cognitive Radio Networks: Aspects of MAC layer Sensing"

[19] Christopher Skarica, Lindasy Broadband and Chris Busch. (2007, Sep) Metro Wi-Fi, Part 1[online]. Available:http://www.cable360.net/ct/strategy/emergingtech/25375.html

[20] “Performance Analysis of Energy Detection Algorithm in Cognitive Radio”, Chandrasekhar Korumilli, Chakrapani Gadde, I.Hemalatha, IJERA Vol. 2, Issue 4, July-August 2012, pp.1004-1009

[21] Guicai YU, Chengzhi LONG, Mantian XIANG and Wei XI, “A Novel Energy Detection Scheme Based on Dynamic Threshold in Cognitive Radio Systems,” *Journal of Computational Information Systems 8: 6 (2012) 2245–2252*

[22] R. Tandra and A. Sahai, “SNR walls for signal detection,” I*EEE Journal of Selected Topics in Signal Processing*, vol. 2, no. 1, pp. 4–17, February 2008.

[23] D. Cabric, R.W. Bordersen, "Physical layer design issues unique to cognitive radio system,"in IEEE 16th International Symposiium on Personal, Indoor and Mobile Radio Communications, Berlin, 2005,PP.759-763