DYNAMIC-DOUBLE-THRESHOLD ENERGY DETECTION SCHEME FOR SPECTRUM SENSING UNDER NOISE UNCERTAINTY IN COGNITIVE RADIO SYSTEM

A Thesis submitted in partial fulfillment of the Requirements for the degree of

Master of Technology
In
Electrical Engineering
(Electronics systems and Communication)

By
SONAM SHRIVASTAVA
Roll No. : 212EE1213

Department of Electrical Engineering
National Institute of Technology Rourkela
Rourkela, Odisha, 769008, India
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Under the Guidance of
Prof. Susmita Das

Department of Electrical Engineering
National Institute of Technology Rourkela
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May 2014

Dedicated to…

My parents and my brother

DEPARTMENT OF ELECTRICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

ROURKELA – 769008, ODISHA, INDIA

Certificate

This is to certify that the work in the thesis entitled **Dynamic-Double-Threshold Energy Detection Scheme for spectrum sensing Under Noise Uncertainty in Cognitive Radio System** by **Sonam Shrivastava** is a record of an original research work carried out by her during 2013 - 2014 under my supervision and guidance in partial fulfillment of the requirements for the award of the degree of Master of Technology in Electrical Engineering (Electronics System and Communication), National Institute of Technology, Rourkela.

Place: NIT Rourkela

Date: 22 May **2014**

Prof. Susmita Das

Professor

DEPARTMENT OF ELECTRICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

ROURKELA – 769008, ODISHA, INDIA

Declaration

I certify that

a) The work contained in the thesis is has been done by myself under the general supervision of my supervisor.

b) The work has not been submitted to any other Institute for any degree or diploma.

c) I have followed the guidelines provided by the Institute in writing the thesis.

d) Whenever I have used materials (data, theoretical analysis, and text) from other sources, I have given due credit to them by citing them in the text of the thesis and giving their details in the references.

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Sonam Shrivastava

22nd May 2014

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SONAM SHRIVASTAVA
mailtosonam24390@gmail.com

ABSTRACT

Nowadays, there is a scarcity of the radio spectrum due to advancement in wireless networks and services such as Wi-Fi, Bluetooth, ZigBee and Wi-max, etc. A survey performed by the spectrum policy task force (SPTF) within the Federal communication Commission (FCC), states that actually licensed spectrum is inefficiently utilized as some bands remain vacant for long time duration in some particular geographical regions, some frequency bands are partially occupied and the other parts of the spectrum bands are densely employed. Because of the huge demand of spectrum, Cognitive Radio (CR) technology gains much attention as it can sense the unused spectrum bands and optimize spectrum utilization and enhance the quality of service for the overall system. CR employs a Radio Frequency (RF) transceiver which is designed to identify that a specific part of the spectrum band is currently engaged or not, and shift speedily into the free spectrum with no or minimal level of interference to existing licensed users. This minimizes the interference to the other licensed users and as well as increases spectrum utilization. Spectrum sensing is a key component for securing the licensed terminals from interference as detects the white spectrum holes to improve the spectrum efficiency and facilitates the unlicensed mobile users to use the empty licensed radio frequency bands of the electromagnetic spectrum. For smooth operation of CR system the sensing should be more accurate and reliable.

Several spectrum sensing techniques exist in the communication engineering literature. It includes the Energy Detection (ED), Matched Filter detection (MFD) and Cyclostationary feature Detection (CFD) techniques. These techniques have different requirements and advantages/disadvantages. In literature, most of the analysis is based on ideal channel condition. In practice, noise power may vary with time, which is known as Noise Uncertainty

(NU). A review of the literature shows that researchers have tried to modify the techniques so that noise uncertainty can be reduced with or without compromising the detection performance.

This dissertation is extensively based on the study of Energy Detection technique for spectrum sensing. Dynamic-Double-Threshold technique on the framework of Energy Detection technique has been proposed and analysed through simulation studies using MATLAB2012a. The performance of the proposed technique has been compared with the existing ED, MFD and CFD techniques, which shows significant performance improvement in terms of detection probability with the consideration of noise uncertainty.

CONTENTS

NOMENCLATURE

$x(n)$: Received signal by the cognitive user

s(n) : Transmitted signal from the primary user

w(n) : Additive white Gaussian noise

h : Channel gain

N : Number of samples during detection period

H_0 : Hypothesis 0: primary user is absent

H_1 : Hypothesis 1: primary user is present

P_d : Probability of detection

P_f : Probability of false alarm

P_m : Probability of miss-detection

$D(x)$: Test statistics

P : Average signal power of primary user

${\sigma_n}^2$: Noise variance

λ : Threshold

E : Energy of received signal

$Q(.)$: Complementary cumulative distribution of standard Gaussian function

SNR : Signal-to-noise ratio

exp : Exponential function

σ^2 : Noise variance

ρ : Noise uncertainty coefficient

T : Noise uncertainty limit

sup : Supremum operator

λ' : Dynamic threshold

ρ' : Dynamic threshold coefficient

max : Maximum operator

min : Minimum operator

λ_1 : Lower threshold bound

λ_2 : Upper threshold bound

$\Delta\lambda$: Delta lambda

${\lambda_1}'$: Dynamic lower threshold

${\lambda_2}'$: Dynamic upper threshold

ABBREVIATIONS

SPTF : Spectrum Policy Task Force

FCC : Federal Communication Commission

CR : Cognitive Radio

MFD : Matched Filter Detection

CFD : Cyclostationary Feature Detection

NU : Noise Uncertainty

DAB : Digital Audio Broadcast

DVB : Digital Video Broadcast

TRAI : Telecom Regulation Authority of India

US : United States

PU : Primary User

DSA : Dynamic Spectrum Access

DSAN : Dynamic Spectrum Access Network

SDR : Software Defined Radio

xG : Next Generation Programme

DARPA : Defence Advanced Research Projects Agency

PDA : Personal Digital Assistant

CSI	:	Channel State Information
DSM	:	Dynamic Spectrum Management
IEEE	:	Institute of Electrical and Electronics Engineers
AWGN	:	Additive White Gaussian Noise
SNR	:	Signal-to-Noise Ratio
SCF	:	Spectral Correlation Function
BPSK	:	Binary Phase Shift Keying
NU*	:	Noise Uncertainty under double threshold condition

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1

INTRODUCTION

In wireless communication systems, there is a paucity of the radio frequency spectrum due to ever expanding wireless networks and services like Wi-Fi, Bluetooth, ZigBee and Wi-MAX, etc. The root of spectrum shortage is fixed spectrum allocation means every new service is having its own fixed frequency block. The day by day increasing demands of spectrum for new services are making spectrum distribution very difficult. Some recent services like Digital Audio Broadcast (DAB), Digital Video Broadcast (DVB), Internet, Wi-Max etc. are presently working on unlicensed spectrum band. Therefore, the concept of Cognitive Radio gains much importance as it allows the unlicensed users to access the licensed band dynamically and opportunistically. However, the radio spectrum bands are operated by the regulatory bodies with higher strictness, in order to protect the licensed users. The unlicensed spectrum allotted to these new emerging technologies is very much less in amount; therefore interference between the cognitive user as well as PU comes into picture.

The first part of this chapter describes the fixed frequency allocation strategy along with adverse effect of it on the spectrum utilization. The concept of cognitive radio is discussed in brief. This chapter has been concluded by objective of the work and thesis layout.

1.1 Motivation

Wireless communication has been the fastest growing area of the communication industry over the past few decades. Therefore, several wireless applications and devices are come in to existence. In accordance with the report given by the Spectrum Policy Task Force (SPTF) under Federal Communication Commission (FCC), it is seen that, some radio frequency spectrum bands are densely engaged whereas some parts of radio frequency bands are either moderately used or unoccupied under the specific geographical region [1], [2], [3]. The electromagnetic spectrum is limited resource and is controlled by government organization like Telecom Regulation Authority of India (TRAI) in India, FCC in United States (US).

The fixed frequency assignment strategy exclusively allots the specific frequency band to a particular service, and unlicensed users cannot access the band, resulting in spectrum holes. Spectrum holes are the band of frequencies allotted to a particular user known as Primary User (PU) or licensed user but remain unoccupied for a long time, in a definite geographical region. The spectrum hole is illustrated in following figure [4]:

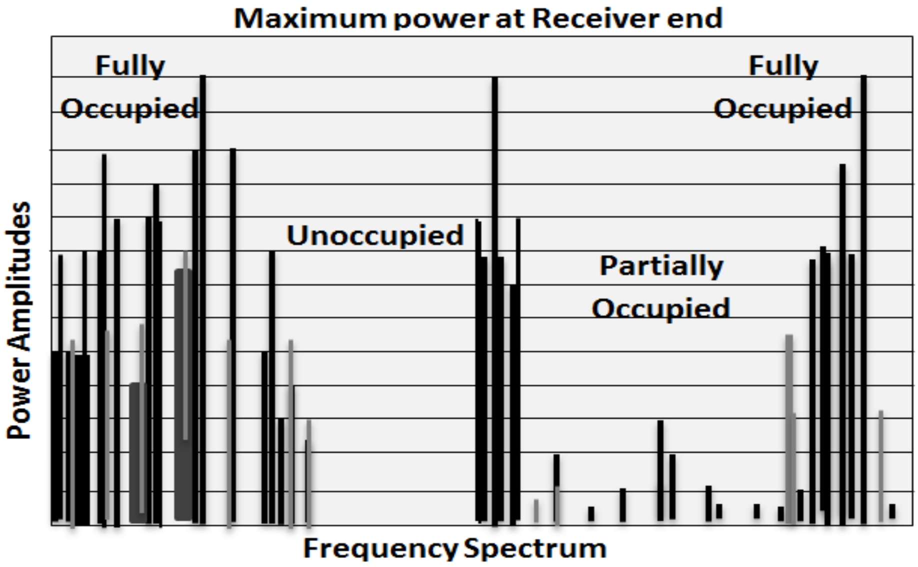

FIGURE 1-1: SPECTRUM UTILIZATION

To utilize the available spectrum up to the full extent it is mandatory to allow the unlicensed users to borrow unused licensed radio spectrum band under the condition that it should not cause any harmful interference to the PU. To meet this specification an intelligent wireless communication system is required, which must be aware of its environment and able to select the spectrum band as well as the parameter (for example, carrier frequency, modulation type, bandwidth, etc.)

Cognitive radio is favourable technology to deal with underutilization of radio frequency spectrum, and it allows the Cognitive Users (CUs) or secondary users to utilize the spectrum holes, also CR can adapt its environment due to its ability of parameter modification [5]. The process of detecting the presence or absence of PU, CR must check the radio frequency spectrum continuously, and it is known as Spectrum Sensing. Spectrum Sensing is the heart of CR system. Until CU will come to know about the availability of the spectrum, it cannot access because of undesirable interference to the PU. At the beginning CR users will scan the licensed spectrum allotted to the specific users to detect the occupancy state of the band. Later depending on the output of scanning, unlicensed or CR users will choose their conveyance approach. In case of the free licensed spectrum, the CR users will transmit over the unused channel, but if PUs are using the allotted spectrum, CR users share the spectrum with the PU by limiting their transmit power until they find any empty spectrum band, and if the band is available, the CU will jump into the new spectrum hole immediately.

1.2 Objective of the Work

The main objective of this work is to address the problem of spectrum sensing under noise uncertainty. The aim is to develop an improved spectrum sensing technique such that the adverse effect of noise power uncertainty is overcome as well as the performance enhancement over existing sensing methods is achieved.

To realise this objective, the following analysis and investigation are required to be undertaken:

- Study and analyse the existing spectrum sensing technique and understand the problem of varying noise power.
- Devise a new method that would preserve the principle of the technique, without adding much complexity along with reduction in the effect of Noise Uncertainty.
- Simulation based testing of the proposed technique to prove its efficacy.

1.3 Literature Survey

The problem of spectrum underutilization and spectrum shortage has been firstly addressed in a report **"The FCC,"** given by **H. Ronald Coase** in 1959, **[3]**. To overcome this spectrum shortage problem the Cognitive Radio word was first coined by J. Mitola III in his Ph.D. dissertation **"Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio,"** in the year 2000, **[8]**. Further **FCC** gives the report on **"Notice of proposed rulemaking and order: Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies,"** in 2005, **[1].** This report clearly indicate that there are parts of licensed spectrum which remain empty for long duration under specific geographic region.

S. Haykin defines the CR in his paper **"Cognitive radio: brain-empowered wireless communications,"** in 2005, **[7],** after this, the concept of dynamic spectrum access was explained by **Clancy III et.al.** in his Ph.D. dissertation in year **2006, [9].** The concept of spectrum holes was explained by **I. F. Akyildiz et.al.** in his journal **"NeXt Generation / Dynamic Spectrum Access / Cognitive Radio Wireless Networks: A Survey,"** in 2006, **[4]**.

Interference temperature is a measure of radio frequency power accessible by the receiver antenna, reflecting the power produced by the noise sources and its concept was explained in detyail by **P.J. Kolodzy** in **"Interference temperature: a metric for dynamic spectrum utilization,"** in the year 2006, **[12]**. The concept of CR and its ability to adapt the environment changes was explained by **A. Gorcin et.al.** in **"A Signal Identification Application for Cognitive radio**," in year 2007, **[5]**. **P. Karnik et.al.** proposed the transmitter detection techniques in **"Transmitter Detection Techniques for Spectrum Sensing in CR Networks,"** in the year 2004, **[17].**

Spectrum sensing is the key concept of CR system and techniques and challenges for it is explained in **"Spectrum awareness: techniques and challenges for active spectrum sensing,"** by **M. Höyhtyä et.al.** in 2007, **[16]**.

Further the concept of energy detection is as older than the CR concept and it was first proposed by **H. Urkowitz** in his paper **"Energy detection of unknown deterministic signals,"** in 1967, **[6].** It explained that the energy detection technique is evaluating the energy of the received PU signal at the cognitive user terminal and it does not require the prior knowledge about PU. The comparative performance evaluation of ED, MFD and CFD techniques has been done by **Ashish Bagwari et.al**. in his papers **"Comparative performance evaluation of spectrum sensing techniques for cognitive radio networks,"** in year 2012, **[19]**. The same comparison has also been presented in the paper **[18]**.

Spectrum sensing technique considered along with the noise variance in literature paper given by **R. tandra** in **"SNR Walls for Signal Detection,"** in the year 2008, **[20]**. The reliability of spectrum sensing under noise uncertain environment is further explained by **Y. Zeng et.al.** in **"Reliability of spectrum sensing under noise and interference uncertainty,"** in year 2009, [22]. Further to overcome the effect of noise uncertainty, concept iof double threshold for energy detection scheme is explained by **J. Zhu, et. al.** in **"Double threshold energy detection of cooperative spectrum sensing in cognitive radio," in year 2008, [26].**

This dissertation has proposed a Dynamic-Double-Threshold based energy detection scheme which improves the detection performance further and give better result than the existing techniques explained in literature.

1.4 Thesis Contribution

Multiple modifications of ED technique exists which try to reduce the adverse effect of noise uncertainty on the detection performance even at lower SNR values. The ultimate goal is to devise such a technique that would use the principle of energy detection and lessen the false alarm probability. The contribution of the thesis is given under following points:

- The Dynamic-Double-Threshold scheme has been proposed on the backbone of energy detection technique for overcoming the noise uncertainty problem, and has been compared with the existing ED, MFD and CFD techniques.
- Detail mathematical analysis of the effect of noise uncertainty on the detection period (number of samples) has been carried out to justify the simulation results.

1.5 Thesis Organization

The thesis has been organised in to six chapters. The ongoing chapter gives the brief introduction to the spectrum shortage, fixed spectrum allocation strategy, cognitive radio, and spectrum sensing. The motivation and objective of the thesis have been addressed in the following subsections, although the uttermost subsection explains the entire thesis organization and literature survey.

Chapter 2: The second chapter discusses the detailed description of cognitive radio including its history, definitions, need, cognitive tasks and applications. Pros and cons of cognitive radio also discussed in the last subsection.

Chapter 3: This chapter gives the introduction to spectrum sensing technique. It also describes the sensing hypothesis and three basic transmitter detection techniques ED, MFD and CFD. The penultimate subsection gives the validation of the theory with simulation results. Comparison of the three techniques has been done on the basis of simulation.

Chapter 4: This chapter introduces the concept of noise uncertainty and its effect on the ED and MFD techniques. A detail of noise uncertainty factor is illustrated, and the simulation results are given to validate the theory.

Chapter 5: The fifth chapter describes the proposed Dynamic-Double-Threshold Energy Detection scheme and illustrates the performance of the same in comparison to the existing transmitter detection techniques. The simulation results obtained have been included in order to validate the theory proposed.

Chapter 6: This chapter presents the conclusion to the entire research work carried out and give light on the future work to the research that has been conferred in the thesis.

2

COGNITIVE RADIO: AN INTRODUCTION

2.1 Introduction

Nowadays, the wireless technology is fast growing area. With the growth of new wireless applications, the demand of high quality radio frequency spectrum is expanding expeditiously. Each and every new technique has its own operating standards and hardware for transmitting and receiving the electromagnetic waves. Therefore, the techniques required their own band of frequency. But a big part of the spectrum band has already been allotted to the licensed users. Due to this there is a huge argument in the allotment of unlicensed spectrum band for these new technologies.

The spectrum regulatory bodies are not granting the permission to use the licensed spectrum bands for unlicensed users. Rather than this fact, the licensed spectrum band is underutilised in several geographical regions. An unlicensed user thus can take this opportunity; thereby spectrum efficiency can be boosted. The cognitive radio comes into picture from this logic of Dynamic Spectrum Access (DSA). Further the chapter gives a brief idea about CR, which includes its past, description, working methodology and utilization.

A cognitive radio is a well-informed and smart radio that can be easily instructed and configured vigorously. Its transmitter and receiver parts are devised in the manner that it automatically chooses the finest wireless channel from its surrounding environment. The CR can alter its parameters according to the current wireless scenario and provide reliable communication in a particular spectrum band. This whole mechanism makes CR dynamically managed spectrum utilization.

2.2 Cognitive Radio: History

The history of CR is not too old; rather it is an evolving technology. The concept of next generation communication networks widely recognized as Dynamic Spectrum Access Networks (DSANs), will provide an opportunity to the unlicensed mobile users to access the wireless channel by way of DSA methodology and conglomerate wireless structure [4]. Most of the time, spectrum utilization is more compelling issue than the physical inadequacy of spectrum. Accordingly, improvement in spectrum utilization is requisite for smooth operation of a CR system.

The thought of CR was proposed by Joseph Mitola III in 1998 in a seminar at the Royal Institute of Technology (KTH) [8]. The term CR evolved from Software Defined Radios (SDRs). The SDR is a class of wireless communication which all the necessary hardware, for example mixer, filter, detectors modulators and demodulators are realised via software means, may be on a computer or embedded system. Therefore, SDRs with understanding can be often called as CR [9].

Cognitive Radio is a combination of many technologies and solution to the problem of inefficient spectrum utilization. Defense Advanced Research Projects Agency abbreviated as DARPA initiates a next generation programme (xG) which is working on intelligent radio recognized as CR.

2.3 Cognitive Radio: Definitions

After Mitola proposed the concept of CR, there are many more organizations, spectrum regulatory bodies and forums that give description in several ways.

- According to Mitola [8], CR is defined as: The point in which the Personal Digital Assistants (PDAs) are adequately smart in calculation about the radio frequency spectrum and associated peer to peer communication, in order to identify first needs of communication in user context and second to make available the radio spectrum and wireless services to these needs.
- Simon Haykin gives description of CR as follows [7]: CR is an smart and knowledgeable wireless communication system, which is receptive towards its neighbouring and uses understanding by building concept so as to modify its methodology according to the radio frequency stimuli via changing its parameters as modulation type, power to be transmitted, frequency range etc., for the two goals: a) Reliable communication and b) Efficient radio spectrum utilization.
- FCC defines CR as: A radio which is able to alter its transmitter parameters according to its operating surrounding [1].
- The definition given by IEEE USA is as follows [10]: CR system is a radio frequency transmitter which is intelligently devised to identify the empty licensed radio frequency spectrum and make use of it temporarily until the licensed user

showed up again, with a condition that it should not cause interference to the licensed user or PU.

Along with these definitions, CR can be defined as: *The radio system that takes input as observation from various actions and adapts itself according to the environment for taking intelligent decision in order to meet the cognitive user's demands*.

2.4 Need of Cognitive Radio

Cognitive radio is a very promising technique it uses many technologies simultaneously for solving two major complications [1]:

- Finding spectrum holes and utilizing it.
- Operating with different leagues of radio having different parameters.

2.5 Cognitive Tasks: Survey

The CR is reconfiguration in nature, but it depends upon the SDR to do so. The other processes of cognitive manners are performed by signal processing techniques and intelligent retrieval process. The CR system begins its process with sensing of radio frequency spectrum and concluded with action [7].

The working of conventional cognitive radio can be explained with a typical cognitive cycle. The cognitive cycle is the way of communication between CR system and its surrounding [7]. The cognitive cycle can be categorized in to three firmly co-dependent online tasks [8], [11]. These three tasks of cognitive cycle are discussed and their main functions are focused under below subsections.

1. **Radio-Scene Analysis,** which cover following functions:
    - Assessment of interference temperature of the radio environment.
    - Identification of white spaces.
2. **Channel identification,** which cover following functions:
    - Assessment of Channel State Information (CSI).
    - Forecasting of channel capacity for transmitter use.
3. **Transmit Power Control And Dynamic Spectrum Management.**

The task 3) is executed at the transmitter and the rest of two at the receiver. These three cognitive tasks interact with the radio frequency environment forms the cognitive cycle. The transmitter and receiver of cognitive system must work in synchronization, which necessitate the feedback connection; therefore, the cognitive radio is a feedback communication system [7]. The cognitive cycle is illustrated in following figure [6]:

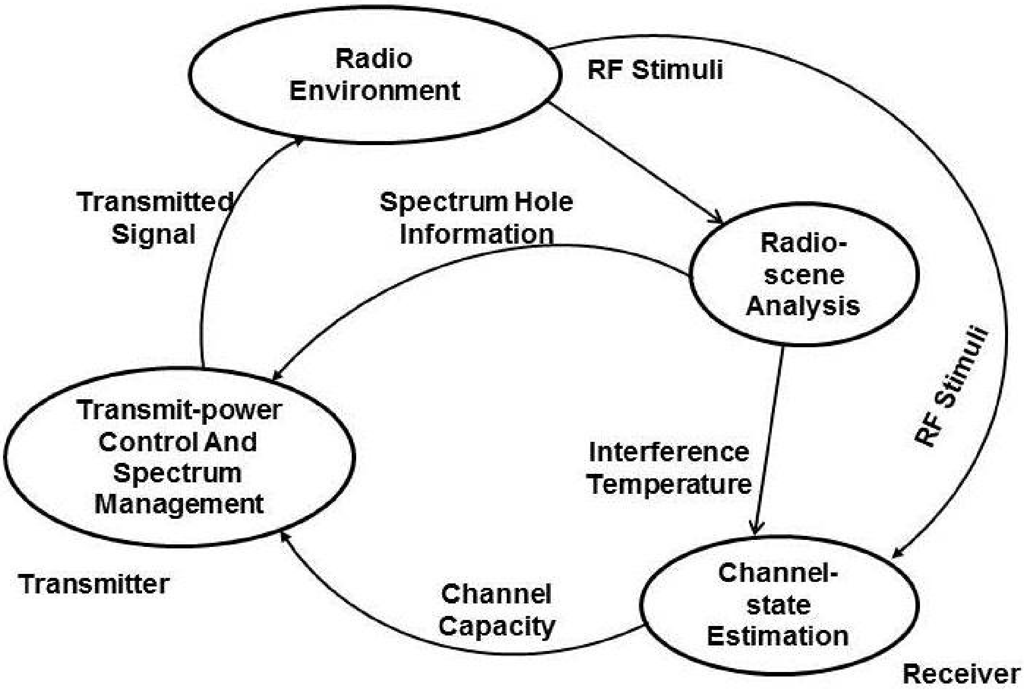

FIGURE 2-1: COGNITIVE CYCLE

2.5.1 Radio-Scene Analysis

During this part of the cycle the various radio arrangements are incited to do an appraisal for interference temperature and the spectrum holes. These two terms are calculated at the receiving end and are explained below.

- **Interference Temperature**

The term interference temperature was suggested by the FCC for the measurement of interference in the wireless environment. The interference temperature can be measured by the radio frequency power accessible by the receiver antenna, reflecting the power produced by the noise sources [12]. To discover the available spectrum different metrics can be used. The conventional approach is to confine the transmitter power of the cognitive devices; it means that the transmitted power should not exceed the recommended amount. The detail is illustrated in below figure.

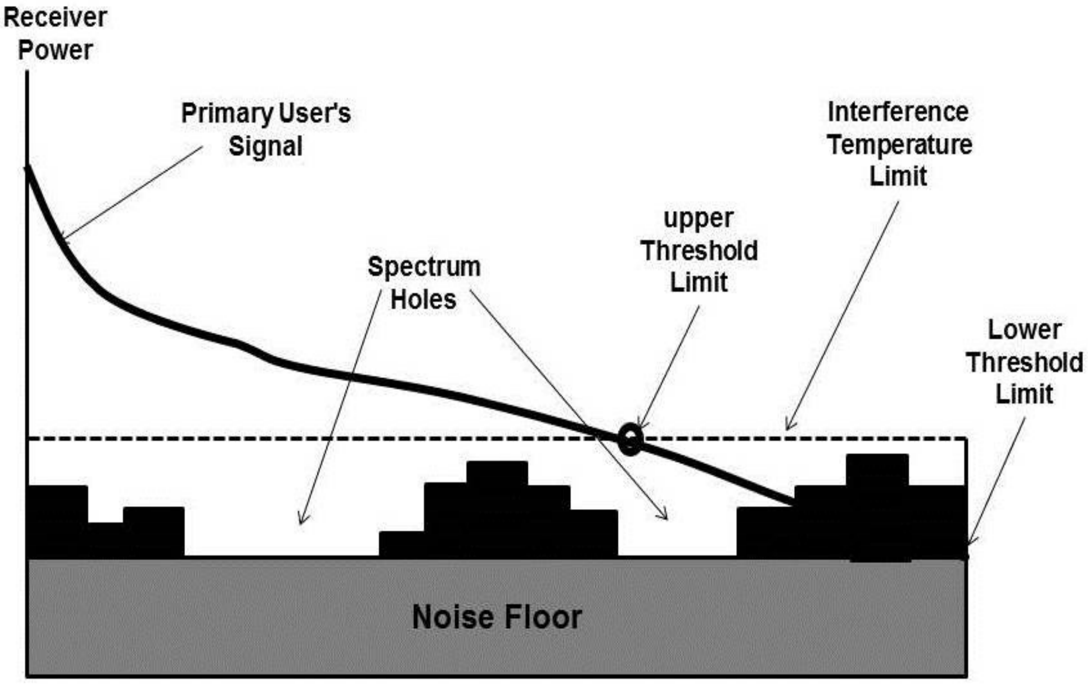

FIGURE 2-2: INTERFERENCE TEMPERATURE

From interference temperature metric two crucial checks can be defined:

i. The upper threshold level above which the channel is declared as occupied.

ii. The lower threshold level below which the channel can be declared empty or available for the other user.

- **Spectrum Holes**

Spectrum holes are the spaces in the spectrum assigned to a particular user, but in a specific time and geographical region, the space is not in use. According to the amount of interference, the spaces or holes are categorized in three parts:

i. White spectrum holes, which are free from interference.

ii. Gary spectrum holes, which are partially occupied.

iii. Black spectrum holes, which occupied with the higher interference level.

Spectrum holes and DSA concept are illustrated in below figure:

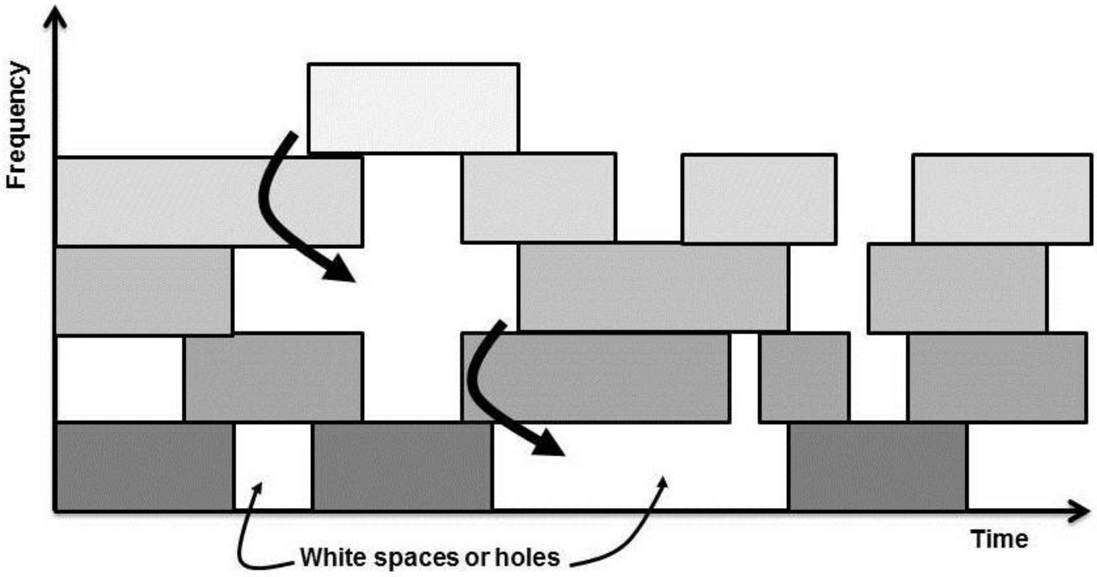

FIGURE 2-3: DSA AND SPECTRUM HOLES

After the spectrum sensing operation, the unlicensed users are allowed to make use of white spaces without restriction, grey spaces with a restraint that they will not cause much interference to the PU, and black holes cannot be used because they are fully occupied and further use will cause interference to the PU [7].

2.5.2 Channel-State Estimation

Channel-State Estimation is also a component of CR [7]. It assesses the channel impulse response and channel's behaviour in context with transmitted signal so as the receiver can devise the equaliser and the transmitter can adjust itself and send an appropriate signal that can overcome the effects.

2.5.3 Distributed Transmit Power Control

This action is performed in the transmitter as well as receiver parts of the cognitive radio systems in a distributed manner. Each and every user should ensure that the signal which it sends approaches the receiver such that:

i. It should be at a higher level than receiver.
ii. Below the level at which it causes interference.

2.5.4 Dynamic Spectrum Management

Dynamic Spectrum Management (DSM) works along with the Distributed transmit power control strategy, and both are carried out at the transmitter side. These two functions are correlated to each other; therefore, they are in the same module in the cognitive cycle, as shown in figure 2-1. Dynamic spectrum management algorithm is allotted with the following tasks:

i. Based on the result of transmit power control and radio scene analysis it picks a modulation strategy which get used to the environmental radio conditions.

ii. Dependable communication guaranteed throughout the radio channel.

2.6 CR, Applications, Pros and Cons

The Cognitive Radio has pros and Cons of the SDR itself. CR has additional benefits over the conventional one as it has the observation, adaptability and intelligence qualities simultaneously.

Important applications of CR:

- Link reliability enhancement
- Spectrum utilization improvement
- Economical radio
- Broadband wireless services
- Emergency communications

Pros of CR:

- Efficient spectrum utilization
- Dependable communication
- Less coordination required than the conventional radio
- Flexible regulation

Cons of CR:

- Loss of control

- Security issues
- Maintaining higher data rate
- Regulatory matters
- Incorrect decisions about spectrum occupancy for hidden primary user and spread spectrum user
- Pricing issues at end user

2.7 Important Organizations working on CR

- DARPA- Defense Advanced Research Projects Agency
- IEEE- Institute of Electrical and Electronics Engineers
- SDR Forum- Software Defined Radio Forum
- FCC- Federal Communication Commission

3

SPECTRUM SENSING TECHNIQUES

Spectrum sensing is a crucial prerequisite task of the xG network [6]. Cognitive Radio is devised to be conscious and receptive towards the variations in the radio environment. The spectrum sensing facilitates the CR to acclimate its surroundings via identifying spectrum holes.

3.1 Introduction

A fundamental demand of CR system is that the unlicensed users should compulsorily catch the existence of the licensed user in the licensed radio spectrum band in prior to make use of the band and jump out of it instantaneously if the associated licensed user comes up for sidestepping the interference to the authorized users [13].

The most competent approach to identify white spaces is to detect the authorized users in the territory of the cognitive user. Spectrum sensing is yet in its evolving phase. It is problematic for the cognitive user to sense the line of sight channel between the cognitive user and the PU transmitter. Thus, the transmitter detection based spectrum sensing is an important issue to deal with [6].

3.2 Spectrum Sensing Hypothesis

Transmitter detection concept is to identify the weak signal transmitted from a PU to the CU. The heart of spectrum sensing is the binary detection hypothesis and can be modelled as follows:

$$\begin{cases} H_0: & x(n) = w(n) & , n = 1,2, \ldots., N \\ H_1: & x(n) = h.s(n) + W(n) & , n = 1,2, \ldots., N \end{cases} \tag{1}$$

Where $x(n)$ the received signal by cognitive user is, $s(n)$ is transmitted signal from PU, $w(n)$ is Additive White Gaussian Noise (AWGN) and h is the channel gain. The hypothesis H_0 and H_1 are defined as:

H_0: Licensed user is absent and channel is vacant.

H_1: Licensed user is present and channel is occupied.

From this hypothesis the following three essential metrics can be drawn [14]:

- Probability of detection (P_d): Channel is vacant and declared as vacant.
- Probability of false alarm (P_f): Channel is vacant and declared as occupied.
- Probability of miss-detection (P_m) : Channel is occupied and declared as vacant.

In terms of probability these metrics can be defined as:

$$\left.\begin{array}{l} P_d = \text{Prob } \{\text{Decision}=H_1/H_1\} \\ P_f = \text{Prob } \{\text{Decision}=H_1/H_0\} \\ P_m = \text{Prob } \{\text{Decision}=H_0/H_1\} \end{array}\right\} \tag{2}$$

3.3 Spectrum Sensing Techniques

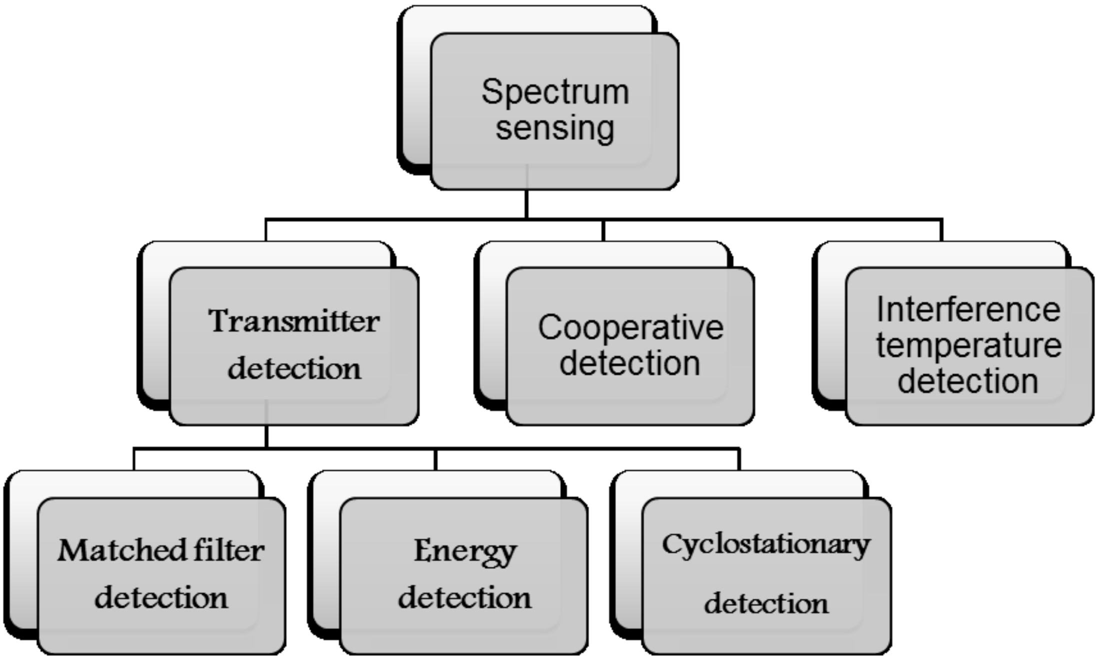

FIGURE 3-1: CLASSIFICATION OF SPECTRUM SENSING TECHNIQUES

Figure 3-1 gives the meticulous categorization of spectrum sensing techniques. They are extensively categorized in three types, transmitter detection, cooperative detection and interference based detection. In transmitter detection techniques, the received signal assessment is the key concept, and the transmitter detection techniques are also known as non-cooperative detection techniques. The transmitter detection technique is again categorized into Matched Filter Detection (MFD) Energy Detection (ED), and Cyclostationary Feature Detection (CFD) Techniques [15]. Following subsections gives the detailed explanation about these three techniques.

3.3.1 Matched Filter Detection (MFD)

One of the eminent detection techniques in the area of signal processing for retrieving the known information from a signal at receiver end is MFD. The MFD is work on the principle of coherent detection. The MF is a linear filter and it is devised in such a way that it enlarges the Signal-to-Noise Ratio (SNR) of the PU signal at the cognitive user terminal under AWGN channel.

MFD technique can be used only when the prerequisite information like modulation type, pilot carrier, pulse shape and spreading codes, etc. are known in prior to the cognitive user. In order to access all the prior information regarding the PU signal, synchronization is must between the cognitive user terminal and the primary user transmitter. Whenever the secondary user has prior information regarding PU signal, the MFD can be applied. The block diagram of MFD is given in the figure below:

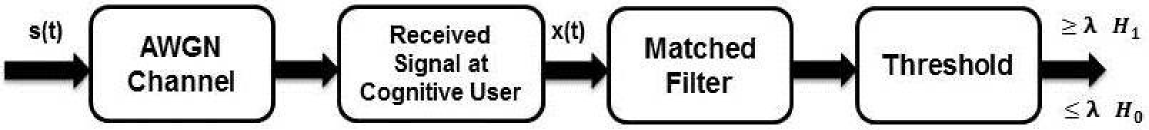

FIGURE 3-2: BLOCK DIAGRAM OF MATCHED FILTER DETECTION TECHNIQUE

The output of the matched filter is compared with the pre-set threshold value in order to determine the spectrum occupancy, i.e. presence or absence of PU.

Since the secondary user is permitted to explore all the information of PU signal, it creates the security threat on licensed spectrum users. Also synchronization between the PU and cognitive user terminal is must, accordingly the synchronization fading causes performance deterioration badly.

In addition, every single PU has its own properties therefore, different types of matched filters required for primary user's signal detection, which raises the CR system intricacy largely.

Matched filter operates is comparable to the correction of received unknown signal within the impulse response of matched filter, which is priory known PU signal, i.e. reference signal, or its time shifted form. Mathematically, the matched filter can be represented as follows:

$$D(x) = \frac{1}{N}\sum_{n=0}^{N-1} x(n) \times s(n) \tag{3}$$

Where, $s(n)$ = prior known signal,

$D(x)$ = test statistics.

Thus from (3) we can deduce that extra hardware are needed for synchronization, and also the information of PU signal is necessary in prior to construction of conjugate signal results in large power consumption and implementation complexity [16].

The test statistic for MFD is given in (3). If the noise variance is assumed to be predetermine, from central limit theorem [18]:

$$D(x) \sim \begin{cases} \mathcal{N}\left(0, P{\sigma_n}^2/N\right) & H_0 \\ \mathcal{N}\left(NP, P{\sigma_n}^2/N\right) & H_1 \end{cases} \tag{4}$$

Where, P is the average PU signal power and ${\sigma_n}^2$ is noise variance.

The spectrum occupancy for licensed user can be declared as:

$$\begin{cases} D(x) > \lambda \;, & H_1: licensed\ terminal\ is\ present \\ D(x) < \lambda \;, & H_0: licensed\ terminal\ is\ absent \end{cases} \tag{5}$$

Where, λ is the threshold value.

The equations for probability of detection (P_d), probability of false alarm (P_f), and probability of mis-detection (P_m) are derived as:

$$P_d = Pr(D(x) > \lambda/H_1) = Q\left(\frac{\lambda - P}{\sqrt{P{\sigma_n}^2/N}}\right) \tag{6}$$

$$P_f = Pr(D(x) > \lambda/H_0) = Q\left(\frac{\lambda}{\sqrt{P{\sigma_n}^2/N}}\right) \tag{7}$$

$$P_m = 1 - P_d = 1 - Q\left(\frac{\lambda - P}{\sqrt{P{\sigma_n}^2/N}}\right) \tag{8}$$

3.3.2 Energy Detection (ED)

When the sufficient information regarding the primary user signal is not available at the cognitive user terminal, the MFD technique cannot be used. Nevertheless, if the identification of the presence of primary user's signal perverted from AWGN is required, then ED technique is worthwhile [19]. The underlying concept at the bottom of ED is evaluation of the power the PU signal received at the cognitive user terminal. The basic block diagram of ED is depicted in figure below.

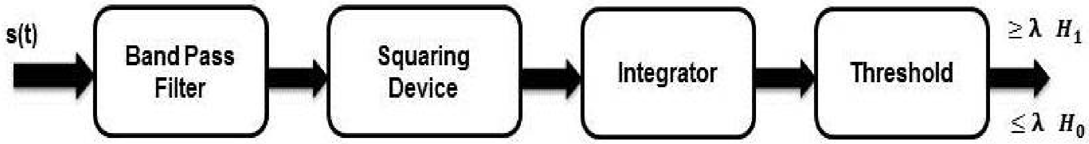

FIGURE 3-3: BLOCK DIAGRAM OF ENERGY DETECTION TECHNIQUE

In order to estimate the energy of PU signal the filtered signal from the BPF is squared and integrated so as to calculate energy and then the final output of integrator is compared with a pre-set threshold value for spectrum occupancy details [20].

The technique is most commonly used because of low computational cost and implementation complexities. ED technique is also known as Blind Detector as it only estimates energy disregarding the type and properties of the signal. Rather than this fact, the ED also suffers from some drawbacks:

- Sensing time is higher
- Cannot discriminate between the PU signal and the cognitive user signal
- Performance degraded in case of noise uncertainty

The calculation of energy can be done by following equation:

$$E = \sum_{n=0}^{N-1} |x(n)|^2 \tag{9}$$

This is also the metric used for comparison. When PU is absent, the input signal will be $x(n) = w(n),\ H_0$. The test statistic for ED technique is given as [18]:

$$D(x) = \frac{1}{N} \sum_{n=0}^{N-1} [x(n)]^2 \tag{10}$$

Here, $D(x)$ is the test statistic, N is the number of sample taken under the observation period. For a single threshold value λ, presence or absence of licensed user can be declared as in (5).

$$\begin{cases} D(x) > \lambda\ , & H_1: licensed\ terminal\ is\ present \\ D(x) < \lambda\ , & H_0: licensed\ terminal\ is\ absent \end{cases}$$

If we assume the noise variance is fixed and the noise uncertainty is not considered, from the central limit theorem [18],

$$D(x) \sim \begin{cases} \mathcal{N}({\sigma_n}^2, {\sigma_n}^4/N) & H_0 \\ \mathcal{N}\big(({\sigma_n}^2 + P), ({\sigma_n}^2 + P)^2/N\big) & H_1 \end{cases} \tag{11}$$

Now, we can derive the probability of detection (P_d), probability of false alarm (P_f), and probability of mis-detection (P_m) as:

$$P_d = Pr(D(x) > \lambda/H_1) = Q\left(\frac{\lambda - (P + {\sigma_n}^2)}{\sqrt{2/_N} \cdot (P + {\sigma_n}^2)}\right) \tag{12}$$

$$P_f = Pr(D(x) > \lambda/H_0) = Q\left(\frac{\lambda - {\sigma_n}^2}{\sqrt{2/_N} \cdot {\sigma_n}^2}\right) \tag{13}$$

$$P_m = 1 - P_d = 1 - Q\left(\frac{\lambda - (P + {\sigma_n}^2)}{\sqrt{2/_N} \cdot (P + {\sigma_n}^2)}\right) \tag{14}$$

Here Q (.) function represents the complementary cumulative distribution of standard Gaussian function and λ represents the pre-set threshold value.

3.3.3 Cyclostationary Feature Detection (CFD)

It has been advised in the literature that the CFD technique is better than the ED and MFD techniques. As it already explained previously that the MFD is coherent type detector and needed information in prerequisite format, and though the ED technique is non-coherent but is unable to differentiate between the PU and the cognitive user signals, and its performance depends upon the noise variance.

Signal showing periodicity is known as cyclostationary signals [21]. Periodicity in the signal comes due to modulation, coding or the pilot data used for synchronization, hopping sequence, spreading code etc. These are having inbuilt periodicity. Whereas the noise is a wide sense, stationary signal with no such properties stated above. Thus extraction of noise from the received signal is feasible using any spectral correlation function. A cyclostationary feature is purposely encapsulated along with the physical property of the signals; these feature can be efficiently generated and identified with the use of moderate intricacy receiver and transmitter. The block diagram for cyclostationary feature detection is shown in the figure below.

FIGURE 3-4: BLOCK DIAGRAM OF CYCLOSTATIONARY FEATURE DETECTION TECHNIQUE

Cognitive user recognizes the arbitrary signal with a distinct modulation type, even though if it exists with a hypothetical noise by employing periodic information like auto correlation and mean of the PU signal, and the autocorrelation and mean can be evaluated via Spectral Correlation Function (SCFs).

The CFD technique has intelligence to distinguish the primary user's signal and noise; therefore, it outperforms the Energy Detection and Matched Filter Detection techniques discussed above. But larger observation time and more computational complexity are the two drawbacks.

For a particular threshold value λ the probability equations can be given as follows [19]:

$$P_d = Pr(D(x) > \lambda/H_1) = Q\left(\sqrt{\frac{2*SNR}{{\sigma_n}^2}}, \frac{\lambda}{\sigma_A}\right) \tag{15}$$

$$P_f = Pr(D(x) > \lambda/H_0) = exp\left(\frac{-\lambda^2}{2{\sigma_A}^2}\right) \tag{16}$$

$$P_m = 1 - P_d = 1 - Q\left(\sqrt{\frac{2*SNR}{{\sigma_n}^2}}, \frac{\lambda}{\sigma_A}\right) \tag{17}$$

Where, exp= exponential function,

SNR= signal-to-noise ratio= $\frac{P}{{\sigma_n}^2}$

$$ {\sigma_A}^2 = \frac{{\sigma_n}^2}{2N+1} \tag{18}$$

3.4 Simulation Results

With a view to verify the hypothesis of detection, the simulations were made for ED, MFD and CFD in MATLAB 2012a on a CPU of 2GB RAM working at 1.86 GHz processor. The transmitter signal or the PU signal is a random bit stream multiplied with a sinusoidal carrier signal to generate BPSK modulated wave. This signal is transmitted in AWGN channel. The detection performance has been analysed on the basis of following cases:

- Plot between P_f vs P_d
- Plot between SNR vs P_d

The various values of the simulation parameters taken are tabulated below:

TABLE 3-1: PARAMETERS CONSIDERED FOR SIMULATION

Parameter Name	Value Considered
Modulation Type	BPSK
Number of Samples (N)	1000
SNR	**-15dB**
Probability of False Alarm (P_f)	**0:0.01:1**
SNR	**-30:5:20**
Probability of False Alarm (P_f)	**0.1**

The detailed description of the simulation results for the MFD, ED and CFD are discussed in subsections below.

3.4.1 Simulation for MFD Technique

Figure 3-5 shows the numerical results for MFD technique plotted between probabilities of false alarm (P_f) vs probability of detection (P_d), at different values of SNR=-10dB, -15dB and -20dB. In the graph for P_f 0 to 0.1, the P_d value varies from 0.8 to 0.98, 0.3 to 0.7 and 0.1 to 0.4 for SNR -10, -15 and -20 dB respectively. Thus, it is clearly visible that the detection performance degraded as SNR is decreasing.

Figure 3-6 depicts the numerical results for MFD technique plotted between P_f vs P_d, at different values of N=500, 1000 and 1500. P_f varies from 0 to 1 in span of 0.01 at SNR=-20dB In the graph for P_f 0 to 0.1, the P_d value varies from 0.46 to 0.82, 0.8 to 0.96 and 0.94 to 1.0 for N 500, 1000 and 1500 respectively. Thus, we can conclude that with increase in N performance can be improved at lower SNR also but with no noise uncertainty criterion.

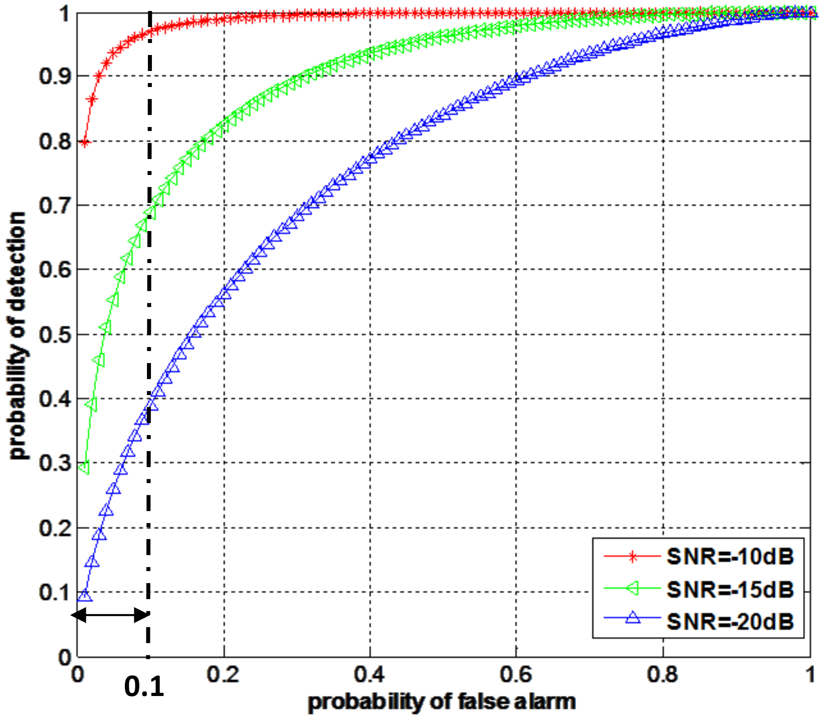

FIGURE 3-5: RECEIVER OPERATING CHARACTERISTIC FOR MFD: N=1000, P_f=0:0.01:1, VARYING SNR

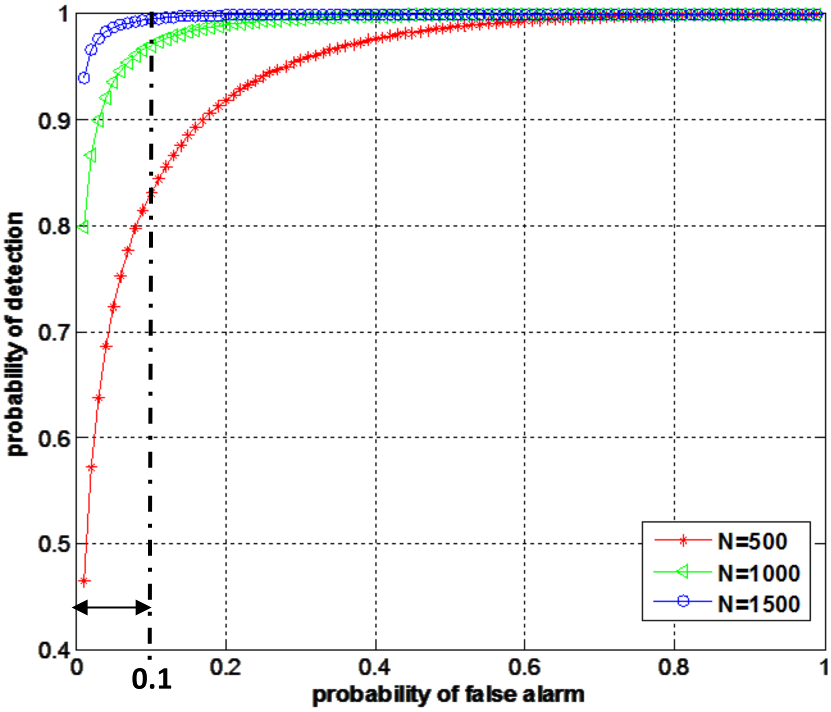

FIGURE 3-6: RECEIVER OPERATING CHARACTERISTIC FOR MFD: N=500, 1000, 1500 P_f=0:0.01:1, SNR=-20dB

3.4.2 Comparison Results for MFD, ED and CFD

Figure 3-7 shows the comparison of the transmitter detection techniques discussed in previous subsections 3.3.1 to 3.3.3. The ROC curves shows that the CFD technique outperforms the other two techniques. The CFD curve attains P_d=1.0 at lower P_f, i.e. from 0.2 to 0.25, whereas the other two attains the same from 0.9 to 1. Also at a particular value of false alarm P_f=0.1, P_d values are 0.91, 0.4 and 0.15 for CFD, ED and MFD respectively. It clearly indicates the better performance of CFD over other two techniques.

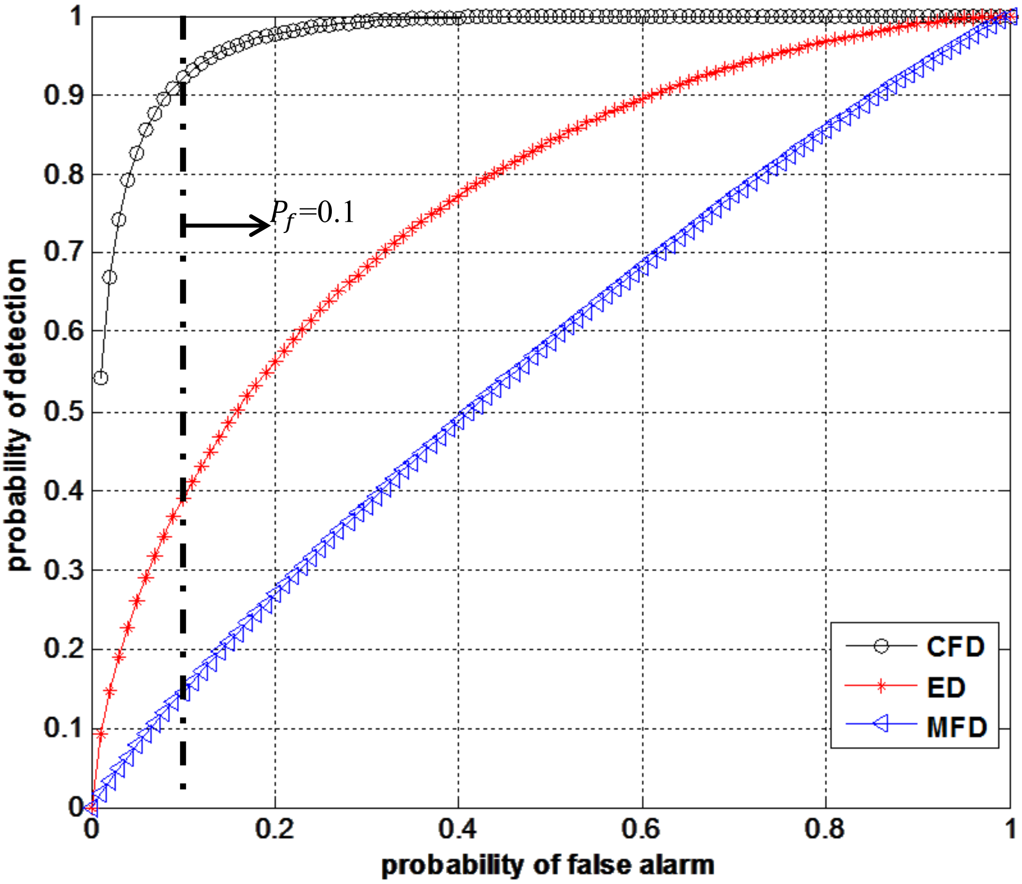

FIGURE 3-7: COMPARISON CURVES FOR MFD, ED AND CFD: N=1000, P_f=0:0.01:1, SNR=-20dB

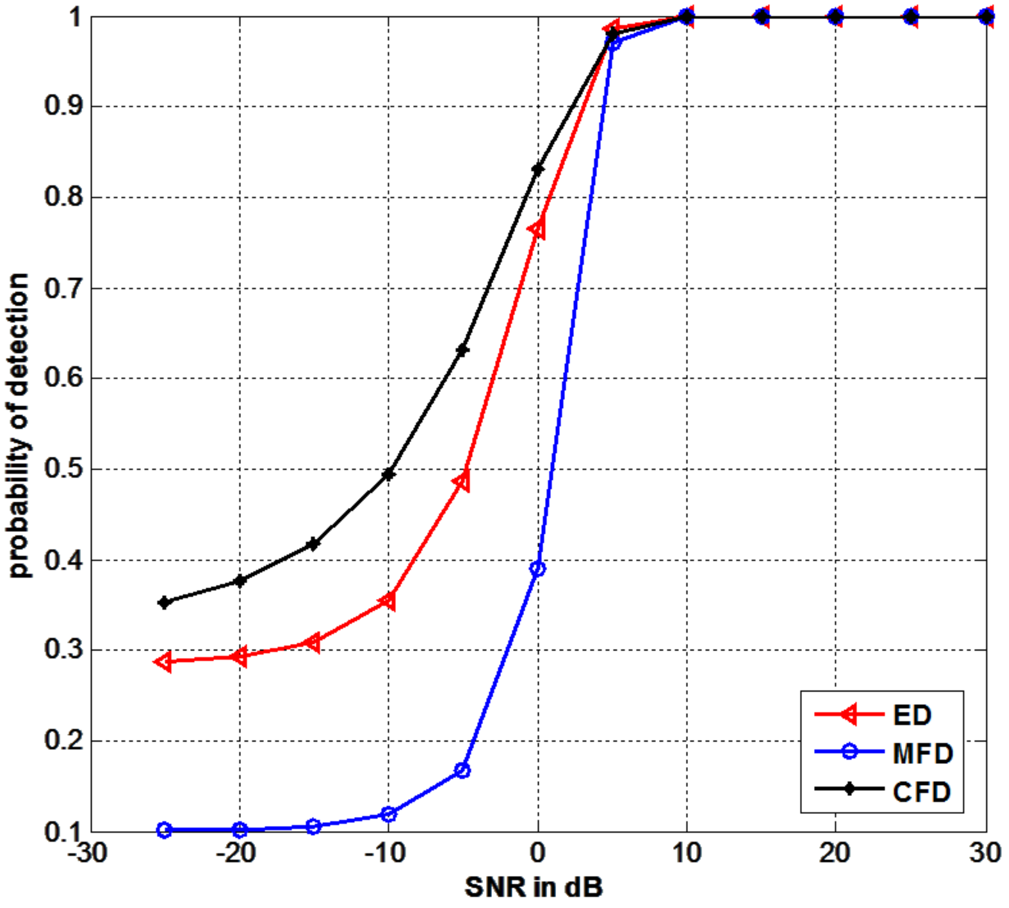

FIGURE 3-8: COMPARISON CURVES FOR MFD, ED AND CFD: N=1000, P_f=0.1, SNR=-30:5:30

In figure 3-8, the value of P_d at SNR=-20 dB are 0, 0.3 and 0.38 for MFD, ED and CFD respectively. After zero dB all techniques achieve $P_d = 1.0$ at approximately same SNR=10 dB, but under lower SNR case the CFD performs better than the other two techniques.

4

NOISE POWER UNCERTAINTY CONSIDERATION

In real-world practical scenario, the communication related parameters cannot be considered to have infinite accuracy. For example, the channel known to be Additive White Gaussian Noise (AWGN), but it is not fully white, neither completely Gaussian nor entirely static, also the Analogue to Digital convertors has some definite precision value. These exemplary uncertainties set an elemental constraint on signal identification performance [20].

Consider a case of the simple detector, which estimates the test statistic and examines it in context with a pre-set threshold value, in order to decide the spectrum occupancy details. Here, the threshold chosen is depended on the ideal scenario. If at all there is minor alteration in channel condition and local noise. The true judgement regarding occupancy may differ well from the forecast. Therefore, focus on the uncertainty is of substantial importance.

The white noise distribution is entirely relying upon its fluctuation of noise power [22]. There are many detection approaches for which it is assumed that the noise power is already known to the receiver side. These methods use this known noise power for calculation of threshold value at particular false alarm value. Nevertheless, the noise power can be vary across the channel at any particular time and geographical region, which bring in the problem of noise uncertainty [20]. As a consequence of noise uncertainty, the exact noise power cannot be retrieved at a specific time and geographic region.

In practical scenario what the receiver (cognitive user) is calculating is the average noise power. If this average noise power is represented as σ^2, and the true noise power is ${\sigma_n}^2$ at a specific time and geographical location then it indicates the presence of noise power uncertainty.

Assuming, $$\sigma^2 = \rho {\sigma_n}^2 \tag{19}$$

Where ρ = noise uncertainty factor (in decibel),

Then the upper limit of this can be given as [20]

$$T = sup\{10 \log_{10} \rho\} \tag{20}$$

Here it is considered that ρ (in decibel) is scattered consistently in the interval [-T, T] [20], [23], [24]. T is called as noise uncertainty limit. Usually, T has the value less than 2 dB for a cognitive user or receiver, and the environmental noise uncertainty is large enough [25]. The noise uncertainty for an energy detection is illustrated in figure 4-1 [20]. The darken region of the diagram indicates the amount of uncertainty in the noise power. Accordingly, it is evident that whenever the test statistic comes under the darken area; the two hypothesis cannot be differentiated. The Noise uncertainty is depicted in below figure:

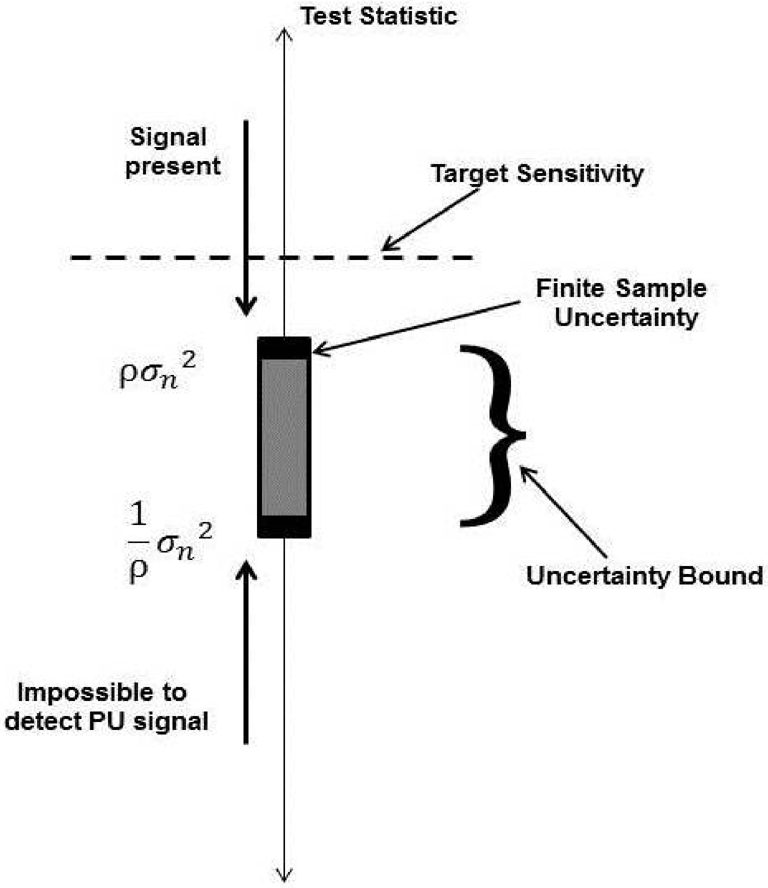

FIGURE 4-1: NOISE UNCERTAINTY DESCRIPTION

The adverse effect of noise uncertainty on the ED and MFD techniques has been discussed and the dynamic threshold implementation for combating its adverse effect is explained in the subsections below. Further, simulation results show the performance improvement for ED and MFD techniques.

4.1 Matched Filter Detection Under Noise Uncertainty and Dynamic Threshold

4.1.1 Noise Uncertainty Consideration for MFD

The discussion in subsection 3.3.1 has been done on the basis of an ideal channel conditions with no noise uncertainty. Now, taking the noise uncertainty in to account the distributional noise uncertainty can be mathematically expressed as [28]:

$$\sigma^2 \epsilon [{\sigma_n}^2/\rho, \rho\, {\sigma_n}^2] \tag{21}$$

Where, ${\sigma_n}^2$ is actual noise power and $\rho > 1$. Noise uncertainty parameter ρ measures the amount of the uncertainty. The probability equations (6) and (7) can be modified under this case as follows:

$$P_d = \min_{\sigma^2 \epsilon [{\sigma_n}^2/\rho,\ \rho\, {\sigma_n}^2]} Q\left(\frac{\lambda - P}{\sqrt{P\sigma^2 / N}}\right)$$

$$P_d = Q\left(\frac{\lambda - P}{\sqrt{P{\sigma_n}^2 / N\rho}}\right) \tag{22}$$

$$P_f = \max_{\sigma^2 \epsilon [{\sigma_n}^2/\rho,\ \rho\, {\sigma_n}^2]} Q\left(\frac{\lambda}{\sqrt{P.\sigma^2 / N}}\right)$$

$$P_f = Q\left(\frac{\lambda}{\sqrt{P\rho{\sigma_n}^2/N}}\right) \tag{23}$$

$$P_m = 1 - P_d = 1 - Q\left(\frac{\lambda - P}{\sqrt{P{\sigma_n}^2/N\rho}}\right) \tag{24}$$

Now, eliminating the threshold value from (22) and (23) we get,

$$P_d = Q\left[\rho . Q^{-1}(P_f) - \sqrt{\rho . N . SNR}\right] \tag{25}$$

$$N = \rho\left[Q^{-1}(P_f) - (Q^{-1}(P_d)/\rho)\right]^2 . (SNR)^{-1} \tag{26}$$

In order to validate the theory simulation has been done in MATLAB 2012a simulator, and the curve for P_f vs P_d has been plotted with N=1000, SNR=-20dB and BPSK modulation.

From figure 4-2, it is noticed that at probability of false alarm$(P_f) = 0.1$, the probability of detection (P_d) values are 0.88, 0.85, 0.8, 0.75 and 0.65 for the noise uncertainty coefficient ρ are 1, 1.5, 2, 2.5, and 3 respectively. Thus, we can deduce that with a slight increase in ρ there is sharp falloff in P_d, so we can say very small change in noise variance will severely deteriorate the detection performance. The plot is in next page.

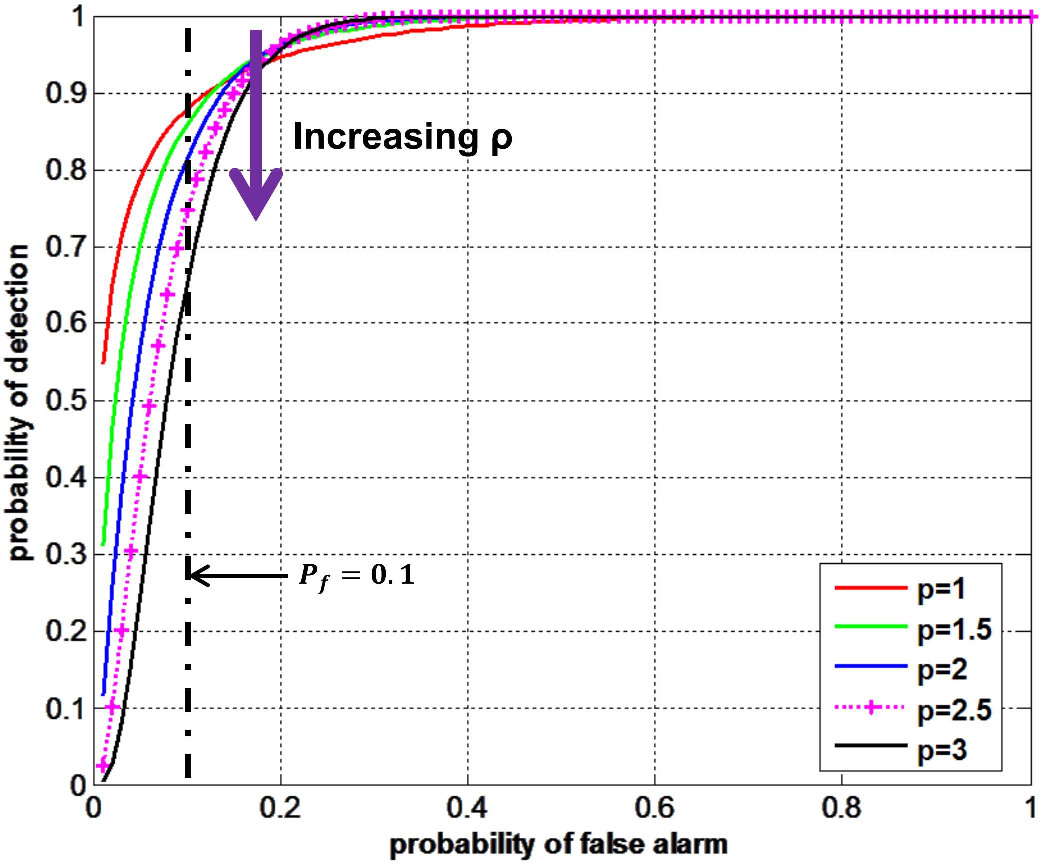

FIGURE 4-2: RECEIVER OPERATING CHARACTERISTIC FOR MFD: N=1000, P_f=0:0.01:1, SNR=-20dB, ρ=1:0.5:3

4.1.2 Dynamic Threshold Implementation for MFD

From figure 4-2 it is clear that the performance of MFD is degraded as noise Uncertainty is increasing. In order to combat the effect of noise uncertainty, *dynamic threshold* is implemented. Considering ρ' as *dynamic threshold factor* and $\rho' > 1$. The distribution of dynamic threshold can be given as follows:

$$\lambda' \in \left[{}^{\lambda}/_{\rho'} \quad ,\rho'\lambda\right] \tag{27}$$

Therefore the equations for detection probability P_d, false alarm probability P_f and miss-detection probability P_m will be modified as follows:

$$P_d = \min_{\lambda' \in \left[\lambda/\rho' \;, \rho'\lambda\right]} Q\left(\frac{\lambda - P}{\sqrt{P{\sigma_n}^2/N}}\right)$$

$$P_d = Q\left(\frac{\frac{\lambda}{\rho'} - P}{\sqrt{P{\sigma_n}^2/N}}\right) \tag{28}$$

$$P_f = \max_{\lambda' \in \left[\lambda/\rho' \;, \rho'\lambda\right]} Q\left(\frac{\lambda}{\sqrt{P{\sigma_n}^2/N}}\right)$$

$$P_f = Q\left(\frac{\rho'\lambda}{\sqrt{P{\sigma_n}^2/N}}\right) \tag{29}$$

Now, eliminating the threshold value from (28) and (29) we get,

$$N = \left[\frac{Q^{-1}(P_f)}{\rho'^2} - Q^{-1}(P_d)\right]^2 (SNR)^{-1} \tag{30}$$

4.1.3 Noise Uncertainty and Dynamic Threshold Implementation for MFD

Here considering the noise uncertainty and dynamic threshold simultaneously, we can define σ^2 as noise variance and λ' as dynamic threshold under this case as:

$$\sigma^2 \epsilon [{\sigma_n}^2/\rho, \rho\, {\sigma_n}^2] \qquad and \qquad \lambda' \in \left[\frac{\lambda}{\rho'}, \rho'\lambda\right]$$

The probability equations will be given as follows:

$$P_d = \underset{\sigma^2 \epsilon [{\sigma_n}^2/\rho, \rho\, {\sigma_n}^2]}{min} \; \underset{{\lambda_2}' \epsilon [\lambda_2/\rho', \rho'\lambda_2]}{min} Q\left(\frac{\lambda' - P}{\sqrt{P\sigma^2/_{N}}}\right)$$

$$P_d = Q\left(\frac{\lambda/\rho' - P}{\sqrt{P{\sigma_n}^2/_{\rho N}}}\right) \tag{31}$$

$$P_f = \underset{\sigma^2 \epsilon [{\sigma_n}^2/\rho, \rho\, {\sigma_n}^2]}{max} \; \underset{{\lambda_1}' \epsilon [\lambda_1/\rho', \rho'\lambda_1]}{max} Q\left(\frac{\lambda'}{\sqrt{P\sigma^2/_{N}}}\right)$$

$$P_f = Q\left(\frac{\rho'\lambda}{\sqrt{P\rho{\sigma_n}^2/_{N}}}\right) \tag{32}$$

$$P_m = 1 - P_d = 1 - Q\left(\frac{\lambda/\rho' - P}{\sqrt{P{\sigma_n}^2/\rho N}}\right) \tag{33}$$

Now, eliminating threshold factor from (31) and (32) we get,

$$N = \frac{1}{\rho}\left[\frac{\rho}{\rho'^2}.Q^{-1}(P_f) - Q^{-1}(P_d)\right]^2 (SNR)^{-1} \tag{34}$$

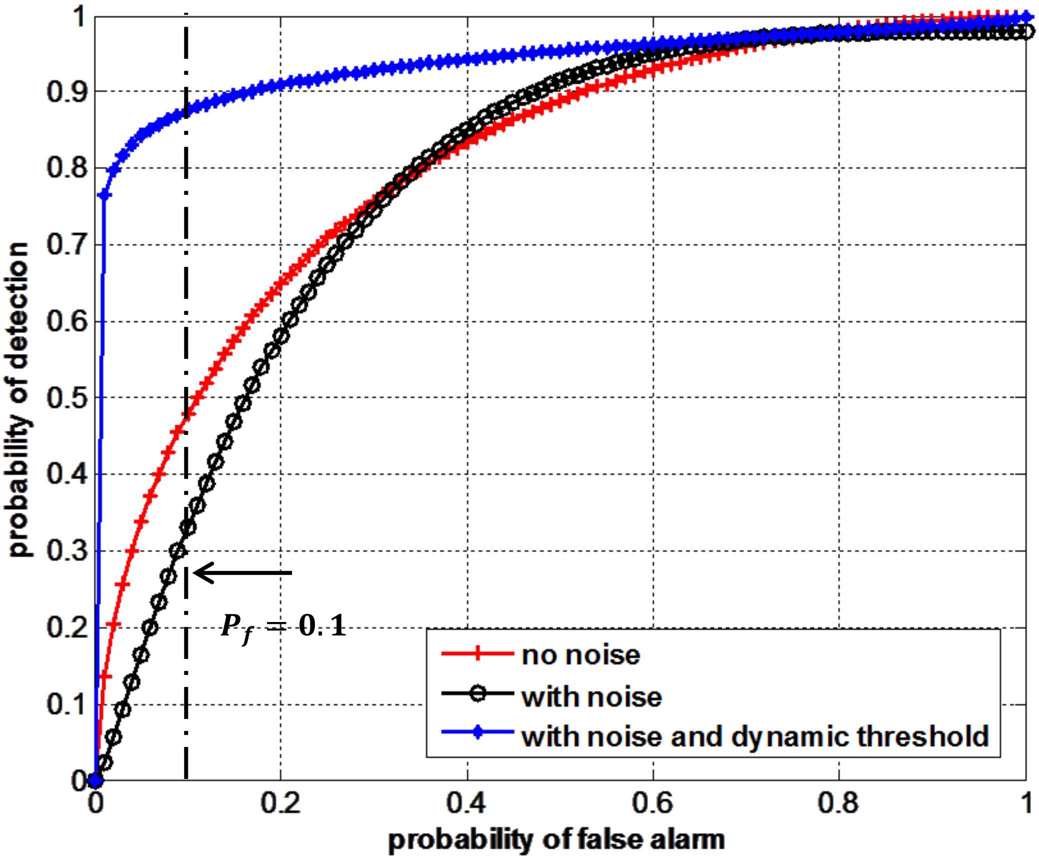

FIGURE 4-3: ROC FOR MFD: N=1000, P_f=0:0.01:1, SNR=-20dB, ρ=1.01, ρ' =1.1

Figure 4-3 shows the results of action taken to reduce the problem of noise uncertainty in MFD technique. The graph has been plotted between P_f vs P_d with N=1000, SNR=-20dB, noise uncertainty coefficient ρ =1.01 and dynamic threshold factor ρ'=1.1 for (31) and (32) in which dynamic threshold coefficient has been implemented. From the graph it is clear that when noise uncertainty has been considered, the performance deteriorates slightly and by using the dynamic threshold the detection performance is increased even under noise uncertainty environment. From the graph, we can deduce that, at $P_f = 0.1$, P_d values are 0.48, 0.35 and 0.88 for conditions without noise uncertainty, with noise uncertainty and with noise uncertainty and dynamic threshold consideration respectively. This indicates that the dynamic threshold improves the performance under noise uncertainty condition.

4.2 ED under Noise Uncertainty and Dynamic Threshold

4.2.1 Noise Uncertainty Consideration for ED

We have already discussed the case of no noise uncertainty for ED method under subsection 3.3.2, now considering the distributional noise uncertainty given as [28]:

$$\sigma^2 \epsilon [{\sigma_n}^2/\rho, \rho\, {\sigma_n}^2]$$

The probability equations (12) and (13) will be modified as:

$$P_d = \min_{\sigma^2 \epsilon [{\sigma_n}^2/\rho,\ \rho\, {\sigma_n}^2]} Q\left(\frac{\lambda - (P + \sigma^2)}{\sqrt{\frac{2}{N}}(P + \sigma^2)}\right)$$

$$P_d = Q\left(\frac{\lambda - (P + {\sigma_n}^2/\rho)}{\sqrt{\frac{2}{N}}(P + {\sigma_n}^2/\rho)}\right) \tag{35}$$

$$P_f = \max_{\sigma^2 \epsilon [{\sigma_n}^2/\rho,\ \rho\, {\sigma_n}^2]} Q\left(\frac{\lambda - \sigma^2}{\sqrt{\frac{2}{N}}\sigma^2}\right)$$

$$P_f = Q\left(\frac{\lambda - \rho{\sigma_n}^2}{\sqrt{\frac{2}{N}}\rho{\sigma_n}^2}\right) \tag{36}$$

Eliminating threshold λ from equation (35) and (36) we get,

$$N = 2\left[\rho Q^{-1}(P_f) - \left(\frac{1}{\rho} - SNR\right)Q^{-1}(P_d)\right]^2 \times \left(SNR - \left(\rho - \frac{1}{\rho}\right)\right)^{-2} \tag{37}$$

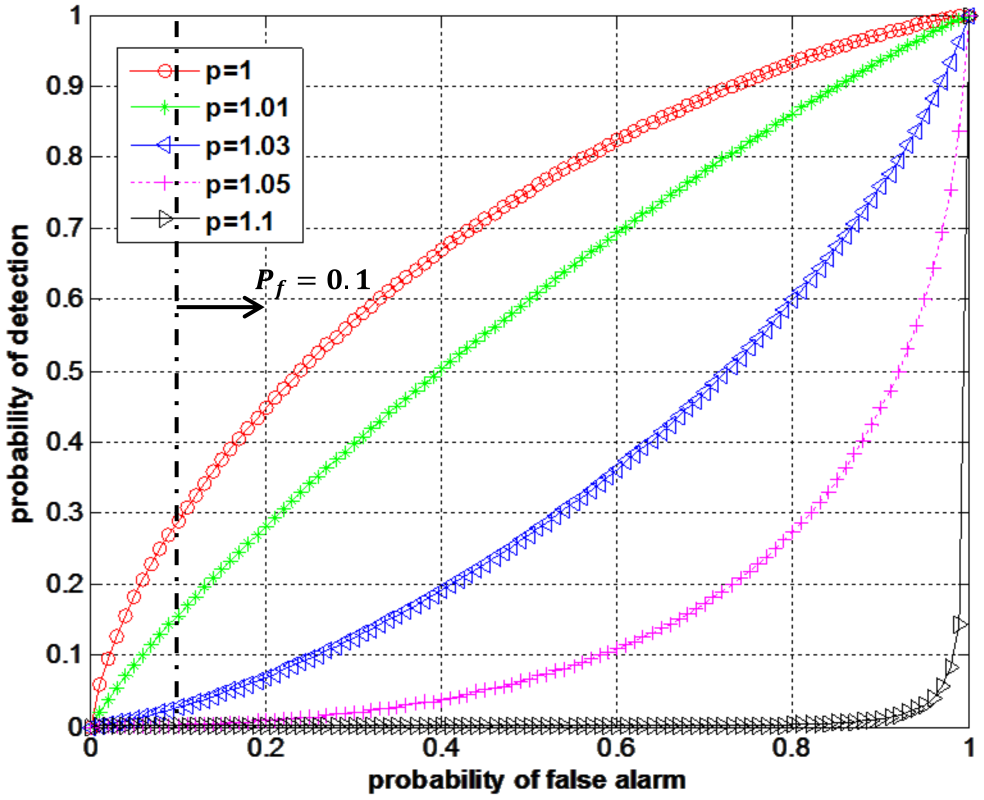

FIGURE 4-4: RECEIVER OPERATING CHARACTERISTIC FOR ED: N=1000, P_f=0:0.01:1, SNR=-20dB, DIFFERENT ρ

From Figure 4-4 it is noticed that at probability of false alarm $P_f = 0.1$, the probability of detection P_d values are 0.58, 0.4, 0.13, 0.02 and 0 for the noise uncertainty coefficient ρ are 1, 1.01, 1.02, 1.03, 1.05 and 1.1 respectively. Thus, we can deduce that with a slight increase in ρ there is sharp falloff in P_d, so we can say very small change in noise variance will severely deteriorate the detection performance. Accordingly, we can say that the ED method is susceptible to noise uncertainty. In order to reduce the adverse effect of noise uncertainty dynamic threshold is implemented in next subsection.

4.2.2 Dynamic Threshold Implementation for ED

The performance of the cognitive radio system is degrading rapidly with increase in noise uncertainty and thus they will cause interference to the Pus. Therefore the dynamic threshold is implemented similarly as in case of MFD.

Considering ρ' as *dynamic threshold factor* and $\rho' > 1$. The distribution of dynamic threshold has been defined in (24):

$$\lambda' \in \left[{}^{\lambda}/_{\rho'} \quad , \rho'\lambda\right]$$

The probability equations (12) and (13) will be modified as:

$$P_d = \underset{\lambda' \in \left[{}^{\lambda}/_{\rho'} \quad , \rho'\lambda\right]}{min} Q\left(\frac{\lambda' - (P + \sigma^2)}{\sqrt{\frac{2}{N}(P + \sigma^2)}}\right)$$

$$P_d = Q\left(\frac{\frac{\lambda}{\rho'} - (P + {\sigma_n}^2)}{\sqrt{\frac{2}{N}(P + {\sigma_n}^2)}}\right) \qquad (38)$$

$$P_f = \underset{\lambda' \in \left[{}^{\lambda}/_{\rho'} \quad , \rho'\lambda\right]}{max} Q\left(\frac{\lambda' - {\sigma_n}^2}{\sqrt{\frac{2}{N}{\sigma_n}^2}}\right)$$

$$P_f = Q\left(\frac{\rho'\lambda - {\sigma_n}^2}{\sqrt{\frac{2}{N}{\sigma_n}^2}}\right) \qquad (39)$$

Eliminating threshold λ from equation (38) and (39) we get,

$$N = 2\left[Q^{-1}(P_f) - \rho'^2(1+SNR)Q^{-1}(P_d)\right]^2 \times \left(\rho'^2 SNR - \left(\rho'^2 - 1\right)\right)^{-2} \tag{40}$$

4.2.3 Noise Uncertainty and Dynamic Threshold consideration for ED

The ED scheme has been explained in context with the noise uncertainty and dynamic threshold separately, now both the cases are simultaneously considered. The noise variance and dynamic threshold is given as in (20) and (24)

$$\sigma^2 \epsilon [{\sigma_n}^2/\rho, \rho\, {\sigma_n}^2]$$

$$\lambda' \in \left[{}^{\lambda}/_{\rho'} \;\; ,\rho'\lambda\right]$$

The probability equations (12) and (13) will be modified as:

$$P_d = \underset{\sigma^2 \epsilon [{\sigma_n}^2/\rho\, ,\rho\, {\sigma_n}^2]}{min}\ \underset{\lambda' \epsilon [\lambda/\rho', \rho'\lambda]}{min} Q\left(\frac{\lambda' - (P+\sigma^2)}{\sqrt{\frac{2}{N}}(P+\sigma^2)}\right)$$

$$P_d = Q\left(\frac{\frac{\lambda}{\rho'} - \left(P + {{\sigma_n}^2}/{\rho}\right)}{\sqrt{\frac{2}{N}\left(P + {{\sigma_n}^2}/{\rho}\right)}}\right) \tag{41}$$

$$P_f = \underset{\sigma^2 \epsilon [{\sigma_n}^2/\rho, \rho\, {\sigma_n}^2]}{max}\ \underset{\lambda' \epsilon [\lambda/\rho', \rho'\lambda]}{max} Q\left(\frac{\lambda' - \sigma^2}{\sqrt{\frac{2}{N}}\sigma^2}\right)$$

$$P_f = Q\left(\frac{\rho'\lambda - \rho{\sigma_n}^2}{\sqrt{\frac{2}{N}}\rho{\sigma_n}^2}\right) \tag{42}$$

Eliminating threshold λ from equation (41) and (42) we get,

$$N = 2\left[\frac{\rho}{\rho'}Q^{-1}(P_f) - \rho'\left(\frac{1}{\rho} + SNR\right)Q^{-1}(P_d)\right]^2 \times \left(\rho' SNR - \frac{\rho}{\rho'} + \frac{\rho'}{\rho}\right)^{-2} \tag{43}$$

Eliminating threshold λ from equation (12) and (13) under no noise case we get,

$$N = 2\left[Q^{-1}(P_f) - Q^{-1}(P_d)(1 + SNR)\right]^2 (SNR)^{-2} \tag{44}$$

On examining (37) and (44) the total expression contributes nothing if ρ value is very small. In addition the terms $(SNR)^{-2}$ and $\left(SNR - \left(\rho - \frac{1}{\rho}\right)\right)^{-2}$ will have greater impact on expression. Considering $\rho = 1$,

$$(SNR)^{-2} \approx \left(SNR - \left(\rho - \frac{1}{\rho}\right)\right)^{-2}$$

But if ρ is slightly greater than 1, $\rho = 1.1$ then $\left(\rho - \frac{1}{\rho}\right) = 0.1909 \approx 0.2$

And at SNR=0.1 (-20 dB)

$$\left(SNR - \left(\rho - \frac{1}{\rho}\right)\right)^{-2} = 0.008 \approx (0)^{-2}$$

Therefore for (37) N will tend to infinite i.e. very large detection period, thus a very small variation in ρ causes severe performance degradation, particularly with low SNR value.

Now in (43) case with noise uncertainty and dynamic threshold simultaneously. When $\rho \approx \rho'$ then $\frac{\rho}{\rho'} \approx \frac{\rho'}{\rho} \approx 1$, then

$$(SNR)^{-2} \approx \left(\rho' SNR - \frac{\rho}{\rho'} + \frac{\rho'}{\rho}\right)^{-2}$$

and $$\rho'\left(SNR+\frac{1}{\rho}\right)\approx(1+SNR)$$

Substituting these approximations back in to (43),

$$N\approx 2\left[Q^{-1}\left(P_f\right)-Q^{-1}(P_d)(1+SNR)\right]^2(SNR)^{-2}$$

This is expression under no noise case. Also when ρ' is slightly greater than ρ,then

$$\left(SNR-\left(\rho-\frac{1}{\rho}\right)\right)^{-2}\gg\left(\rho' SNR-\frac{\rho}{\rho'}+\frac{\rho'}{\rho}\right)^{-2}$$

Thus N value is reduced markedly with suitable dynamic factor. And detection period will be shortened. Thus detection performance can be improved with dynamic threshold implementation under noise uncertainty scenario.

Figure 4-5 shows the results of action taken to reduce the problem of noise uncertainty in energy detection technique. The graph has been plotted between probability of false alarm $\left(P_f\right)$ and probability of detection (P_d) with N=1000, SNR=-20dB, noise uncertainty coefficient ρ =1.01 and dynamic threshold factor ρ'=1.1 for (41) and (42) in which dynamic threshold coefficient ρ' has been implemented.

From the graph it is clear that when noise uncertainty has been considered, the performance deteriorates somewhat and by using the dynamic threshold the detection performance is increased even under noise uncertainty environment. From the graph 4-5, we can deduce that, at $P_f = 0.1$, P_d values are 0.3, 0.15 and 0.9 for conditions without noise uncertainty, with noise uncertainty and with noise uncertainty and dynamic threshold consideration. This indicates that the dynamic threshold improves the performance under noise uncertainty condition.

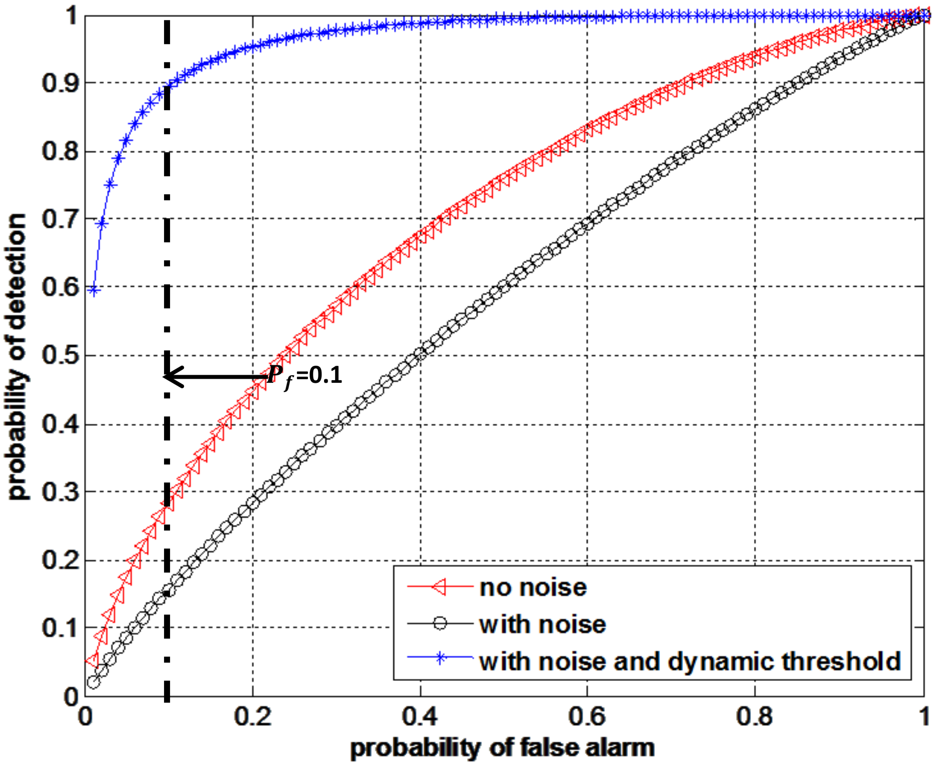

FIGURE 4-5: ROC FOR ED: N=1000, P_f=0:0.01:1, SNR=-20dB, ρ=1.01, ρ' =1.1

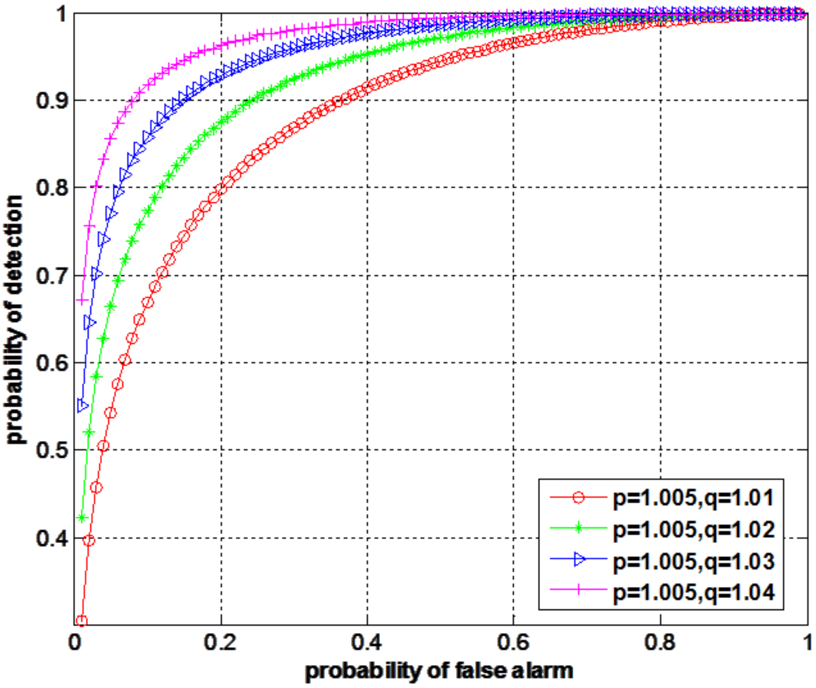

FIGURE 4-6: ROC FOR ED: N=1000, P_f=0:0.01:1, SNR=-20dB, WITH DIFFERENT ρ AND ρ'

Figure 4-6 shows the graph has been plotted between probability of false alarm (P_f) and probability of detection (P_d) with N=1000, SNR=-20dB, at different values of noise uncertainty coefficients (ρ) and dynamic threshold factors (ρ'). From the curve it can be deduced that by keeping ρ at a fix value, and increasing ρ' slightly, we are getting improvement in detection probability. Thus we can say that, if suitable value for dynamic threshold factor will be chosen, the performance can be enhanced even under noise uncertainty environment.

5

PROPOSED DYNAMIC-DOUBLE-THRESHOLD ENERGY DETECTION SCHEME

Spectrum sensing is a basic requirement for cognitive radio networks. To detect the existence of a licensed user in the radio spectrum is an important task for successful implementation of cognitive radio systems in present scenario of spectrum paucity. In this chapter, problem of noise uncertainty is taken in to consideration for the existing energy detection technique, and a solution to the problem is proposed in form of *Dynamic-Double-Threshold Energy Detection Scheme*. This new approach solves the complication of fluctuating noise variance in the wireless channel, as well as improves the detection performance even, under low signal to noise ratio.

From MFD, ED and CFD basic transmitter detection techniques, Energy Detection is generally used because of its low complexity and implementation cost. In ED calculation of the test statistics is much easier than the CFD. The double threshold logic technique is introduced in [26]. Most of the techniques presented on the basis of invariant noise power, whereas in total noise is present due to various factors like quantization, leakage of signals, thermal noise, etc., thus we can say noise is not perfectly Gaussian also not stationary [20]. Thus, under practical scenario we cannot fix the noise variance of received signal which, results in the noise uncertainty condition.

The problem of noise uncertainty is corrected by using the proposed Dynamic-Double-Threshold Energy Detection Scheme. Here we are taking two varying thresholds, which will result in high detection probability, while keeping false alarm probability at fixed lower value as in the case of fixed noise condition. The steps involved in the advancement of the basic energy detection scheme are given below:

5.1 Employing The Double Threshold Logic

The selection of single threshold, inability to detect the spread spectrum signal and inability to differentiate between the interference signal and PU signal under low SNR condition are the main flaws in the case of the existing energy detection scheme. To mitigate these drawbacks the new dynamic-double-threshold scheme has been proposed.

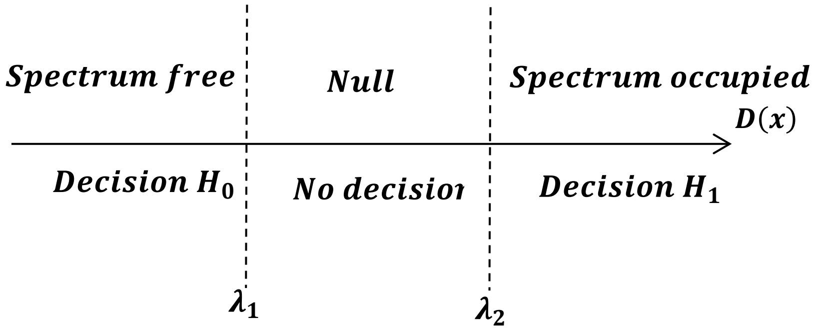

FIGURE 5-1: DOUBLE THRESHOLD BASED SPECTRUM SENSING

In order to improve the reliability of decision double threshold scheme is implemented. The two thresholds λ_1 and λ_2 are illustrated in Figure 5-1. Also, we define:

$$\lambda_2 - \lambda_1 = \Delta\lambda \tag{45}$$

Here, λ_1= lower threshold bound,

λ_2 = upper threshold bound.

Considering this criterion the cognitive terminal with test statics $D(x)$ lies between $\lambda_1$and $\lambda_2$will not be considered and sensing will be performed again. When value of $D(x)$ is greater than the threshold value λ_2 hypothesis H_1 will be declared and when it is less than the threshold value λ_1 hypothesis H_0 will be declared. The probability equation will be modified as follows:

$$P_d = Pr(D(x) > \lambda_2/H_1) = Q\left(\frac{\lambda_2 - (P + {\sigma_n}^2)}{\sqrt{{}^2/_N\,(P + {\sigma_n}^2)}}\right) \tag{46}$$

$$P_f = Pr(D(x) > \lambda_1/H_0) = Q\left(\frac{\lambda_1 - {\sigma_n}^2}{\sqrt{{}^2/_N\,{\sigma_n}^2}}\right) \tag{47}$$

$$P_m = 1 - P_d = 1 - Q\left(\frac{\lambda_2 - (P + {\sigma_n}^2)}{\sqrt{{}^2/_N\,(P + {\sigma_n}^2)}}\right) \tag{48}$$

The performance of this scheme will depend upon value of $\Delta\lambda$. In case if we consider the higher value of $\Delta\lambda$ then the probability that the test statistics will fall in null region is more, resulting in more number of sensing cycles for selection of white spectrum hole, and if we take the lower value, it will result in either miss detection or false alarm. This is illustrated in figure 5-2. Thus Proper value of $\Delta\lambda$ should be chosen for betterment of detection performance.

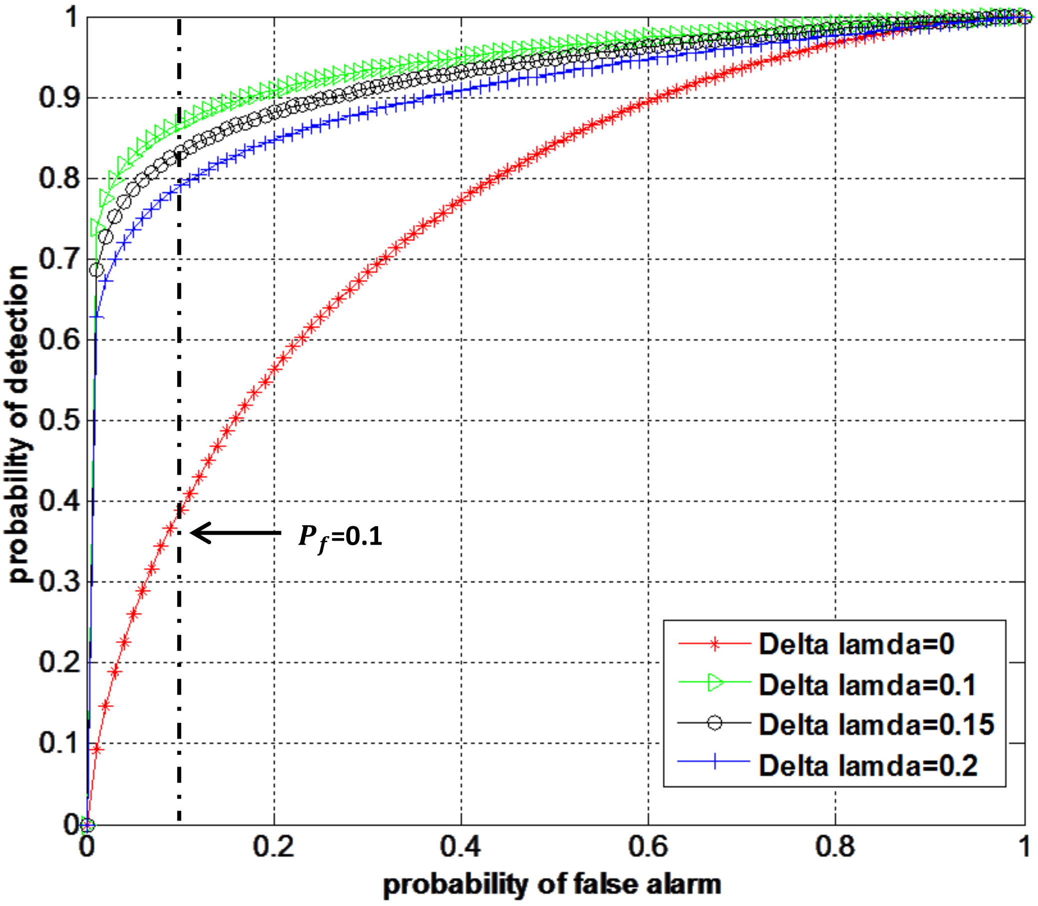

FIGURE 5-2: COMPARISON CURVE FOR DOUBLE THRESHOLD BASED ED SCHEME WITH NO NOISE UNCERTAINTY: $\Delta\lambda = 0, 0.1, 0.15, 0.2$ N=1000, P_f=0:0.01:1, SNR=-20dB

Figure 5-2 shows the numerical receiver operating characteristic (ROC) curves for comparison of the single threshold and double threshold schemes for energy detection technique. The curve has been plotted between probability of false alarm (P_f) and probability of detection (P_d). For P_f value at 0.1 the values for P_d are 0.4, 0.78, 0.82 and 0.88 for single threshold, i.e. $\Delta\lambda = 0$, and $\Delta\lambda$ values 0.2, 0.15, 0.1 respectively. The result shows that at $\Delta\lambda$ equal to 0.1, the proposed scheme performs best among all; it is because as we go on increasing the value of $\Delta\lambda$, the null probability increases and sensing will be performed again. Therefore, appropriate value of $\Delta\lambda$ should be selected for best performance.

5.2 Implementation of Noise Uncertainty Condition and its Impact on Detection Method

The detection performance has been discussed without considering noise uncertainty in to account. Whereas the noise variance is not fixed as the wireless channel is continuously changing. Now, considering a case of varying noise variance as $\sigma^2 \epsilon [{\sigma_n}^2/\rho \,, \rho {\sigma_n}^2]$ [27] [28], where ρ represents the noise uncertainty coefficient and value of ρ is close to 1, i.e. $\rho >$ 1and $\rho \approx 1$. So (46) and (47) will be modified as:

$$P_d = \underset{\sigma^2 \epsilon [{\sigma_n}^2/\rho,\ \rho\,{\sigma_n}^2]}{min} Q\left(\frac{\lambda_2 - (P + \sigma^2)}{\sqrt{{}^2/_N\,(P + \sigma^2)}}\right)$$

$$P_d = Q\left(\frac{\lambda_2 - (P + {\sigma_n}^2/\rho)}{\sqrt{{}^2/_N\,(P + {\sigma_n}^2/\rho)}}\right) \qquad (49)$$

$$P_f = \underset{\sigma^2 \epsilon [{\sigma_n}^2/\rho,\ \rho\,{\sigma_n}^2]}{max} Q\left(\frac{\lambda_1 - \sigma^2}{\sqrt{{}^2/_N\,\sigma^2}}\right)$$

$$P_f = Q\left(\frac{\lambda_1 - \rho{\sigma_n}^2}{\sqrt{{}^2/_N\, \rho{\sigma_n}^2}}\right) \tag{50}$$

$$P_m = 1 - P_d = 1 - Q\left(\frac{\lambda_2 - (P + {\sigma_n}^2/\rho)}{\sqrt{{}^2/_N\, (P + {\sigma_n}^2/\rho)}}\right) \tag{51}$$

5.3 Dynamic-Double-Threshold Energy Detection Scheme

It can be seen from Figure 5-2 that the performance is degraded sharply as the noise uncertainty coefficient is increasing, which results in severe interferences to the licensed terminals. In order to contend this problem the dynamic threshold scheme is implemented. ρ' is the dynamic threshold factor and it is closer to 1 i.e. $\rho' > 1$. The limits for dynamic-double-threshold can be defined as [27] [28]:

$$\begin{cases} {\lambda_1}' \epsilon [\lambda_1/\rho',\ \rho'\lambda_1] \\ {\lambda_2}' \epsilon [\lambda_2/\rho',\ \rho'\lambda_2] \end{cases} \tag{52}$$

While, considering dynamic-double-threshold under noise uncertainty, (49) and (50) will be modified as:

$$P_d = \min_{\sigma^2 \epsilon [{\sigma_n}^2/\rho,\, \rho\, {\sigma_n}^2]}\ \min_{{\lambda_2}' \epsilon [\lambda_2/\rho',\, \rho'\lambda_2]} \left(\frac{{\lambda_2}' - (P + \sigma^2)}{\sqrt{{}^2/_N\, (P + \sigma^2)}}\right)$$

$$P_d = Q\left(\frac{\lambda_2/\rho' - (P + {\sigma_n}^2/\rho)}{\sqrt{{}^2\!/_N\,(P + {\sigma_n}^2/\rho)}}\right) \tag{53}$$

$$P_f = \underset{\sigma^2 \epsilon [{\sigma_n}^2/\rho,\, \rho\, {\sigma_n}^2]}{max}\ \underset{{\lambda_1}' \epsilon [\lambda_1/\rho',\, \rho' \lambda_1]}{max}\ Q\left(\frac{{\lambda_1}' - \sigma^2}{\sqrt{{}^2\!/_N\, \sigma^2}}\right)$$

$$P_f = Q\left(\frac{\rho' \lambda_1 - \rho {\sigma_n}^2}{\sqrt{{}^2\!/_N\, \rho {\sigma_n}^2}}\right) \tag{54}$$

$$P_m = 1 - P_d = 1 - Q\left(\frac{\lambda_2/\rho' - (P + {\sigma_n}^2/\rho)}{\sqrt{{}^2\!/_N \cdot (P + {\sigma_n}^2/\rho)}}\right) \tag{55}$$

These equations show that the dynamic-double threshold scheme is main idea to deal with the noise uncertainty issue. Here, unlike the traditional dynamic threshold scheme [28], the dynamic factor is associated with both the upper and lower bounds of the two thresholds in (53) and (54), which causes the performance enhancement [27].

Figure 5-3 shows the results of action taken to reduce the problem of noise uncertainty in sensing technique. The graph has been plotted between (P_f) and (P_d) for (53) and (54) in which dynamic-double-threshold scheme is proposed. From the graph we can deduce that at $P_f = 0.1$, P_d values are 0.69, 0.66 and 0.88 for conditions without noise uncertainty, with noise uncertainty and with the proposed dynamic-double-threshold scheme. This indicates that the proposed scheme improves the performance under noise uncertainty condition.

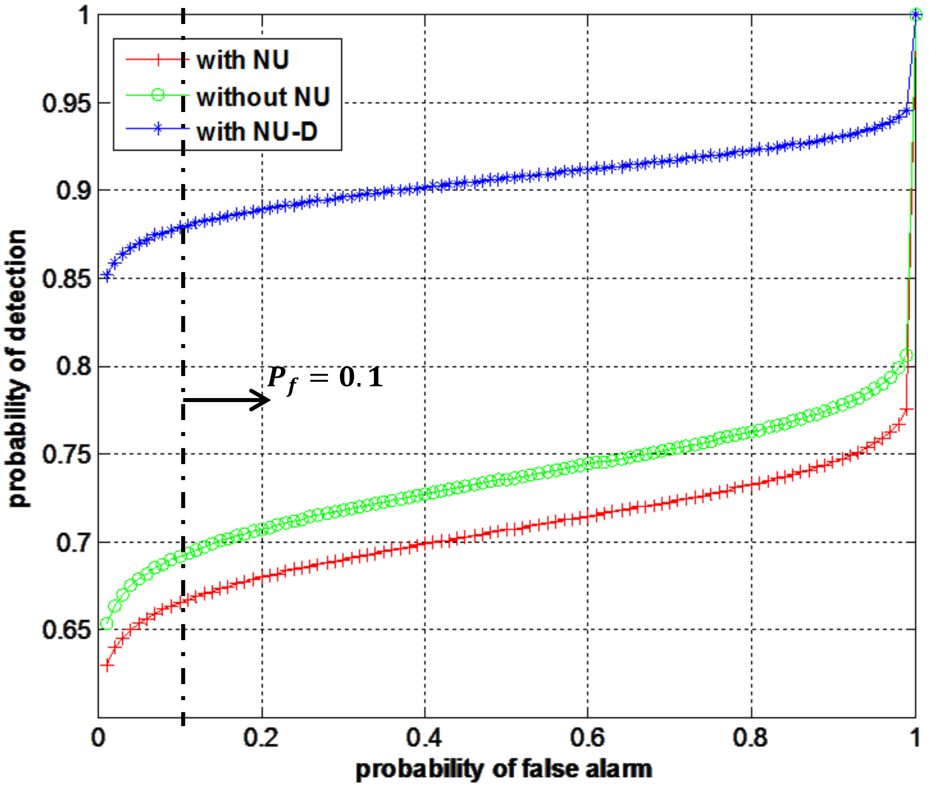

FIGURE 5-3: ROC CURVE FOR DYNAMIC DOUBLE THRESHOLD ED SCHEME WITH NOISE UNCERTAINTY: N=1000, P_f=0:0.01:1, SNR=20dB

Figure 5-4 compares the single threshold and proposed dynamic-double-threshold scheme under these three conditions:

i) Without considering noise uncertainty

ii) Considering noise uncertainty

iii) With noise uncertainty and dynamic threshold

Here NU^* represents noise uncertainty under double threshold scheme, $NU - D^*$ represents noise uncertainty under proposed dynamic-double-threshold scheme and NU represents noise uncertainty under the single threshold scheme. The curves are plotted between the false alarm probabilities and detection probability, with N=1000, and SNR=-20 dB. BPSK signal of a random bit stream is assumed to be the PU signal.

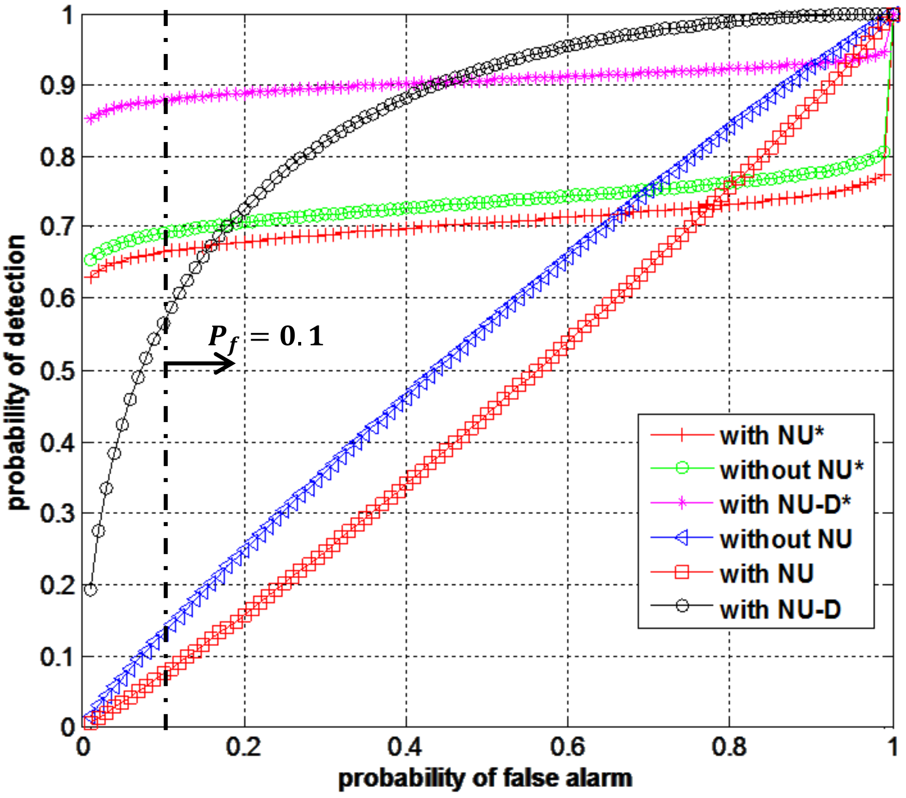

FIGURE 5-4: COMPARISON OF ENERGY DETECTION FOR SINGLE THRESHOLD AND PROPOSED SCHEME WITH NOISE UNCERTAINTY CONSIDERATION.: N=1000, P_f=0:0.01:1, SNR= -20dB

From the result, we can deduce that under our proposed scheme, at $P_f = 0.1$, P_d values are 0.89 and 0.6 for single threshold and proposed scheme considering noise uncertainty. It clearly indicates the performance improvement.

The figure 5-5 shows the comparison curve of proposed scheme with the existing three transmitter detection techniques named ED, MFD and CFD. The improvement in the detection performance is clearly visible from the graph; at lower probability of false alarm. The proposed scheme is the modified form of energy detection method with noise uncertainty environment. From the graph, we can deduce that the proposed dynamic-double-threshold energy detection scheme (DDTED) is best among ED, MFD and CFD. In terms of numerical values, at $P_f = 0.1$, the $P_d = 0.89$ for proposed scheme and 0.4, 0.25 and 0.14 for CFD, ED and MFD respectively. Thus the proposed technique outperforms the other three.

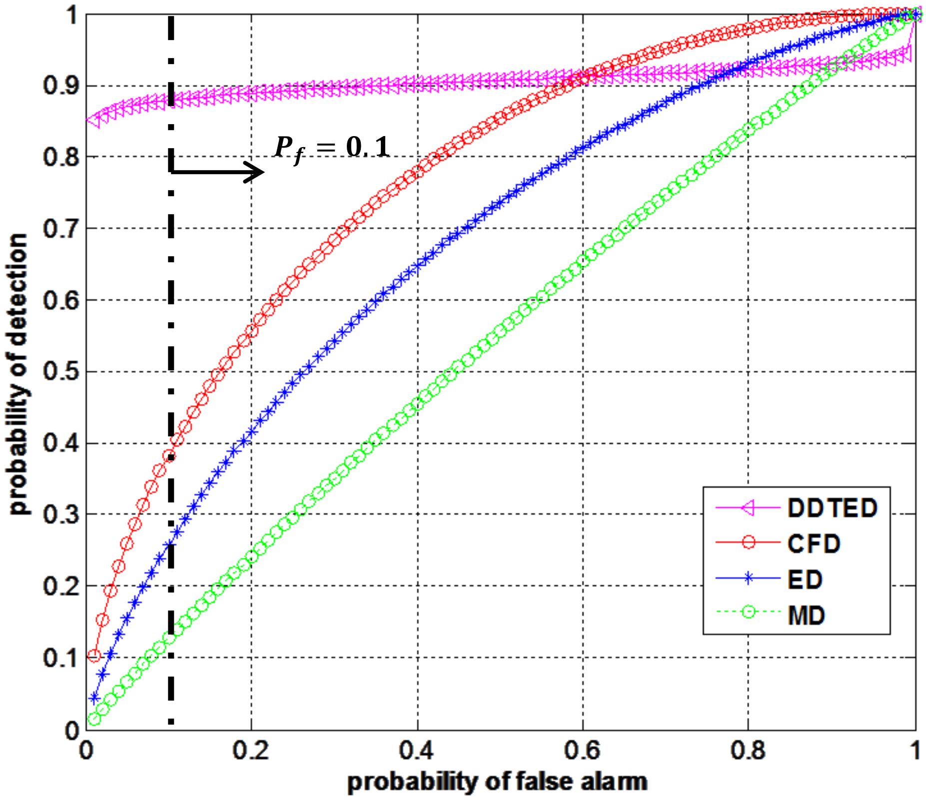

FIGURE 5-5: COMPARISON OF PROPOSED SCHEME WITH ED, MFD AND CFD: N=1000, P_f=0:0.01:1, SNR= -20dB

From the above discussion on the numerical simulation results it is observed that the proposed scheme is performing better under noise uncertainty. Also it outperforms the ED, MFD and CFD techniques.

6

CONCLUSION

6.1 Conclusion

The most remarkable technology in use in the modern wireless industry is cognitive radio indeed. All the emerging technology is using CR for its entire system or as a supporting system. Accordingly, all the systems have to deal with the primitive demand of spectrum sensing in CR. There are numerous techniques, which have been implemented to check the spectrum occupancy details of the underutilized licenced spectrum bands. The thesis explores the three basic spectrum sensing techniques with their benefits and lacunas, and their performance have been analysed under noise uncertain environment. To overcome the effect of uncertain noise power, the dynamic threshold implementation has been done on the transmitter detection techniques.

The fixed frequency allocation strategy is the main problem of spectrum utilization, which results in spectrum shortage. The concept of cognitive radio sorts out this difficulty up to some extent. The spectrum sensing techniques has been discussed and it is observed that the cyclostationary feature detection technique outperforms the ED and MFD techniques. From simulation results it is clear that the performance improves with more number of samples during certain detection period even at low SNR value.

The adverse effect of noise power uncertainty on the ED and MFD techniques has been explained. The detection performance can be improved with implementation of the dynamic threshold concept. The simulation results in chapter 4 shows that the, performance of the ED scheme is degraded with increasing noise uncertainty; at P_f =0.1, the P_d values are 0.58, 0.4, 0.13, 0.02 and 0 for noise uncertainty factor 1, 1.01, 1.02, 1.03, 1.05 and 1.1 respectively figure 4-4. The dynamic threshold coefficient is implemented and it gives the performance improvement from 0.08 to 0.58 under noise uncertainty consideration and noise uncertainty and dynamic threshold implementation. From the numerical analysis done in the chapter 4, it is concluded that the detection performance and the number of samples becoming very large which is not feasible in practical scenario considering noise uncertainty and the introduction of dynamic threshold results in reduced N value, which is achievable.

The energy detection technique has been used amongst the basic transmitter detection techniques because of its less intricacy and implementation cost. This method is very much susceptible towards the noise uncertainty problem due to varying channel condition and also systems noise. This dissertation proposed dynamic-double-threshold energy detection scheme in order to lessen the effect of varying noise uncertainty and it performs better even under low signal-to-noise ratio (SNR) condition.

The proposed technique has been simulated, and the graphs have been plotted between the probabilities of false alarm vs probability of detection. A comparison has been done among the four and it has been clearly visualized that the proposed technique gives detection probability 0.89 at probability of false alarm 0.1, which is far better than the MFD CFD and ED schemes.

6.2 Limitation and Future Work

In this thesis the theoretical analysis supported by mathematical derivation has been carried out. For simulation assumption has been made for the PU signal that the random bit stream is converted in to a BPSK signal, and simulation study considering the real spectrum data or in real environment has not been attempted.

Validation using Monte Carlo simulation for practical scenario will further enhance the applicability of the proposed scheme. New technique like adaptive threshold can be used to further improvise the detection performance.

DISSEMINATION:

- Sonam Shrivastava, Ravi Tiwari and Susmita Das, **“Comparative Performance Evaluation of a New Dynamic-Double-Threshold Energy Detection Scheme with Basic Spectrum Sensing Techniques,”** *IEEE International Conference on Green Computing, Communication and Electrical Energy (ICGCCEE’14),* Coimbatore 6th - 8th march 2014.
- Sonam Shrivastava, Ravi Tiwari and Susmita Das, **“A Novel Dynamic-Double-Threshold Energy Detection Scheme under Noise Uncertainty Environment in Cognitive Radio System,”** *IEEE International Conferences for Convergence of Technology*, Pune, 6th - 8th April 2014. doi 978-1-4799-3759-2/14/.

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