ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

Performance Enhancement of Spectrum Detection Using Hybrid of Energy and Matched filter Detection Algorithms in Cognitive Radio

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Declaration

I, the one signed below, announce that the thesis is my own work, has not been done to get degree here or other university, and a full acknowledgement has been given for the sources and materials that I used during my work.

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This thesis has been submitted for examination with my approval as a university advisor.

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Abstract

Nowadays, there has been an increase in wireless technologies, which are used for variety of applications and services. The need of using wireless services and applications also increased from day to day that brings a higher demand on radio spectrum leading to shortage and congestion. In addition, the fixed assigning of a radio spectrum to a specific user leads to under-usage of available spectrum which brings wastage of spectrum. After several studies, cognitive radio exists to minimize problems regarding to the limited and wasted spectrum resource. This technology, cognitive radio searches a free or unused portion of spectrum and enables secondary users to access that free part of spectrum.

Spectrum sensing methods are very important in cognitive radio for detecting the availability of unused spectrum and allow secondary users to use the spectrum band in non-interference manner. Energy and matched filter detector are the most common type of transmitter detection techniques to detect the user. Even though energy detector used most of the time, its performance of detection poorly decrease and degraded at weak received SNR and noise uncertainty scenario. Beside of this, matched filter detector is an alternative and good sensing algorithm in lower SNR value, since it enlarges SNR of the signal received and gives a better performance compared to energy detection.

This thesis aims to develop an efficient hybrid detection technique, by combining energy with matched filter detector to enhance energy detector at low SNR value in specific, and improve spectrum detection performance in general. The performance of proposed hybrid detector with conventional energy detector and other hybrid detection technique is analyzed and compared. Receivers operating curve (ROC), false alarm probability, detection probability and SNR values are the basic performance evaluation matrices. MATLAB software has been used to evaluate the performance of detection technique. In simulation result, the detection performance has been evaluated based on the plotting Pd vs Pf, Pd vs SNR, Pmd vs SNR and Pd vs noise uncertainty for both fading and non-fading channel model which are Rayleigh and AWGN channel respectively. From the result obtained, the proposed hybrid detection performs better than energy detection and other hybrid detection under AWGN and Rayleigh fading channel. The proposed hybrid detection enables to reduce the effect of noise uncertainty and fading on detection performance.

Key Words: ***Spectrum sensing, Cognitive radio, Energy detector, Matched Filter Detector, Fading Channel, Primary user, ROC.***

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List of Abbreviations

AWGN: Additive white Gaussian noise.
ADC: Analog to Digital Converter.
BPF: Band Pass Filter
BWRC: Berkeley Wireless Research Centre
CR: Cognitive Radio
DSA - Dynamic Spectrum Access
DFT: Discreet Fourier Transform
ED: Energy Detection
FC: Fusion Center
FCC: Federal Communication commission of USA.
FFT: Fast Fourier Transform.
FSA - Fixed Spectrum Allocation
Ho: The absences of PU signal.
H1: The presence of PU in the system
Pd: Correct detection Probability
Pfa: False alarm detection Probability
Pmd : Missed Detection Probability
PDF : Probability Density Function
PU: Primary User
ROC: Receiver Operative Curve
RF : Radio Frequency
SNR: Signal to Noise Ratio
SPTF : Spectrum Policy Task Force
SU: Secondary User

List of Symbols

B: Bandwidth of signal

δ_w^2 : Noise variance

λ : Threshold value.

r(t): Received signal

Y(t): Input signal

H_1 The presence of PU in the channel

H_0 : No PU is available

T (x): Test statistics of the detector

$P(H_0|H_0)$: Probability of non-detection

$P(H_1|H_1)$: Probability of correct detection

$P(H_1|H_0)$: Probability of false detection

$P(H_0|H_1)$: Probability of miss detection

$s(n)$: Prior known signal

R_x () : autocorrelation

E [.] : Expectation value signal

w_c : Angular frequency

$R_x{}^{\alpha}$: Cyclic auto correlation

Kα: Bin of the index frequency

$n_i\ (t)$: Matched noise component

x_{2d}^2 : Distribution of central chi-square

$\Gamma(\,.\,)$: Function of modified gamma

$Q_d(x, y)$: Marcum-Q function

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Chapter One : Introduction

1.1 Background

Wireless communications have been significantly increasing from day to day. Due to the increment of this wireless communication systems, different wireless services and technologies which includes mobile communications, different medical usage, marine communication, remote controlling device and wireless internets come in to existence. Accordingly, wireless communications are highly reliant on radio frequency spectrum which was allocated by government bodies. Therefore, when the amount of services that can be provided by wireless communication is further increased, the demand for accessing the spectrum also increased accordingly. Obviously, with the development of new wireless applications and services, spectrum resources are facing higher demands and this demand of spectrum brings a lot of challenge and congestion on radio spectrum which is a limited resource. Moreover to the higher claim for radio spectrum, the traditional static or fixed allocation of spectrum is another big challenge to the existed wireless communication.

From different studies it is observed that the radio frequency band is not used all the time which means some of the spectrums in frequency band are highly free or the bands, radio spectrum are partially used and the others part of frequency may be largely used. Due to this scenario there exists improper usage of radio spectrum. Since spectrum is a limited and congested resource it must be utilized in efficient and proper manner. Therefore two basic problems are challenging the present wireless communication technology one is the shortage of radio spectrum and the second one is under-usage due to fixed allotment of spectrum and this leads to a lowered level of user satisfaction. In order to overcome and combat these problems an innovative and best solution comes in to existence which is the cognitive radio. Cognitive radio (CR) is a kind of wireless communication that enhances the spectrum utilization by allowing secondary client to use the spectrum band when the primary or licensed users are inactive in a non-interfering manner [1]. It is good solution to alleviate and minimize the under usage and congestion of the limited radio spectrum band.

For the effectiveness of CR, spectrum sensing mechanisms are the most essential scenario for the sake of detecting the unused spectrum band and minimizing interference with the authorized user. When the licensed user left the channel secondary user will occupy the band but if the authorized users are available on the spectrum band secondary user shall continuously sense the spectrum to avoid interference. So it is essential to apply good spectrum sensing methods to avoid interference between users and minimize under-usage or wastage of spectrum in cognitive radio.

The free portion of radio spectrum in cognitive radio is said to be spectrum hole where by the secondary user is going to access that part. But in order to identify this free or unused portion spectrum sensing techniques play an important role even to avoid interference with the authorized user. The opportunity of spectrum hole or unused spectrum will exists in time, frequency and geographical location [2] for unlicensed users, all the frequency spectrum are not used all the time. The dynamic spectrum access enables the radio spectrum to be shared among the secondary and primary users so that under-usage of free spectrum will be minimized. Detecting the usage of available frequency channel in the territory of time will identify unused time channel for opportunistic usages. The following figure shows spectrum opportunity scenario.

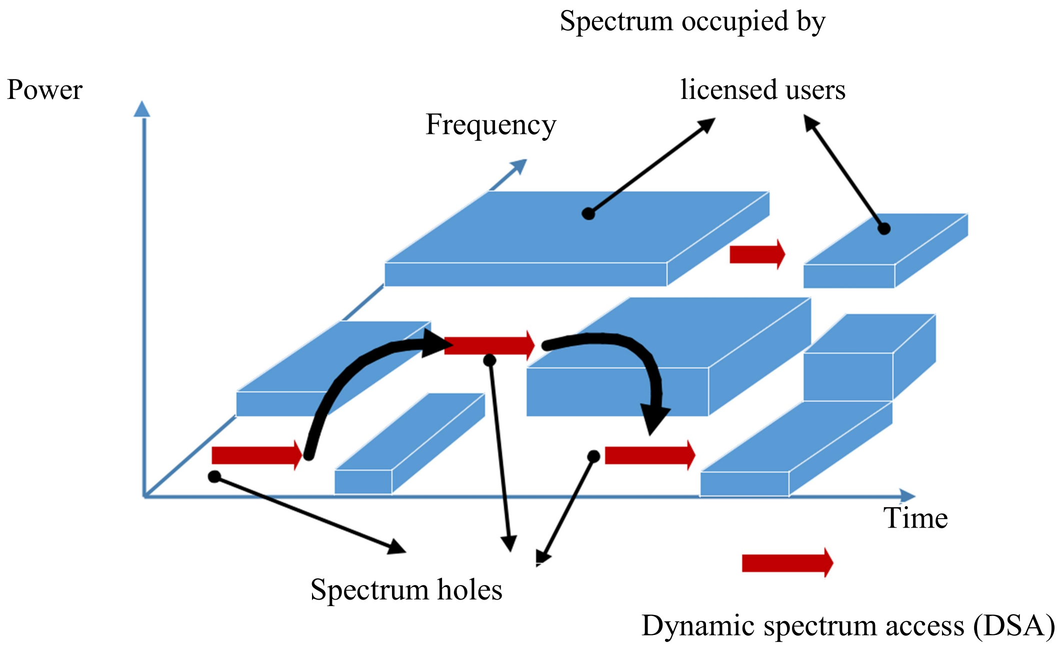

Figure 1.1: Spectrum holes and spectrum in use [3].

Spectrum opportunity is a free portion at a band of radio spectrum in which the bands are not utilized or occupied by the authorized users in a particular interval of time at a particular location of geography. In this case, in opportunity of spectrum, three basic dimension of radio spectrum including, time, frequency and space will be exploited. In case, there will be an occasion or chance of spectrum in frequency domain at a particular time regarding to geographical area and distance of licensed users. In addition at a certain interval of time, the primary user may not use the licensed band. So by using these two opportunities which are spectrum opportunity in time and opportunity in frequency, secondary user can access the unused spectrum band at a minimum level of interference. Since primary user may unfortunately send their information to occupy the band in this scenario the secondary user should leave the spectrum band with no interference. To do so spectrum sensing mechanisms are crucial.

The existence of cognitive radio is aimed at two critical objectives the first one is to improve the exploitation radio spectrum and the second is to accomplish the existed wireless communication reliability and efficiency. By using spectrum sensing methods secondary user will gather some information about the target frequency band including the authorized user activity if they are in the band or not. Many spectrum sensing mechanisms are applied to identify the unused portion of radio frequency which includes energy, matched filter, cyclostationary and eigenvalue based detection.

In this thesis work hybrid spectrum detection by combining energy with matched filter detection mechanism have been done as part of thesis work for a better spectrum sensing and interference minimization. Since energy detector performance at smaller received signal to noise ratio get degrades besides to this matched filter detector is good at detecting at smaller SNR so that combining the two detectors (Energy with matched filter detector) will create good detector. Noise uncertainty effect on spectrum detection performance has been analyzed and performed. Simulation analyses were done for both fading and non-fading channels which are Rayleigh and additive white Gaussian noise (AWGN) channels respectively.

1.2 Problem Statement

Recent advancements and growth in the technology of wireless communication have brought congestion on radio spectrum due to the increasing demand for spectrum. The existing permanent allotment of a frequency spectrum to a particular user has led to underutilization of available spectrum and also there is inefficient usage of radio spectrum since primary users don't occupy the spectrum permanently. In cognitive radio, spectrum sensing techniques are very crucial and important to identify the free spectrum band and check activeness of licensed user on the band. If the primary users are not properly detected, there exist an interference with them or secondary user will miss the opportunity of vacant spectrum.

Among the common spectrum sensing techniques, energy detector is the most common spectrum sensing algorithms with lower implementation and cost value. A lower value of signal-to-noise ratio (SNR) at the secondary receivers and presence of fading, which causes the received signal power to fluctuate dramatically, are the basic factors of spectrum sensing algorithm. When the received SNR is too low energy detector performance will be degraded and the detector will face a challenge to identify the signal from noise. Matched filter detector is another type of spectrum detection which maximizes and enlarges the SNR received at the unlicensed user in a noisy environment. To minimize the problem of energy detector and enhance its detection performance at low SNR region and fading environment, this thesis work proposed hybrid of matched filter detector and energy detection techniques.

1.3. Motivation

In the current scenario, wireless technology has been the fastest growing area in which several wireless applications and devices have come in to existence. The development of applications in wireless communication has brought the need for very wide spectrum usage. Due to the high demand of spectrum consumption, limitation and under usage of spectrum are the challenges for the modern communication era. According to the report given by the policy of spectrum (SPTF) under the US, Federal Communication Commission (FCC), it has been observed that, some of the bands of radio spectrum are highly engaged whereas some parts of radio frequency bands are either partially used or unoccupied under the specific geographical region [1,2].Researchers have gained a good solution with the idea of opportunistic access of spectrum and cognitive radio to mitigate those scarcity, congestion and wastage of spectrum.

The technology, cognitive radio indeed, introduces an opportunistic utilization of the unoccupied band of spectrum that is not utilized by the licensed user. Spectrum sensing are the most critical part in cognitive radio to remove interference to PU and properly utilize the vacant spectrum. Among the detection technique energy detector is the most common one but have a limitation at detecting smaller SNR, at noisy environment. So the under-usage of the limited spectrum and weak energy detector performance at low SNR are the motivating areas for this thesis. Here hybrid detection by combining energy detection with matched filter detector to enhance spectrum detection performance in general and upgrade energy detector in particularly.

1.4 Literature Review

There are various studies regarding spectrum sensing mechanisms in order to optimize and enhance the use of sparsed radio spectrum in cognitive radio. The studies focused on enhancing the way of spectrum detection techniques. The following papers are some of the reviewed researches to the scope of this thesis and that deals with the general problems in spectrum detection mechanisms.

Originally, energy detection method was done by Urkowitz in [4], where signals and noise variance are assumed to be deterministic and exactly known respectively. The signals in this case passed through a filter and then through a squaring and integrator or sum to compare with the threshold for the identification of user on the band. A binary hypothesis and spectrum detection mechanisms are applied to check the authorized user. Energy detector algorithm is among the common transmitter detection technique that is used in most cases since it is simple to implement. However energy detector performance is lowered and degraded in the area where the received SNR is too small and at noise uncertainty scenario. So to enhance and optimize energy detector performance different researchers try their best to bring a solution. Among the papers the following are the reviewed ones:

The authors in [5] proposed an enhanced spectrum detection mechanisms using hybrid of energy and cyclostastionary sensing algorithms. In this paper two sensing methods, energy and cyclostastionarry techniques are used together to enhance spectrum detection performance at low SNR region. It is known that energy detector gets difficulty to sense in lower received SNR at the receiver. In this case cyclostastionary detector algorithm is used together with energy detector and sensing performance was enhanced and optimized so that there will be a proper utilization of spectrum. They compared the outcome of proposed hybrid sensing methodology with a single energy detector and show an enhancement in performance and detection time. In their work they try to minimize consumption of computational power, sensing time and improve detection speed and error [5].

The paper in [6] presented the combination or hybrid of two sensing techniques, using energy and spectral covariance based detection for improving spectrum sensing and energy detector. It is obvious that energy detector is the popular one, but it becomes suspected in the region where the received SNR is lowered. To overcome such problem the authors in [6] used spectral covariance together with energy detector since it is good in smaller SNR. In the first stage the signal received is detected using energy detector and in the second stage where the signal is too weak spectral covariance detector used. At the end the existence of unused spectrum was detected. In this study the detection time is lowered and spectrum detection performance is enhanced by using hybrid algorithm using energy and spectral covariance techniques.

The paper studied in [7] presents on the SNR enhancement of energy detector algorithm using adaptive wiener filter in cognitive radio. This paper attempts to analyze and compare energy detector performance by inserting adaptive weiner filter in front of energy detector [7]. The mathematical formulas for detection and miss detection probability for AWGN and Rayleigh fading channel models were presented and based on these, various simulations plot were presented for those channels. Generally the insertion of adaptive Weiner filter (RLS filter) on the front end of energy detector has improved the entire performance matrices indicator for energy detector specifically and enhances the performance spectrum detection for secondary user in general.

As discussed and studied in the research paper [8], a hybrid detection method using energy and Eigen value detection for improving spectrum sensing performance in cognitive radio is proposed. For achieving a better sensing mechanism this paper also proposed by combining energy detector with that of Eigen value detection method. The average of higher and lower Eigen value has been used to sense the existence of signal in Eigen value detector (EVD) as discussed in [8]. Probability of false detection is calculated by using a theorem which is based on random matrix theorem. This method overcomes the noise uncertainty problem. In this study the result shows that at low SNR Pd value of hybrid detector is higher, but for energy detector Pd is very low.

The research in [9] presents and proposed an improved energy detection method using double-squaring operation. The authors also discussed energy detector and the way of enhancing model. In this case cubic and double squaring operations are used to improve the performance of conventional energy detector. Instead of using squaring device on energy detection model, they substitute double squaring and cubic device to improve detection probability for different channels including AWGN [9] channel. From this paper we see that the increment false alarm probability improve detection probability alarm but as much as possible false alarm detection must be lowered. For improving energy detection algorithm, the paper in [10] proposed an adaptive threshold based energy detector algorithm. The authors in this paper improve the detection performance at low SNR region. Adaptive threshold is based on detection threshold versus SNR of the primary user received at the sensing node [10]. So the authors used an adaptive threshold rather than double and single threshold values and the simulation result shows that the detection performance of the proposed scheme is much better than the fixed threshold based energy detector at low SNR region.

The paper in [11] discussed about the proposed method of enhancing energy detector algorithm using algebraic method for spectrum sensing mechanisms. This paper deals with the proper utilization of the limited resource which is the radio spectrum and enhancing energy sensing technique at lowered region of SNR. Since the existence of primary user can be shown on the amplitude of spectrum by the presence of critical spike in the occupied frequency band, this method enables to divide occupied bands and unused ones. The detector is based on the algebraic method used for the location of spike [11] for making the detection more effective in a noisy area and the detection model introduces a preprocessing of an algebraic approach to eliminate the effect of noise and enhance the detector performance at lower SNR. In this paper the authors introduced the algebraic preprocessing block as a temporal blind smoother bloc [11] so that no need of any knowledge regarding to noise and signal behavior. The insertion of preprocessing block before energy detector, enhance energy detector performance and this achieves a higher probability of detection in a noisy environment.

As stated in the paper in [12] noise measurement method is proposed for enhancing energy detection. It is clear that energy detector performance is weak for a smaller received SNR and in addition threshold selection is another challenge this is due to that the noise is uncertain. So in this paper the authors select or used a dynamic sensing threshold by measuring the power of noise level existed at the signal received by using a blind technique and their proposed model was implemented and tested using GNU Radio software and USRP units [12]. In this work it has been shown that the use of dynamic threshold based on the measured level of noise present in the received signal in sensing time increases detection probability and decreases false alarm probability compared to a static threshold. The level of noise is measured using a blind mechanism depending on the signal received of the sample covariance matrix of the eigenvalue. In order to split or divide the eigenvalues of the signal and eigenvalues of noise, the total eigenvalue is calculated and a minimum amount of length describing criterion is used.

Another approach as stated in [13] is the use of double threshold for energy detector in the technique of spectrum detection to improve energy detection algorithm. As discussed in this paper, when a single-threshold is used energy detector may bring a harmful interference to the licensed user. In order to alleviate such interference, a double-threshold is used for energy detection algorithm [13]. They add another detection threshold to the traditional single-threshold based energy detector algorithm, and it becomes a double-threshold based energy detector algorithm with two detection thresholds.

In summary it can be said that there are various literatures that are reported and studied regarding the improvement of energy detection algorithms. From the literature there are some gaps including Rayleigh channel model, noise uncertainty consideration and to further improve the performance of detection techniques. Depending on the gaps from the literatures, this thesis work proposed an enhanced hybrid detection technique to improve energy detection at low SNR for Rayleigh channel in the uncertainty of noise. The reason to choice hybrid of energy and matched filter detector is due to the research gap in the literature and has not been done before for fading (Rayleigh) channel and noise uncertainty scenario.

1.5 Objectives

1.5.1 General Objective

- The main objective of this thesis work is to improve and enhance the performance of spectrum detection using hybrid of energy and matched filter detector algorithm.

1.5.2 Specific Objectives

The specific objectives of this study are:

- To develop a hybrid spectrum detection algorithm for enhancement of cognitive radio network.
- To evaluate and analyze the performance of hybrid detection techniques for both non-fading and fading channels which are AWGN and Rayleigh models respectively.
- To study and compare the result of energy detector with proposed hybrid detection algorithms and with other hybrid detection method using detection evaluation metrics.
- To analyze and study the effect of noise uncertainty on spectrum detection performance for energy matched filter detector and for proposed hybrid detectors.

1.6 Methodology

In order to achieve the objectives given above, various literature reviews on cognitive radio and spectrum detection by different authors which help to understand necessary theoretical background for thesis work have been made. Based on the limitation of spectrum detection which is energy detector in fact, a hybrid method of detection, combining energy with matched filter is selected and different evaluation metric is also followed. Mathematical description of the detection techniques is illustrated and a closed form expressions of detection probability for AWGN and Rayleigh channels are described. By analyzing the theoretical and mathematical description for the detection techniques system model and flow chart development has been designed. Simulation results and performance of sensing is evaluated by using Matlab software. Finally, spectrum detection performance will be enhanced using hybrid of energy detection and matched filter detection techniques to detect signal of primary user.

1.7 Scope of the Study

Due to the advancement of wireless technologies and systems, the need of spectrum utilization increased accordingly. As different study shows there is improper use of available spectrum beside of scarcity and congestion of resource. Researchers develop a technology which is called cognitive radio that enable secondary users to access the unused part of spectrum and minimize spectrum scarcity. Thus, to combat shortage of spectrum an attention must be applied on cognitive radio and their performance of spectrum sensing. The study from this thesis contributes to show an improved and enhanced spectrum sensing algorithm which avoids a harmful interference with the licensed users. A detailed discussion and analysis about the proposed hybrid detection, by combining energy and matched filter detector together have been discussed and analyzed. A system that senses the environment and able to detect unused spectrum so that secondary user can access the spectrum in non-interference manner have proposed.

1.8 Thesis Outline

General concept of spectrum sensing and cognitive radio are discussed throughout thesis, and the paper will consists of six different chapters starting with introduction in chapter one. The outline of this thesis has been organized in the following manner: Chapter one deals with an introduction about general thesis concept regarding detection techniques. Chapter two is about cognitive radios overview and theoretical background including brief definition and function. Chapter three provides spectrum sensing for cognitive radio, spectrum sensing model and types of spectrum sensing. Chapter four is about the system model and enhanced spectrum detection flow charts of the hybrid transmitter detection performance evaluation metrix. Chapter five is about results and discussion. At the end chapter six presents conclusion and recommendation for future work.

Chapter Two

Cognitive Radio: An Overview and Theoretical Background

2.1 Overviews

The ultimate growth of wireless services of all types in the area of communication production or manufactory in recent time has been exploiting. Due to the quick growth of those wireless applications, the need for spectrum usage also increased accordingly. So that spectrum shortage is becoming a challenge due to the increasing demand of users for the limited resource that is radio spectrum. Besides to limitation in spectrum there is a wastage or under-usage of the spectrum due to the fixed allotment of spectrum by the owner. Cognitive radio is introduced to face problem of spectrum shortage and under-utilization of radio spectrum. This technology which is cognitive radio in fact, identify an opportunity for the secondary users when the authorized users are inactive through sensing the band.

In cognitive radio the detector is aimed at sensing the spectrum band whether the channels are actively used or not and then it instantly switch or move to another empty channel in order to avoid the busy channel [15]. This system will maximize the use of radio spectrum and also minimizes an interference with other client. The principal objective of CR is extremely faithful communication with authorized and unlicensed users and effective use of spectrum in such a way that wastage and limitation of spectrum will be enhanced accordingly. Allocation of current radio spectrum is modeled based on fixed spectrum allocation (FSA) policy and according to this policy; licensed users are enabled to use the band for a long time [14]. More over this fixed allotment of available radio spectrum will leads to wastage of resources since most portion of the licensed frequency bands are not used properly especially when the authorized users are free of services. In cognitive radio there are two important users one is the primary or licensed user and the second is secondary or unlicensed user. The users who have higher priority for accessing the channel are licensed user and those users who have the right to use the channel only when the authorized users are inactive or leave the channel are said to be secondary users.

The experiment performed by Federal Communication Commission (FCC) shows that those licensed radio spectrum located between the range of 80% and 90% remains under usage which means they are not properly utilized. The recent study from US shows that the spectrum utilization under a fixed spectrum allotment (FSA) is in a range of 15% to 85% [17]. As illustrated in the figure below measurements from FCC shows that some frequency are heavily utilized while others rarely used leading to congestion and wastage of spectrum respectively. So the temporarily unused portion of spectrum bands are said to be spectrum hole which are ready to be accessed by the secondary user. If the unused part or spectrum holes are not used properly it will leads to spectrum wastage. Thus deficiency and under-usage of spectrum management require a quick solution to optimize radio spectrum usage and develop a good network performance by sharing the unused portion of the band with secondary user without interfering the primary users. From several studies, dynamic spectrum usage with cognitive radio is proposed to overcome problems regarding to spectrum allocation and wastage. In contrast with fixed spectrum access, dynamic spectrum access permits spectrum to be shared along primary and secondary users in which the spectrum is partitioned to various bands allotted to one more dedicated users [16]. In order to support opportunistic spectrum access unlicensed user needs to detect or sense radio spectrum availability by using the proper sensing algorithms.

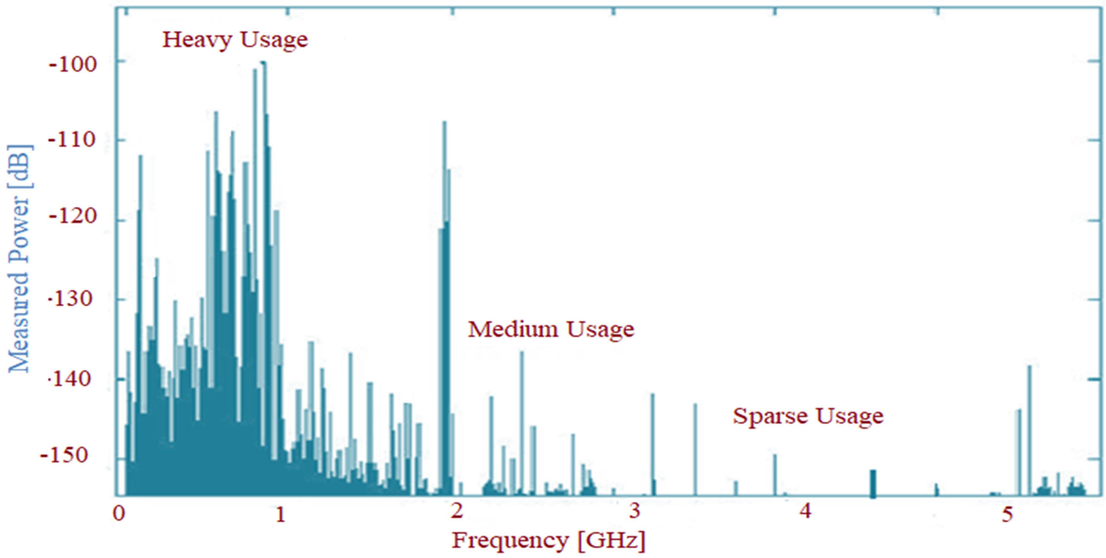

Figure 2.1: Measurement and utilization of radio spectrum at BWRC [16].

Different studies and measurements shows that even though the available spectrum is used highly and become limited, most of the spectrums are not utilized in all time. This statement and measurement can be illustrated as shown in the figure above that is done by Berkeley in urban area. From the charts shown above some spectrums are used hardly and others used in medium manner and the spectrums ranging from 3GHz to 6GHz is not used most of the time. So we can deduce that there exist free portion of radio spectrum to be accessed by secondary user in non-interfering way. In this chapter some brief history regarding to the existence and basic definition of cognitive radio will be presented. In addition, schematic diagram about the architecture of CR followed by functional blocks and cycles has been discussed.

2.2 Definition and Brief History of Cognitive Radio

Cognitive radio is a rising technology, for the proficient utilization of restricted radio spectrum in an opportunistic manner. Nevertheless, as wireless communications are increased the need to use radio spectrum also significantly increased. CR is a smart radio frequency spectrum transmitter technology designed for detecting the available channels in a wireless spectrum and changes the transmission criterion providing more communication and improves radio operating behavior [27]. This technology which is cognitive radio has the ability to make a significant distinction in how we can access the radio spectrum with much enhanced usage. The first person who has proposed the idea cognitive radio was by Joseph Mitola III in a seminar at KTH and the detailed description of cognitive radio is also given in the paper which is written by Mitola III and Gerald Q. Maguire. The meaning of cognitive radio is given in different literature even the time in which the technology come in to existence. Cognitive radio resulted from the combination of different advanced technologies coming to each other to form the technique for the existence of the application so that cognitive radio is not a simple or unique technological system.

A more general definition of cognitive radio is given by Simon Haykin [28].

Cognitive radio is a tangible or smart wireless communication frame work that is notified to its encompassing environment (that is exterior world) and uses the technique of understanding by building to adapt or memorize from the surrounding and adjust its internal state to factual varieties in approaching RF boosts by rolling out related improvements in certain working parameters.

- *Highly faithful communication when it is needed.*
- *Use the limited spectrum effectively.*

Cognitive radio is also defined by Joseph Motila [35] as follows.

Cognitive radio identifies the point at which wireless individual computerized assistants and the related networks are adequately computationally sensible about resources of radio and related computer-to-computer communications to distinguish client communications needs as a work of utilize context, and to supply radio resources and remote services most appropriate to those needs.

The US Federal Communication commission (FCC) in IEEE gives the definition of cognitive radio as [8].

A radio frequency transmitter or receiver that is designed for determining and identification of some part of radio spectrum and check if there is a user on the band and move to another unused spectrum portion quickly with no interference with that of the primary users when data is released.

Cognitive radio technology existed to solve different problems related with radio spectrum limitation by using an opportunistic access of spectrum or searching a free spectrum band and utilizing it and enables to use an interoperable mechanism. From different studies, spectrum allocation is carried out using a fixed allotment scenario so that a portion of radio spectrum allotted to a primary user and this user may not always use all the time. This implies that some part of the spectrum are not always occupied and in this time cognitive radio technology will determine the unused part of spectrum by using spectrum detection technique to allow unauthorized users.

2.3 Functional Blocks and Cycles of Cognitive Radio Networks

The cognitive cycle enable to have a tangible communication between the cognitive radio framework and its environment so it is simply one way of communication between cognitive radio system and its surrounding. The cognitive radio cycle in the figure below shows the processes and how they are related within the surrounding of radio spectrum and the tasks are needed for adapting the operation in open spectrum [11].

In the cycle of CR networks, there are four basic block process. These are consisting of spectrum sensing, spectrum mobility, spectrum management and spectrum sharing. The first step in the cycle is spectrum sensing and checkup the available of the primary users for the aim of identifying the spectrum holes. Spectrum management concerned with the estimation of the time by which the spectrum holes are remained for the utilization by secondary user. Spectrum sharing enables to the fair distribution of unused frequency resource together with secondary user. Spectrum mobility is enables to have fixed communication with the licensed user for a better radio spectrum usage at time of transmission [31].

2.3.1 Spectrum Sensing

The basic aim of spectrum sensing is dealing with the identification of vacant bands and deciding the presence of licensed user on the band and to estimate the spectrum behavior and activity by continuously sensing the targeted frequency band. So spectrum sensing has significant roles in avoiding collision with the authorized user and enhancing the proper usage of spectrum, [32]. It is a process of decision making regarding to spectrum utilization by taking some measurements on the radio spectrum parts [28]. Thus, spectrum sensing is to sense weather a primary user is available or not on a specified band of frequency and give the permission for secondary user to access the free band channel. In fact, the unlicensed users should continuously check the status of the licensed users and find the spectrum bands that can be used by the cognitive users without interfering with the licensed users. These free spectrum bands are known as spectrum holes.

2.3.2 Spectrum Management

In the cycle of cognitive radio network spectrum management is needed for the scheduling of spectrum sensing methods for sharing existence users. Spectrum management is the task of identifying the most free and existed spectrum to confront the need of user's communication. Cognitive radios needs to identify the best spectrum band to meet a good service requirement in all existed spectrum bands, so that functions of spectrum management are needed for cognitive radios.

If the free or unoccupied spectrum band is determined, then white space or channel is quickly chosen by secondary user. Before using unallocated spectrum band cognitive radio checks data rates, transmission mode and catch the most available spectrum according to the user requirement.

Spectrum management includes the activity of making a decision based on spectrum sensing information to allow cognitive radio to select when to start its operation, operating frequency and its corresponding technical parameters. The critical objective of cognitive radio is to deliver information without causing much interference to the licensed users. The following figure represents cognitive cycles which consist of the basic blocks.

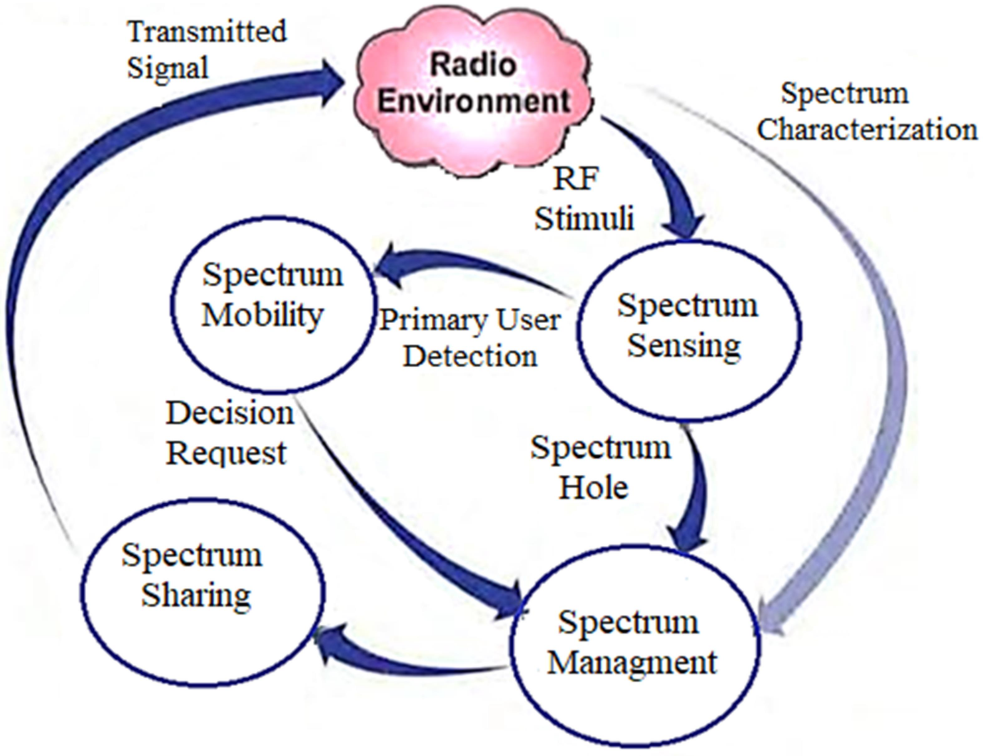

Figure 2.2: Basic cognitive radio cycle [20]

2.3.3 Spectrum Sharing

It deals with giving equal spectrum scheduling strategy and it is the most challenge issue in open spectrum utilization. Spectrum sharing enables to coordinate the existence of cognitive radios users in a shared situation with no interference with each other. Technique of spectrum sharing permits the cognitive users to co-exist with licensed users in the same frequency bands as long as secondary users consider the effect of their transmissions on the reception quality of the primary licensee [34]. Users in the open spectrum sharing scenario have an equal chance to access the channels and the spectrum sharing among cognitive users for the unlicensed bands without making harmful interference. In spectrum sharing process cognitive radio enables secondary users to use the spectrum as long as primary users don't utilize the band. Based on the monitored quality of service, cognitive radio users select the proper bands and adjust their transmission power [37] to yield a good service requirements as well as resource fairness. Spectrum access enables various cognitive radio users to share spectrum resources by identifying who will use the channel or when a primary user may occupy the channel [38].

2.3.4 Spectrum Mobility

Spectrum mobility is the process in which a user performs a movement and transformation from one spectrum band to another unused radio spectrum [39]. In this process when a secondary user plans to use the unused portion of the spectrum they must operate on a movable way to avoid interference with primary users. This implies that when an authorized (primary) user come back to the chosen band, the secondary user should vacant or leave the channel for the licensed user.

After a secondary user selects or picks the channel and begins to delivering data on it, a primary user may occur on that identical band; in this case the secondary user needs to transform and searching for another unused channel and left the band so that interference will be avoided with primary user.

Chapter Three

Spectrum Sensing for Cognitive Radio Networks

3.1 Introduction

Cognitive radio is a smart technology that is existed for the sake of minimizing the under-usage and shortage of radio spectrum. This technology, cognitive radio permits secondary users to access the unused spectrum in unlicensed situation via spectrum sensing. Since cognitive radio has some basic characteristics which includes ability to estimate, sense, learn, and be assured of the parameters of radio spectrum character including about existence of spectrum and interference [24]. To identify a vacant spectrum cognitive user must continuously detect the spectrum band. There is a technique to detect and identify the vacant spectrum in cognitive radio which is spectrum sensing. The most important approach to detect the authorized clients in the territory of the cognitive user is spectrum sensing.

Spectrum sensing refers for detecting the vacant or unused spectrum and sharing that free spectrum to the secondary user or unauthorized user without having a harmful intervention with other users. They are very critical to avoid interference and minimize inefficient usage so that utilization of limited spectrum will be improved in cognitive radio. So it is obvious that the most essential and important strategy and tasks in cognitive radio is spectrum sensing. Since spectrum sensing enables cognitive users to learn to its surrounding by sensing the hole in radio spectrum. Detecting the primary user that is getting information within the region of a cognitive radio will be the prior effective way for checking the presence of some slots of the spectrum. However, the challenge in cognitive radio is that there may be no perfect channel communication or measurement between a primary transmitter and receiver.

The main principle of spectrum detection is depicted in the figure below. As we have observed in the figure information is transmitted from the PU transmitter to the PU receiver in the authorized spectrum band and the aim of cognitive users is to use the available free spectrum. To avoid interference with the transmitter of licensed user, the secondary user transmitter must detect the presence of primary receivers in the range of the secondary user transmitter. To identify the existence of primary user receiver, secondary transmitter required to sense the existence of PU signals. But when the power level of primary user is below the noise power, this condition is not always perfect. So in this case the available of primary user can be detected using the proper threshold of the auto-correction function of the signal received. But, there is a difference in the detection of primary user transmitter and receiver in terms of radius or coverage area and this brings a certain obstacle and challenges. This challenge can be described as, when the primary receiver is out off the coverage of the primary transmitter detection, the vacant spectrum may be missed. Most spectrum detector or cognitive users mainly concentrate on detecting primary user transmitter instead of detecting a primary receiver [5] and [9]. There are various kinds of spectrum detection techniques used in the identification of vacant spectrum and for enhancing probability of detection.

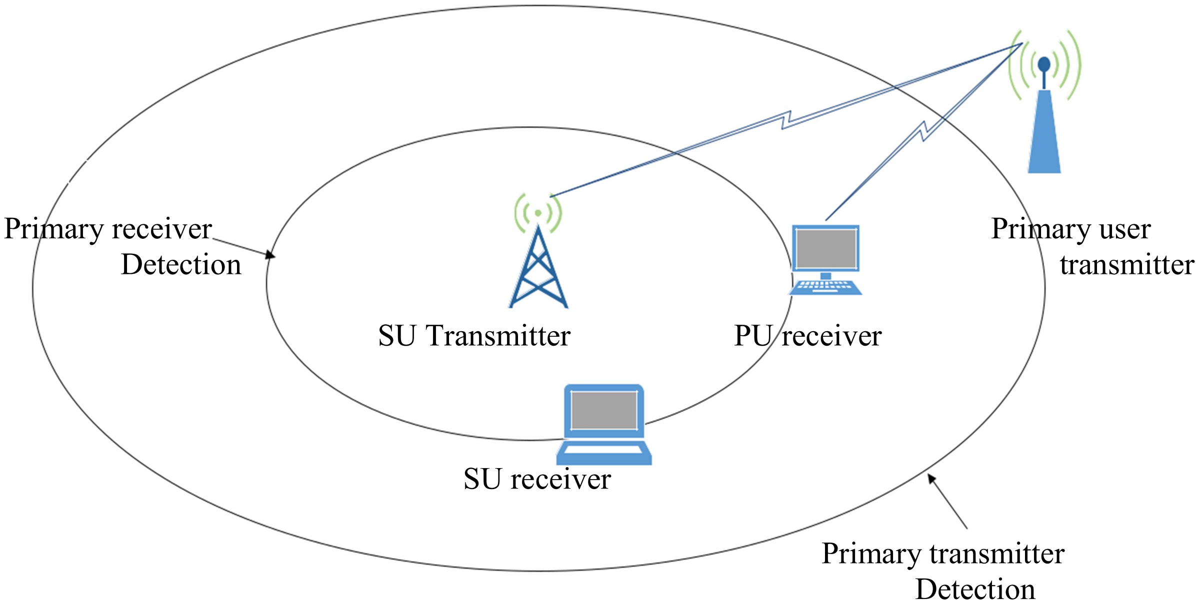

Figure 3.1: Spectrum sensing principles [14]

3.2 General Model and Hypothesis of Spectrum Sensing

In favored of avoiding an interference with the licensed user and enhancing spectrum usage efficiently, spectrum sensing has a remarkable role in CR [17]. Spectrum detection is a task of detecting the existence of a licensed user in the band to give the unlicensed users permission to use the free channel. Therefore, cognitive users required to sense the primary transmitter's signals for identifying between occupied and unoccupied band of spectrum. In fact, the unlicensed users need to periodically monitor the behavior of the licensed users and find the spectrum bands that can be used by the cognitive users without interference. The figure displayed below shows the general model of the spectrum detection which is almost applicable for all detection techniques.

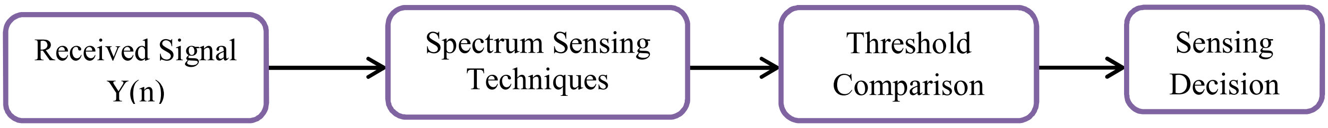

Figure 3.2: Spectrum sensing general model [12]

From the above general spectrum detection model, the cognitive radio user which is the secondary user in fact, receives the signal as Y(n). Then the test static of the signal received will be determined depending on the kind of detection technique applied. Then the test static calculated before is going to be compared with pre-defined threshold that is different for all detection techniques accordingly. If test static of detector is higher than the threshold value, spectrum is occupied by the user which means it busy otherwise the test statics below the threshold value it is to mean that the spectrum is not actually busy and free to be used by secondary user.

The above general model of spectrum detection is applicable for all sensing algorithms only the block of spectrum sensing technique will be changed. The basic task that is performed in spectrum sensing scenario is that of the binary detection hypothesis and this hypothesis can be modeled. Since spectrum detection is related with decision making issue and due that it falls in to the broad category which is known as a detection theory or binary hypothesis.

The general spectrum sensing using binary hypothesis can be analyzed as:

$$y(n) = \begin{cases} w(n), & \mathrm{H}_0 \\ h * x(n) + w(n), & \mathrm{H}_1 \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.1$$

$y(n)$ is the signal received sampled by secondary user, $x(n)$ is the transmitted signal samples from primary user, $w(n)$ is an AWGN channel noise with zero mean and variance δ_w^2 , h is channel gain. From the above model the hypothesis H_0 implies that licensed user is absent and channel is vacant, only noise exist, and the alternative hypothesis H_1 indicates that there is a signal transmitted, licensed user is present and channel is occupied.

The main task of binary hypothesis test is to make a decision by comparing the received signal with a certain threshold value and which of the two hypotheses has been occurred. If there is only one received sample, the decision can be easily taken by comparing the received sample with the threshold and declare H_1 if the received sample is above the estimated threshold and H_0 otherwise. To perform detection of licensed user signal different sensing mechanisms are applied which enables to make a decision about H_0 and H_1 hypotheses. To decide about the existence of licensed user, the decision making statistics will be compared with threshold. If licensed user is not available on the channel, then secondary user will use that free channel but if the user is available SU didn't access the channel since interference may be occurred.

Generally if T is the test statistics of the detector and λ is detector threshold then detecting decision can be performed as follows.

$$\begin{cases} T \geq \lambda, & \mathrm{H}_1 \quad \text{PU available} \\ T \leq \lambda, & \mathrm{H}_0 \quad \text{No PU exists} \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ldots\ldots. 3.2$$

The relation between binary hypothesis tests with their possible outcomes in terms of their probability weather the spectrum is occupied or not can be analyzed with the figure depicted below. Analytically, when the resolution on the available of a primary user is to be made, then it is minimized to an identification problem [41].

The presence or absence of primary user can be formulated the binary hypothesis as follows:

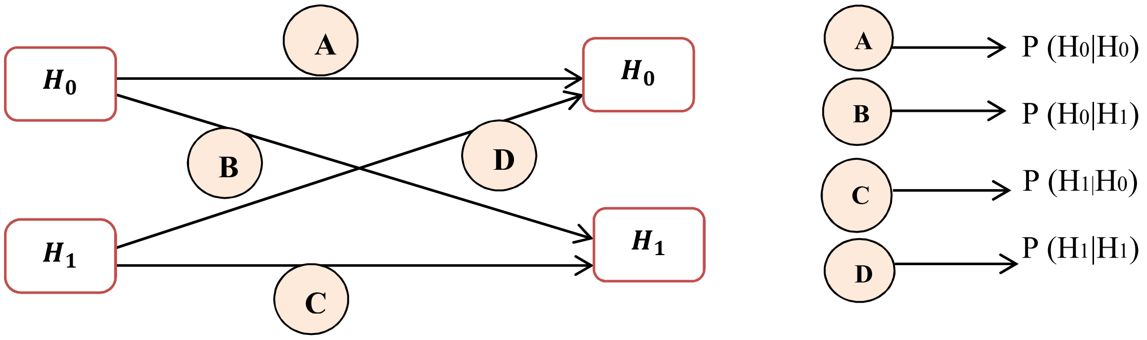

Figure 3.3: Relation between binary hypothesis tests with their respective probabilities [42]

From the above figure there are four possible scenarios that can be performed from the binary hypothesis test for the detected signals which includes;

1. Declaring H_0 when H_0 is true ($H_0|H_0$)
2. Declaring H_0 when H_1 is true ($H_0|H_1$)
3. Declaring H_1 when H_0 is true ($H_1|H_0$)
4. Declaring H_1 when H_1 is true ($H_1|H_1$)

Following this binary hypothesis three basic detection evaluation metrics can be drawn [18], which are probability of detection (Pd) which implies a correct detection and if the channel is not occupied and it will be declared as vacant. At the case of false alarm probability (Pf) , when the band is not occupied, the detector will declared as occupied and probability of miss-detection (Pm) this implies the spectrum band is occupied but the detector will declare as vacant.

3.3 Types of Spectrum Sensing Techniques

The most important part in cognitive radio is that of spectrum detection. The basic aim of spectrum sensing is to identify and get the vacant spectrum band or spectrum hole and also aimed at avoiding an intervention between the primary user and unlicensed user during exchange of data. So if the spectrum detector identified the free band, secondary users can broadcast their transmission in these spaces in a way that no interference is caused to the primary users [15]. Spectrum sensing techniques may be used to identify and examine the radio spectrum to determine occupied and unoccupied bands to access unused frequency bands. On the other hand spectrum sensing mechanism will be performed in terms of detecting a received signal [40]. Signal detection is a method for examining the available of a signal in a noisy surrounding.

Cognitive radio transceivers detects a vacant spectrum in terms of band, location and time and anticipate the way of accessing the free band without having an interference with the transmission of the licensed user. It is stated that in radio frequency spectrum there is a free band which is said to be spectrum hole and this slot is permitted to be used by a cognitive user or secondary user. This use of free spectrum in cognitive radio is possible by sensing the presence or absence of licensed client for the sake of avoiding disturbance. So spectrum sensing methods are very important in cognitive radio. Hence it is possible to find unused portion of spectrum band that is not utilized by the authorized user at any certain time interval. When using the free band it must be not disturb the rights of licensed user. Different types of spectrum detection mechanisms have been proposed to investigate the availability of the primary user signal transmission. These techniques will provide to have a good spectrum usage opportunities to the secondary users with no intervention or intrusive to the primary users. There are three basic categories for spectrum detection which are namely:

- Transmitter-based (non-cooperative) detection
- Interference-based detection and
- Receiver-based (cooperative) detection

These classes of spectrum sensing techniques are presented in the figure below and the detail and feature of each sensing mechanisms are discussed one by one [19]. In the receiver-based detection method, wireless sensors placed in the nearness of the primary user receivers and are used to measure the power leakage released by their local oscillators [20]. Interference-based detection is depending on the assumption that if two signals can interfere with each other, it means they are in the same communication vicinity; hence detection can be based on their interference [21]. In the transmitter-based detection, weak signals from a primary transmitter are detected by local observations of the cognitive radio users [22]. The two basic transmitter-based spectrum detection method basically energy and matched filter detection are studied in thesis work.

Sensing the radio spectrum surrounding in cognitive radio consists of different activity which are taking samples from the input signal and then performing digital signal processing operations that produce a decision statistic. As displayed in the figure below those are the sensing algorithms that have been applied for spectrum detection. In transmitter detection type weak signals are detected from the transmitter of primary users by local observation of the signal then decide on the possibility of spectrum utilization [40]. For transmitter detection approach to be effective task, cognitive radio must be available in the coverage range of the primary user transmitter.

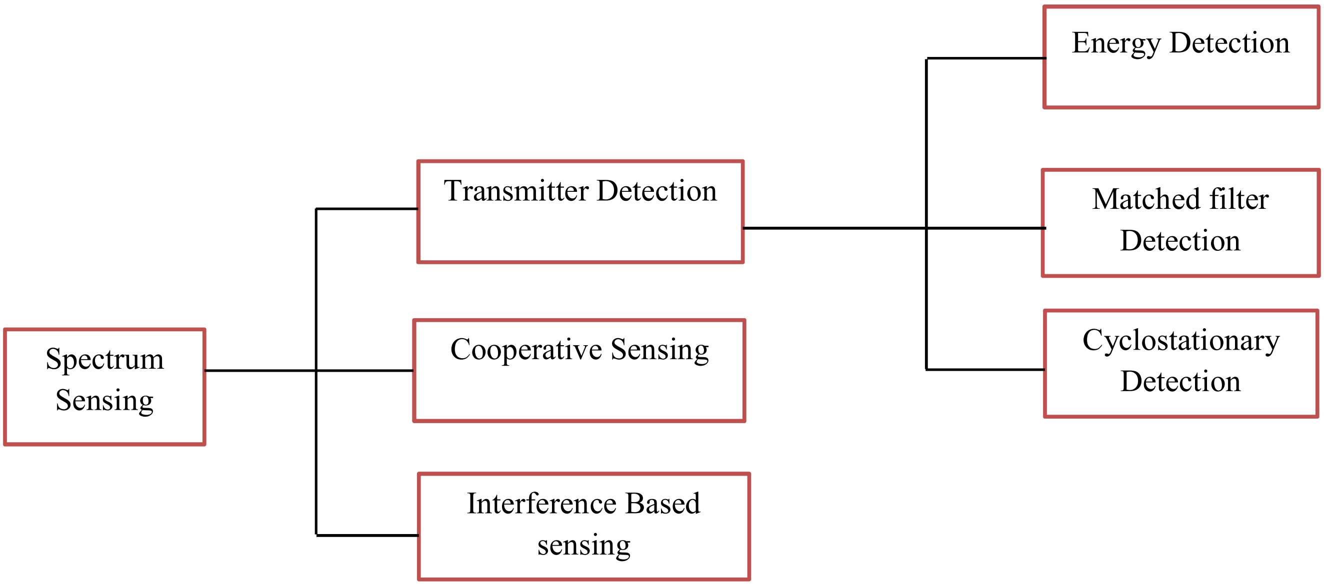

Figure 3.4: Types of Spectrum Sensing techniques [19]

Spectrum detection which is based on Interference level is another spectrum sensing method defined by FCC [16], aimed at measuring the level of interference at the primary receiver. On the other hand cooperative spectrum sensing is performed by a number of cognitive radio users in which a particular band is being detected in collaboration with each other to decide on any access opportunity [8], [13]. These basic types of spectrum sensing techniques are discuss and literate briefly next.

3.3.1 Non-cooperative Detection Techniques

Non-cooperative spectrum detection is the most common spectrum sensing mechanisms. This sensing scheme is used to identify a signal from a licensed transmitter to determine whether it is occupied or not occupied and the SU must be able to check whether a signal from a licensed user is locally available in the frequency slot. In transmitter detection approach there is no cooperation or collaboration between various secondary users that will detect the same free band of spectrum which means that primary user signals can be sensed by cognitive user independently. So each particular user identifies the availability of an authorized user individually and will take an action in accordingly. In general this detection approach is the easiest and the most common mechanism used to sense the presence of primary user over the range of frequencies of which operates [43]. It can be implemented with low infrastructure cost and minimum system requirements. However, this type of detection mechanism lacks an intelligent knowledge about the existence of primary users.

In its simplest form, the concept of transmitter detector is just to get the activities of primary transmitters at a given interval by using local observation and measurements. So detecting the primary user is performed based on the received signal at the secondary user from primary transmitter. In order to identify the availability of vacant spectrum, the secondary user estimate the level of received signal and decision will be made. The decision of the vacant spectrum will be done based on the binary hypothesis test [44].There are two basic problems related to transmitter based spectrum detection: one is primary receiver uncertainty second is hidden problem or shadowing [45]. The three most commonly used transmitter detection technique includes energy, matched filter and cyclostationary detection [10].The detail of each of the transmitter detection techniques will be discussed next.

3.3.1.1 Energy Detection

Energy detection is among the types of transmitter detection mechanism for sensing of a primary user signal. Since it is easy in terms of implementation and does not require any prior data and information regarding to primary user signal, energy detection becomes the common type of detection techniques [4]. It uses the principle of signal detection method that identifies the presence of the licensed user signal based on the level of sensed energy [10].

When there is no prior data available or when a cognitive radio is unable to get enough knowledge regarding the signal of primary user, energy detector mechanism will become a maximum sensing method. Since energy detector detects or estimates only energy of the signal regardless of signal type and properties, it is said to be blind detector [22] and calculates the energy of input signal over a specific time interval and then compares it with pre-calculated threshold that depends on the noise floor.

Calculating the received signal's energy gives the decision statistic and this will be compared to a pre-calculated value of threshold [13]. After squaring the signal, it will be given to the integrator operation over the interval of time. Finally, the energy of the received signal will be compared with a pre-calculated threshold to decide the existence of licensed or primary user in the band. If the received signal's energy at the cognitive radio exceeds the sated threshold, the alternate hypothesis H_1 is validated and the primary user is concluded to be present. If the energy is lower than the threshold value, the hypothesis H_0 is validated, thus implying the presence of a spectrum hole [26].

The general model energy detection which is used to identify the presence or absence of primary signal is shown below.

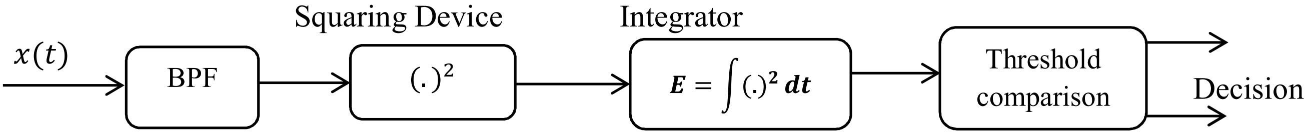

Figure 3.5: System model of Energy Detection [44]

The calculation of energy can be done by following equation. When PU is absent, the input signal will be $x(n) = w(n),\ H_0$.

$$E = \sum_{n=o}^{N-1} |x(n)|^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.3$$

Energy detector test statistic can be formulated as [18].

$$\mathrm{T}(x) = \frac{1}{N}\sum_{n=o}^{N-1}[x(n)]^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.4$$

Here, $\mathrm{T}(x)$ is the test statistic, N is the number of sample taken under the observation period and $x(n)$ is the received signal.

For a value of single threshold λ, the presence or absence of licensed user can be declared as

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

The detail mathematical analysis for energy detector test statistics including Pd, Pf and Pmd will be discussed in the next chapter.

3.2.1.2 Matched filter Detection

Matched filter detector is transmitter spectrum detection method that is used to optimize and enlarge the SNR of the primary user signal at the secondary user end in the additive noise environment. When secondary user has an idea or knowledge about the authorized user signal or in short if the signal transmitted from the source is known, matched filter detection method is used in this scenario [9]. In matched filter detection techniques, information about primary user activities including frequency, bandwidth, modulation type and pulse shaping of the received signal is required [31]. In order to perform all the prior data about the licensed user signal, there must be synchronization at the terminal of the cognitive user and the primary user transmitter. It is a coherent detection technique that needs shorter time to perform a certain false alarm or detection probability compared to other sensing algorithm.

In spectrum detection technique, matched filter detector needs short time to accomplish the process of determining the signal and also has a good strength to noise uncertainty with moderate computational complexity. If the primary user transmitter delivers the pilot stream at the same time with the data, the signals and pilot streams will also be received by the secondary user. In matched filter detection technique having a prior knowledge about the behavior of primary signal enables to increase the detectors speed and perfectness.

In this detector technique correlation takes place between the pilot signal, which is the prior data of the primary signal and the received signal, then the output of this is compared with the threshold value to check the presence of the licensed user signal.

When performing primary user signal identification, matched filter detector follows the following block diagram.

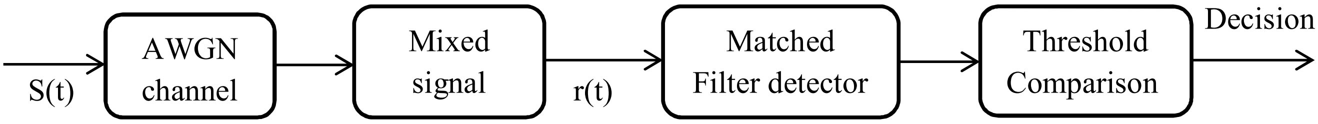

Figure 3.6: System model of Matched filter detection [9]

In the above figure s(t) is the received signal and this signal is given to or pass on AWGN channel. The combined or mixed signals which are the noise and received signal are given to the matched filter detector. Then matched filter will correlates the mixed signal with known pilot signal of PU and then the result of this is compared the result with predetermined threshold and decision is taken about the presence and absence of the primary user signal.

The test statistics of a matched filter can be determined as other detection types have. This is performed from the correlation of received signal with the prior known signal of the primary users. Analytically, the matched filter detector can be manipulated as follows:

$$T(x) = \frac{1}{N}\sum_{n=o}^{N-1} x(n) \times s(n) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.5$$

Where, $T(x)$ is test statistics and $s(n)$ is prior known signal and $x(n)$ is the received signal. Starting from this test statistics equation, detection and of false alarm probabilities can be performed which will be discussed on the next chapter briefly in detail.

3.2.1.3 Cyclostationary Detection

Cyclostationary detection is among the common transmitter detection techniques. Cyclostationary signals is due to statistical periodicity behavior of signals which may happen in coding scheme or modulation. Wireless signals show a periodicity features utilizing this features to detect random signals in the region of noisy environment and other modulated signal is known as cyclostastionary detector [46]. To identify the availability of authorized user signal on the band, cyclostationary detector uses the periodicity feature of the licensed user signal. These characteristics which are periodicity feature indeed, is commonly incorporated with primary user signal which includes pulse train, sinusoidal signal carriers, spread code hopping sequence or cyclic prefixes. In addition to periodicity feature, cyclic spectral correlation function is used in cyclostationary detector technique to sense the presence of primary user signal in the band [33]. It is said to be that those signals present in cyclostationary detector will have the behavior of both the characteristics of statistical periodicity feature and spectral correlation.

Cyclostationary detector algorithms have the ability to identify the noise present in the primary user signal. Since the signal is wide sense stationary having no correlation because of duplication of periodicity of signals the modulated signals are cyclostationary with spectral correlation. In wide-sense cyclostationary time-series it is implied that for all t, τ mean E_X and the autocorrelation R_x (t, τ) of the signal exhibit periodic properties with time. Its periodicity can be expressed as

$$E[x(t+To)] = E[x(t)] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.6$$

$$R_x(t+To,\tau)] = R_x(t,\tau) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.7$$

where the autocorrelation function is defined as

$$R_x(t,\tau) = E[x(t+\tau)x(t)] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.8$$

Where E [.] is the expectation value or the mean of the signal.

Since R_x is a periodic function it is possible to express in Fourier series as [33]:

$$R_x\left(t+\frac{\tau}{2}, t-\frac{\tau}{2}\right) = \Sigma_\alpha R_x^\alpha(\tau)e^{j2\pi\alpha} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.9$$

From the above α includes the sum of overall integer multiple of the reciprocal of the fundamental period T_0 and $R_x{}^{\alpha}$ is the cyclic auto correlation of the signal and its Fourier coefficient $R_x{}^{\alpha}(\tau)$ is given by [33]:

$$R_x^{\alpha}(\tau) = \frac{1}{To} \int_{-To/2}^{To/2} Rx\left(t + \frac{\tau}{2}, t - \frac{\tau}{2}\right) e^{-j2\pi\alpha t} dt \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 3.10$$

Due to the periodicity nature the cyclostationary, the signal shows high correlation property between widely separated spectrum components.

The spectral cyclic autocorrelation function in Eqn 3.10 has the Fourier transform [33]:

$$Sx(f) = \int_{-\infty}^{\infty} R_x^{\alpha}(\tau) e^{-j2\pi\alpha}\, d\tau \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 3.11$$

Given N samples of signal, the estimated spectral correlation function SCF $S_x^{\alpha}(\tau)$ (f) is given by [34]

$$S_x^{\alpha}(\tau) = \frac{1}{N} \sum_{n-1}^{N} Xl(n, K + \frac{K\sigma}{2}) XL\left(n, K - \frac{K\sigma}{2}\right) \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 3.12$$

Where

$$X_L(n, k) = \frac{1}{\sqrt{L}} \sum_{l=n-\frac{L}{2}}^{l=n+\frac{L}{2}-1} X(l) e^{-\frac{j2\pi kl}{L}} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 3.13$$

Equation 3.13 is an L point DFT at nth samples of the signal received and Kα =αL/Fs is bin of the index frequency corresponding to cyclic frequency α and received signal. It is correlated with known priory signal and compared to the threshold value to check the existence of primary signal in the system. In cyclostationary detection algorithm to identify the PU signal a binary hypothesis is performed based on the periodic characteristics of the received signal x(t) as shown below. The noise present in this detector are wide sense stationary so that the primary user signal and noise has no correlation and can be identified with no more difficulty for cyclostationary detector.

When the noise level becomes uncertain cyclostationary detector becomes more efficient in such environment. Determining the spectral correlation of the licensed user signal at the detector enables to identify if the user signal is present or not.

The block diagram representation of cyclostationary detection system can be depicted in the figure below.

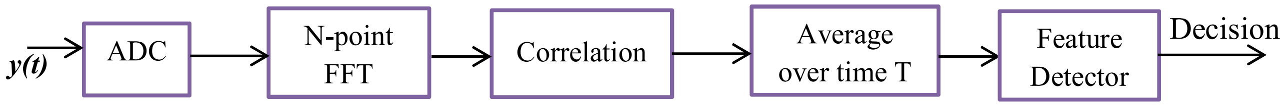

Figure 3.7: Block diagram of cyclostationary detector [33]

Generally cyclostionary detector is an optimal sensing mechanism since it can differentiate the noise part from the primary user signal in such a way that spectral correlation function enables to isolate the signal and noise energy. After isolation of the signal, primary user channel is determined whether they are present or not. An approximate expression of false alarm probability for a fixed value of λ in cyclostationary detector can be performed as stated in [47].

$$P_f = P_r\,(H_1|H_0) \qquad \text{………………………………………..……..…..….3.14}$$

$$P_f = \exp\left(\frac{-\lambda^2}{2\sigma_A^2}\right) \qquad \text{…………………………………….…………3.15}$$

Where, λ = Threshold value exp () = exponential function and

$$\sigma_A^2 = \frac{\sigma_\omega^2}{(2N+1)} \qquad and\ \ \sigma_\omega^2\ \ is\ noise\ varience$$

Now, the probability of detection of primary user signal for the cyclostationary detector algorithm can also be determined as follows [47].

$$P_d = P_r\,(H_1|H_1) \qquad \text{…………………………………...……..3.16}$$

$$P_d = Q\left(\frac{\sqrt{2\gamma}}{\sigma_\omega}, \frac{\lambda}{\sigma_A}\right) \qquad \text{…………………………………..…………3.17}$$

3.2.2 Interference Based Detection

The interference based spectrum detection is another type of spectrum sensing mechanism. It is known that interference will takes place on the receiver client and this can be overcome at the user in the secondary transmitter. To correctly measure and reduce the amount of interference at the receiver side an interference temperature model is established by FCC [51]. In the model of interference temperature the limit of interference temperature is recommended which is an acceptance amount of interference at the primary receiver. Since interference detection type is a kind of centric detection mechanism in which the amount of radiated power is monitored and overcome at the transmitter. The total temperature effect in the system will become higher when a numerous transmitter deliver signal evidence or data on the channel.

In this detection type interference temperature limit is the maximum permitted or granted interference on the receiver side in which unauthorized transmitters are not allowed to exceed this limit in order not to have any harmful interference on the receiver of the licensed transmitter. For interference based spectrum detection handling the interference is essential in cognitive radio this is due to the fact that secondary user is permitted only if secondary user interference does not affect the primary user quality of service below an acceptable level. For managing and controlling the interference in the primary user there are three techniques which includes interference avoidance, interference control, and interference mitigation [52].

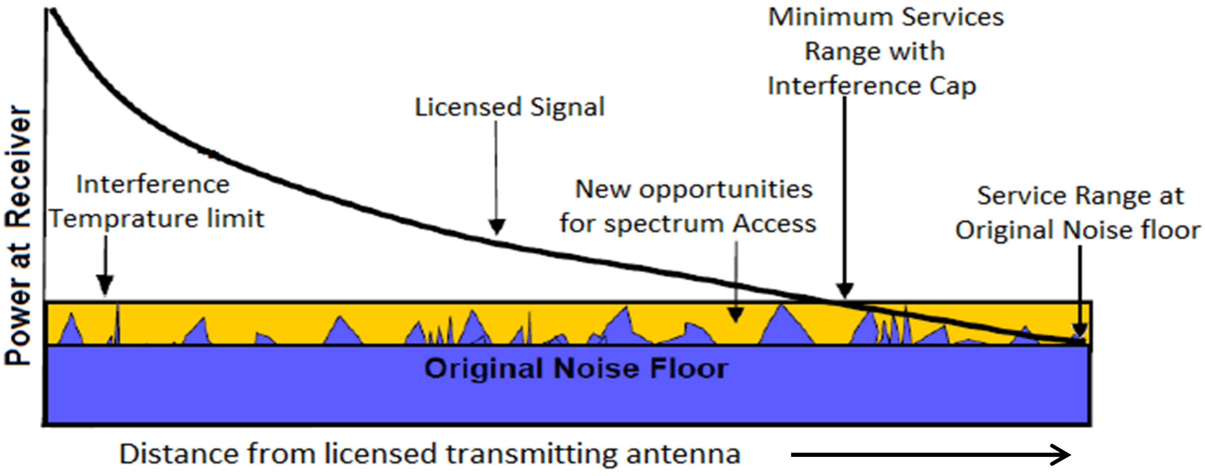

Figure 3.8: Interference Temperature model[40]

The above figure shows the received power by the licensed signal transmission as the distance from the transmitter. There is an interference temperature limit for each of the primary receiver that defines the amount of noise and interference that will be guaranteed and tolerated. From the above figure if the transmission is on top of the interference temperature limit should it must be cancelled and taken as noise by the primary receiver, since if there is higher interference temperature limit the maximum range of the licensed primary transmission will be reduced. This model enable cognitive radios to measure and model the interference region and can adjust their transmission for the opportunistic use of the spectrum. When the transmitted power level with respect to noise is below receiver signal sensitivity, the information signal may arrive at the noise level and the receiver consider this signal as a noise.

3.2.3 Cooperative Detection Techniques

Cooperative or collaborative detector is another type of spectrum sensing mechanism. In non-cooperative sensing techniques we have seen that there is no cooperation between primary and secondary users. Due to this manner they are challenged by multipath fading or shadowing, primary user hidden problem and noise uncertainty. To mitigate those challenges and when there is a lack of communication and interaction between the secondary user and primary user, cooperative detection is proposed and become a good solution. In cooperative detection multiple cognitive users communicate in collaborative manner to ascertain the availability of free spectrum and use opportunistically.

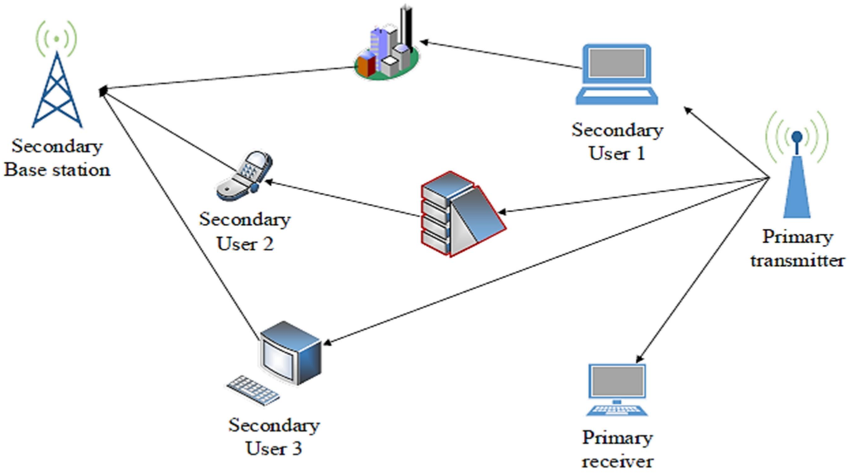

Figure 3.9: Cooperative spectrum sensing concept [58]

The cognitive radio users incorporated and collaborated among each other to share information and sensing the primary user signal. When there is sharing of information there will be an accurate detection and minimize level of interference. In cooperative detection mechanisms, all individual cognitive radio send their sensing data to a central node for fusion so that decision regarding to availability of spectrum user will be made based on the combined outcome [48].

Cooperative detection techniques are advantageous in terms of lowering the time in sensing signals and mitigating the effect of fading and unwanted noise. As can be seen in the figure above, for secondary user 2, the received signal that arrives at the SU will becomes weak to be sensed due to the fact that those obstacle blocks the primary signal. The primary receiver will be in the transmission area of secondary users but, if secondary transmitter is unable to detect the existence of primary transmitter interference will affect primary user transmission. Cooperative spectrum detection is proposed for the sake of addressing problems such as noise uncertainty, shadowing and fading effects so that secondary users will coordinate and collaborated to each other to minimize the effect on detection performance [26].

Even though cooprative detection have an advantage it also have some drawbacks which includes an increament of costs when secondary users increased,higher traffic and system complexity and finally the demand for power consumption also increased.

Based on how the cognitive radio user sent and share their measured information to the system or network center there are three basic types of cooperative detection techniques, namely centralized, distributed and relay-assisted and these detection types are discussed and shown in the following.

3.2.3.1 Centralized Cooperation Spectrum Detection

In centralized cooperative spectrum detection, as the name implies there is a center point or node which is a fusion center for collecting all secondary users sensing results about the availability of vacant spectrum in the band. In this case the opportunity of spectrum will be delivered to all cognitive clients or the fusion center by itself will manage the traffic level by sharing the detected spectrum opportunistically in an optimum manner [44]. Shortly, in centralized cooperative detection all the activities of the secondary users regarding to spectrum sensing are managed by the central unit.

There are three activities that are performed in centralized cooperative detection. The first one is to sense the user locally, the second is reporting of the outcomes and the third one is that of information fusion. In local sensing scenario, for opportunistic access, a targeted band of frequency will be chosen and each cooperative cognitive radio user will perform a task of spectrum sensing on that slot or band. After sensing the target frequency all cooperative cognitive radios will make a report about the result of their sensing measurements to the central unit or fusion center. At the end the fusion center will collect all the received and locally detected information to make a decision about the availability of primary user on the band and inform back to the cooperative secondary users.

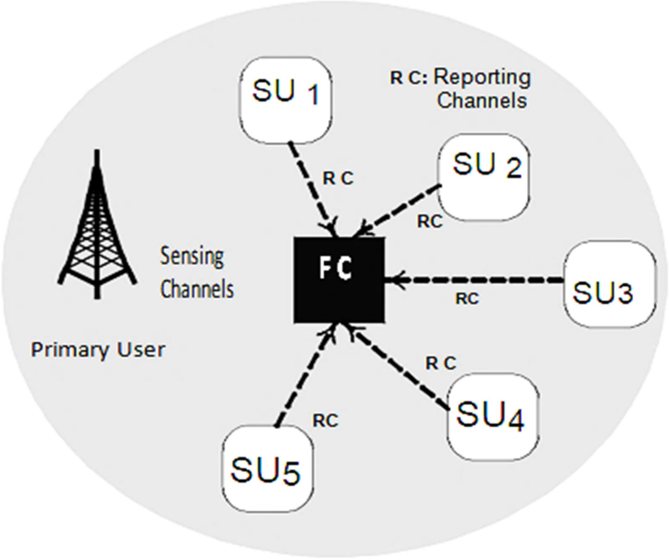

Figure 3.10: Centralized Cooperative Spectrum Sensing [23]

As shown in the figure above, all the secondary users from SU_1- SU_5 are the cooperative secondary users which are connected to the master node called fusion center. All the individual users are reporting the channel behavior or information to the fusion center. The central node which is the fusion center in fact combines the sensing measurements or data from SU_1-SU_5, which identifies the unoccupied spectrum and delivers or divides the information to those cooperative secondary users [23].

3.2.3.2 Distributed Cooperation Spectrum Detection

The second type of cooperative detection technique is distributed type. In distributed cooperative detection there is no central unit for managing the cooperation and decision of the spectrum band. In this case those multiple secondary users do not depend on the fusion center rather the users interact with each other and combined to a specified decision to the availability of primary users iteratively. As depicted in the figure below distributed cooperative detection follows three basic steps for cooperative usage [44]. In the first step each cooperative user sends or shares their locally sensed information to other neighborhood users. Secondly, the cooperative users collect or combine their own data with the received sensed information with other users to decide the vacant spectrum or decision making scenario. Finally when cognitive users are unable to identify the free spectrum, secondary users send combined or collected sensed data to other users in the next iteration [44].

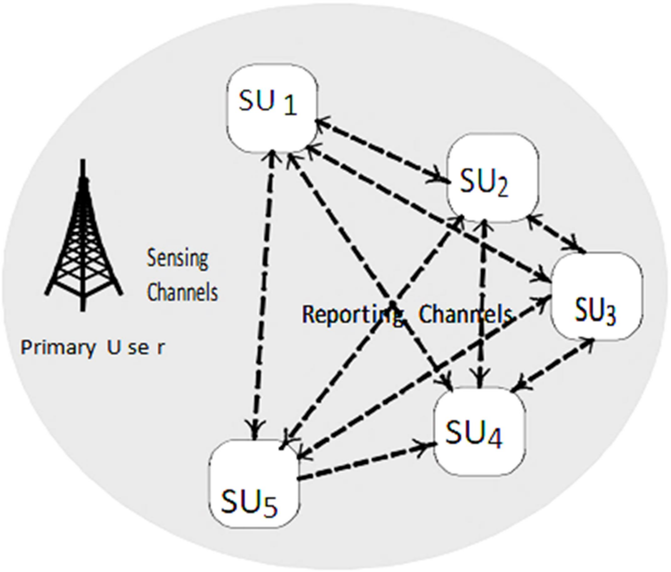

Figure 3.11: Distributed Cooperative Spectrum Sensing [23]

3.2.3.3 Relay-assisted Cooperation Spectrum Detection

Besides centralized and distributed cooperation detection, relay-assisted is another approach of cooperative spectrum detection mechanism. When there is imperfectness between reported information and sensed channel relay assisted cooperative spectrum detection will be applied. This is to mean that a secondary user having with weak sensed channel and a secondary user with strong reported channel, and a SU experienced a strong sensed channel and a weak reported channel can collaborated with each other to improve the total performance of the cooperative spectrum detection [49].

As shown in the figure below the users which are SU_1, SU_4, and SU_5, sensed a strong PU signals and this users sustain from reporting a weak channel and also the users SU_2 and SU_3 who have strong reporting channels serve as relays to assist in transferring sensed results from SU_1, SU_4, and SU_5 to the fusion center [50].Relay assisted cooperative sensing also called decentralized uncoordinated which means there is a fusion center but there is imperfection in the reported channel from the fusion center to the cognitive user and un able to get the final decision from central unit. So in this scenario those CR's that have a strong interconnection with the fusion center can be used as relay for the other weak reporting channel.

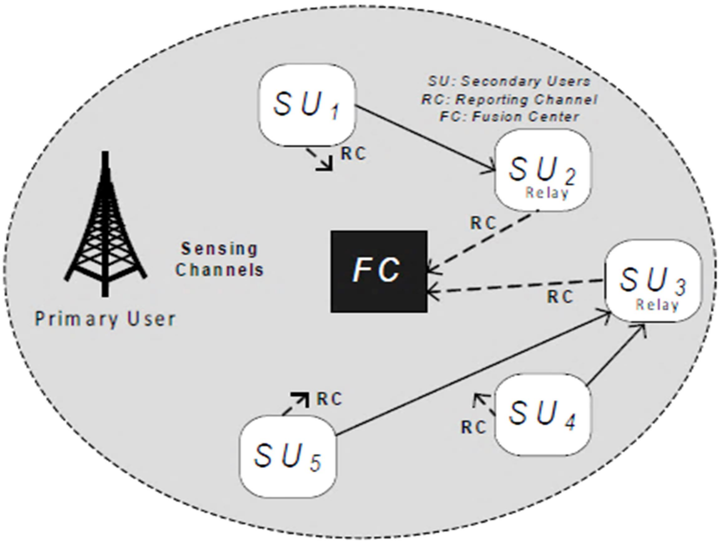

Figure 3.12:Relay-assisted cooperative sensing approach [50]

Generally we have seen about the three basic transmitter detection techniques which are energy, matched filter and cyclostationary detection. The following table will summarizes the performance of the three sensing algorithms in terms of evaluation metrics for the sake of comparison [7].

Table 1:Performance comparison of transmitter based spectrum sensing methods

Evaluation Metrics	**Spectrum Sensing Methods**		
	Energy detection	Matched filter detection	Cyclostationary detection
Detection Accuracy	- Good performance at high SNRs - Poor performance at low SNRs - High noise region leads to false detection [7]	- Very good performance at all SNRs values (if Rx has Prior knowledge of Tx)	- Have good performance at moderate SNRs values
Complexity	- Low computation and implementation complexity	- Has a moderate complexity (requires a dedicated Rx for each primary signal class)	- Most complex in terms of implementation
Robustness	- Does not need any prior information of Tx signal - Knowledge of noise power required - Does not work for spread spectrum signals	- It needs near perfect Tx information at Rx	- Rx must know Tx signal fundamental frequency
Design Choices	- Difficult to select about decision threshold	- Tx characteristics can be selected to improve perfection	- Cyclostationarity can be intentionally induced to improve accuracy

Chapter Four

System Model, Flow Chart and Performance Analysis of Proposed Hybrid Detection

In the previous chapter, discussions about cognitive radio, types of spectrum sensing algorithms are presented briefly. The advantage and drawback of transmitter detection techniques are also summarized by means of a table with evaluation metrics. The detection of a user signal in the area of higher noise needs a good spectrum sensing technique. In order to optimize probability of detection for secondary user and to sense a user at lower SNR value, a hybrid detector which is a combination of energy and matched filter detector algorithm has been proposed. If energy detector is not sure of about the existence of licensed user, matched filter detector will be applied to enlarge the weak received SNR so that user's signal will be detected in the area of noise.

So this chapter will discuss and examine system model, system flow chart and mathematical analysis of proposed hybrid spectrum detection algorithm. Performance of detection analysis for energy and matched filter detector including proposed hybrid detection algorithm in both fading and non-fading channel are also part of the discussion.

4.1 Proposed System Model for Hybrid Detection

By observing the weakness of energy detector at smaller SNR value and to minimize the drawback, hybrid detection technique using a matched filter detector is proposed. Matched filter detector is used after energy detector to enlarge the smaller SNR. This hybrid technique enables to sense user signal at smaller SNR value in an efficient manner. The block diagram of proposed hybrid detection looks as shown below.

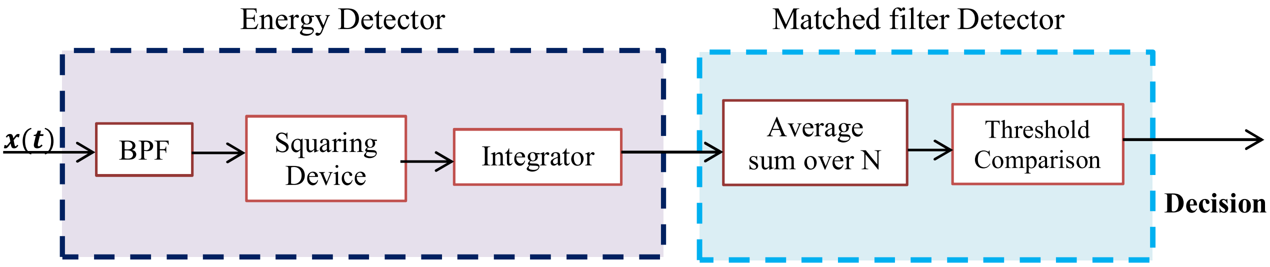

Figure 4.1: System Model of Proposed Hybrid Detection

As shown in the proposed model above two sensing algorithms, energy and matched filter detector are combined together to enhance spectrum detection performance generally. The signal that is received by a SU from the transmitter of primary user is passed through a band pass filter (BPF), which enables to eliminate a certain needed frequencies ranges and the signal that is received will be correlated with pilot signal of the primary user and sum up over an observation interval. After this stage the resulting signal will feed to a squaring device, to square the signal energy and then integrating the result of squared signal over an observation time interval. At the end the output from the integrating operation that is the signal energy is compared with the pre-calculated value of threshold to detect and decide the presence of primary user signal.

4.2 Flow Chart for Proposed Hybrid Detection Technique

The flow chart for proposed hybrid detection is shown in the figure below. As shown in the designed flowchart, first the received signal by secondary user passes through and sensed by energy detection. Then, energy of received signal is compared with threshold and if it exceeds the threshold value it shows that the spectrum is occupied and primary user is available in the band. When the received signal energy is below the threshold value the spectrum is free and no PU on the channel but in the case where the signal is weak, energy detection gets difficulty to detect and declared as noise.

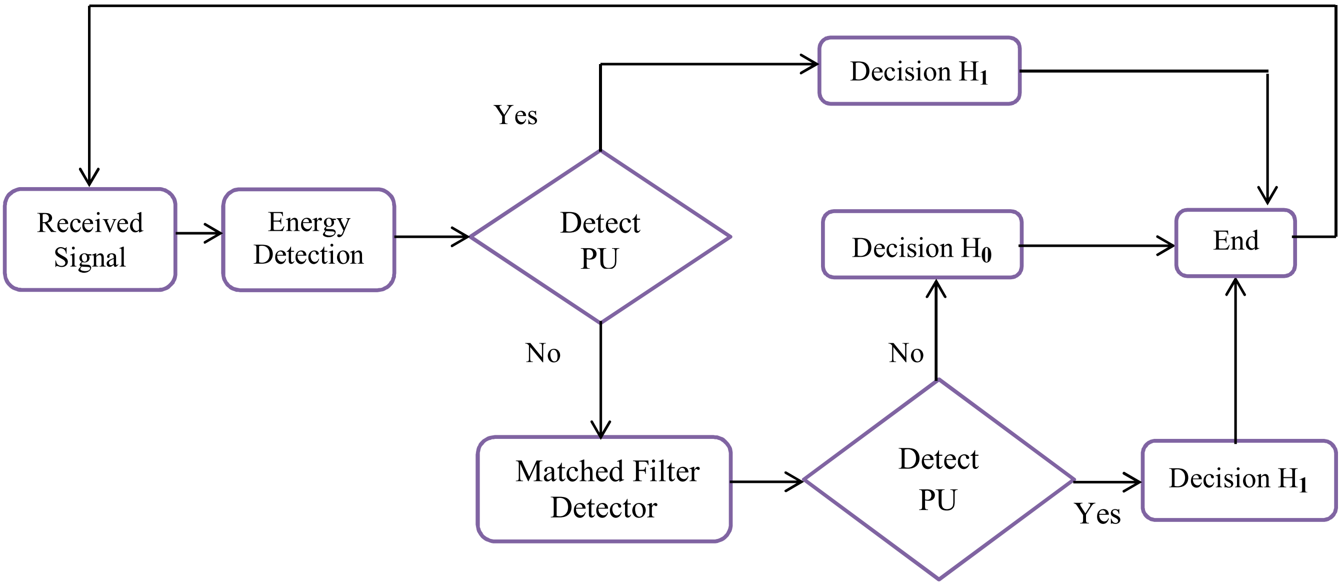

Figure 4.2: System flow chart for proposed detection

In the case where the received SNR is too small and weak, energy detector gets difficulty and in this case matched filter detector is applied to sense that weak signal and identify the free channel for secondary user. For higher SNR, hybrid sensing will perform using energy detection and for low SNR value, matched filter detector is performing in hybrid sensing.

When there is miss detection by energy detection, matched filter detector is applied. The probability of detection undergoing on matched filter detector in hybrid scheme is equal to Probability of a missed detection by energy detection.

4.3 Detection Performance Measurements and Analysis

The detection performance of the spectrum sensing technique can be quantified by the performance metric values and measurements which determine the correctness of the presence of the spectrum hole or channel in the system. The performance metric in evaluating hybrid detector is specified by the following general metrics:

1. The probability of detection, (Pd)
2. The probability of false alarm, (Pfa)
3. The probability of missed detection, (Pmd).
4. The receiver operating characteristics curve (ROC)

Probability of detection: Refers to the probability that the secondary user correctly detect and declares that a primary user is existed on the band. Pd specifies that a detector makes a correct decision that a channel is occupied. High detection performance will bring and implies that the probability of detection is maximized.

Probability of false alarm (Pfa): Refers to the probability that the cognitive user incorrectly declares that a licensed user is present, but the PU is not actually present. Too many false alarms signify that spectrum opportunities are being missed. A false alarm yields undetected spectrum holes. Hence, to maximize spectrum efficiency the probability of false alarm must be minimized.

Probability of missed detection (Pmd): It specifies the probability that the secondary user declares that the primary user is absent, when the licensed user or primary user is actually present. Occurrence of misdetection may result in interference of the PU by the SU; therefore probability of misdetection has to be monitored to avoid too many collisions.

In addition to Pd,Pfa and Pmd, the basic performance measurement tool is the Receiver Operating characteristics (ROC). The performance matrices ROC curve measures the sensitivity of the detector and can be used in binary hypothesis system. A receiver operating curve (ROC) is a technique for plotting the graph and has been used to evaluate the performance of the detector. In this thesis work the analysis of the above detection metrics which are Pd, Pfa and Pmd are discussed for the three detection techniques, energy detector matched filter detector and hybrid detection in both AWGN and Rayleigh channel.

4.4 Test Statistics Analysis for Energy Detector

In order to identify the vacant spectrum energy detector applies detection alarms which include detection, miss detection and false alarm probabilities and it is necessary to derive these detection metrics. Since the received signal y(t) pass through the band pass filter after that the filtered signal go through the A/D converter then the sample function of the noise n(t) in the band-pass random process can be expressed as [51].

$$n(t) = n_i(t) \cos w_c t - n_q(t) \sin w_c t \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.1$$

Where w_c is angular frequency, $n_i(t)$ is in phase noise component, $n_q(t)$ is quadrature phase component. Now, if a sample function has Bandwidth B and duration T, then it can be described approximately by a set of sample values *2BT* or degrees of freedom will be 2BT.Thus $n_i(t)$ and $n_q(t)$ each will have degrees of freedom, *d* equal to $2B_N$T.

Energy of noise over time period T can be approximated in [53] as.

$$E = \int_0^T n^2(t)dt = \frac{1}{2}\int_0^T [\, n_i^2(t) + n_q^2(t)]dt \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.2$$

According to sampling theorem, the in phase noise component $n_i\ (t)$ can be written as [53]

$$n_i(t) = \sum_{k=-\infty}^{\infty} c_{ik}\ sinc\ (B_N\mathrm{T} - \mathrm{k}\ ) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.4.3$$

Where sincx = $\dfrac{sin\pi x}{\pi x}$ and $c_{ik} = w_i\ (\frac{k}{B_N})$ is a Gaussian random variable with zero mean and variance $\sigma_k^2 = 2N_0B_N$ for all k. Now, using the fact as in [52],

$$\int_{-\infty}^{\infty} sinc(B_N\mathrm{T} - \mathrm{k})sinc(B_N\mathrm{T} - \mathrm{m})dt = \begin{cases} \dfrac{1}{B_N}, & k = m \\ 0\ , & k \neq m \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots.4.4$$

Then using 4.3 and 4.4 together

$$\int_{-\infty}^{\infty} w_i^2\ (t)dt = \frac{1}{B_N}\sum_{k=-\infty}^{\infty} c_{ik}^2 \qquad \ldots\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..4.5$$

As $n_i\ (t)$ has degree of $B_N\mathrm{T}$ over the interval (0,T) the in phase noise component will be [52].

$$n_i\ (t) = \sum_{k=1}^{B_N\mathrm{T}} c_{ik}\ sinc(B_N\mathrm{T} - \mathrm{k}), 0 < t < T \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.4.6$$

And the integral $\int_{-\infty}^{\infty} n_i^2\ (t)dt$ over the interval (0,T) can be written as

$$\int_{0}^{T} n_i^2\ (t)dt = \frac{1}{B_N}\sum_{k=-\infty}^{\infty} c_{ik}^2 \qquad \ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots4.7$$

Similarly the quadrature component will be

$$\int_{0}^{T} n_q^2\ (t)dt = \frac{1}{B_N}\sum_{k=-\infty}^{\infty} c_{qk}^2 \qquad .\ldots\ldots\ldots..\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots4.8$$

Substituting $\frac{c_{ik}}{\sqrt{2B_N N_0}} = d_{ik}\ and\ \frac{c_{qk}}{\sqrt{2B_N N_0}} = d_{qk}$ in (4.7) and (4.8) and using (4.2) we arrive at [52].

$$\int_0^T n^2(t)dt = \left[\sum_{k=1}^{B_NT} d_{ik}^2 + \sum_{k=1}^{B_NT} d_{qk}^2\right].N_0 \qquad \ldots 4.9$$

Similarly, considering transmitted signal x(t) as a band-pass process [51] we have

$$\int_0^T x^2(t)dt = \left[\sum_{k=1}^{B_NT} b_{ik}^2 + \sum_{k=1}^{B_NT} b_{qk}^2\right].N_0 \qquad \ldots 4.10$$

Or

$$\sum_{k=1}^{B_NT} b_{ik}^2 + b_{qk}^2 = \frac{E_s}{N_0} \qquad \ldots 4.11$$

Where

$b_{ik} = \frac{x_i(\frac{k}{B_N})}{\sqrt{2\,B_N N_0}}, \quad b_{qk} = \frac{x_q(\frac{k}{B_N})}{\sqrt{2\,B_N N_0}}, \quad and\ E_s = \int_0^T x^2(t)dt$ is the signal energy.

The output of the integrator is Y = $\frac{1}{T}\int_0^T y^2(t)dt$ .Test statistic can be or any quantity monotonic with Y. Taking y as test statistics [51]

$$Y = \frac{1}{N_0}\int_0^T y^2(t)dt \qquad \ldots 4.12$$

Now, under hypothesis H_0 , the received signal is only noise which is $y(t) = w(t)$, therefore using (4.9) test statistic Y' can be written as:

$$Y = \sum_{k=1}^{B_NT} d_{ik}^2 + d_{qk}^2 \qquad \ldots 4.13$$

Thus, Test statistic Y under H_0 is chi-square distributed [53] with degrees of freedom or $2\,B_N$T.

Under hypothesis H_1, received signal is the sum of signal and noise i.e. Again considering as a band-limited process [51], using equations (4.2- 4.10), we arrive at [55]:

$$\int_0^T y^2(t)dt = \left[\sum_{k=1}^{B_N T}(d_{ik} + b_{ik})^2 \sum_{k=1}^{B_N T}(d_{qk} + b_{qk})^2\right].N_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.14$$

Then, using (4.12) and (4.14), test statistic Y' can be written as:

$$Y = \left[\sum_{k=1}^{B_N T}(d_{ik} + b_{ik})^2 \sum_{k=1}^{B_N T}(d_{qk} + b_{qk})^2\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.15$$

Thus, test statistic Y' under H_1 has a non-central chi-square distribution [53] with 2 B_NT degrees of freedom and a non-centrality parameter λ given by $\frac{E_s}{N_0}$ [52]. Now, Defining Signal to Noise Ratio,γ in terms of non-centrality parameter as in [54]:

$$\gamma = \frac{E_S}{N} = \frac{E_S}{2N_0} = \frac{\lambda}{2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.16$$

Thus, test statistic Y under H_1 : $Y \sim x_{2d}^2\ (\gamma)$ and for H_0 : $Y \sim x_{2d}^2$ [54], where x_{2d}^2 is the central chi-square distribution and d is the time bandwidth product at the node.

We can also express the probability density function of Y as [53].

$$f_y(y) = \begin{cases} \frac{1}{2^d \Gamma(u)} y^{d-1} e^{-\left(\frac{y}{2}\right)}, & H_0 \\ \frac{1}{2}\left(\frac{y}{\lambda}\right)^{\frac{d-1}{2}} e^{-\left(\frac{\lambda+y}{2}\right)} I_{d-1(\sqrt{\lambda})}, & H_1 \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.17$$

Where $\Gamma(\,.\,)$ is the modified gamma function defined as Γ (x, a) $= \int_a^\infty e^{-t}\, t^{-(x-1)}(t)dt$ and I_v (.) is the Vth -order modified Bessel function of first kind. Using the above probability density function (PDF) equations we can derive the probability and false alarm detection for different channel models specifically AWGN and Raleigh channel.

4.5 Probability of Detection for AWGN Channel

It is known that detection probability, false alarm probability and miss detection probability are the three basic sensing metrics in spectrum detection scenario and the channel which is additive white Gaussian noise is a typical noise that is found in communication channel and Rayleigh channel is also included in the channel model. Accordingly, Pd is the probability of detection in which hypothesis H_1 is selected when the primary user signal is available on the channel and Pfa is probability of false alarm where by hypothesis H_0 is selected.

We also assume that the threshold value of λ is selected hence the exact closed form expressions of Pd and Pfa can be evaluated respectively [54] as

$$P_d = \mathrm{P}(Y > \lambda | \, H_1) \tag{4.18}$$

$$P_f = \mathrm{P}(Y > \lambda | \, H_0) \tag{4.19}$$

Where λ is the decision threshold. Also, P_f can be written in terms of probability density function as [55]:

$$P_f = \int_{\lambda}^{\infty} f_Y(y) \, dy \tag{4.20}$$

Inserting the value of $f_Y(y)$ in the above equation we get

$$P_f = \frac{1}{2^d \Gamma(d)} \int_{\Lambda}^{\infty} y^{d-1} e^{-\left(\frac{y}{2}\right)} \, dy \tag{4.21}$$

Dividing and multiplying the R.H.S. of above equation by 2^{d-1}, we get

$$\frac{1}{2^d \Gamma(d)} \int_{\Lambda}^{\infty} \left(\frac{y}{2}\right)^{d-1} e^{-\left(\frac{y}{2}\right)} dy \tag{4.22}$$

Substituting $\frac{y}{2} = t \quad \frac{dy}{2} = dt$ and changing the limits of integration to ($\frac{\lambda}{2}$, ∞) we get

$$P_f = \frac{1}{\Gamma(d)} \int_{\frac{\lambda}{2}}^{\infty} (t)^{d-1} e^{-(t)} dt \qquad \text{… … … … … … … … … … … … … … 4.23}$$

Then finally the probability of false alarm for energy detector can be described as [52]

$$P_f = \frac{\Gamma(u,\frac{\lambda}{2})}{\Gamma(u)} \qquad \text{……………………………………4.24}$$

Where $\Gamma(.,.)$ is the incomplete gamma function, $\Gamma(.)$ is the complete gamma function u is the time bandwidth and λ threshold value and Pfa is independent of SNR value.

Now, Probability of detection can be written by making use of the cumulative distribution function [55].

$$P_d = 1 - F_Y(\mathrm{y}) \qquad \text{………………………………………………4.25}$$

$$F_Y(y) = 1 - Q_d(\sqrt{\lambda} \ ,\sqrt{y}) \qquad \text{……………………………………………4.26}$$

Then using the above two equations together the Probability of detection for energy detector in AWGN channel will be evaluated using the expression as follows.

$$P_{d,ED} = Q_d(\sqrt{2\gamma} \ ,\sqrt{\lambda}) \qquad \text{……………………………………………………4.27}$$

Where, $Q_d(x, y)$ is the generalized Marcum-Q function.

4.6 Probability of Detection for Rayleigh Channel

When a signal moves between transmitter and receiver, they follow different paths to arrive at the desired destination and there will be fading due to multipath propagation and shadowing. Those propagated signals can be generally represented by fading distribution models. From the fading model, Rayleigh channel is the most common way of fading representation. This model used as a tool for examining of typical environment having both multipath and path loss behavior in which the received signals are not on a line of sight from the source and the amplitude of signal follows a feature of Rayleigh distribution [44].

In Rayleigh fading channel the attenuation of the signal will be distributed in Rayleigh manner that makes exponential distribution of SNR at every node. Probability of detection and probability of false alarm can be derived for Rayleigh channel as it is done for non-fading or AWGN channel. An expression for P_d in Rayleigh fading channel can be determined by averaging P_d in the case of AWGN channel [54]. Since false alarm probability is independent of SNR the expression of P_{FA} didn't change for fading channel at all, which means the same as in AWGN channel. If the amplitude the signal have a feature of Rayleigh distribution , then the SNR γ follows an exponential probability density function (PDF) and can be exprssed as [54].

$$f(\gamma) = \frac{1}{\gamma}\exp\left(-\frac{\gamma}{\bar{\gamma}}\right) \qquad \gamma \geq 0 \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 4.28$$

Then to obtain the probability of detection for Energey detection for Rayleigh channels, the exponential probability density function is averaged over P_d of AWGN channel ,equation (4.28) over equation (4.27) i.e.;

$$P_{D\ ray=} \int_0^{\infty} P_d\, f(\gamma)d\gamma \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 4.29$$

from (4.27) ,

$$P_{D\ Ray=} \frac{1}{\gamma}\int_0^{\infty} Q_d(\sqrt{2\gamma}, \sqrt{\lambda}) \ \exp\left(-\frac{\gamma}{\bar{\gamma}}\right) d\gamma \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 4.30$$

Substituting $\sqrt{\gamma} = x$; $\Rightarrow d\gamma = 2xdx$ above, yields;

$$P_{dE\ Ray=} \ \frac{2}{\gamma}\int_0^{\infty} x.\ Q_d(\sqrt{2x}, \sqrt{\lambda}) \ \exp\left(-\frac{x^2}{\bar{\gamma}}\right) dx \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 4.31$$

Substituting $P^2 = \frac{2}{\bar{\gamma}}$, $a = \sqrt{2}$, $b = \sqrt{\lambda}$ and M = d yields the Probability of detection in Rayleigh channel as:

$$P_{d\ Ray} = e^{-\frac{\lambda}{2}} \sum_{n=0}^{d-2} \frac{1}{n!}\left(\frac{\lambda}{2}\right)^n + \frac{(1+\bar{\gamma})^{d-1}}{\bar{\gamma}}\left(e^{-\left(\frac{\lambda}{2(1+\bar{\gamma})}\right)} - e^{-\frac{\lambda}{2}} \sum_{n=0}^{d-2} \frac{1}{n!} \left(\frac{\lambda\bar{\gamma}}{2(1+\bar{\gamma})}\right)\right) \qquad \dots\dots\ 4.32$$

Where $\bar{\gamma}$ is the average SNR, λ is the threshold, $d = TBw \ and \ n$ = d/2

4.7 Detection Analysis of Matched filter Detector Algorithm

Matched filter detection is an optimal detection scheme as it maximizes the output of the received SNR [12] and also needs shorter time to perform a certain probability of false alarm or probability of detection as compared to other detection techniques. On the other hand matched filter detector needs some priori knowledge regarding to the feature of primary users' which includes bandwidth, frequency, modulation type that enables to the demodulation of received signals. But in this work we assume that the primary user transmitter forwards the pilot stream together with the data and the secondary user will receive both the signal and pilot data from the PU. So spectrum detection speed and accuracy will increase due to the presence of priori knowledge at the secondary user. Matched filter detector is therefore considered as the most efficient method for primary user detection as it takes smaller time to determine the probability of detection and false alarm [10] and also it enlarges the smaller received SNR value in the presence of noise. The general spectrum sensing model of matched filter detector algorithm looks like the following.

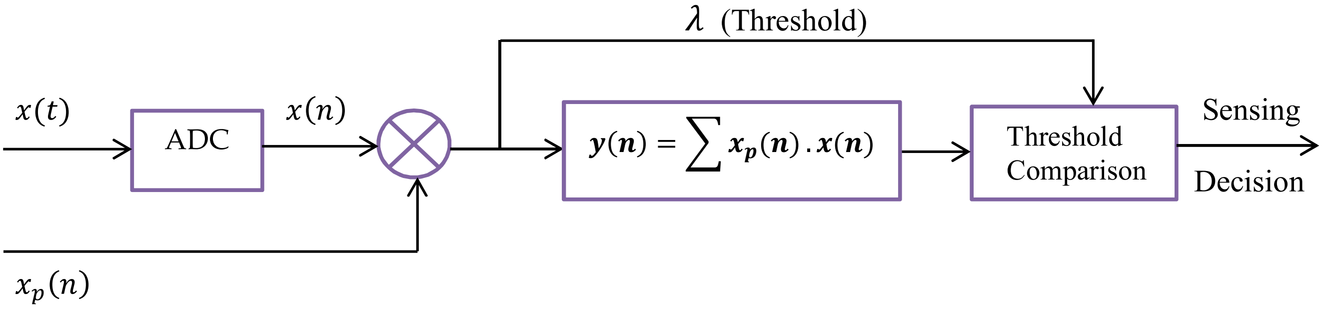

Figure 4.3: Matched filter detection algorithm

As shown in the figure above $x(t)$ is the secondary user received signal and $x_p\,(n)$ is the prior pilot stream regarding to PU signal containing pilot data's. The input signal is given to analog to digital convertor and the output from this will be multiplied with the prior primary signal and those multiplied signal will be given to summation block to get the decision statistics of matched filter detector. Finally, the output from matched filter detector is compared to the threshold value in order to identify weather the licensed user signal is present or absent.

The test statistics for matched filter detector can be obtained as in [47]

$$T_{MFD} = \frac{1}{N} \sum_{n=0}^{(N-1)} \left(x\,[n] * \, x_p\,[n] \right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .4.33$$

Where $x_p\,(n)$, is the primary user signal and $x(n)$ is the secondary user received signal. To give sensing decision about the availability of PU signal, the test statistics T_{MFD} from matched filter detector is then compared with that of pre-identified threshold. It is assumed that the received signal at secondary user which is transmitted signal by primary user and T_{MFD} are approximated to be a Gaussian random variables. Since if the two single signals are Gaussian random variable it is clear that their linear combination will also be Gaussian random variable that why T_{MFD} becomes Gaussian random variable.

Since the test statistic of matched filter detector T_{MFD} is normally distributed under H_0 and H_1 hypotheses [47], thus

$$T_{MFD} \sim \begin{cases} N\left(0, \quad \sigma_v^2\ \varepsilon_p\ \right) & : \ for\ \ H_0 \\ N\left(\varepsilon_p, \quad \sigma_v^2\ \varepsilon_p\right) & : \ for\ \ H_1 \end{cases} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .4.34$$

Where ε_p , is the average primary user signal energy and σ_v is noise variance. Then to get the corresponding probability density function (PDF) and to see the performance of matched filter detector we divide equation 4.34 by $\sqrt{\sigma_v^2\ \varepsilon_p}$ and the test statistics for matched filter will be

$$T_{MFD} \sim \begin{cases} N\,(0, \qquad 1\ \ ) & : \qquad for\ \ H_0 \\ N\left(\sqrt{\varepsilon_p\,/\sigma_v^2}\ , \qquad 1\right) & : \qquad for\ \ H_1 \end{cases} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .4.35$$

4.7.1 Probability of Detection Alarm

After test statistics of matched filter detector is determined, probability of detection for this detector algorithm can be calculated by the given equations. Then from the Neyman-Pearson hypothesis and criterion as expressed in [56] the probability of detection and false alarm can be calculated as follows.

$$Pd = \Pr(H_1 \mid H_1) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.36$$

$$Pd = \Pr(T_{MFD} > \boldsymbol{\lambda} \mid H_1) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.37$$

$$P_{dmf} = P\left(T_{MFD} > \frac{\lambda}{\sqrt{\sigma_v^2 \ \varepsilon_p}} \mid H_1 \right)$$

$$P_{D,MF} = Q\left(\frac{\lambda_m - \varepsilon_p}{\sqrt{\varepsilon_p \, \sigma_v^2}}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.38$$

Where, λ_m = Threshold Value, σ_v is noise variance, Q (,) and ε_p are the Generalized Marcum Q-function and received primary signal energy respectively.

4.7.2 Probability of False Alarm:

Similarly probability of false alarm for matched filter detector can also be determined and manipulated as follows;

$$Pf = \mathrm{P}\,(H_1 | H_0) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.39$$

$$Pf = P\,(T_{MFD} > \lambda \mid H_0) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.40$$

$$P\left(T_{MFD} > \frac{\lambda}{\sqrt{\sigma_v^2 \ \varepsilon_p}} \mid H_0 \right)$$

The final expression for probability of false alarm for matched filter detector is given by,

$$P_{fa,MF} = \mathrm{Q}\left(\frac{\lambda_m}{\sqrt{\varepsilon_p\,\sigma_v^2}}\right) \qquad \text{……………….………..…………… 4.41}$$

Where, λ_m = Threshold Value $\qquad$ σ_v^2 = Noise variance.

$\varepsilon_p = \frac{1}{N}\ \sum_{n=1}^{N}\ (\,x_p\,(n)\,)^2$ denotes the input pilot signal's energy.

The sensing threshold λ_m is expressed as a function of the PU signal energy and noise variance [15]:

$$\lambda_m = Q^{-1}(P_{fa})\sqrt{\varepsilon_p\sigma_v^2} \qquad \text{…….……………………...…….………4.42}$$

Now, probability of miss detection is the complement of probability of detection and the decision is H_0 while H_1 is true which is given by.

$$P_{md} = \mathrm{P}(H_0|H_1) \qquad \text{..……………….……………………….4.43}$$

$$P_{md} = 1 - P\,(T_{MFD} > \lambda\,|H_1) \qquad \text{……………………………..……………4.44}$$

From the equation 4.38 the probability of miss detection for Matched filter detection method can be calculated as follows:

$$P_{md,MF} = (1 - P_{D,MF})$$

$$P_{md,MF} = 1 - Q\left(\frac{\lambda_m - \varepsilon_p}{\sqrt{\varepsilon_p\,\sigma_v^2}}\right) \qquad \text{…………………………………….…. 4.45}$$

4.8 Analysis of Noise Uncertainty on the Performance of Proposed Hybrid Detection Algorithm

When signals or information are delivered from the source to destination or from transmitter to receiver they will experience different challenges and obstacles. One of the challenges in spectrum detection is that of noise uncertainty. Noise uncertainty is caused by the variation or fluctuation of noise power. When there is uncertainty in noise density spectrum detection performance will be degraded and affected in which there can be confusion in identifying the noise from signal. In order to reduce the effect of noise uncertainty on detection performance hybrid detection by combining energy with matched filter detector is proposed in thesis work.

Analysis is made on the single energy and matched filter detector about the effect of uncertainty in noise. Finally the proposed hybrid detection is compared with that of energy and matched filter detection which shows significant performance enhancement regarding probability of detection by considering noise uncertainty.

At the receiver side the secondary user will calculate the amount of noise power to identify unoccupied channel. Most of the time average noise power is represented by σ^2 where as σ_n^2 represent the true noise power at a critical time and geographical location that shows the existence of noise uncertainty [57].

Assume, $\sigma^2 = \rho\sigma_n^2$ Where ρ is noise uncertainty factor

By taking noise uncertainty in to consideration the mathematical expression of distributional noise uncertainty can performed as [57].

$$\sigma^2 \in \left[\frac{\sigma_n^2}{\rho}, \rho\sigma_n^2\right] \qquad \text{……..…………………………………4.46}$$

Where σ_n^2 is the normal noise power and the parameter ρ is noise uncertainty factor that measure the amount of noise uncertainty.

Under the consideration of noise uncertainty, the probability of detection and probability of false alarm for matched filter detection can be determine as follows. This equation enables to analyze the result using matlab simulation. The average noise power approaches $\sigma^2 = \rho\sigma_n^2$ or $\sigma^2 = \frac{\sigma_n^2}{\rho}$ then substituting this, we get the following [47]. Where P is the signal energy value and N is the number of sample.

$$P_d = Q\left(\frac{\lambda - P}{\sqrt{\frac{P\sigma_n^2}{N\rho}}}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.47$$

The probability of false alarm can also be calculated as

$$P_f = Q\left(\frac{\lambda}{\sqrt{\frac{P\rho\sigma_n^2}{N}}}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.48$$

For energy detection algorithm the test statistics which are Pd and Pf can be modified and determined in noise uncertainty consideration as

$$\mathrm{P}_d = Q\left(\frac{\lambda - (P + \rho\sigma_n^2)}{\sqrt{\frac{2}{N}}(P + \rho\sigma_n^2)}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.49$$

Considering noise uncertainty, probability of false alarm for energy detector is also given as

$$\mathrm{P}_f = Q\left(\frac{\lambda - \rho\sigma_n^2}{\sqrt{\frac{2}{N}}\rho\sigma_n^2}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.50$$

Then by combing the two detectors, energy and matched filter detector together the effect of noise uncertainty on detection performance will be minimized. The analysis how to combine the two detectors detection alarm will be discussed next. In order to see and verify the above theoretical analysis a simulation is done using matlab software and a curve is plotted with Pd vs Noise uncertainty and Pmd vs noise uncertainty with a variable noise uncertainty coefficients.

4.9 Test Statistics Analysis for Proposed Hybrid Detection Techniques

In the previous discussion we have seen the test statistics which are false alarm, detection probability and miss detection probabilities for the individual energy and matched filter detectors. The flow chart for the enhanced hybrid detection is also presented and elaborated. Here we will present the performance evaluation methods including P_d , P_f and P_{md} for the proposed hybrid sensing techniques. The proposed hybrid detection is the combination of the two sensing techniques, which are energy and matched filter detector algorithms. Even though energy detector used most of the time, there is a limitation in detecting the user signal at smaller received signal to noise ratio. So when the SNR is weak energy detector may get difficulty in identifying the availability of unused frequency band and also a harmful interference may occur with licensed user. In this case when there is a missed detection by energy detection at smaller SNR value, matched filter detection is applied on the system since matched filter is good at detecting poor received signal to noise ratio value.

So in this work the proposed hybrid detection is more effective in detecting the available spectrum and also good at detecting lower SNR values and also minimize interference with primary user. The probability of detection alarm undergoing on matched filter detection ($P_{d,MF}$) in hybrid scheme over AWGN and Rayleigh channels can be expressed as follows.

In the proposed hybrid detection the probability of detection of matched filter detector is equal to probability of miss detection by energy detection which is given as,

$P_{d,MF}$ = Probability of a missed detection by Energy detection

$P_{d,MF}$ = 1- $P_{d,ED}$ $= P_{md,ED}$ which is

$$P_{d,MF} = P_{m,ED} \quad \text{…..……..……………………….………..4.51}$$

$$P_{d,MF} = 1 - Q(\sqrt{2\gamma} \, ,\sqrt{\lambda} \quad \text{……..…..………..……………………..4.52}$$

So the overall mathematical analysis of hybrid detection for probability of detection, probability of false alarm and for miss detection alarm can be performed in the following way.

The analysis is done for both fading and non-fading channel.

$$P_{d,hybrid} = P_{d,ED} + (1 - P_{d,ED})(P_{d,MF}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.53$$

$$P_{d,hyb} = P_{d,ED} + P_{md,ED} * P_{d,MF} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.54$$

Where $P_{md,ED}$ is probability of miss detection by energy detector and $P_{d,MF}$ is probability detection for matched filter detector.

Similarly probability of false alarm for the proposed hybrid detection is given by

$$P_{fa,hybrid} = P_{fa,ED} + (1 - P_{fa,ED})(P_{fa,MF}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.55$$

Then the missed detection probability ($P_{d,hybr}$) of hybrid scheme is given as

$$P_{md,hybr} = 1 - P_{d,hybri} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.56$$

For hybrid of energy and cyclostationary detector probability of detection is given as follows. We substitute cyclostationary detector in the place matched filter detector which is given by

$$P_{d,hybr} = P_{d,ED} + (1 - P_{d,ED})(P_{d,cyclo})$$

The above mathematical equation is also applied in the cause of noise uncertainty and the proposed hybrid detection offers a good detection performance than the single detector and hybrid of energy and cyclostationary detector. Simulation results and discussion have been carried out in the next chapter briefly.

Chapter Five

Simulation Results and Discussion

In the previous chapters we have discuss the mathematical analysis and the system model for the desired energy and proposed hybrid detection. The mathematical analysis enables to describe and present about the theoretical concept of detecting user signal energy in radio spectrum. In this chapter the performance of energy, matched filter and proposed hybrid spectrum detection method are evaluated and enhanced. The efficiency of the detection algorithm is measured based on the key performance measurements which are probability of detection, probability of false alarm, probability of misdetection and the signal-to noise ratio. These detection performance measurements are illustrated by the receiver operating characteristics (ROC) curve which is a plot of Pd versus Pf , Pd versus SNR or Pd versus Pm and Pd versus noise uncertainty.

Based on the mathematical analysis, results were done for both non-fading and fading channel (AWGN and Rayleigh channel) using MATLAB simulation.

5.1 Simulation Parameters and Discussion

The various values of the simulation parameters taken are tabulated as follows:

Table 2: Parameter names and values for simulation results

Parameter Name	Value and Type Considered
Channel type	AWGN and Rayleigh
Detector Type	Energy, Matched filter and Hybrid Detector
Noise Uncertainty Range	1 to 10
Transmitted signal (SNR) range	-30dB to 10dB
Probability of false alarm	0 to 1
Number of monte carlo simulation	100000
Simulation platform	Matlab2013a
Number of Samples N	40, 60
Cognitive user	Single user

5.1.1 Matlab Simulation Results and Discussion of Energy, Matched filter and Proposed Hybrid Detection for AWGN Channel

The following result shows the performance of probability of detection with signal to noise ratio for energy matched filter and hybrid detection. The result depicts for an AWGN channel and probability of false alarm is set to be fixed at P_{FA} =0.08 with number of monte carlo samples of 10000 and a variable signal to noise ratio (SNR) ranging from -30dB to 5 dB. As shown from the result in the region of lower SNR value from -30 to -10dB the detection performance is poor for energy detector which is tabulated in the table below. But for matched filter detector probability of detection for those smaller SNR value is better than energy detector. Then by combining energy and matched filter detector together, probability of detection can be enhanced at lowered user signal value as depicts in the plot below. Probability of detection at -30 dB is 0.02 for energy detection and 0.18 for proposed hybrid detection.

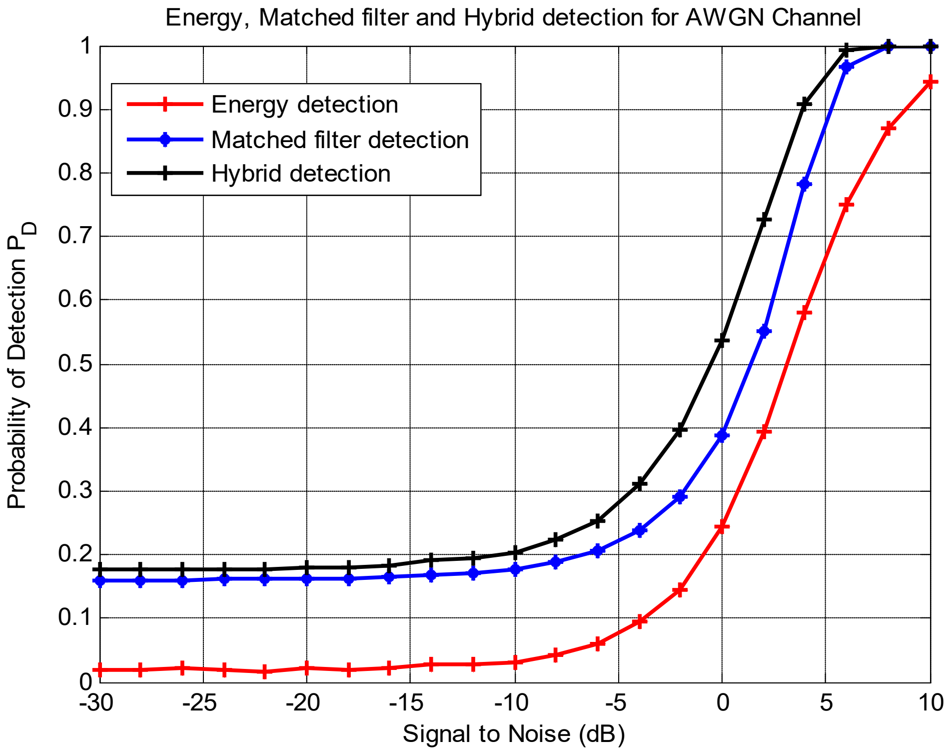

Figure 5.1: Probability of detection Vs SNR of Energy, Matched filter and Hybrid Detection

The result tabulated below shows probability of detection for energy detection, matched filter detection and proposed hybrid detection as a function of variable SNR ranging from -30 dB to 10dB to see the detection condition at lower and higher SNR value. From table 4 under smaller SNR value where by the signal amount is lower than noise value energy detector performs weak detection but the proposed hybrid detection performs well. So spectrum detection is enhanced by combing energy and matched filter detector together.

Table 3: Simulation result of Pd vs SNR for energy matched filter and hybrid detectors.

SNR (dB)	P_{ED}	P_{MFD}	P_{HD}	SNR(dB)	P_{ED}	P_{MFD}	P_{HD}
-30	0.0201	0.1603	0.1770	-10	0.0315	0.1780	0.2039
-28	0.0203	0.1604	0.1775	-8	0.0412	0.1890	0.2224
-26	0.0210	0.1606	0.1783	-6	0.0592	0.2072	0.2542
-24	0.0201	0.1609	0.1788	-4	0.0951	0.2382	0.3107
-22	0.0172	0.1613	0.1792	-2	0.1459	0.2920	0.3953
-20	0.0205	0.1619	0.1797	0	0.2435	0.3872	0.5365
-18	0.0208	0.1629	0.1800	2	0.3922	0.5505	0.7268
-16	0.0217	0.1645	0.1827	4	0.5815	0.7830	0.9092
-14	0.0282	0.1671	0.1907	6	0.7498	0.9657	0.9914
-12	0.0289	0.1713	0.1945	8	0.8713	0.9997	1

The next result as depicted in figure 5.2 shows receiver operating characteristics curve of probability of detection with false alarm probability for AWGN channel model. The plot carried out for a fixed received SNR value of -15 dB. As shown in the plot probability of detection increases for matched filter and proposed hybrid detection even at smaller Pf value of 0.01 but for the case of energy detector probability of detection increases after a Pf value of 0.26.

The simulated plot shows the area covered by energy detector is lower than the prosed hybrid detection at specific probability of false alarm. If we take Pf value of 0.3 then Pd for energy detector is 0.03 and for proposed hybrid detection Pd is 0.39 at that pf value. So the proposed hybrid detection offers good performance detection. The physical significance of this graph is that energy detector at higher Pf value energy detector unfortunately cross matched filter detector and it leads to miss spectrum opportunity.

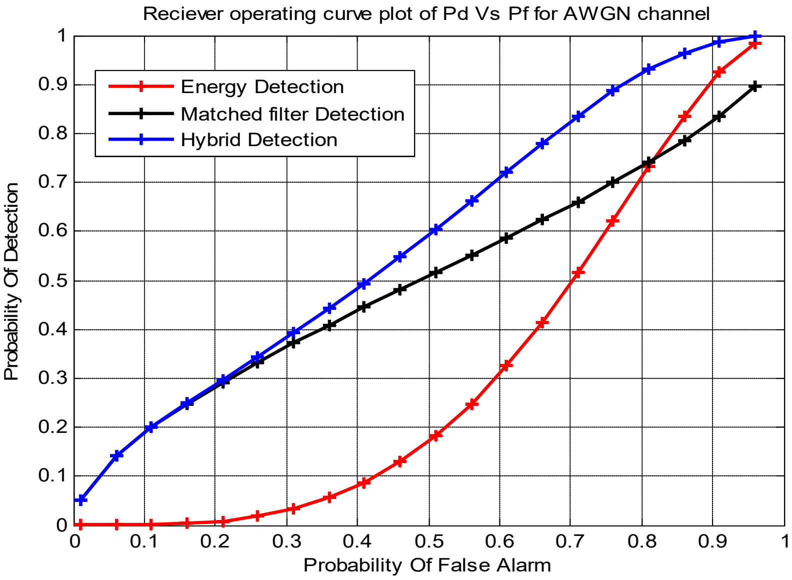

Figure 5.2: Probability of detection Vs Pf of Energy, Matched filter and Hybrid Detection

The result of the above plot is summarized and tabulated in the table shown below.

Table 4: Simulation result of Pd vs Pf for energy matched filter and hybrid detectors AWGN channel.

Pf	P_{ED}	P_{mfD}	P_{HD}	Pf	P_{ED}	P_{mfD}	P_{HD}
0.01	1.63e-7	0.0523	0.0523	0.51	0.1823	0.5159	0.6042
0.06	9.59e-5	0.1407	0.1408	0.56	0.2477	0.5513	0.6625
0.11	8.36e-4	0.1990	0.1997	0.61	0.3255	0.5870	0.7214
0.16	0.0032	0.2479	0.2504	0.66	0.4151	0.6232	0.7796
0.21	0.0084	0.2918	0.2978	0.71	0.5149	0.6604	0.8352
0.26	0.0178	0.3326	0.3446	0.76	0.6220	0.6990	0.8862
0.31	0.0331	0.3713	0.3921	0.81	0.7315	0.7399	0.9301
0.36	0.0557	0.4086	0.4415	0.86	0.8361	0.7841	0.9646
0.41	0.0872	0.4449	0.4933	0.91	0.9256	0.8340	0.9876
0.46	0.1291	0.4805	0.5476	0.96	0.9853	0.8962	0.9985

The next result as depicted in figure 5.3 shows complementary receiver operating characteristics curve of probability of miss detection as a function of variable signal to noise ratio (SNR) value. As shown in the plot probability of miss detection increases for smaller value of received signal to noise ratio especially for energy detector. At smaller SNR around -5 dB probability of miss detection for energy detector is 0.94 and it is 0.72 for proposed hybrid detection. So probability of miss detection is lowered for proposed hybrid detection in smaller SNR than the single energy detection.

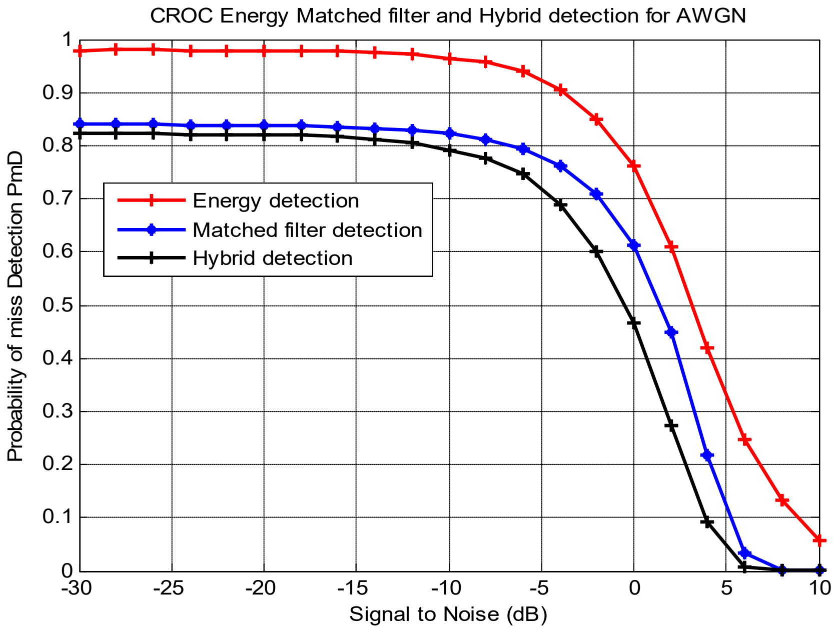

Figure 5.3: Probability of Miss Detection Vs Signal to Noise Ratio (SNR) for the three Detectors.

Table 5: Result of Probability of miss detection Vs SNR for three detector types

SNR (dB)	P_{mdED}	P_{mdMF}	P_{mdHD}	SNR(dB)	P_{mdED}	P_{mdMF}	P_{mdHD}
-30	0.9812	0.8892	0.8771	-10	0.9509	0.7303	0.7138
-28	0.9790	0.8646	0.8533	-8	0.9397	0.7113	0.6921
-26	0.9788	0.8438	0.8339	-6	0.9062	0.6871	0.6575
-24	0.9778	0.8201	0.8067	-4	0.8524	0.6530	0.6097
-22	0.9766	0.8060	0.7962	-2	0.7593	0.6016	0.5369
-20	0.9745	0.7914	0.7801	0	0.5998	0.5208	0.4138
-18	0.9740	0.7800	0.7668	2	0.4153	0.3974	0.2615
-16	0.9739	0.7707	0.7597	4	0.2570	0.2294	0.1087
-14	0.9679	0.7593	0.7464	6	0.1280	0.0675	0.0196
-12	0.9509	0.7462	0.7331	8	0.0547	0.0037	0.0052

5.1.2 Matlab Simulation Results and Discussion of Energy, Matched filter and Hybrid Detection for Rayleigh Channel

Figure 5.4 shows probability of detection with probability of false alarm at a fixed SNR value for Rayleigh channel. When false alarm rate increases from 0 to 1, detection probability also increases. When we consider Pf = 0.2 then the detection area is more improved in proposed hybrid detection than energy detection. That is Pd=0.45 for hybrid detection and Pd= 0.06 for energy detector at Pf =0.2. But when probability of false alarm approaches to 0 unfortunately detection probability decreased down 0 especially for energy detection. As shown in the plot, energy detection is somehow far away from the proposed hybrid detection that is due to the effect of fading channel. The curve of energy detector is different from AWGN due to the effect of Rayleigh channel, the non- line-of-sight communication between the transmitter & the receiver.

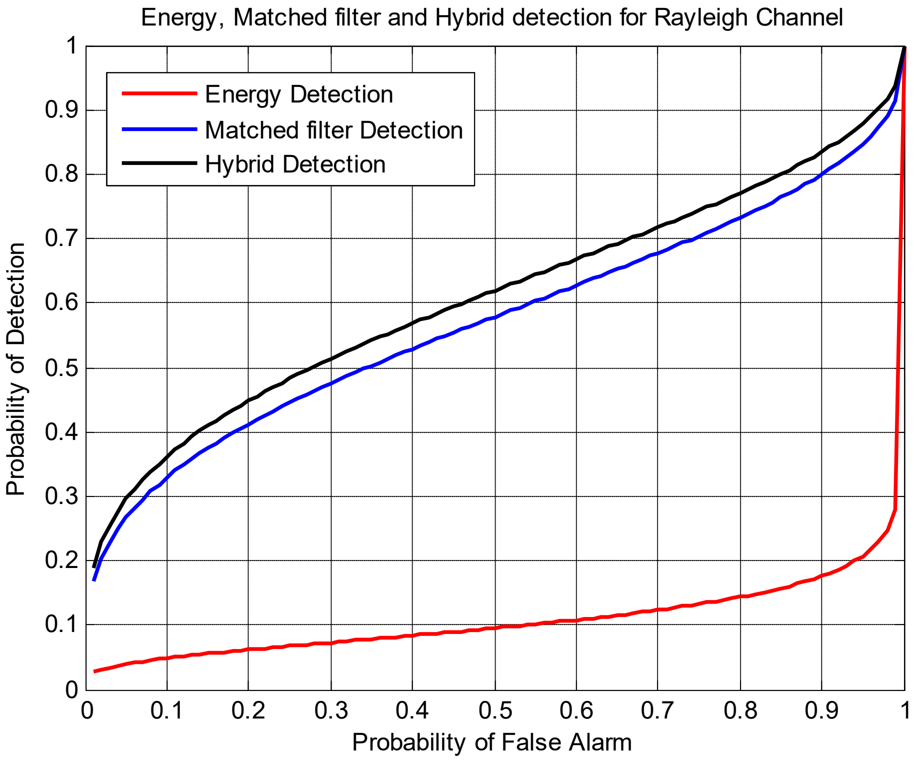

Figure 5.4: Probability of detection Vs Probability of false alarm for Energy, Matched filter and Proposed Hybrid Detection in Rayleigh Channel.

Table 6: Result of Pd Vs Pf for energy detector matched filter detector and hybrid detector

Pf	P_{ED}	P_{mfD}	P_{HD}	Pf	P_{ED}	P_{mfD}	P_{HD}
0.01	0.0270	0.1674	0.1899	0.50	0.0953	0.5788	0.6190
0.05	0.0399	0.2665	0.2958	0.55	0.1015	0.6032	0.6435
0.10	0.0487	0.3293	0.3620	0.60	0.1081	0.6276	0.6640
0.15	0.0557	0.3748	0.4096	0.65	0.1153	0.6523	0.6924
0.20	0.0617	0.4122	0.4485	0.70	0.1233	0.6776	0.7174
0.25	0.0674	0.4450	0.4824	0.75	0.1325	0.7041	0.7433
0.30	0.0729	0.4748	0.5131	0.80	0.1434	0.7323	0.7707
0.35	0.0783	0.5025	0.5415	0.85	0.1571	0.7634	0.8005
0.40	0.0838	0.5288	0.5684	0.90	0.1760	0.7994	0.8347
0.45	0.0894	0.5542	0.5940	0.95	0.2477	0.8464	0.8782

Figure 5.5 depicts the matlab result of energy and the enhanced hybrid detector as a function of Pd with variable SNR value for Rayleigh channel . Comparing to the result found in AWGN channel the detection found here for energy detector and proposed hybrid detection is some how decreased at lower SNR. This due to the effect of fading channel which is rayleigh channel.But here at SNR= -25dB, Pd is 0.013 for energy detector and it is 0.12 for proposed hybrid detection.So at smaller SNR and in fading channel the proposed hybrid detection has a good performance than energy detector.

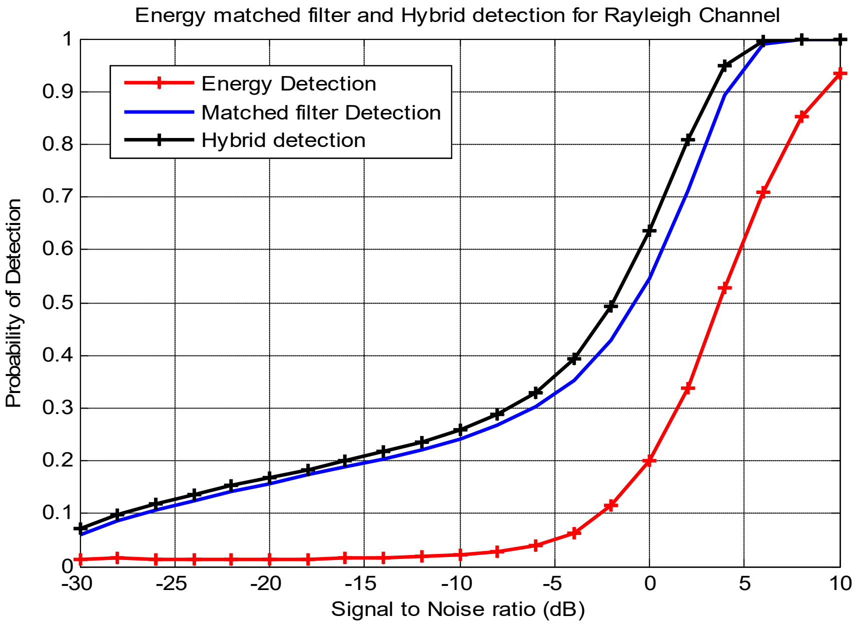

Figure 5.5: Probability of detection Vs SNR for Energy, Matched filter & Hybrid detector for Rayleigh channel

Table 7: Matlab result for energy matched filter and hybrid detector of Pd vs SNR at Rayleigh channel

SNR (dB)	P_{ED}	P_{MFD}	P_{HD}	SNR(dB)	P_{ED}	P_{MFD}	P_{HD}
-30	0.0118	0.0561	0.0702	-10	0.0315	0.2439	0.2621
-28	0.0125	0.0831	0.0944	-8	0.0412	0.2707	0.2905
-26	0.0129	0.1053	0.1164	-6	0.0592	0.3064	0.3336
-24	0.0126	0.1232	0.1347	-4	0.0951	0.3571	0.4012
-22	0.0138	0.1421	0.1549	-2	0.1459	0.4322	0.4976
-20	0.0139	0.1569	0.1687	0	0.2435	0.5478	0.6360
-18	0.0144	0.1722	0.1828	2	0.3922	0.7139	0.8134
-16	0.0150	0.1872	0.1994	4	0.5815	0.8943	0.9353
-14	0.0159	0.2043	0.2168	6	0.7498	0.9898	0.9505
-12	0.0160	0.2233	0.2375	8	0.8713	1.0000	0.9971

The simulation result depicted in figure 5.6 below shows ROC of false alarm detection with that of probability of miss detection at Rayleigh channel. From the plot at smaller value of Pf probability of miss detection become higher especially for energy detector. Here the simulation is made for a fixed value of SNR. From the result, at Pf = 0.3 P_{mED} = 0.92 for energy detector and P_{mHD}= 0.48 for hybrid detection. Here the curve is different from AWGN channel due to large number of reflective path.

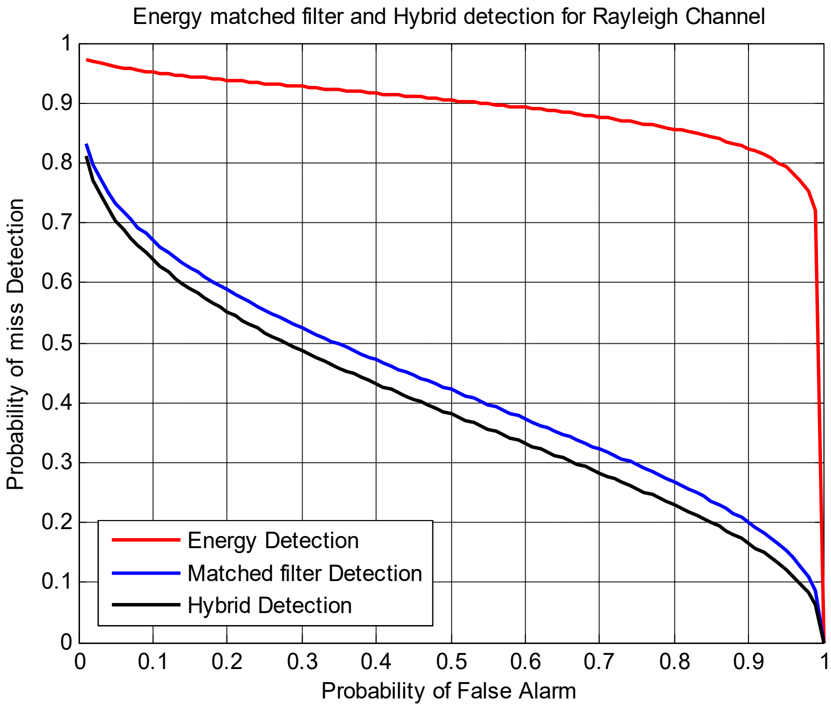

Figure 5.6: Probability of miss detection vs probability of false alarm for Energy, Matched filer and Proposed Hybrid Detector.

Table 8:ROC result of Pmd Vs Pf for energy, matched filter and proposed hybrid detector

P_f	P_{mED}	P_{mMFD}	P_{mHD}	P_f	P_{mED}	P_{mMFD}	P_{mHD}
0.01	0.9730	0.8325	0.8001	0.50	0.9046	0.4211	0.3809
0.05	0.9601	0.7334	0.7042	0.55	0.8985	0.3967	0.3564
0.10	0.9512	0.6706	0.6379	0.60	0.8919	0.3723	0.3320
0.15	0.9443	0.6251	0.5903	0.65	0.8847	0.3476	0.3075
0.20	0.9382	0.5877	0.5514	0.70	0.8766	0.3223	0.2825
0.25	0.9325	0.5549	0.5175	0.75	0.8674	0.2958	0.2566
0.30	0.9270	0.5251	0.4868	0.80	0.8565	0.2676	0.2292
0.35	0.9216	0.4974	0.4584	0.85	0.8428	0.2366	0.1994
0.40	0.9161	0.4711	0.4316	0.90	0.8240	0.2005	0.1652
0.45	0.9105	0.4458	0.4059	0.95	0.7928	0.1535	0.1217

5.1.3 Matlab Simulation Results and Discussion of Energy, Matched filter and Proposed Hybrid Detection in the Uncertainty of Noise

The result that is depicted in figure 5.7 below shows the effect of noise uncertainty on detection performance. The plot is performed for a fixed value of Pf and SNR and varying the noise uncertainty.

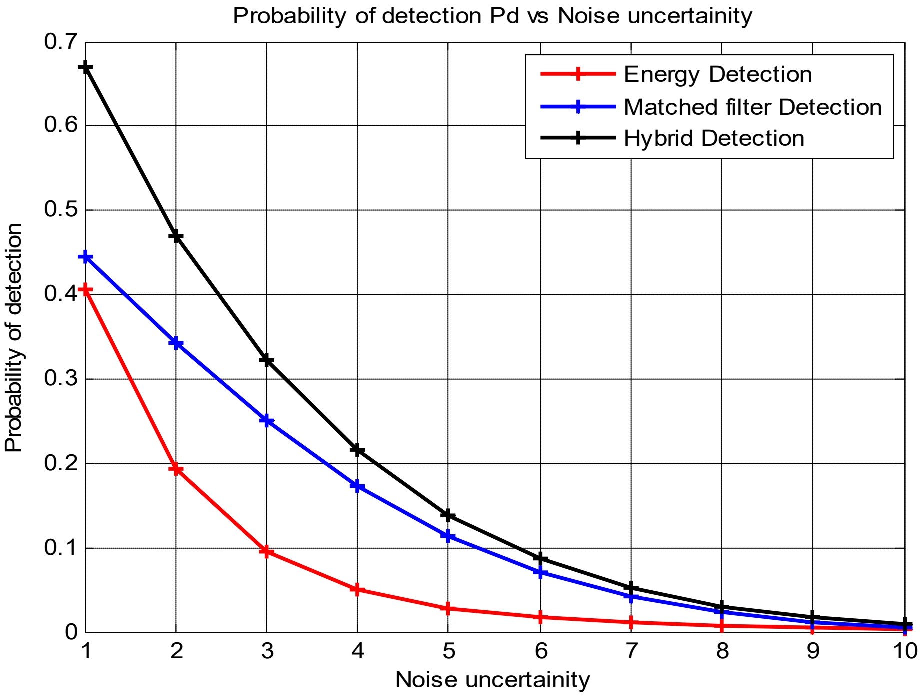

Figure 5.7: Pd Vs Noise uncertainty for Energy, Matched filter and Proposed Hybrid Detectors

As shown on the matlab plot in the above figure probability of detection is inversely proportional to noise uncertainty which means when the value of noise uncertainty increases, probability of detection will decrease. At noise uncertainty value of 3, probability of detection for energy detector P_{ED} = 0.095 and for that of proposed hybrid detection P_{HD}= 0.32 at smaller received SNR of -4 dB. But when we decrease SNR from -4 dB to -6 dB, noise uncertainty affect the detection performance especially that of energy detector but the performance of detection in proposed hybrid detection is better even in higher noise uncertainty and smaller SNR. This due to the fact that matched filter detector is good enough to detect at noisy environment and combing with energy detector becomes effective.

The following table summarizes about the analysis of noise uncertainty on detection performance on energy, matched filter and hybrid detection at two different values of signal to noise ratio SNR value. When noise uncertainty value increases and SNR decreases detection performance degrades.

Table 9: Output of Pd Vs Noise uncertainty for energy, matched filter and hybrid detectors

	Probability of detection SNR= -4 dB			Probability of detection SNR= - 6 dB		
Noise Uncertainty	P_{ED}	P_{MFD}	P_{HD}	P_{ED}	P_{MFD}	P_{HD}
1	0.4068	0.4442	0.6703	0.2642	0.4259	0.5776
2	0.1939	0.3422	0.4698	0.0846	0.3253	0.3824
3	0.0949	0.2506	0.3217	0.0322	0.2360	0.2606
4	0.0498	0.1739	0.2151	0.0147	0.1623	0.1745
5	0.0282	0.1141	0.1391	0.0078	0.1054	0.1123
6	0.0172	0.0706	0.0866	0.0046	0.0645	0.0688
7	0.0111	0.0411	0.0518	0.0029	0.0372	0.0401
8	0.0075	0.0225	0.0300	0.0021	0.0201	0.0222
9	0.0053	0.0116	0.0170	0.0015	0.0102	0.0118
10	0.0039	0.0056	0.0096	0.0011	0.0049	0.0060

The following simulated graph that is depicted in figure 5.8 shows the relation of complementary ROC of probability of miss detection with noise uncertainty. As shown on plot probability of miss detection increases when the noise uncertainty approaches to 10. Compared to energy and matched filter detection, the proposed hybrid detection performs well by minimizing probability of miss detection even at higher noise uncertainty scenario. With numerical and simulation results as shown below with noise uncertainty value of 4, $P_{md} = 0.95$ for energy detection and $P_{md} = 0.7$ for proposed hybrid detection at fixed SNR of -4 dB.

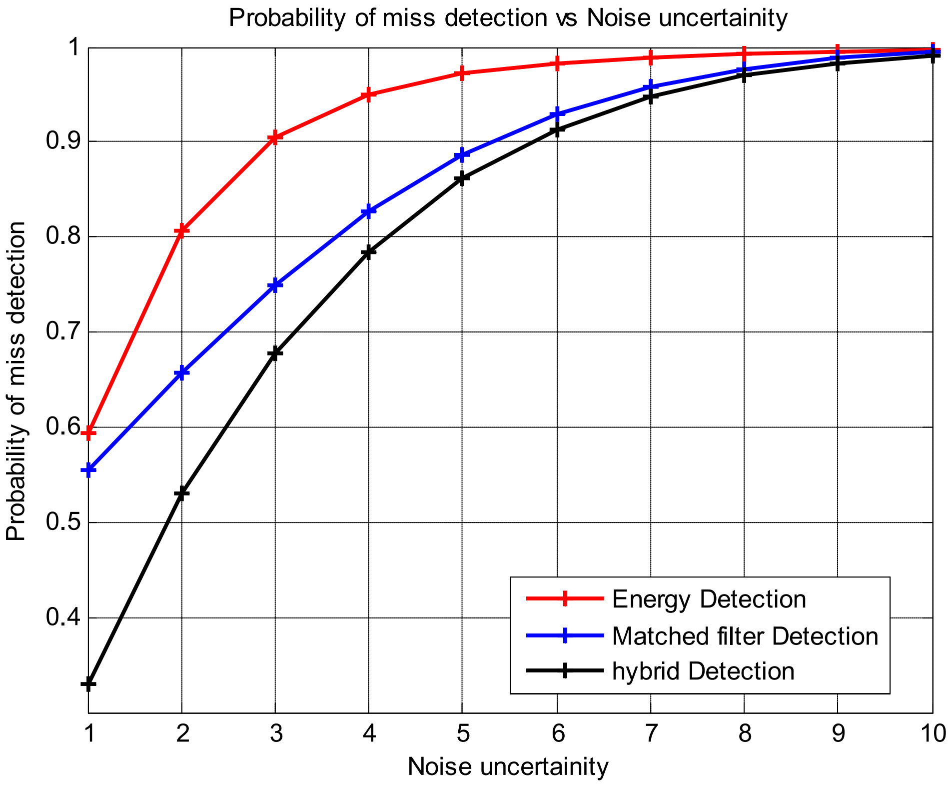

Figure 5.8: ROC of Pd Vs Noise uncertainty for Energy, Matched filter and Hybrid Detectors

The above discussion and simulated graph is numerically summarized and tabulated in the table shown below. Two SNR values are considered and probability of false alarm is fixed here. The noise uncertainty varies from 1 up to 10 to get a visible result. As observed in graph as well as in the numerical result table, it can be conclude that the proposed hybrid detection performs well in the uncertainty of noise.

Table 10: ROC result for Pd Vs Noise uncertainty for Energy, Matched filter and Hybrid Detectors

	Probability of miss detection SNR= -4dB			Probability of miss detection SNR= - 6dB		
Noise Uncertainty	P_{mED}	$P_{m\ MFD}$	P_{mHD}	P_{mED}	P_{mMFD}	P_{mHD}
1	0.5931	0.5557	0.3296	0.7357	0.5740	0.4223
2	0.8060	0.6577	0.5301	0.9153	0.6746	0.6175
3	0.9050	0.7493	0.6782	0.9677	0.7639	0.7393
4	0.9501	0.8260	0.7849	0.9852	0.8377	0.8254
5	0.9717	0.8858	0.8608	0.9922	0.8945	0.8876
6	0.9828	0.9293	0.9133	0.9953	0.9354	0.9311
7	0.9888	0.9588	0.9481	0.9970	0.9627	0.9598
8	0.9924	0.9774	0.9700	0.9979	0.9798	0.9777
9	0.9946	0.9883	0.9830	0.9984	0.9897	0.9882
10	0.9960	0.9943	0.9904	0.9988	0.9950	0.9939

5.1.4 Performance Comparison and Result discussion of Proposed Hybrid Detection with other Hybrid Detection Algorithms for Rayleigh Channel

The result of proposed hybrid detection which is the combination of energy with matched filter detection is performed for both fading and non-fading channel. As shown in the result below, the detection performance between hybrid of energy and cyslostastionary detector is compared with proposed hybrid of energy and matched filter detection algorithms. From the result obtained, at SNR value of -20 dB, probability of detection for hybrid of energy and cyclostationary detector is 0.09 and for proposed hybrid of energy and matched filter detector, it is 0.165. From this work, matched filter detector performs good detection performance at a lower SNR region and enhance energy detector.

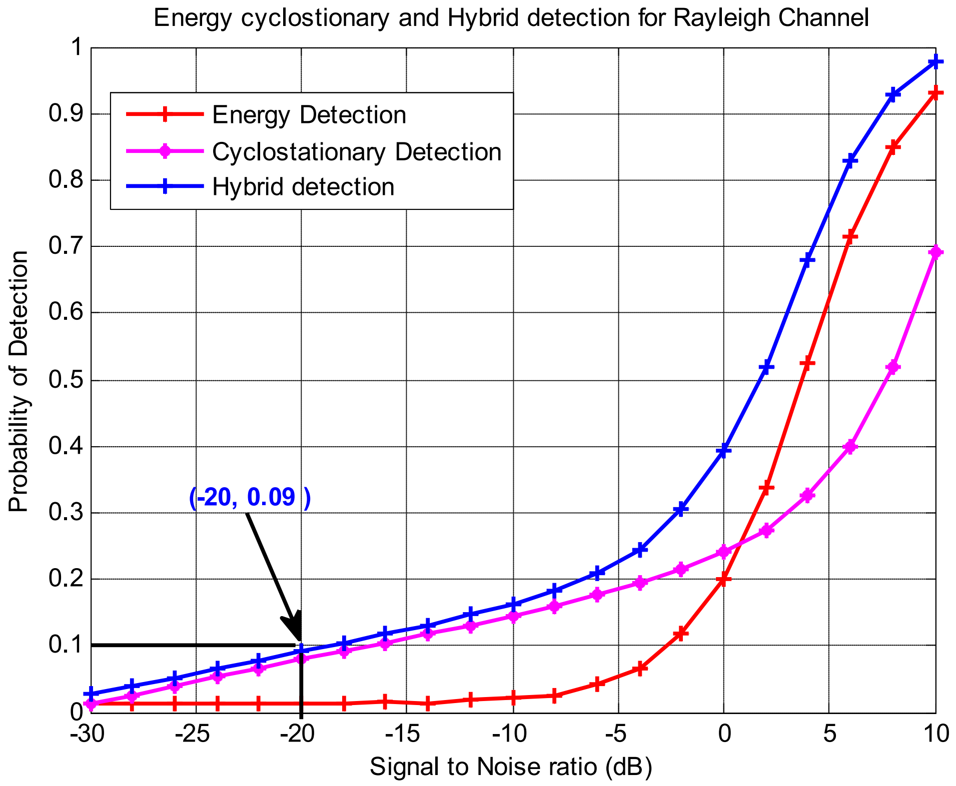

Figure 5.9 : Result of Pd Vs SNR for Energy, Cyclostationary and Hybrid Detectors for Rayleigh channel

Table 11: Matlab result for energy, cyclostationary and hybrid detector of Pd vs SNR at Rayleigh channel

SNR (dB)	P_{ED}	P_{CyD}	P_{HD}	SNR(dB)	P_{ED}	P_{CyD}	P_{HD}
-30	0.0142	0.0138	0.0278	-10	0.0208	0.1456	0.1633
-28	0.0126	0.0261	0.0383	-8	0.0258	0.1598	0.1815
-26	0.0126	0.0399	0.0520	-6	0.0419	0.1757	0.2102
-24	0.0132	0.0539	0.0664	-4	0.0646	0.1935	0.2456
-22	0.0132	0.0661	0.0784	-2	0.1183	0.2137	0.3067
-20	**0.0134**	**0.0795**	**0.0918**	**0**	**0.2014**	**0.2400**	**0.3931**
-18	0.0131	0.0920	0.1039	2	0.3384	0.2740	0.5197
-16	0.0147	0.1046	0.1178	4	0.52570	0.3251	0.6799
-14	0.0146	0.1177	0.1306	6	0.7144	0.4004	0.8287
-12	0.0191	0.1303	0.1469	8	0.8496	0.5200	0.9278

As observed in the result at figure 5.9 and 5.10 the presence of fading channel somehow affects hybrid of energy and cyclostationary detector than proposed hybrid of energy and matched filter detector.

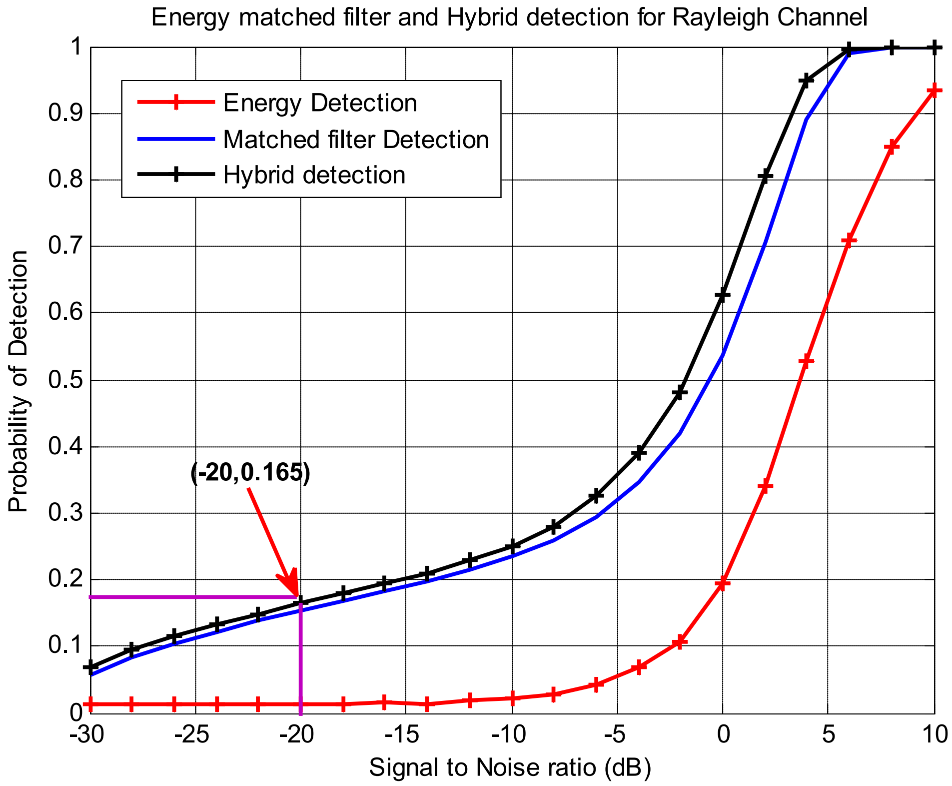

Figure 5.10: Result of Pd Vs SNR for Energy, Matched filter and Hybrid Detectors for Rayleigh channel

Table 12: Matlab result for energy matched filter and hybrid detector of Pd vs SNR at Rayleigh channel

SNR (dB)	P_{ED}	P_{MFD}	P_{HD}	SNR(dB)	P_{ED}	P_{MFD}	P_{HD}
-30	0.0118	0.0561	0.0702	-10	0.0315	0.2439	0.2621
-28	0.0125	0.0831	0.0944	-8	0.0412	0.2707	0.2905
-26	0.0129	0.1053	0.1164	-6	0.0592	0.3064	0.3336
-24	0.0126	0.1232	0.1347	-4	0.0951	0.3571	0.4012
-22	0.0138	0.1421	0.1549	-2	0.1459	0.4322	0.4976
-20	**0.0139**	**0.1569**	**0.1687**	**0**	**0.2435**	**0.5478**	**0.6360**
-18	0.0144	0.1722	0.1828	2	0.3922	0.7139	0.8134
-16	0.0150	0.1872	0.1994	4	0.5815	0.8943	0.9353
-14	0.0159	0.2043	0.2168	6	0.7498	0.9898	0.9505
-12	0.0160	0.2233	0.2375	8	0.8713	1.0000	0.9971

5.1.5 Matlab Simulation Result and Discussion of Energy, Cyclostationary and Hybrid Detection in the Uncertainty of Noise

As shown in the result below the effect of noise uncertainty for cyclostationary and hybrid detection technique is performed. Compared to the proposed hybrid of energy and matched filter detection, the noise uncertainty affects hybrid of energy and cyclostationary detector.

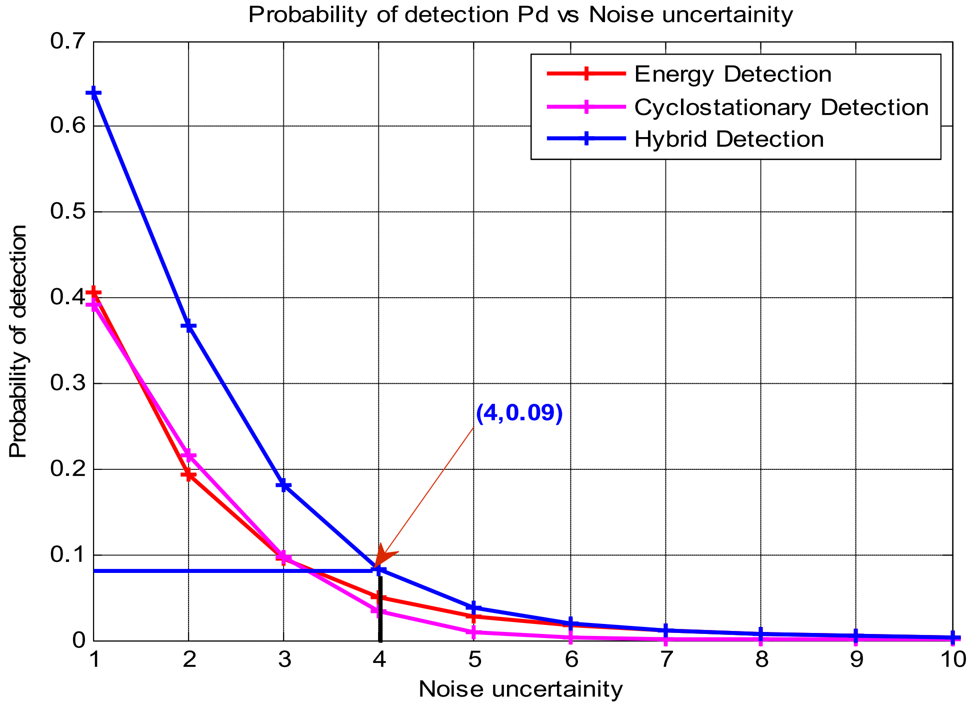

Figure 5.11: Pd Vs Noise uncertainty for Energy, Cyclostationary and Proposed Hybrid Detector

Table 13: Output of Pd Vs Noise uncertainty for energy, cyclostationary and hybrid detectors

	Probability of detection SNR= -4 dB			Probability of detection SNR= - 6 dB		
Noise Uncertainty	P_{ED}	P_{CyclD}	P_{HD}	P_{ED}	P_{CyclD}	P_{HD}
1	0.4068	0.3929	0.6392	0.2642	0.3582	0.5282
2	0.1939	0.2156	0.3678	0.0846	0.1902	0.2587
3	0.0949	0.0963	0.1821	0.0322	0.0819	0.1114
4	**0.0498**	**0.0345**	**0.0826**	**0.01470**	**0.0282**	**0.0425**
5	0.0282	0.0098	0.0378	0.0077	0.0016	0.0154
6	0.0171	0.0021	0.0193	0.0046	0.0002	0.0062
7	0.0111	0.0018	0.0115	0.0029	3.65e-5	0.00323
8	0.0075	0.00015	0.0076	0.0020	3.65e-6	0.0021
9	0.0053	0.00005	0.0054	0.0015	2.86e-7	0.0015
10	0.0039	0.00001	0.0040	0.0011	2.86e-8	0.0011

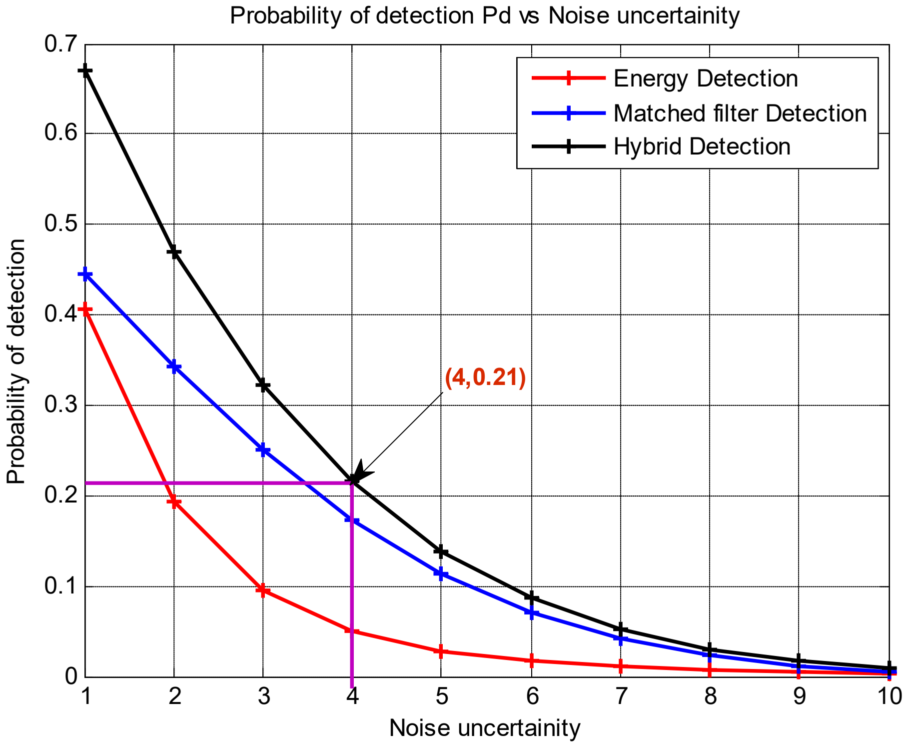

Figure 3.12: Pd Vs Noise uncertainty for Energy, Matched filter and Proposed Hybrid Detectors

The result depicted in figure 3.13 shows the relation of complementary ROC of probability of miss detection with noise uncertainty for energy, cyclostation and hybrid detection. As noise uncertainty increases probability of miss detection also increase. At noise uncertainty of 4, Pmd for cyclostationary and hybrid detection is 0.96 and 0.91 respectively. For matched filter and proposed hybrid detection Pmd is 0.82 and 0.78 respectively at the same noise uncertainty. From this the proposed hybrid of energy and matched filter detector performs a lower probability of miss detection at noise uncertainty of 4 than hybrid of energy and cyclostationary detector.

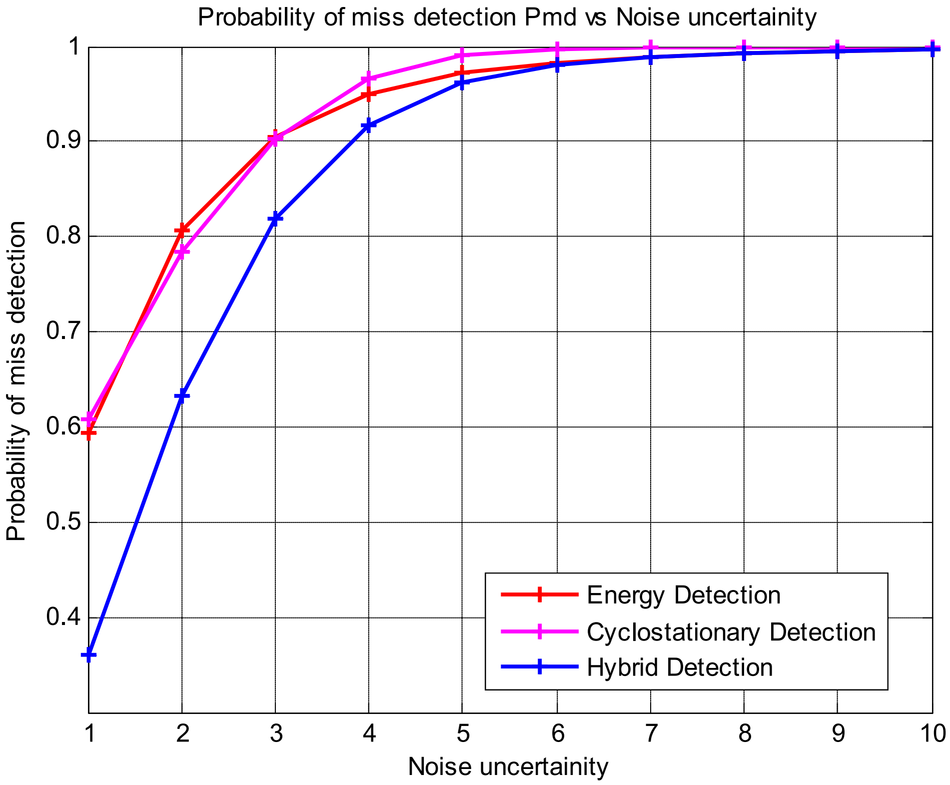

Figure 3.13: Pmd Vs Noise uncertainty for Energy, Cyclostationary and Proposed Hybrid Detectors

Chapter Six

Conclusion and Recommendation

In this chapter a conclusion regarding on the thesis work is presented. The basic results and plots are observed and conclusions are drawn from the results. Besides to the conclusions, directions and recommendation for the future work is discussed.

6.1 Conclusions

In this thesis, studies have been performed on hybrid spectrum detection algorithm which are the combination of energy and matched filter detector techniques. The proposed hybrid detection has been compared with hybrid of energy and cyclostationary detector. From the simulation results and plots, it has been shown that the proposed hybrid sensing techniques enhance the performance of spectrum detection in general and that of energy detection in particular. To detect very weak signals at lower SNR region, in fading environment and in noise uncertainty factor, hybrid spectrum detection is proposed in this thesis work. Probabilities of detection, false alarm probability, probability of miss detection, SNR and noise uncertainty are performance matrix used for the detection techniques. Simulation results were performed and plots of probability of detection vs probability of false alarm, Pd vs SNR, Pd vs Pmd, Pmd Vs SNR and Pd vs noise uncertainty have been carried out and analyzed for both AWGN and Rayleigh channel.

From the simulated result energy detector performs better for SNR above -5dB,but when the SNR value decreased to -30dB the performance of energy detector become poor that is Pd=0.02. On the other hand the proposed hybrid detection performs better even at lower SNR that is at SNR= -30dB Pd = 0.18 is achieved. Energy detection reaches the peak value which is Pd= 0.98 for a higher SNR value of 10 dB for AWGN channel. For ROC curves probability of miss detection is higher for smaller SNR values and Pmd is 0.86 for energy detection and lowered in the proposed hybrid detection which is 0.6 at SNR of -4 dB in AWGN channel. Moreover, an important minimization in probability of miss detection of received signal was achieved by using the proposed hybrid detection algorithm even at lower SNR value.

The effect of fading channel and noise uncertainty on detection performance is also analyzed. In fading channel which is modeled using Rayleigh distribution, the performance of spectrum detection specially energy detector gets degraded at smaller SNR value. In Rayleigh channel at SNR value of -20 dB, Pd is 0.01 for energy detector but it is 0.02 in AWGN channel at the same SNR. For the proposed hybrid detection Pd =0.16 for SNR of -20 dB in Rayleigh channel. From the result it can be concluded that even in fading channel the proposed hybrid detection performs better at smaller SNR values. Finally the effect of noise uncertainty on the performance of spectrum detectors was also analyzed. From the result, when the noise uncertainty increases and ranges from 1 to 10 the probability of detection decreases unfortunately. The increment of noise uncertainty more of challenge to energy detector than proposed hybrid detector especially at smaller received signal to noise ratio. At noise uncertainty factor of 5, probability of detection is 0.028 for energy detector and it is 0.14 for proposed hybrid detection.

6.2 Recommendations for Future Works

From different researches and literature it is known that shortage and wastage of spectrum are the challenges of the current wireless technology. Researchers developed cognitive radio and for this technology to be effective and to utilize the unused portion of the channel, spectrum sensing algorithms play a great role to avoid intervention with primary user. In this work a hybrid detection using both energy and matched filter detector is proposed to enhance spectrum detection in smaller SNR region for both AWGN and Rayleigh channel. Closed form analysis is also done in terms of noise uncertainty effect. To further enhancement of energy detector the following are recommended for future work.

I. To get a more efficient spectrum detection algorithm, combine any other two detection technique together such as energy detector with Eigen value detector.

II. This study focuses on AWGN and Rayleigh channels and recommended to see the performance on other fading channel such as Racine and Nakagami-m channel.

III. Use various parameters to enhance the performance of spectrum detection such as different modulation order, variable threshold.

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