Improved Double Threshold Energy Detection in Cognitive Radio Networks

A THESIS SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Electronics Systems and Communication

By

Aravind Puttupu

Department of Electrical Engineering

National Institute of Technology, Rourkela

Rourkela-769008

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CERTIFICATE

This is to certify that the thesis entitled**, “Improved Double Threshold Energy Detection in Cognitive Radio Networks”** submitted by Mr. Aravind Puttupu in partial fulfillment of the requirements for the award of Master of Technology Degree in electrical Engineering with specialization in **“Electronics systems and communication”** during session 2011-2013 at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any degree or diploma.

Date:

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Aravind Puttupu

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List of Abbreviations used:

AWGN	**Additive White Gaussian Noise**
CAV	**Covariance Absolute Value**
CDF	**Cumulative Distribution Function**
CDMA	**Code Division Multiple Access**
CR	**Cognitive Radio**
CSI	**Channel State Information**
DAB	**Digital Audio Broadcast**
DARPA	**Defence Advanced Research Projects Agency**
DFT	**Discrete Fourier Transform**
DSP	**Digital Signal Processing**
DVB	**Digital Video Broadcast**
FCC	**Federal Communication Commission**
FER	**Frame Error Rate**
HDTV	**High-Definition Television**
PSD	**Power Spectral Density**
RF	**Radio Frequency**
RKRL	**Radio Knowledge Representation Language**
ROC	**Receiver Operating Characteristics**
SCF	**Spectrum Correlation Function**

Abstract

Cognitive radio is an exciting emerging technology that has the potential of dealing with the stringent requirement and scarcity of the radio spectrum. Such new and transforming technology represents a paradigm shift in the design of wireless systems, as it will allow the efficient utilization of the radio spectrum. One of the most crucial challenges for cognitive radio systems is to identify the presence of primary (licensed) users over a wide range of spectrum specific geographic location and at a particular time. To enhance the reliability of detecting primary users in case of hidden terminal problem, we consider cooperative spectrum sensing in cognitive radio systems.

Based on conventional single-threshold energy detection algorithm, we discuss about double-threshold version of Energy detector in cognitive radio system, and then, we analyse the detection probability, false alarm probability, probability of miss detection and their relationships. Further, we use two more parameters for performance evaluation: the probability of collision between the cognitive user and the primary user, and the probability of spectrum unavailable spectrum for the cognitive user. Comparing to the single, double-threshold energy detection algorithm, simulation results show that the double-threshold energy detection algorithm can make a lower collision probability between the primary user and the cognitive user, despite a little increasing of the spectrum unavailable probability. Finally by proposed Improved Double threshold Energy detector, by which reduction in the probability of detection is less reduced.

Chapter-1

Introduction

1.1. Introduction and Motivation

With the development of a host of new and ever expanding wireless applications and services, spectrum resources are facing huge demands. At presently, spectrum allotment is done by providing each new service with its own fixed frequency block. As day passes demand for spectrum are expected to increasing rapidly and it would get in future. As more and more technologies are moving towards fully wireless, demand for spectrum is enhancing.

As Most of the primary spectrum is already assigned, so it becomes very difficult to find spectrum for either new services or expanding existing services. Currently government policies do not allow the access of licensed spectrum by unlicensed users, constraining them instead to use several heavily populated, interference-prone frequency bands. As the result there is huge spectrum scarcity problem in certain bands. In particular, if we were to scan the radio spectrum, including the revenue-rich urban areas, we find that some frequency bands in the spectrum are unoccupied for some of the time, and many frequency bands are only partially occupied, whereas the remaining frequency bands are heavily used [1].The radio spectrum is limited resource and is regulated by government agencies such as Telecom Regulation Authority of India (TRAI) in India, Federal Communications Commission (FCC) in the United States.

Within the current spectrum regulatory framework, all the frequency bands are exclusively allocated to specific services and no violation from unlicensed users is allowed. The spectrum scarcity problem is getting worse due to the emergence of new wireless services. Fortunately, the worries about spectrum scarcity are being shattered by a recent survey made by Spectrum Policy Task Force (SPTF) within FCC. It indicates that the actual licensed spectrum is largely under-utilized in vast temporal and geographic dimensions [2].A remedy to spectrum scarcity is to improve spectrum utilization by allowing secondary users to access under-utilized licensed bands dynamically when/where licensed users are absent.

Cognitive radio is a novel technology which improves the spectrum utilization by allowing secondary users to borrow unused radio spectrum from primary licensed users or to share the spectrum with the primary users. As an intelligent wireless communication system, cognitive radio is aware of the radio frequency environment, selects the communication parameters (such as carrier frequency, modulation type, bandwidth and transmission power) to optimize the spectrum usage and adapts its transmission and reception accordingly. By sensing and adapting to the environment, a cognitive radio is able to able to fill in the spectrum holes and serve its users without causing harmful interference to the licensed user. To do so, the cognitive radio must continuously sense the spectrum it is using in order to detect the re-appearance of the primary user [15]. Once the primary user is detected, the cognitive radio should withdraw from the spectrum instantly so as to minimize the interference. This is very difficult task as the various primary users will be employing different modulation schemes, data rates and transmission powers in the presence of variable propagation environments and interference generated by other secondary users [1].

1.2. LITERATURE REVIEW:

The fundamental concept of Cognitive Radio has been discussed in detail in a paper by S.Haykin, [1].This paper states that spectrum utilization can be improved significantly by making it possible for a secondary user (who is not being serviced) to access a spectrum hole unoccupied by the primary user at the right location and the time in question. Cognitive radio has been proposed to promote the efficient use of the spectrum by exploiting the existence of spectrum holes.

H. Urkowitz [3] from his paper he explain Energy detection of unknown deterministic signals .The basics of Energy detector has been discussed in detail in a paper by F.F.Digham et al.,[3] in this paper he states when the received signal energy (V) is greater than detection threshold (V_{th}) , it indicates that the presence of primary user .

One of the major problem in Cognitive radio network is Hidden terminal problem due to showing, multi-path fading .K. Ben Letaief and W. Zhang [5] explain a solution for the above problem. And he also describes about the reporting, sensing errors occurred in cognitive radio netwoks .The analytical formulation of co-operative spectrum sensing is based on the papers by A.Ghasemi and E.S.Sonsa [6] and F.F.Digham et al [2].

In some communication applications maximizing the probability of detection is of more interest, while in some other application mitigating the probability of false alarm is of more important .In these cases good detection performance is required, which can be done by Improved Energy detector. Basics of Improved Energy Detector has been discussed more in detail in a paper by Yunfei chen,[2] . In this paper he explain the way to improve the detection performance in a Energy detector based spectrum sensing.

The concept of Double Threshold Energy Detector has been discussed in a paper by Jinbo Wu.,[7] . He states that Double Threshold Energy detection can be implemented by adding one more detection threshold to the conventional single-threshold Energy Detection algorithm, by using this algorithm Probability of collision between the Primary user and the secondary user is reduced. From the advantage of Double Threshold Energy Detector discussed in paper by Jinbo Wu.,[7] , we moved to the paper of Jiang Zhu and Zhengguang Xu[8] there we discuss how probability of miss-detection is reduced in this case .

Finally from the knowledge of above papers we realize the necessity of improvement needed in probability of detection and reduction in Probability of collision in Energy detection Spectrum Sensing. Here in this thesis we propose a new method with above requirements.

1.3 Objective

The main aim of this work is to explain the problem of spectrum sensing, various spectrum sensing methods, Energy detection, Double Threshold Energy Detection, Improved Energy Detection .Then we discuss about hidden terminal problem occurred in spectrum sensing, and solution for it. Later we discuss about the proposed Improved Double Threshold Energy Detector Spectrum sensing method to improve the spectral efficiency in Energy detection based method.

1.4 Thesis Layout

The thesis is organized as follows.

Chapter 2 describes an introduction to cognitive radio. This chapter discusses various stages of cognitive radio, its emergent behaviour, applications, standards, and various research organizations dealing with cognitive radio.

Chapter 3 discuss the spectrum sensing problem, overview of various spectrum sensing methods and the performance of energy detector spectrum sensing algorithm in cognitive radio and discusses the performance of cooperative spectrum sensing in cognitive radio systems.

Chapter 4 discussion of Simulation results of different Energy detector based Spectrum sensing methods for both Cooperative, Non Cooperative Cognitive Radio networks.

Chapter 5 The overall conclusion of the thesis and some of the future work which can be taken up in this field of Cognitive Radio Spectrum Sensing is outlined.

Chapter-2

COGNITIVE RADIO

2.1 Introduction

New radio technologies keep coming along Wi-Fi, WiMAX, Bluetooth, ZigBee, the growing panoply of cellular voice and digital services, broadcast satellite, and more. Each requires a unique hardware appropriate to its special way of sending and receiving radio waves. Due to the large number of standards, spectrum availability has become an important issue. Spectrum usage regulations not allowing unlicensed users to operate in a licensed spectrum. However, it has been observed that the entire licensed spectrum is not used at all places all the time. An unlicensed user can take advantage of such a situation to communicate thereby increasing spectrum efficiency. This is the basic idea behind Cognitive Radio (CR) [1].This chapter presents a brief history, definition, functionality and applications of CR.

2.2 Brief history of CR

The Cognitive radios do not have the history of a century; rather the development of cognitive radio is still at a conceptual stage. The Cognitive Radio is an emerging technology, for the efficient use of the limited spectrum available. Nevertheless, as we look to the future, we see that cognitive radio has the capability to make a significant difference to the way the radio spectrum can be accessed, with much improved utilization. A cognitive radio could enhance the flexibility of personal wireless services, through a new language called the "Radio Knowledge Representation Language" (RKRL) [13]. The idea of RKRL was further expanded in Mitola's doctoral dissertation, presented at the Royal Institute of Technology in May 2000 [13] at Sweden.

Cognitive radio is not a single technology to be very precisely and clearly. It resulted from many technologies coming together to result in the Cognitive Radio technologies, due the fact that exists among its applications. For example, the development of digital signal processing (DSP), development of signal processing, math tools and source coding of data, voice and image etc. It is technology which is built on Software defined Radio which is brain child of Defence Advanced Research Projects Agency (DARPA). Later, DARPA launched the next Generation program (XG) that focused on "the enabling technologies and system concepts to dynamically redistribute allocated spectrum." [11] The successful conclusion of the XG project, the FCC realized that CR was the answer to stimulate growth of open spectrum.

2.3 Definition of CR

1) Simon Haykin defines Cognitive Radio, it as follows [1]: "Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation technique) in real-time, with two primary objectives in mind:

 Highly reliable communications whenever and where ever needed;

 Efficient radio spectrum utilization.

2) While assisting the FCC in its efforts to define cognitive radio, IEEE USA offered the following definition [21].A radio frequency transmitter or receiver that is designed to intelligently detect whether a particular segment of the radio spectrum is currently in use, and to jump into (and out of, as necessary) the temporarily-unused spectrum very rapidly, without causing interference with the transmissions of other authorized users

3) The regulatory bodies focus on the operation of transmitter like FCC defines the cognitive radio as: A radio that can change its transmitter parameters based on interaction with the environment in which it operates [21].

2.4 Why Cognitive Radio

Cognitive radio is a excellent tool for solving two major problems

• Accessing the spectrum (finding an open frequency and using it)

• Interoperability (talking to legacy radios using a variety of incompatible waveforms)

The following Figure.2.1 shows the utilization of spectrum [10,11]. From this it is observed that heavily used bands, medium used bands and unused bands in the spectrum.

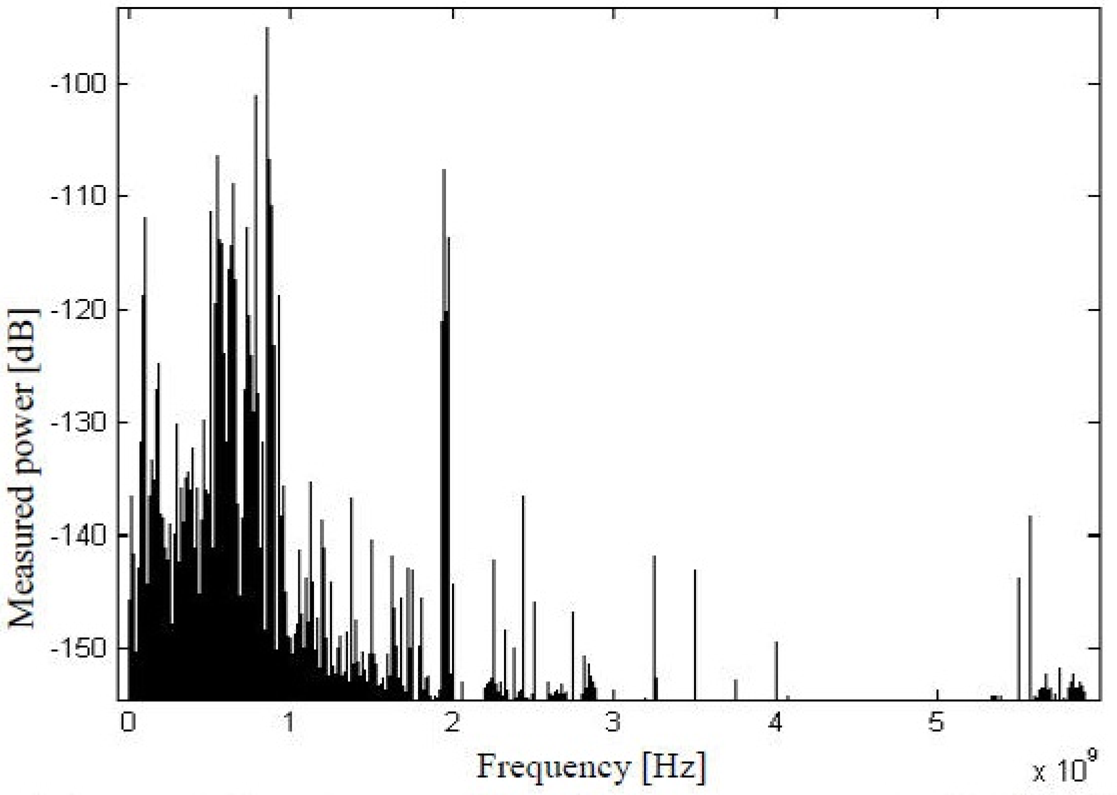


Figure.2.1. Spectrum utilization [10, 11]

2.5. Cognitive Radio

Cognitive radio technology is the key technology that enables an xG network to use spectrum in a dynamic manner. The term, cognitive radio, can formally be defined as follows A ‘‘Cognitive Radio’’ is a radio that can change its transmitter parameters based on interaction with the environment in which it operates.

From this definition, two main characteristics of the cognitive radio can be defined:

• **Cognitive capability:**

- Cognitive capability refers to the ability of the radio technology to capture or sense the information from its radio environment.
- This capability cannot simply be realized by monitoring the power in some frequency band of interest but more sophisticated techniques are required in order to capture the temporal and spatial variations in the radio environment and avoid interference to other users.

- Through this capability, the portions of the spectrum that are unused at a specific time or location can be identified. Consequently, the best spectrum and the appropriate operating parameters can be selected.

• **Reconfigurability:**

- The cognitive capability provides spectrum awareness whereas reconfigurability enables the radio to be dynamically programmed according to the radio environment.
- More specifically, the cognitive radio can be programmed to transmit and receive on a variety of frequencies and to use different transmission access technologies supported by its hardware design

The ultimate objective of the cognitive radio is to obtain the best available spectrum Through cognitive capability and reconfigurability as described before.

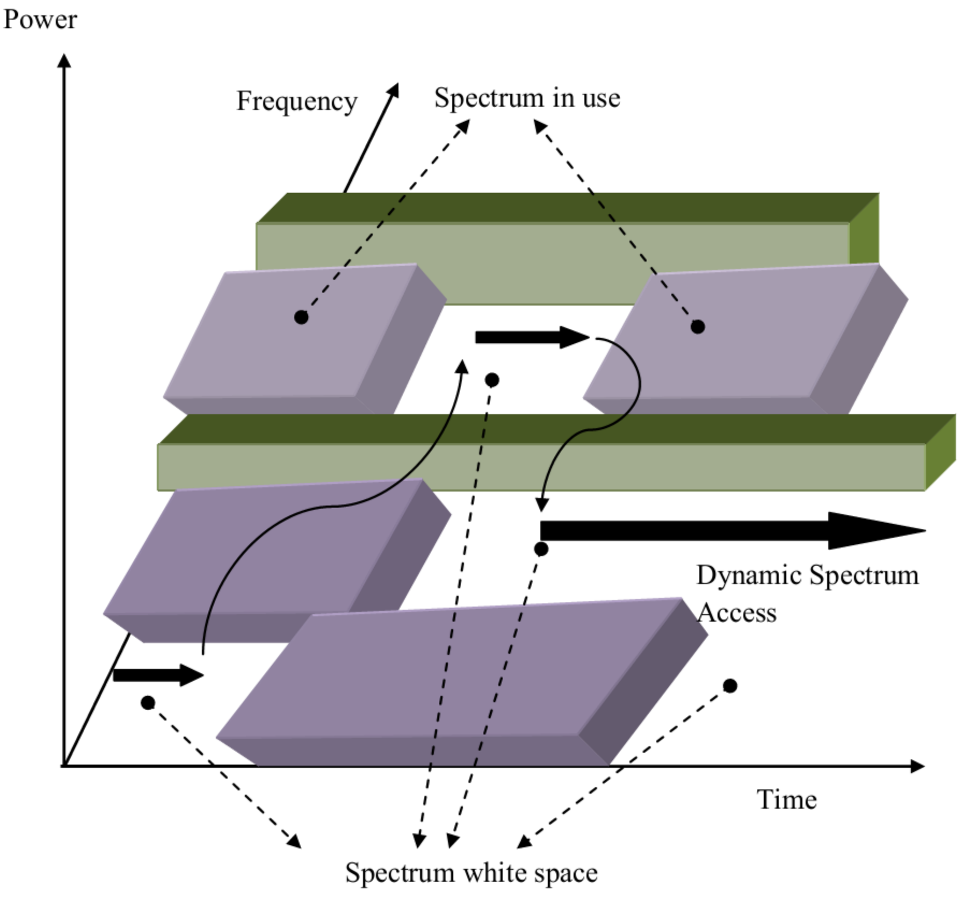


Figure.2.2. Spectrum White space and spectrum in use [10]

- Since most of the spectrum is already assigned, the most important challenge is to share the licensed [10] without interfering with the transmission of other licensed users as illustrated in Figure. 2.2

- The cognitive radio enables the usage of temporally unused spectrum, which is referred to as spectrum hole or white space.
- If this band is further used by a licensed user, the cognitive radio moves to another spectrum hole or stays in the same band, altering its transmission power level or modulation scheme to avoid interference as shown in Figure. 2.2

In the following subsections, we describe the physical architecture, cognitive functions and re-configurability capabilities of the cognitive radio technology.

2.4. Physical architecture of the cognitive radio

A generic architecture of a cognitive radio transceiver is shown in Figure. 2.3(a) [10,22]. The main components of a cognitive radio transceiver are the

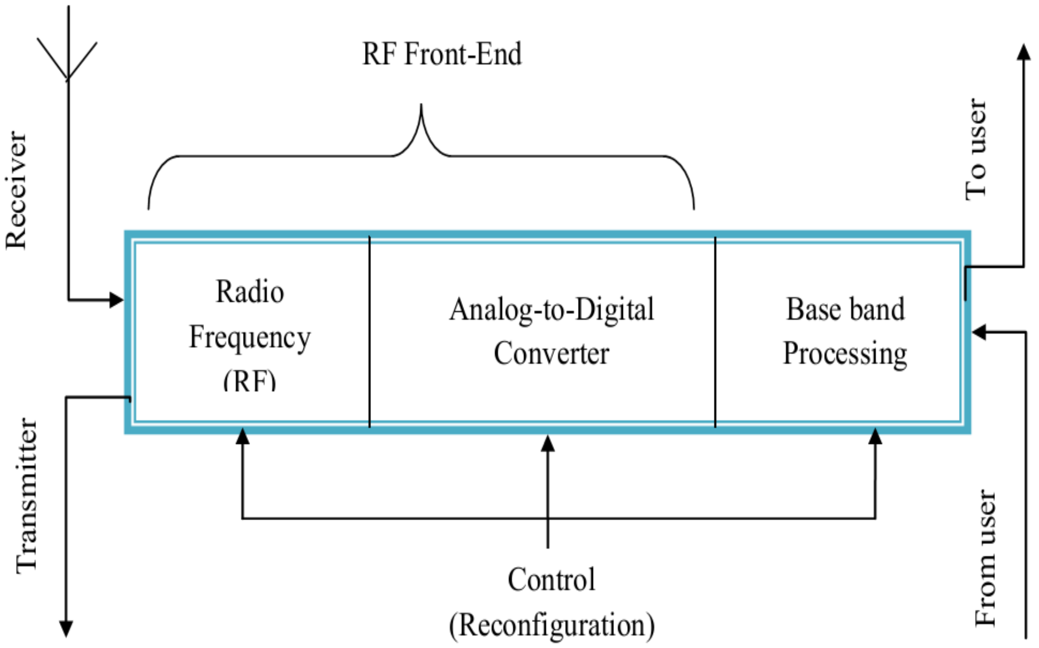


Figure.2.3.(a). Cognitive radio transceiver

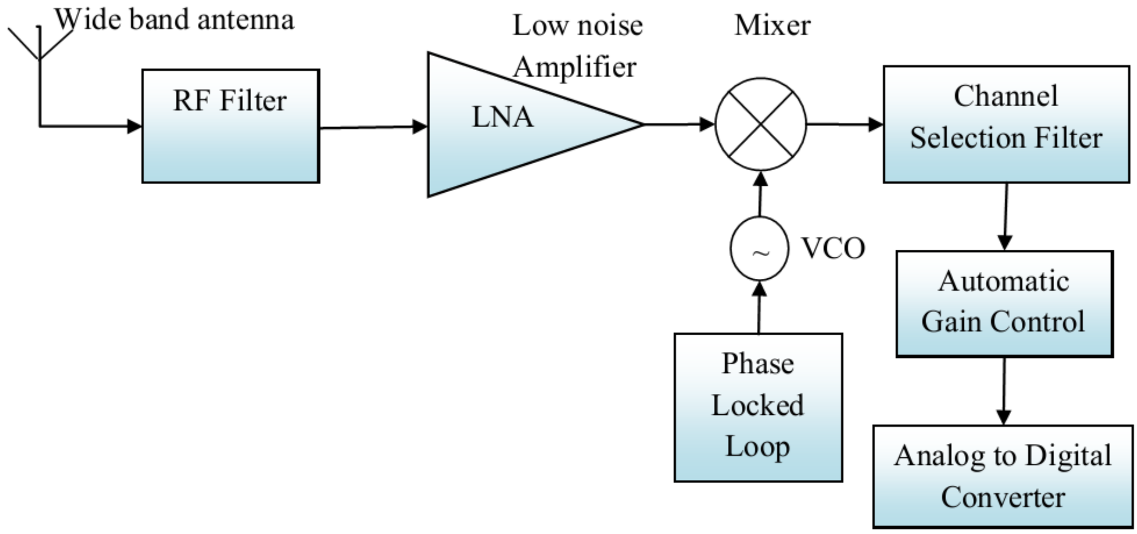


Figure.2.3.b). Radio front-end [10, 12]

a) Radio front-end
b) Baseband processing unit:

- Each component can be reconfigured via a control bus to adapt to the RF environment.
- In the RF front-end, the received signal is amplified, mixed and A/D converted.
- In the baseband processing unit, the signal is modulated/demodulated and encoded/decoded. The baseband processing unit of a cognitive radio is essentially similar to existing transceivers.
- However, the novelty of the cognitive radio is the RF front-end.
- The novel characteristic of cognitive radio transceiver is a wideband sensing capability of the RF front-end.
- This function is mainly related to RF hardware technologies such as wideband antenna, power amplifier, and adaptive filter.
- RF hardware for the cognitive radio should be capable of tuning to any part of a large range of frequency spectrum.
- Also such spectrum sensing enables real-time measurements of spectrum information from radio environment.
- Generally, a wideband front-end architecture for the cognitive radio has the following structure as shown in Figure. 2.3(b) [10, 14].

The components of a cognitive radio RF front-end are as follows:[10]

- RF filter: The RF filter selects the desired band by band pass filtering the received RF signal.
- Low noise amplifier (LNA): The LNA amplifies the desired signal while simultaneously minimizing noise component.
- Mixer: In the mixer, the received signal is mixed with locally generated RF frequency and converted to the baseband or the intermediate frequency (IF).
- Voltage-controlled oscillator (VCO): The VCO generates a signal at a specific frequency for a given voltage to mix with the incoming signal. This procedure converts the incoming signal to baseband or an intermediate frequency.
- Phase locked loop (PLL): The PLL ensures that a signal is locked on a specific frequency and can also be used to generate precise frequencies with fine resolution.
- Channel selection filter: The channel selection filter is used to select the desired channel and to reject the adjacent channels. There are two types of channel selection filters [23]. The direct conversion receiver uses a low-pass filter for the channel selection. On the other hand, the super heterodyne receiver adopts a band pass filter.
- Automatic gain control (AGC): The AGC maintains the gain or output power level of an amplifier constant over a wide range of input signal levels.

2.5 How is a Cognitive Radio Different from Other Radios

Conventional Radio	Software Defined Radio	Cognitive Radio
1. Traditional RF design	Conventional Radio + Software Architecture	SDR + Intelligence
2.Traditional baseband design	Reconfigurability	Reconfigurability + Awareness

Table.2.1. Comparison between Cognitive Radios with SDR

2.6. Cognitive Radio Applications, Advantages and Drawbacks

The cognitive has the more benefits than a conventional radio. The following are the advantages and disadvantages of cognitive radio.

Applications are

1. Multimedia downloads
2. Emergency communications (with priority flag)
3. Broadband wireless services
4. Multimedia wireless networking.

2.6.1. Advantages of CR:

- For mitigating and solving spectrum access issues Cognitive radios are expected to be powerful tools.
- Improves current spectrum utilization (Fill in unused spectrum and move away from occupied spectrum).
- Improves performance of wireless network through increased user throughput and system reliability

2.6.2. Drawbacks of CR:

- Security
- Loss of control
- Regulatory concerns
- Fear of undesirable adaptations
- Significant research has remains to be done to realise commercially practical cognitive radio.

2.7. Important Institution and forums working on CR

Some of the important institution, forums and research organization where extensive research is going on are listed below [11,21].

- ✓ DARPA- is exploring many different aspects of cognitive radio as part of the XG program and other on-going programs. Unfortunately, many of the results of the DARPA programs are not currently in the public domain
- ✓ IEEE- has started the IEEE 1900 group to study the issue of cognitive radio and giving standard like 802.22

- ✓ SDR Forum- chartered two groups in 2004 to explore cognitive radio issues: the Cognitive Radio Working Group and the Cognitive Radio Special Interest Group. The working group is tasked with standardizing a definition of cognitive radio and identifying the enabling technologies for cognitive radio.
- ✓ FCC- On May 19, 2003, the FCC convened a workshop to examine the impact that cognitive radio could have on spectrum utilization and to study the practical regulatory issues that cognitive radio would raise.
- ✓ Virginia Tech, Work is being performed exploring techniques to exploit collaborative radio to improve network performance.
- ✓ Win lab Rutgers University is developing a cognitive radio test bed for disaster response using commercially available components.
- ✓ E2R-European initiative into supporting End-to-End Reconfigurability with numerous participating European universities and companies.
- ✓ BWRC-Berkeley wireless research centre is currently developing a cognitive radio for sensing and opportunistically using the spectrum.

Chapter-3

SPECTRUM SENSING

3.1. SPECTRUM SENSING

- Spectrum sensing refers to detecting the spectrum holes (unused spectrum) and sharing it without harmful interference with other cognitive users.
- In cognitive radio technology, primary users the users who have the most priority on the usage of a specific part of the spectrum.
- Secondary users have lower priority, and should not expect to cause any interference to the primary users when using the channel.
- Spectrum sensing is still in its early stages of development. A number of various methods are proposed for identifying the presence signal in transmissions.
- In some another approaches, characteristics of the identified transmission are detected for deciding the signal transmission as well as identifying the type of signal [24].
- The well-known spectrum sensing techniques used are matched filter detection, energy detection, cyclostationary detection.

One of the most important components of CR is the ability to measure, sense, learn, and be aware of the parameters related to the radio channel characteristics, availability of spectrum and power, interference and noise temperature, radio's operating environment, user requirements, and applications [24]. In CR, the PUs are referred to those users who have higher priority or legacy rights on the usage of a part of the spectrum. Spectrum sensing is a key element in CR communications, as it enables the CR to adapt to its environment by detecting spectrum holes. The most effective way to detect the availability of some portions of the spectrum is to detect the PUs that are receiving data within the range of a CR. However, it is difficult for the CR to have a direct measurement of a channel between a primary transmitter and receiver. Therefore, most existing spectrum sensing algorithms focus on the detection of the primary transmitted signal based on the local observations of the CR.
In the following, we denote $x(t)$ the received signal at the CR. To enhance the detection probability, many signal detection techniques can be used in spectrum sensing. In this section, we give an overview of some well-known spectrum sensing techniques.

1) Matched Filter Detection:
    - When a secondary user has a prior knowledge of the PU signal, the optimal signal detection is a matched filter, as it maximizes the signal-to-noise ratio (SNR) of the received signal.

- A matched filter is obtained by correlating a known signal, or template, with an unknown signal to detect the presence of the template in the unknown signal. This is equivalent to convolving the unknown signal with a time-reversed version of the template.
- The main advantage of matched filter is that it needs less time to achieve high processing gain due to coherent detection [16].
- Another significant disadvantage of the matched filter is that it would require a dedicated sensing receiver for all primary user signal types.
- In the CR scenario, however, the use of the matched filter can be severely limited since the information of the PU signal is hardly available at the CRs.
- The use of this approach is still possible if we have partial information of the PU signal such as pilot symbols or preambles, which can be used for coherent detection [23].
- For instance, to detect the presence of a digital television (DTV) signal, we may detect its pilot tone by passing the DTV signal through a delay-and-multiply circuit.
- If the squared magnitude of the output signal is larger than a threshold, the presence of the DTV signal can be detected.

2) Energy Detection:
    - If prior knowledge of the PU signal is unknown, the energy detection method is optimal for detecting any zero-mean constellation signals [16].
    - In the energy detection approach, the radio-frequency (RF) energy in the channel or the received signal strength indicator is measured to determine whether the channel is idle or not.
    - First, the input signal is filtered with a band pass filter to select the bandwidth of interest. The output signal is then squared and integrated over the observation interval.
    - Lastly, the output of the integrator is compared to a predetermined threshold to infer the presence or not of the PU signal.
    - Although the energy-detection approach can be implemented without any prior knowledge of the PU signal, it still has some drawbacks.

- The first problem is that it has poor performance under low SNR conditions. This is because the noise variance is not accurately known at the low SNR, and the noise uncertainty may render the energy detection useless [16].
- Another challenging issue is the inability to differentiate the interference from other secondary users sharing the same channel and the PU [25].
- Furthermore, the threshold used in energy selection depends on the noise variance, and small noise power estimation errors can result in significant performance loss.

3).Cyclostationary Detection:

- Cyclostationary detection is more robust to noise uncertainty than an energy detection.
- If the signal of the PU exhibits strong cyclostationary properties, it can be detected at very low SNR values by exploiting the information (cyclostationary feature) embedded in the received signal [5,20].
- A signal is said to be cyclostationary , if its autocorrelation is a periodic function of time t with some period.[26]

This detection can be performed as follows

- First, the cyclic autocorrelation function (CAF) of the observed signal x(t) is calculated as $E\{x(t+T)\ x^{*}(t+T)e^{-2\pi\alpha t}\}$,and α is called the cyclic frequency.
- The cyclic spectrum density (CSD) which is obtained by taking the Fourier transform of the cyclic auto-correlation function (CAF) represents the density of the correlation between two spectral components that are separated by a quantity equal to the cyclic frequency.
- The following conditions are essential to be filled by a process for it to be wide sense cyclo-stationary:-

$$E\{x(t+T)\}=E\{x(t)\} \tag{3.1}$$

$$R_x\{t+T,\tau\}=R_x\{t,\tau\} \tag{3.2}$$

Where $R_{x=}$ E{x(t+T)x(t)}

- Here both the mean and auto-correlation function for such a process needs to be periodic with some period say T, The cyclic auto-correlation function (CAF) is represented in terms of Fourier co-efficient as

$$R_x^{n/T} = \frac{1}{T}\int_{-T/2}^{T/2} R_x(t,\tau)e^{-j2\pi\left(\frac{n}{T}\right)t}\,dt \qquad (3.3)$$

Here n/t denoted by α which is represented by cyclic frequency.

- The cyclic spectral density (CSD) representing the time averaged correlation between two spectral components of a process which are separated in frequencies by *'α'* is given as

  - $$s(f,\alpha) = \int_{-T/2}^{T/2} R_x^{\alpha}(t,\tau)e^{-j2\pi f\tau}\,dt \qquad (3.4)$$

    - The power spectral density (PSD) is a special case of cyclic spectral density (CSD) for 'α=0'. It is equivalent to taking the Fourier transform of special case of wide sense cyclo-stationary for '*n/T0*= α=0'.

3.2. ENERGY DETECTION BASED SPECTRUM SENSING

- Energy detection is the simple and most popular spectrum sensing method since it is simple to implement and does not required any prior information about the primary signal.[18].
- An energy detector (ED) simply treats the primary signal as noise and decides on the presence or absence of the primary signal based on the energy of the observed signal.
- Since it does not required any a priori knowledge of the primary signal, the ED is robust to the variation of the primary signal.
- Moreover, the ED does not involve complicated signal processing and has low complexity.

3.3. Block Diagram of Energy Detection

Energy detector is composed of four main blocks [3, 27]:

1) Pre-filter.

2) Squaring Device.

3) Integrator.

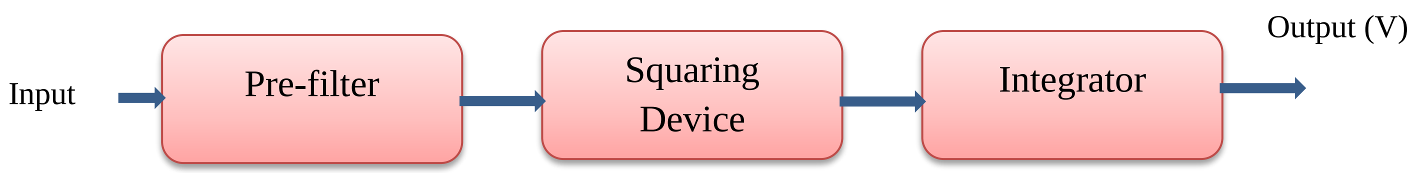


Figure.3.1. Block Diagram of Energy Detection Based Spectrum Sensing Using Squaring Operation

The output that comes out of the integrator is energy of the filtered received signal over the Time interval T and this output is considered as the test statistic to test the two hypotheses H_0 And H_1 [3].

$H_{0\,:}$ Primary user is absent

H_1 : Primary user is present

Concept of two hypotheses (Analytical Model) :

Spectrum Sensing is a primary element in cognitive radio network. In fact it is the first step that needs to be performed for communication to take place. Spectrum sensing can be simply reduced to an identification problem, modeled as a hypothesis test. The sensing equipment has to just decide between for one of the two hypotheses:-

H1: y(t)=x(t) + n(t)

H0: y(t)=n(t)

where 'x*(t)*' is the signal transmitted by the primary users.

'y*(t)*' being the signal received by the secondary users.

'n*(t)*' is the additive white Gaussian noise with variances.

Hypothesis 'H0' indicates absence of primary user and that the frequency band of interest only has noise whereas 'H1' points towards presence of primary user.

Thus for the two state hypotheses numbers of important cases are:-

 H1 turns out to be TRUE in case of presence of primary user i.e. P(H1/H1) is known as **Probability of Detection (Pd).**

 H0 turns out to be TRUE in case of presence of primary user i.e. P(H0/H1) is known as **Probability of Miss-Detection (Pm).**

 H1 turns out to be TRUE in case of absence of primary user i.e. P(H1/ H0) is known as **Probability of False Alarm (Pf).**

The probability of detection is of main concern as it gives the probability of correctly sensing for the presence of primary users in the frequency band. Probability of miss-detection is just the complement of detection probability. The goal of the sensing schemes is to maximize the detection probability for a low probability of false alarm. But there is always a trade-off between these two probabilities. Receiver Operating Characteristics (ROC) presents very valuable information as regards the behavior of detection probability with changing false alarm probability (Pd v/s Pf) or miss-detection probability (Pm v/s Pf).

3.3.1 Probability of Detection for AWGN Channel

Probability of detection P_d and false alarm P_f can be evaluated respectively by [2]

$P_d = P(V > V_{th} / H_1)$

$P_f = P(V > V_{th} / H_0)$

Where V_{th} is the decision threshold. Also, P_f can be written in terms of probability density Function as:[19, Eq. (4-16) & Eq. (4-22)]

$$n(t) = n_c(t) cos w_c t + n_q(t) sin w_c t \qquad (3.5)$$

$$\int_0^T n^2(t)dt = \frac{1}{2}\int_0^T [n_i{}^2(t) + n_q{}^2(t)]dt \qquad (3.6)$$

$$n_i(t) = \sum_{k=-\infty}^{\infty} a_{ik} \; sinc\,(2wt - k) \qquad (3.7)$$

$sinc\ x = \sin \pi x / \pi x$ And $a_{ik} = w_i(\frac{k}{B_N})$ is a Gaussian random variable with zero mean and variance $\sigma_k{}^2 = 2N_0 B_N$, $\forall\, k$

$$\int_{-\infty}^{\infty} sinc(B_N\, t - k) sinc(B_N t - m)dt = \begin{cases} \frac{1}{B_N} \;, k = m \\ 0 \;\;, k \neq m \end{cases} \qquad (3.8)$$

Therefore using (3) and (4) , we obtain :

$$\int_0^T n_i{}^2\,(t)dt = \left(\frac{1}{B_N}\right) \sum_{k=-\infty}^{\infty} a_{ik}{}^2 \qquad (3.9)$$

As $n_i(t)$ has $B_N T$ degree of freedom over the interval (0,T) [3] ,therefore

$$n_i(t) = \sum_{k=1}^{B_N T} a_{ik} \; sinc\,(2B_N t - k)\,, \;\; 0 < t < T \qquad (3.10)$$

And the integral $\int_0^T n_i{}^2\,(t)dt$ over the interval (0,T) can be written as

$$\int_0^T n_i{}^2\,(t)dt = \left(\frac{1}{B_N}\right) \sum_{i=1}^{TB_N} a_{ik}{}^2 \qquad (3.11)$$

$$\int_0^T n_q{}^2\,(t)dt = \left(\frac{1}{B_N}\right) \sum_{i=1}^{TW} a_{qk}{}^2 \qquad (3.13)$$

Substituting $\frac{a_{ik}}{\sqrt{2B_N N_0}} = b_{ik}$ and $\frac{a_{qk}}{\sqrt{2B_N N_0}} = b_{qk}$ in (7),(8) and from (2)

$$\int_0^T n^2(t)dt = \left[\sum_{i=1}^{TB_N} b_{ik}^{\ 2} + \sum_{i=1}^{TB_N} b_{qk}^{\ 2}\right].N_0 \qquad (3.14)$$

Similarly, for transmitting signal x(t) [23], we have

$$\int_0^T x^2(t)dt = \left[\sum_{i=1}^{TB_N} b_{ik}^{\ 2} + \sum_{i=1}^{TB_N} b_{qk}^{\ 2}\right].N_0 \qquad (3.15)$$

or,

$$\sum_{k=1}^{B_NT}(b_{ik}^{\ 2} + b_{qk}^{\ 2}) = \frac{E_S}{N_0} \qquad (3.16)$$

where $b_{ik} = \frac{x_i(\frac{k}{B_N})}{\sqrt{2B_NN_0}}$, $b_{qk} = \frac{x_i(\frac{k}{B_N})}{\sqrt{2B_NN_0}}$ and $E_s = \int_0^T x^2(t)$ 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 Y or any quantity monotonic with Y. taking Y' as the test statistic [3] :

$$Y' = \frac{1}{N_0}\int_0^T y^2(t)\,dt\ldots \qquad (3.17)$$

Now , Under Hypothesis H_0, the received signal is only noise ,i.e. y(t)=n(t) ,therefore

Using (9) test statistic Y' can be written as :

$$Y' = \sum_{k=1}^{B_NT}(d_{ik}^{\ 2} + d_{qk}^{\ 2})\ldots \qquad (3.18)$$

Thus , the Test statistic Y' under H_0 is chi-square distributed [4] with $2B_NT$ degree of freedom or $Y' \sim \mathcal{X}_{2d}^2$[2] . Under hypothesis H_1 .recieved signal is the sum of signal and noise ,i.e . y(t)=x(t) + n(t)

$$\int_0^T y^2(t)dt = \left[\sum_{i=1}^{TB_N}(b_{ik+}d_{ik)}{}^2 + \sum_{i=1}^{TB_N}(b_{qk} + d_{qk)}{}^2\right].N_0 \qquad (3.19)$$

Then, using (12) and (13) test statistic Y' under H_1 has a non-central chi-square distribution [4] with $2B_NT$ degree of freedom and a non-centrality parameter λ given by $\frac{E_S}{N_0}$ [3]. Now, defining Signal to Noise ratio, γ in terms of non-centrality parameter as in [22]:

$$\gamma = \frac{E_S}{N} = \frac{E_S}{2N_0} = \frac{\lambda}{2} \qquad (3.20)$$

Thus , test statistic Y' under H_1 : $Y' \sim \mathcal{X}_{2d}^2(\lambda)$ .Also , probability density function of Y' can be expressed as [4,Eq. (2.3-21) & Eq. (2.3-29)]:

$$f_{Y'}(\mathrm{y}) = \begin{cases} \frac{1}{2^d \Gamma(u)} y^{d-1} e^{-(\frac{y}{2})} & , H_0 \\ \frac{1}{2}\left(\frac{y}{\lambda}\right)^{\left(\frac{d-1}{2}\right)} e^{-\left(\frac{\lambda+y}{2}\right)} I_{d-1}\left(\sqrt{\lambda}\right) & , H_1 \end{cases} \quad (3.21)$$

3.3.2.Probability of Detection for AWGN Channel

Probability of detection P_d and Probability of false alarm P_f can be evaluated respectively by [22]

$$P_d = P(Y' > V_{th}/H_1) \quad (3.22)$$

$$P_f = P(Y' > V_{th}/H_0) \quad (3.23)$$

Where V_{th} is the decision threshold. Also,P_f can be written in terms of probability density function as:[19, Eq. (4-16) & Eq. (4-22)]

$$\mathrm{Pf} = \int_{Th}^{\infty} f_{Y'}(y) dy \quad (3.24)$$

Using (19)

$$P_f = \frac{1}{2^d \Gamma(d)} \int_{Th}^{\infty} y^{d-1} e^{-(\frac{y}{2})} dy \quad (3.25)$$

$$P_f = \frac{1}{2\,\Gamma(d)} \int_{Th}^{\infty} \left(\frac{y}{2}\right)^{d-1} e^{-(\frac{y}{2})} dy \quad (3.26)$$

Substituting $\frac{y}{2} = t$, $\frac{dy}{2} = dt$ and changing the limits from $\left(\frac{V_{th}}{2}, \infty\right)$, we get

$$P_f = \frac{1}{\Gamma(d)} \int_{\frac{V_{th}}{2}}^{\infty} (t)^{d-1} e^{-t} dt \quad (3.27)$$

or ,

$$P_f = \frac{\Gamma\left(d, \frac{V_{th}}{2}\right)}{\Gamma(d)} \quad (3.28)$$

Where $\Gamma(\,,\,)$ is the incomplete gamma function.

Now, Probability of detection can be written by making use of the cumulative distribution function [19, Eq. (4.22)].

$$P_d = 1 - F_{Y'}(V_{th}) \quad (3.29)$$

The cumulative distribution function (CDF) of can be obtained (for an even number of Degrees of freedom which is in our case) as [4, Eq. (2.1-124)]:

3.4. COOPERATIVE SPECTRUM SENSING

The critical challenging issue in spectrum sensing is the hidden terminal problem, which occurs when the CR(Cognitive Radio) is shadowed or in severe multipath fading [5].

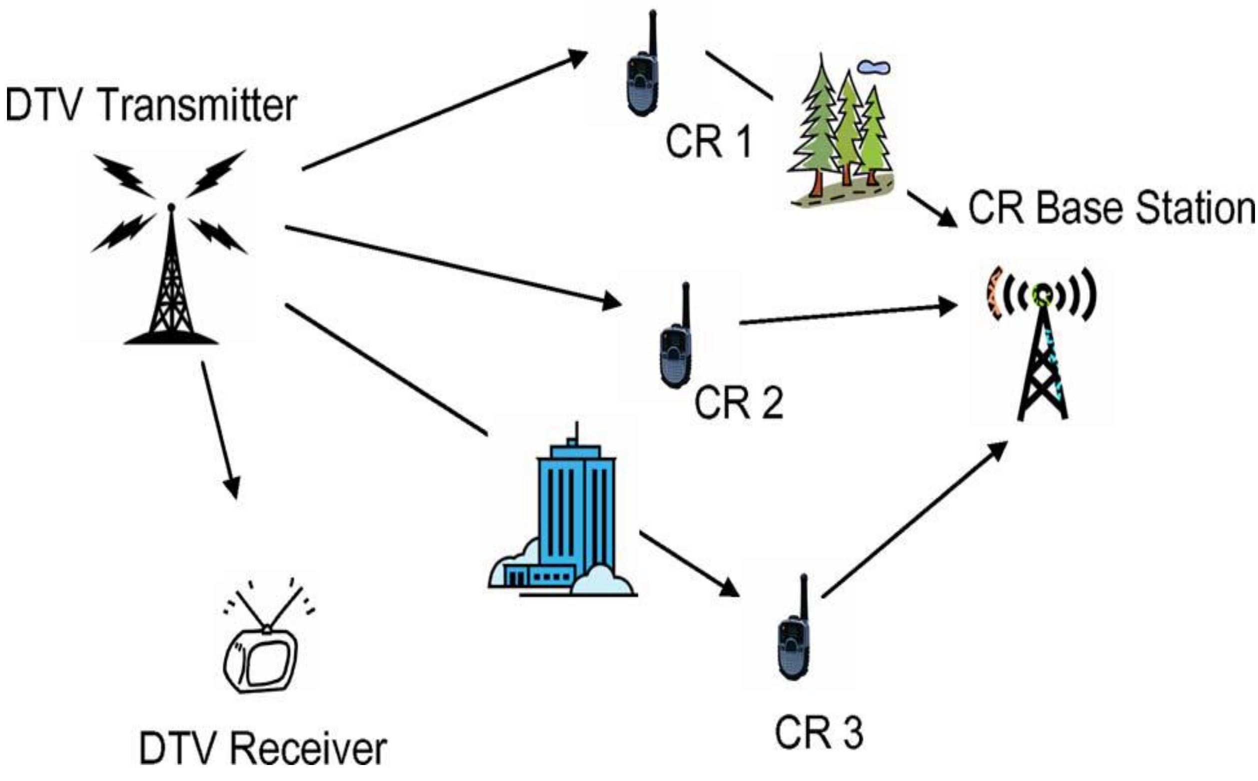


Figure.3.2. Cognitive Radio Network

In this case, the CR cannot always sense the presence of the primary user, and thus it is allowed to access the channel while the PU is still in operation. To solve this issue, multiple CRs can be designed to collaborate in spectrum sensing [5]. Recent work has shown that cooperative spectrum sensing can greatly increase the probability of detection in fading channels. In general, cooperative spectrum sensing can be performed as described below.

Cooperative Spectrum Sensing:

1) Every CR performs its own local spectrum sensing measurements independently and then makes a binary decision on whether the PU is present or not.

2) All of the CRs forward their decisions to a common receiver.

3) The common receiver fuses the CR decisions and makes a final decision to infer the absence or presence of the PU.

We consider a CR network composed of K CRs (secondary users) and a common receiver. The common receiver manages the CR network and all associated K CRs. We assume that each CR performs local spectrum sensing (using Energy Detection method) independently. The energy detection is performed by measuring the energy of the received signal $x_i(t)$ in a fixed bandwidth W over an observation time window T. [2] , [6]

Over Rayleigh fading channels, the average probability of false alarm(P_f), the average probability of detection(P_d), and the average probability of missed detection(P_m) for a CR(without Cooperative Communication) are given by [5]

$$P_f^{(i)} = \frac{\Gamma\left(u, \frac{\varsigma_i}{2}\right)}{\Gamma(u)} \tag{3.30}$$

$$P_d^{(i)} = e^{\frac{-\varsigma_i}{2}} \sum_{p=0}^{u-2} \frac{1}{p!} \left(\frac{\varsigma_i}{2}\right)^p + \left(\frac{1+\bar{\gamma}_1}{\bar{\gamma}_1}\right)^{u-1} \times \left[e^{\frac{-\varsigma_i}{2(1+\bar{\gamma}_1)}} - e^{\frac{-\varsigma_i}{2}} \sum_{p=0}^{u-2} \frac{1}{p!} \left(\frac{\varsigma_i \bar{\gamma}_1}{2(1+\bar{\gamma}_1)}\right)^p\right] \tag{3.31}$$

$$P_m^{(i)} = 1 - P_d^{(i)} \tag{3.32}$$

Where $\bar{\gamma}_i$ denotes the average SNR at the i^{th} CR and $\Gamma(a, x)$ is the incomplete gamma function given by

$$\Gamma(a, x) = \int_x^{\infty} t^{a-1} e^{-t}\, dt$$

And $\Gamma(a)$ is the gamma function.

Let $D_i \in \{0,1\}$ denote the local spectrum sensing result of the i^{th} CR. Specifically, {0} indicates that the CR infers the absence of the PU in the observed band. In contrast, {1} infers the operating of the PU. At the common receiver, all 1-bit decisions (decision fusion) are fused together according to the following logic rule.

$$Z = \sum_{i=1}^{K} D_i \begin{cases} \geq n, & \mathcal{H}_1 \\ < n, & \mathcal{H}_0 \end{cases}$$

Where $\mathcal{H}_1$ denotes that PU signal is transmitted. The false alarm probability Q_f and the missed detection probability Q_m of cooperative spectrum sensing are given by, assuming that all CRs have same P_f, P_m

$$Q_d = \sum_{i=n}^{K} \binom{K}{i} P_d^{\,i} (1 - P_d)^{K-i} \qquad (3.33)$$

$$Q_f = \sum_{i=n}^{K} \binom{K}{i} P_f^{\,i} (1 - P_f)^{K-i} \qquad (3.34)$$

Let $P_e^{(i)}$ denote the error probability of signal transmission over the reporting channels between the i^{th} CR and the common receiver. Then, the cooperative spectrum sensing performance can be given by

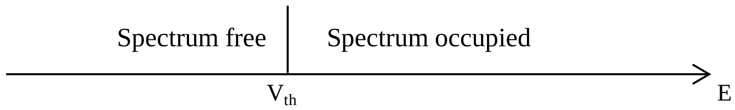
$$Q_f = 1 - \prod_{i=1}^{K} \left[\left(1 - P_f^{(i)}\right)\left(1 - P_e^{(i)}\right) + P_f^{(i)} P_e^{(i)} \right] \qquad (3.35)$$

$$Q_m = \prod_{i=1}^{K} \left[P_m^{(i)} \left(1 - P_e^{(i)}\right) + \left(1 - P_m^{(i)}\right) P_e^{(i)} \right] \qquad (3.36)$$

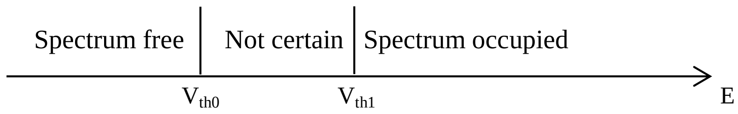
3.5. Double Threshold Energy Detection:

Based on conventional single-threshold energy detection algorithm, we discuss about double-threshold Energy detection in cognitive radio system, and then we analyse the detection probability, false alarm probability, probability of missed detection and their relationships. Further we define two parameters for performance evaluation they are probability of collision between the primary user and the secondary user, and the probability of spectrum unavailable to the cognitive user. Comparing to the single-threshold energy detection algorithm simulation results show that the proposed double-threshold energy detection algorithm can make a lower collision probability between the cognitive user and the primary user, with a little increasing of the spectrum unavailable probability.

3.5.1 THE CONVENTIONAL SINGLE-THRESHOLD ENERGY DETECTION ALGORITHM:



a).Single Threshold



b).Double Threshold

Figure.3.3. Energy Detector Decision

Neyman-Pearson criterion [3] is always used in conventional single-threshold energy detection algorithm. In Figure. 3.3(a), there is only single detection threshold. When the received signal energy V is greater than the detection threshold V_{th} it is concluded that the primary user presents, depicted as H_1, on the contrary, the primary user is not presented, depicted as H_0.

We can work out the detection probability, false alarm probability, and miss probability [2], respectively:

$$p_d = \Pr(V > V_{th}/H_1) = Q_u(\sqrt{2\gamma}, \qquad (3.37)$$

$$p_f = \Pr(V > V_{th}/H_0) = \frac{\Gamma(u, V_{th}/2)}{\Gamma(u)} \qquad (3.38)$$

$$p_m = \Pr(V \leq V_{th}/H_1) = 1 - p_d \qquad (3.39)$$

Here γ is the SNR (Signal-Noise Ratio) received by cognitive user, Vth is the detection threshold, Q_u (a, b) is normalized Marcum function with the order u . Γ(a, b) is a non-complete gamma function; Γ(a)is complete gamma function.

3.5.2. DOUBLE-THRESHOLD ENERGY DETECTION ALGORITHM:

- We have shown in the above Figure.3.3(a) that single-threshold energy detection algorithm may be cause serious interference to the primary user. In order to alleviate them we propose a double-threshold energy detection algorithm shown in Figure. 3.3(b).[7]

- We add another detection threshold within the conventional single-threshold energy detection algorithm, and it becomes a double-threshold energy detection algorithm with two detection thresholds (V_{th0} and V_{th1}).
- The primary user will be detected if and only if V> V_{th1} , and will not be presented if and only if V< V_{th0} , corresponding toH1 and H0, respectively.

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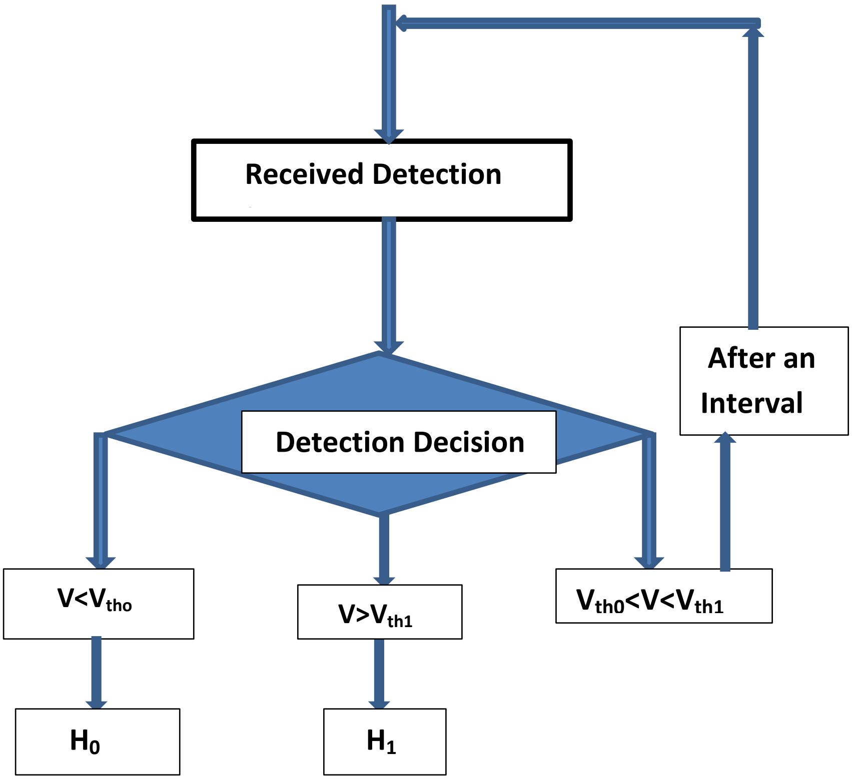

Flow chart: Double Threshold Energy Detection

When the detected energy V is in (V_{th0}, V_{th1}], this result is invalid because of easy to

mistaken. It needs redetection.

From what we have discussed, we can calculate the performance indicator of the double-threshold energy detection algorithm, such as the detection probability, false alarm probability and missing probability:

$$p_d' = \Pr(V' > V_{th1}/H_1 = Q_u\left(\sqrt{2\gamma'}, \sqrt{V_{th1}}\right) \qquad (3.40)$$

$$p_f' = \Pr(V' > V_{th1}/H_0) = \frac{\Gamma(u, V_{th1}/2)}{\Gamma(u)} \qquad (3.41)$$

$$p'_m = \Pr(V' \le V_{th0} / H_1) = 1 - p'_d \qquad (3.42)$$

Here p'_d: is the correct detection probability when the primary user presents.

p'_f: is the probability of the primary user detected presently, but in fact it does not present.

p'_m:is the probability of the primary user perhaps may not be detected, but in fact it does present.

In order to analyse our algorithm deeply, two definitions are given:

i) The probability of collision between the cognitive user and the primary user:

$$p_c = \Pr(V' < V_{th0} / H_1)$$

It is the probability of the primary user which is not detected, but in fact it is existed, and this unoccupied spectrum will be allocated to the cognitive user. It indicates the interference of the cognitive user to the primary user because of the uncertainty of the spectrum detection. The larger the probability of collision between the primary user and the cognitive user is, the more serious the interference of the cognitive user to the primary user is, on the contrary, there is less interference.

Ii) The probability of restricting the cognitive user to use spectrum, that is, the spectrum unavailable probability:

$$p_{na} = \Pr(V' > V_{th0} / H_0)$$

It is the probability of the primary user may be detected, while in fact it is not present, and this "busy" spectrum should not be allocated to the cognitive user in order to avoid interfering the primary user. It indicates the efficiency of the spectrum usage, that is, whether there are enough spectrums for the cognitive user to access the system timely. The larger the spectrum unavailable probability is, the less efficiency of the spectrum usage is. On the contrary, the spectrum is allocated efficiently.

Generally, it has $V_{th0} < V_{th} < V_{th1}$, because of adding detection threshold, from equation (33)-(39)

$Q_u(\sqrt{2\gamma'}, \sqrt{V_{th1}}) < Q_u(\sqrt{2\gamma}, \sqrt{V_{th}})$, i.e $p'_d < p_d$

$$p'_m > p_m$$

$$p'_f < p_f$$

It is clear that in the conventional single-threshold energy detection algorithm the probability of collision between the cognitive user and the primary user is also the miss probability, $p_{c1}=p_m$ and the spectrum unavailable probability is also the false alarm probability, $p_{na1}=p_f$.

Now, calculation of the probability of collision between the cognitive user and the primary user, the spectrum unavailable probability:

The collision probability $p'_{c2} = \Pr(V' < V_{th0} / H_1)$

$$= 1 - \Pr(V' > V_{th0} / H_1)$$

$$= 1 - Q_u\left(\sqrt{2\gamma'}, \sqrt{V_{th0}}\right) \quad (3.43)$$

The spectrum unavailable probability: $p_{na2} = \Pr(V' > V_{th0} / H_0)$ (3.44)

Then one can observe from equation(10) that $p_{na1} < p_{na2}$. it can be concluded that the probability of collision between the cognitive user and the primary user can be decreased effectively, avoiding the cognitive user interfering the primary user. At the same time, this algorithm decreases a little bit spectrum used efficiency. In other words, there is still a possibility to improve the spectrum is used efficiency.

3.6. DOUBLE THRESHOLD ENERGY DETECTION OF COOPERATIVE SPECTRUM SENSING

In conventional energy detections, each secondary user makes their local decisions by comparing its observational value with a pre-fixed threshold, as illustrated in Figure.3.4 [6]

Here Not certain region is represented by $O_i = (V_{th0}, V_{th1})$ denotes the collected energy value of the i_{th} secondary user. Decision H_0 *and* H_1 will be made when O_i is greater or less than the threshold value V_{th}, respectively.**[8]**

- Introduced a two thresholds method as shown in Figure 3.4. In this model, two thresholds V_{th0} and V_{th1} are used to help the decision of the secondary user.
- If energy value exceeds V_{th1}, then this user reports H_1, which means that it 'sees' the primary user. If *i O* is less than V_{th0}, decision H_0 will be made.

- Otherwise, if O_i is between V_{th0} and V_{th1}, then we also allow the secondary user reporting its observational energy value.
- So in our model, the fusion centre receives two kinds of information: local decisions and observational values of the secondary users, i.e. local energy values.

Following are the performing schemes of the double threshold energy detection cooperative spectrum sensing method.

Each secondary user *i*, for *i*= 1,2,……, *N* , performs spectrum sensing individually, i.e., if the energy detection with a result of O_i satisfies $V_{th0} < O_i \leq V_{th1}$ then the *i*th secondary user sends the energy detection value O_i to the fusion centre. Otherwise, it will report its local decision L_i according to O_i. We use R_i to denote the information that the fusion centre receives from the i^{th} secondary user, then it can be given by [8]

$$R_i = \begin{cases} O_i \ , \text{Vth0} < O\text{i} \leq \text{Vth1} \\ L_i \ , \qquad otherwise \end{cases}$$

$$L_i = \begin{cases} 0 \ ,0 \leq \sum_{i=1}^{N-K} O_i \leq \text{Vth} \\ 1 \ , \qquad \sum_{i=1}^{N-K} O_i > \text{Vth} \end{cases}$$

Here, we assume that the fusion centre receives *K* local decisions and *N-K* energy detection values among *N* secondary users. Then the fusion centre makes an upper decision according to *N -K* energy detection values, which is given by

$$D = \begin{cases} 0 \ ,0 \leq \sum_{i=1}^{N-K} O_i \leq \text{Vth1} \\ 1 \ , \qquad \sum_{i=1}^{N-K} O_i > \text{Vth1} \end{cases}$$

These *N - K* secondary users couldn't distinguish between the absence and the presence of the primary user, so the fusion centre collects their observational values and makes an upper decision instead of the local decision of themselves.

$$Qm = \sum_{k=0}^{N-1} \binom{N}{K} \prod_{i=K+1}^{N} \Delta_{1,i} [1 - Q_{(N-k)u}\left(\sqrt{2\gamma}, \sqrt{V_{th}}\right) + \prod_{i=1}^{N} P_{m,j} \qquad (3.45)$$

$$Q_f = 1 - \prod_{i=1}^{N} 1 - \Delta_{o,i} - P_{f,i}$$

$$= -\sum_{K=0}^{N-1} \binom{N}{K} \prod_{i=1}^{K} 1 - \Delta_{o,i} - P_{f,i} \prod_{i=K+1}^{N} \Delta_{o,i} \left[1 - \frac{\Gamma\left\{N - K\,u, \frac{\lambda}{2}\right\}}{\Gamma(N - K\,u)} \right] \quad (3.46)$$

$$Q_m = 1 - Q_d \quad (3.47)$$

3.7. IMPROVED ENERGY DETECTOR

- Improved energy detector for random signals in Gaussian noise is proposed by replacing the squaring operation of the signal amplitude in the conventional energy detector with an arbitrary positive power operation. [9]
- By choosing the optimum power operation, new energy detectors with better detection performances can be derived.
- These results give useful guidance on how to improve the performances of current wireless systems using the energy detector.
- In some communication applications, maximizing the probability of detection is of more importance, while in some other cases minimizing the probability of false alarm is of more important.
- In such cases better detection performance is required. This can be achieved with improved Energy Detector.
- The derivation is based on a simple modification to the conventional energy detector in [2], [4], [9] by replacing the squaring operation of the signal amplitude with an arbitrary positive power operation.
- Numerical results show that the best power operation of the signal amplitude depends on the probability of false alarm, the probability of detection, the average signal-to-noise ratio(ASNR) or the sample size, but it generally does not equal to two as in the conventional energy detector.

Using the generalized likelihood ratio test approach, the conventional energy detector can be derived as [4]

$$W = \frac{1}{n}\sum_{i=1}^{n} \left(\frac{y_i}{\sigma}\right)^2 \gtrless_{H_0}^{H_1} T \quad (3.48)$$

where the signal sample y_i is normalized with respect to the noise standard deviation and then squared, and T is the detection threshold to be determined.

In order to improve the detection performance of the conventional energy detector, the improved energy detector is proposed as [4]

$$W' = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{y_i}{\sigma}\right)^p \gtrless_{H_0}^{H_1} T' \qquad (3.49)$$

Where p>0 is an arbitrary constant and T' is the detection threshold to be determined. One sees that the conventional energy detector is a special case of the new energy detector when p= 2. Here W' can be well approximated as a Gamma random variable by matching the mean and the variance. This approximation enables us to determine the detection threshold T' for the improved energy detector in (5), which is otherwise difficult to obtain without the distribution of W'.

The approximation of PDF of W' under H_0 as a Gamma distribution is given by shape parameter and scale parameter k_0, Θ_0. [9]

$$k_0 = n.\frac{\Gamma^2\left(\frac{p+1}{2}\right)}{\Gamma\left(\frac{2p+1}{2}\right)\sqrt{\pi}-\Gamma^2\left(\frac{p+1}{2}\right)} \qquad (3.50)$$

$$\theta_0 = \frac{2^{p/2}}{n}.\frac{\sqrt{\pi}\Gamma\left(\frac{2p+1}{2}\right)-\Gamma^2\left(\frac{p+1}{2}\right)}{\Gamma\left(\frac{p+1}{2}\right)\sqrt{\pi}} \qquad (3.51)$$

Similarly the PDF of W' under H_1 as a Gamma distribution is given by shape parameter and scale parameterk_1, Θ_1.

$$k_1 = n.\frac{\Gamma^2\left(\frac{p+1}{2}\right)}{\Gamma\left(\frac{2p+1}{2}\right)\sqrt{\pi}-\Gamma^2\left(\frac{p+1}{2}\right)} \qquad (3.52)$$

$$\theta_1 = \frac{2^{p/2}(1+\gamma)^{p/2}}{n}.\frac{\sqrt{\pi}\Gamma\left(\frac{2p+1}{2}\right)-\Gamma^2\left(\frac{p+1}{2}\right)}{\Gamma\left(\frac{p+1}{2}\right)\sqrt{\pi}} \qquad (3.53)$$

Finally, using (17) to (20), the detection threshold and detection probability are

$$T' = F^{-1}_{W'/H_0}\left(1 - P_F, k_0, \theta_0\right)$$
$$P_D = 1 - F_{W'/H_1}\left(T', k_1, \theta_1\right) \quad (3.54)$$

where F^{-1}_{W'/H_0} is inverse CDF of *W'* under H_0 and F_{W'/H_1} is CDF of *W'* under H_1.

Improved energy detector the detection performance is increased, but for a good cognitive radio network the interference should be less between primary user and cognitive user. To achieve this double-threshold energy detection has been proposed

3.8. IMPROVED DOUBLE THRESHOLD ENERGY DETECTOR:

Now by using by proposed Improved Double Threshold Energy Detector we are using two thresholds values (V_{th0}, V_{th1}) in improved energy detector. Here by adding the advantage of less probability of collision of Double threshold algorithm ,with advantage of better Detection of Improved Energy detection of spectrum sensing , we are getting the better performance in the Energy detection method of spectrum sensing .Expressions for detection probability, false alarm, collision probability and spectrum non-available probability are

$$P_c = \Pr(V < V_{th0}/H_0) = F_{W'/H1}(V_{th0}, k_1, \theta_1) \quad (3.55)$$

$$P_{na} = \Pr(V > V_{tho}/H_0) = 1 - F_{W'/H0}(V_{th0}, k_0, \theta_0) \quad (3.56)$$

$$P_f = \Pr(V > V_{th1}/H_0) = F_{W'/H0}(V_{th1}, k_0, \theta_0) \quad (3.57)$$

$$P_d = \Pr(V > V_{th1}/H_1) = 1 - F_{W'/H1}(V_{th1}, k_1, \theta_1) \quad (3.58)$$

Chapter-4

SIMULATION RESULTS

4.1) ROC plot for ENERGY DETECTOR based spectrum sensing:

Pm=probability of missed detection

Pd= probability of detection

Pf= probability of false alarm

Pc= probability of collision

Detection probability (P_d), False alarm probability (P_f) and missed detection probability (P_m) are the key measurement metrics that are used to analyze the performance of spectrum sensing techniques. The performance of an spectrum sensing technique is illustrated by the receiver operating characteristics (ROC) curve which is a plot of P_d versus P_f (or) P_d versus $P_{m.}$

The performance of energy detector is analysed using ROC (Receiver operating characteristics) curves. Monte-Carlo method is used for simulation. The plot of Probability of false alarm versus Probability of detection for different values of probability of false alarm is illustrated in Figure.4.1 and it can be interpreted from Figure.4.2 that the performance of energy detector improves with increase in SNR and increase in probability of false alarm respectively.

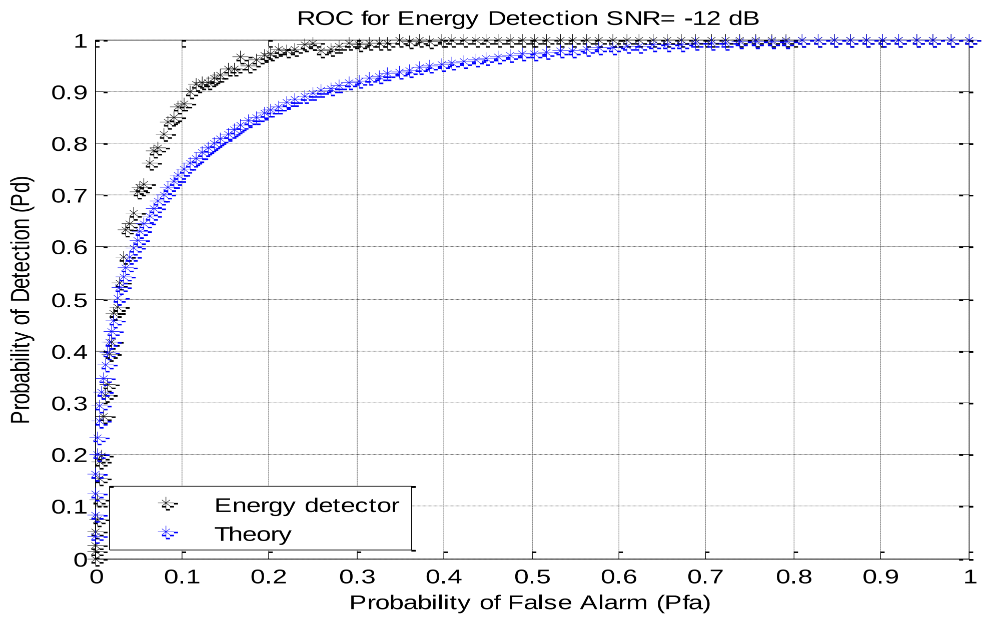

Figure.4.1. ROC curve for Energy detector based spectrum sensing

In the simulation study input random bit stream is multiplied by 1 MHz sinusoidal carrier signal to get 1 MHz BPSK modulated signal, which is transmitted in AWGN channel. The detection performance can be performed by varying the probability of false alarm from 0 ,0.01,0.02,….,1 and finding the probability of detection by using Monte Carlo simulation for each case as shown in Figure.4.2. Here the number of sample points taken is N=2000 and SNR is -12dB. Probability of false alarm on X-axis and probability of detection on Y-axis as shown in Figure.4.2.

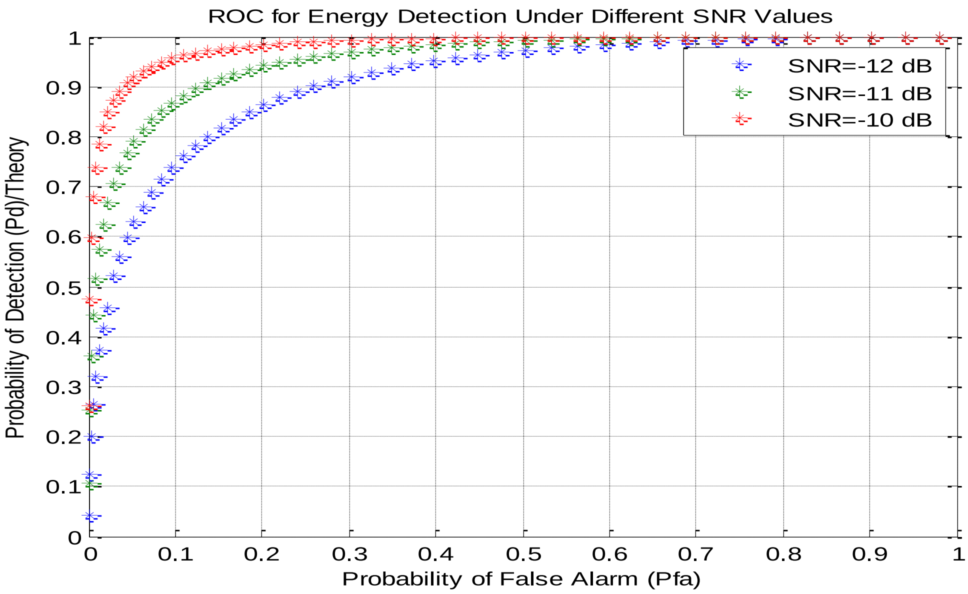

Figure.4.2. Roc curve for Energy Detector under different SNR values

Here we have taken probability of false alarm is (0,1), N=2000 and the SNR at three different values -10dB,-11dB,-12dB.from the Figure.4.2 it is observed that detection performance improved by increasing SNR value .

Figure.4.2. above illustrates the ROC (Receiver Operating Characteristics) curves i.e. Pd versus Pfa using Energy detection method for spectrum sensing. This conventional method uses squaring operation. The graph is plotted for different SNR values over AWGN channel and it shows that with increase in SNR (Signal to Noise Ratio), the probability of detection increases and is quantified in Table 4.1.

Probability of False Alarm	Probability of Detection (SNR= -11 dB)	Probability of Detection (SNR= - 10 dB)	Improvement (in times)
0.01	0.107	0.2614	1.44
0.1	0.5752	0.7841	0.26
0.2	0.7662	0.9066	0.1832
0.3	0.8682	0.9564	0.101
0.5	0.961	0.9907	0.029

Table.4.1: Improvement in Probability of detection with increase in Signal to Noise Ratio in Energy Detection Method for AWGN Channel.

From the Table 4.1 shows **that 1 dB increase** in Signal to Noise Ratio; increases the probability of detection (at SNR=-11 dB) up to 1.44 times as compared to probability of detection (at SNR=-10dB) for AWGN Channel.

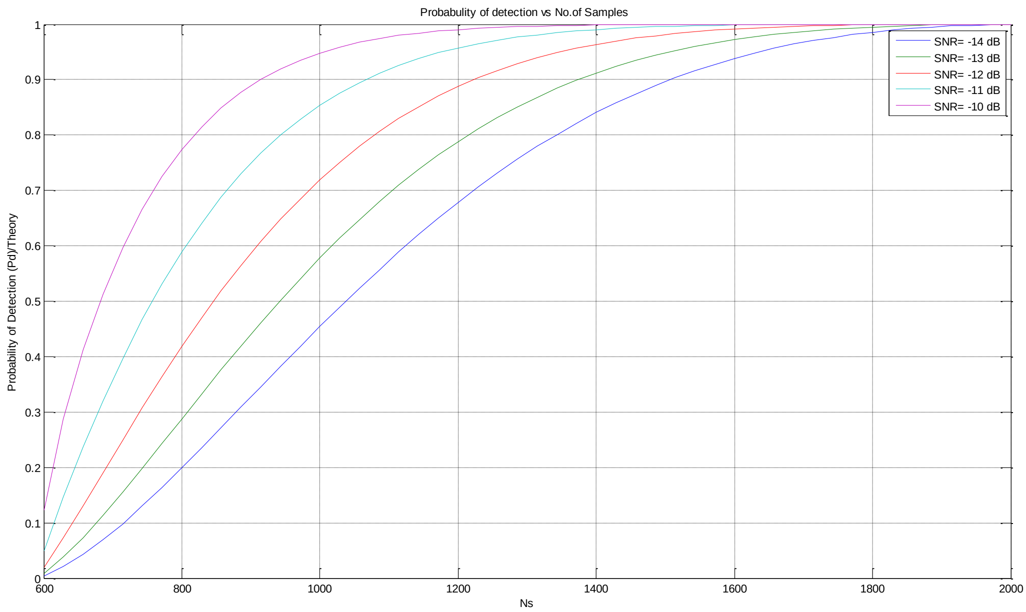

Figure.4.3. Plot between Probability of Detection vs The number of samples(Ns) , for different SNR values

Here the number of sample points taken as different values of N=600,650,700…..2000. It is observed from Figure.4.3 that by increasing the number of sample points the detection performance can be improved at lower SNR values.

No.of Samples (N_s)	Pd (SNR = -14dB)	Pd (SNR = -10dB)	Improvement
600	0.041	0.1232	2 times
700	0.0428	0.412	8 times
900	0.1639	0.7251	3.4 times
1200	0.3821	0.91	1.3 times

Table.4.2: Improvement in Probability of detection with increase in Signal to Noise Ratio in Energy Detection Method using Squaring operation for AWGN Channel.

So from results shown in Table 4.2, as for the different values of N_s , probability of detection ($P_{d)}$ increases as Signal to noise ratio increases .

4.2. ROC curve for Energy detector under Rayleigh fading Channel: ROC (receiver operating curve) for different SNR=0dB,10dB,20dB

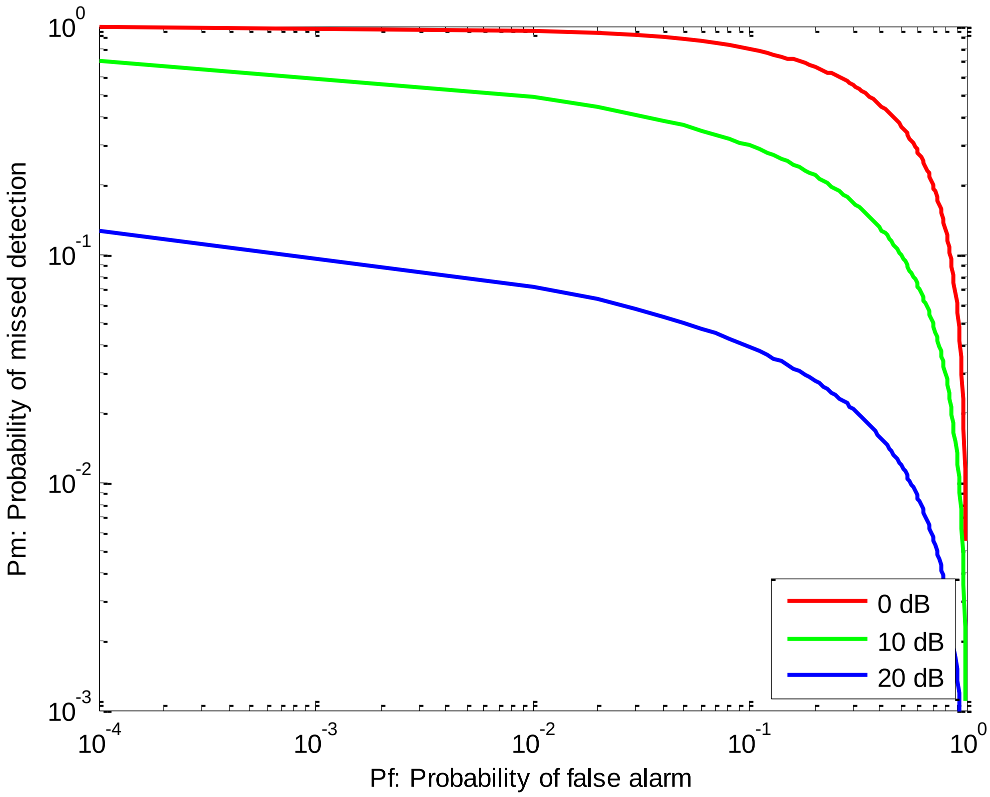

Figure.4.4. Spectrum Sensing Performance

From Figure.4.4 above illustrates the ROC (Receiver Operating Characteristics) curves i.e. versus using Energy detection method for spectrum sensing. This conventional method uses squaring operation. The graph is plotted for different SNR values over Rayleigh channel and it shows that with increase in SNR (Signal to Noise Ratio), the probability of detection increases and is quantified in Table 4.2.

P_f	Pm (SNR=0dB)	Pm (SNR= 10dB)	Pm (SNR= 20dB)
0.001	0.99	0.79	0.127
0.101	0.79	0.298	0.0392
0.201	0.661	0.22	0.0278
0.301	0.554	0.169	0.0209
0.401	0.453	0.1302	0.453

Table 4.3: Improvement in Probability of detection with increase in Probability of False Alarm in Energy Detection Method using Squaring operation for Rayleigh Channel.

Table 4.3 shows that 10 dB increase in Signal to Noise Ratio; increases the probability of detection (at SNR=20 dB) up to 0.7 times as compared to probability of detection (at SNR=10 dB) .

Roc for AWGN,Rayleigh fading channel:

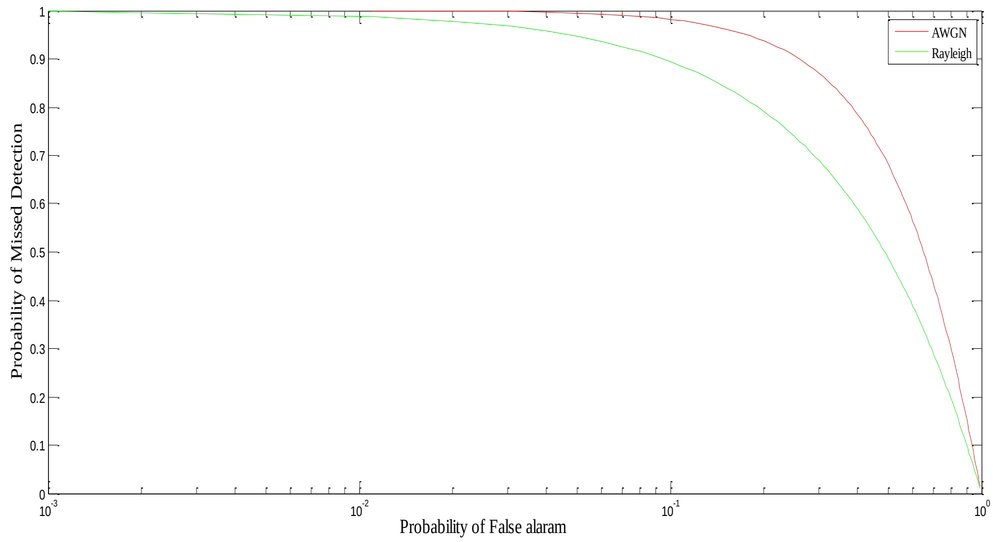

Figure.4.5 Roc for AWGN ,Rayleigh fading channel

Figure.4.5 shows ROC plot for Rayleigh Channel, increases the probability of miss detection (at SNR=-10 dB) up to 4.1 times as compared to AWGN channel for probability of false alarm value varies between (0.001,1) . Figure.4.5 shows the degradation in performance of energy detector in Rayleigh fading channel.

P_f	P_m (AWGN)	P_{m} (Rayleigh)	Increment
0.201	0.4207	0.7911	0.88
0.301	0.2734	0.6896	1.5
0.401	0.1730	0.5890	2.4
0.501	0.1045	0.4891	3.7

Table: 4.4. Performance Comparison between AWGN, Fading channel

4.3. COOPERATIVE SPECTRUM SENSING:

Cooperative Spectrum Sensing Performance using OR AND, MAJORITY rule

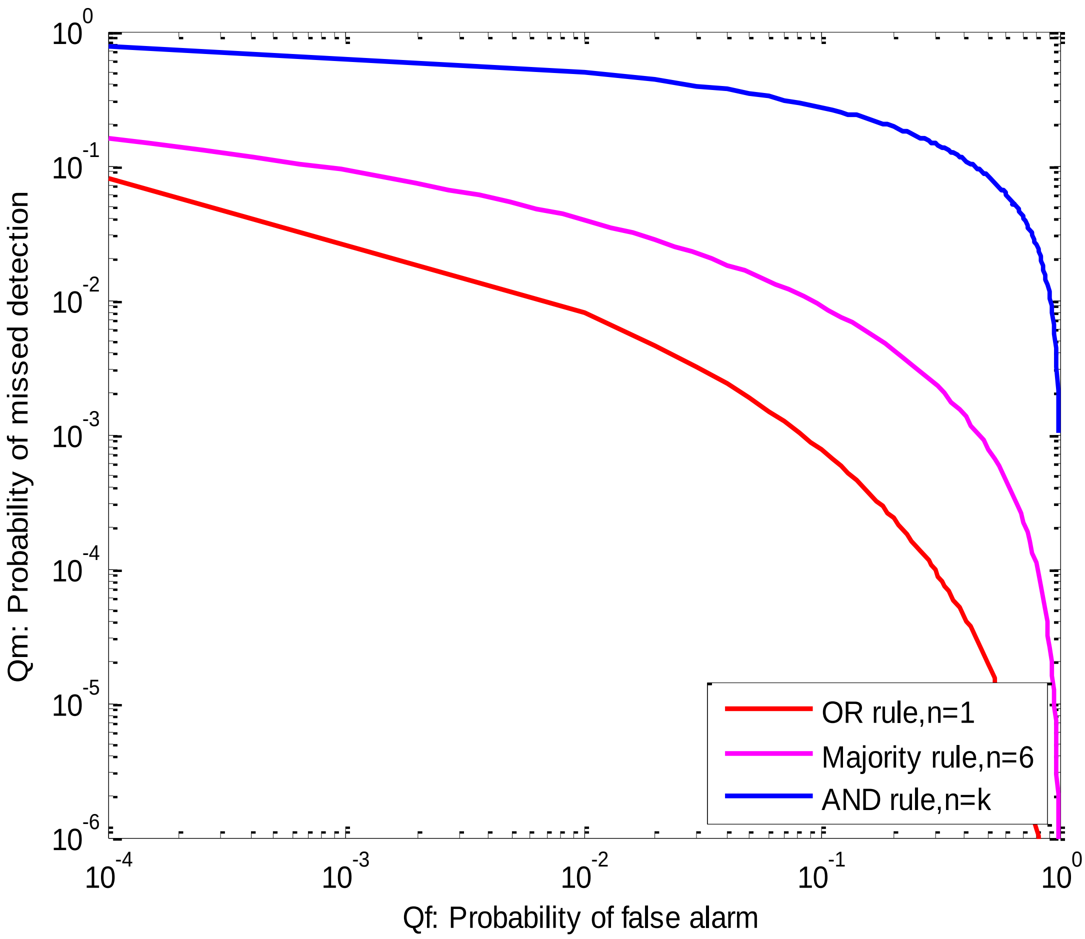

Figure.4.6. Cooperative Spectrum Sensing Performance

Figure.4.6 shows the cooperative spectrum sensing performance with different fusion rules. Here Using equations (29),(30) , It can be seen that the OR rule (n=1) is the best among the fusion rules. In the plotting we consider SNR=10dB and n=1, 6, 10 respectively.

Cooperative sensing for K=1, 2,5,10, here k=no.of cognitive users

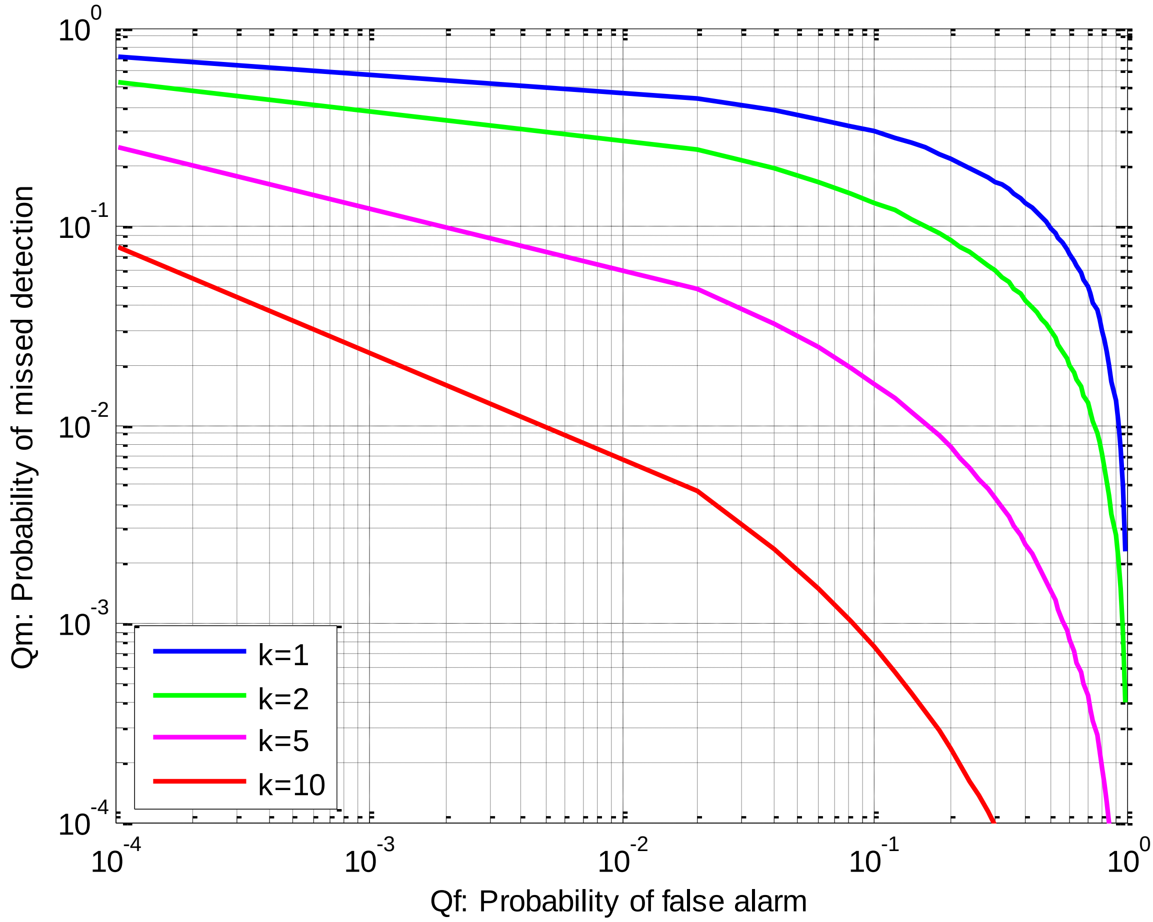

Figure.4.7. Cooperative sensing for K=1, 2,5,10

From the Figure.4.7 using equations (29),(30) shows the performance results of cooperative spectrum sensing for different numbers of CRs over Rayleigh fading channels with an SNR= 10 dB. It is seen that the probability of missed detection is greatly reduced when the number of cooperative CRs increases for a given probability of false alarm. It is seen that the probability of missed detection is greatly reduced when the number of cooperative CRs increases for a given probability of false alarm.

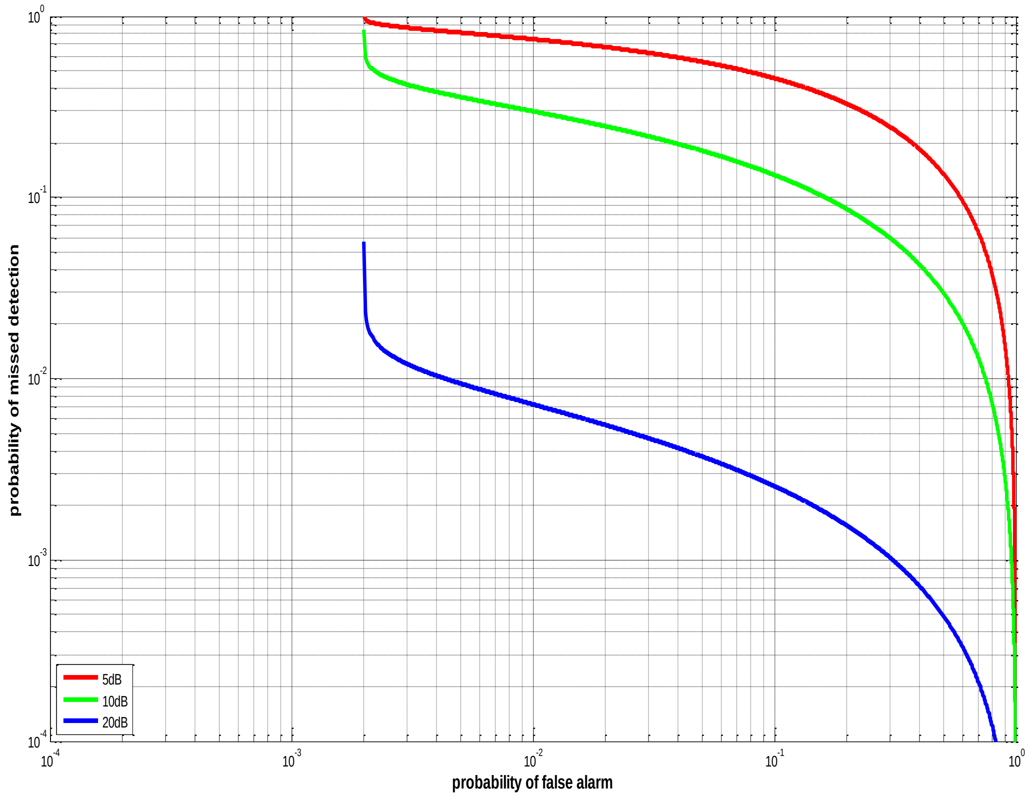

Fig.4.8 Cooperative Sensing with Reporting error, Pf vs. Pm

From the above Figure.4.8 using equation (31),(32) shows the ROC curves under different average SNRs for two CRs with P_e=0.001. It can be seen that Q_f is limited by a lower bound. Here from the Figure.4.8 we can observe that detection performance of cooperative spectrum sensing is improved with increasing SNR value, ie the probability of miss detection is reduced.

4.3.2. DOUBLE THRESHOLD ENERGY DETECTION

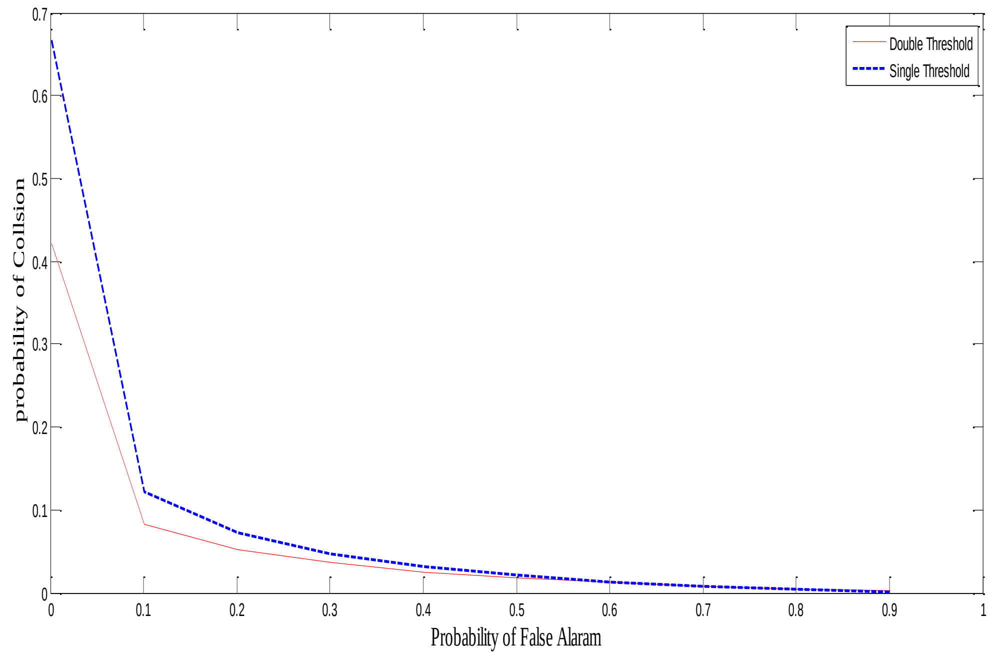

Figure.4.9: Performance Comparison between Single, double Threshold Energy Detection using Probability of collision Pc vs probability of false detection plot

In Figure.4.9 here we plot the probability of collision between the cognitive user and the primary user, changing with the different probability of false alarm comparing to the single-threshold energy-detection algorithm. our algorithm decreases the probability of collision between the cognitive user and the primary user comparing to the single-threshold detection algorithm.

Double Threshold Energy detector increases a little the spectrum unavailable probability, for instance, Vth =15dB, the spectrum unavailable probability increases, It decreases the spectrum efficiency.

From analysis of results above, it can be concluded that double-threshold energy detection algorithm can decrease the probability of collision between the cognitive user and the primary user, decreasing the interference of the cognitive user to the primary user with sacrificing a little bit spectrum efficiency.

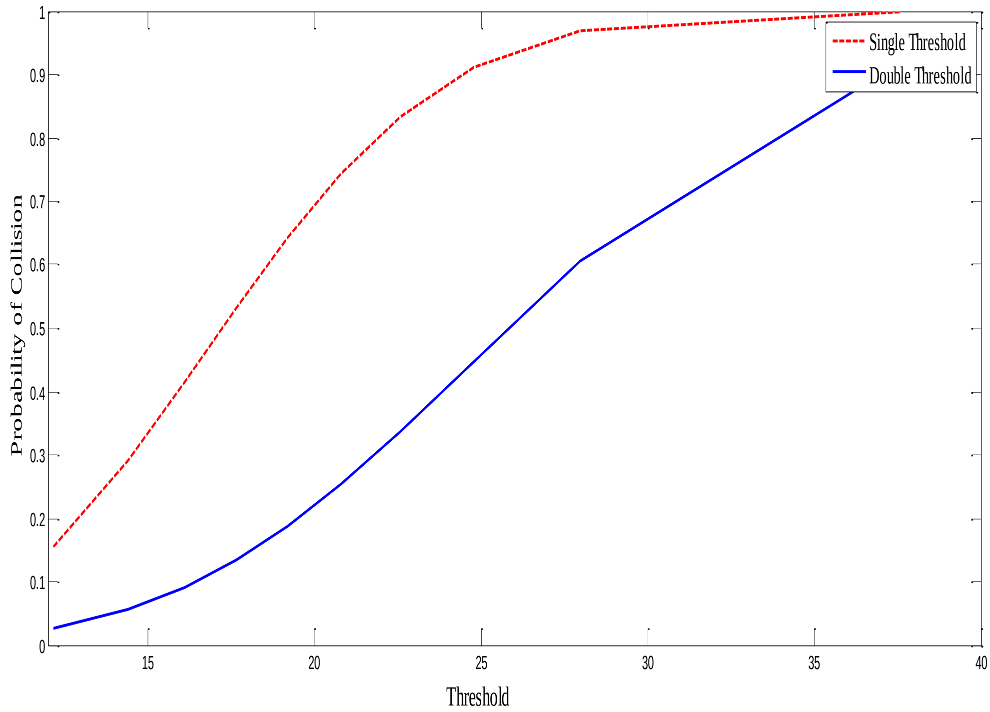

Figure.4.10: Collision Probability vs Threshold detection for Energy Detector, Double Threshold Energy detector

Threshold(V_{th})	P_c (Single Threshold)	P_c (Double Threshold)	Reduction
12	0.15	0.02	0.86
16	0.41	0.09	0.78
20	0.64	0.18	0.71
24	0.9	0.4	0.55

Table:4.5 Comparison between Energy detector, Double Threshold Energy detector

From the Figure 4.10 ,table 4.5 Probability of collision between Double Threshold Energy detector is Reduced than Energy detector ,So these observation concludes better performance improvement in Double threshold energy detector.

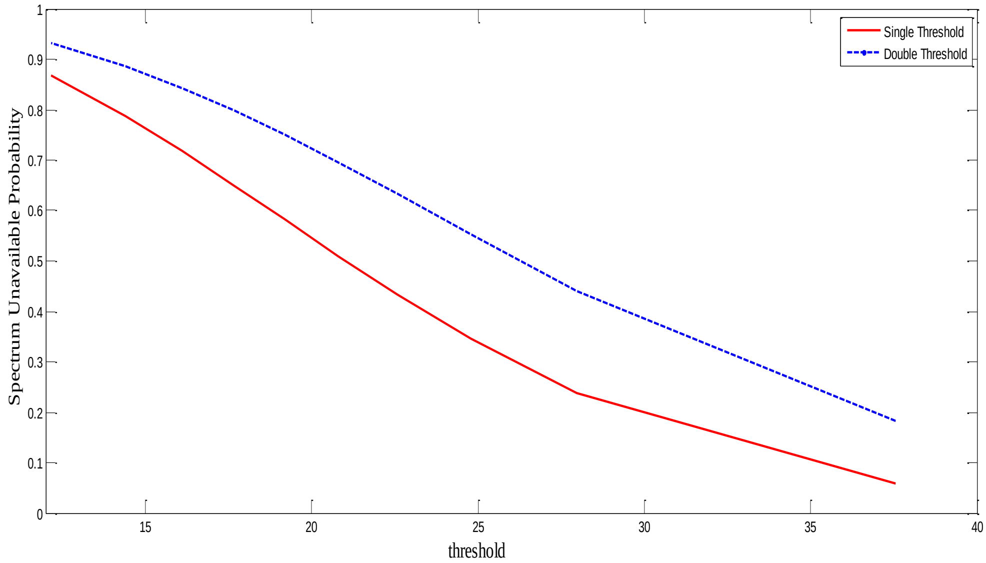

Figure.4.11 Spectrum Unavailable probability vs Threshold detection for Energy Detector , Double Threshold Energy detector

4.4. ROC plot for DOUBLE THRESHOLD ENERGY DETECTION with $\nabla_{0,i} = \nabla_{1,i} = 0.01$ using co-operation

we only concentrate on the AWGN channels, realistic fading and shadowing are ignored. The results of the conventional method, i.e., $\nabla_{0,i} = \nabla_{1,i} = 0$ is used in conventional method. And $\nabla_{0,i} = \nabla_{1,i} = 0.01$ is used in double threshold energy detection.

Other common simulation parameters are given as follows:

- SNR $\gamma_1 = \gamma_2 \ldots\ldots = \gamma_N$=10dB

- u=5

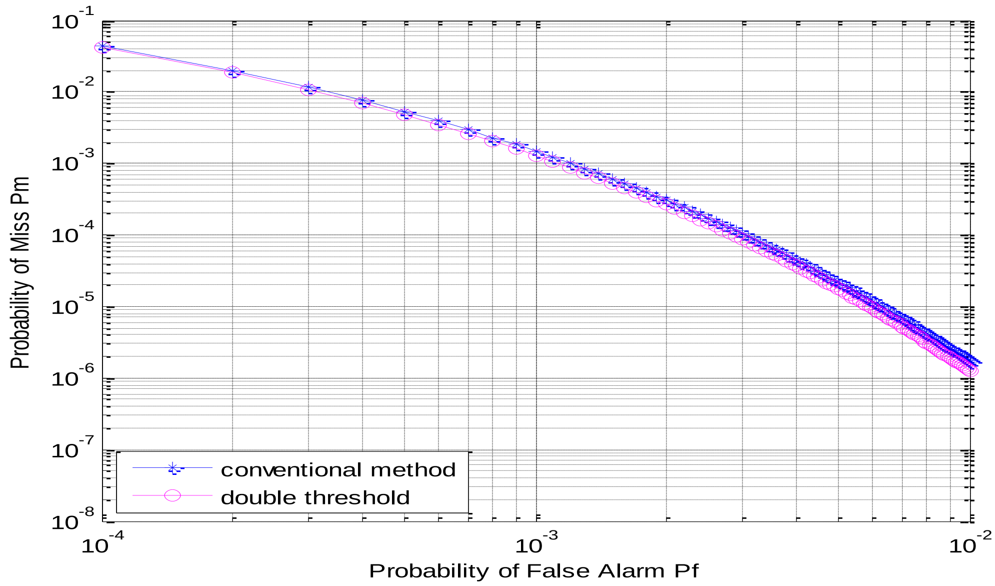

Figure.4.12 .Comparison between the conventional , Double threshold Energy detector with , $\nabla_{0,i} = \nabla_{1,i} = 0.01$

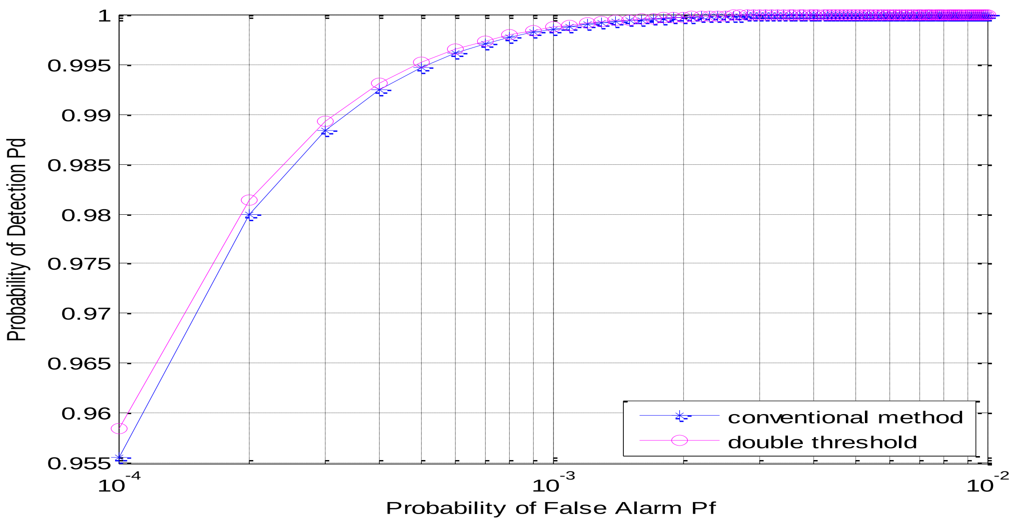

Figure.4.13. Comparison between the conventional, Double threshold Energy detector with, $\nabla_{0,i} = \nabla_{1,i} = 0.01$

DOUBLE THRESHOLD ENERGY DETECTION with $\nabla_{0,i} = \nabla_{1,i} = 0.1$ using Cooperation

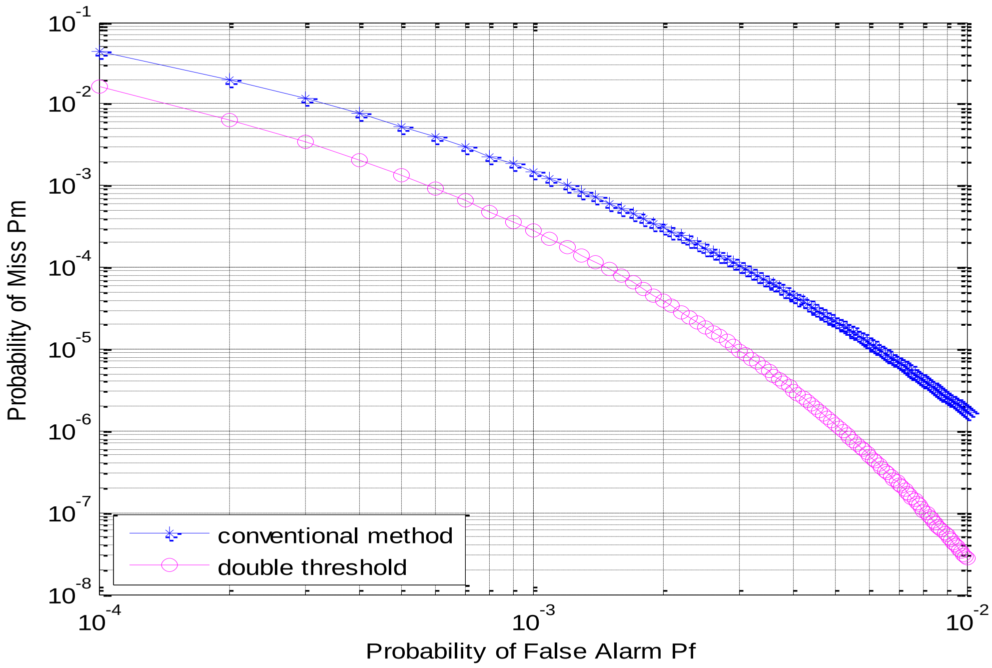

Figure.4.14 .ROC plot

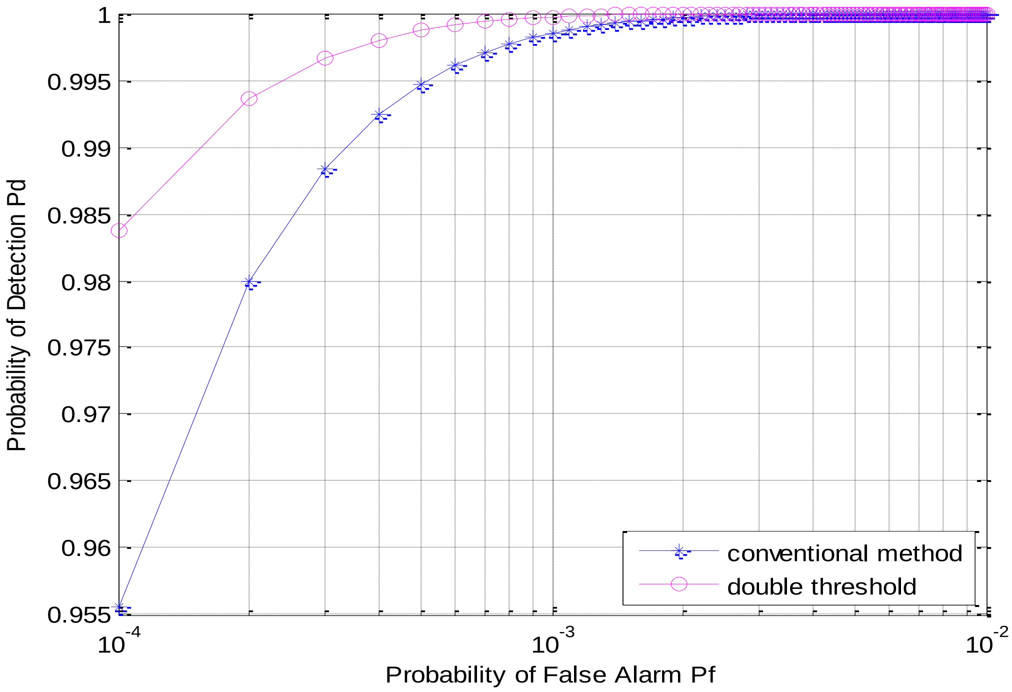

Figure.4.15 ROC plot

from Figure.4.14 that the double threshold energy detector method has a little performance improvement from the conventional, cooperative method. When we increase when we increase $\nabla_{0,i}$ and $\nabla_{1,i}$ as shown in Figure.4.14, 4.15 the detection performance has improved significantly. While Q_f equals 0.0001, our method achieves 0.035 extra detection probability.

4.4.1. Conventional, Double threshold Energy detector for different SNR values i.e., SNR=0dB, 10dB:

Here pc1 for conventional, pc2 for double….

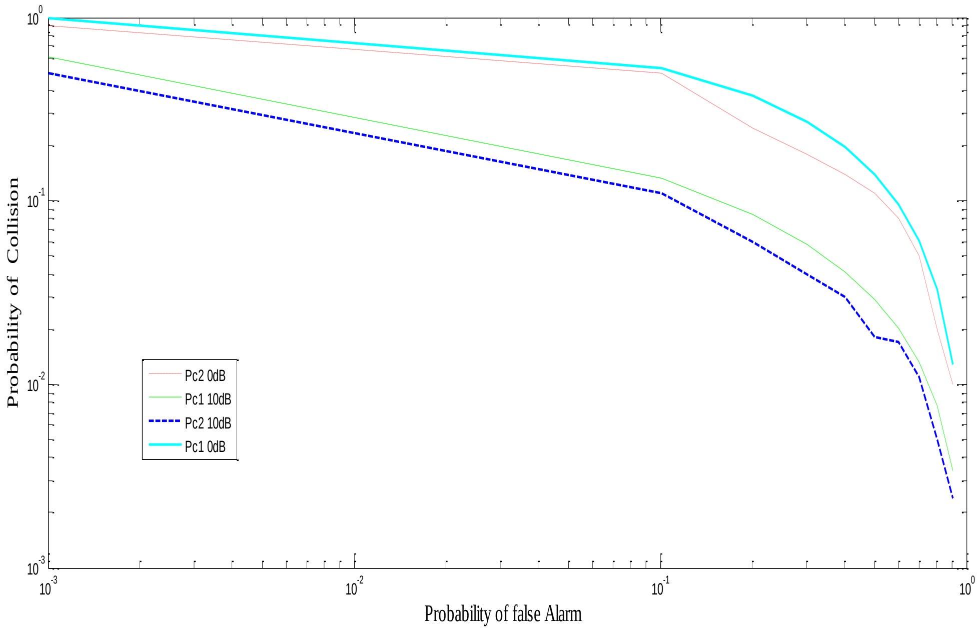

Figure.4.16: Roc plot for Conventional, Double threshold Energy detector for different SNR values i.e., SNR =0dB, 10dB

From the above plot, As the SNR value increases from 0dB, 10dB, in the both the normal Energy Detector and the Double –Threshold Energy detector improves Detection Performance. Here we observe that for equal SNR value Double Threshold Energy Detector gives better performance .

4.5)Roc plot of Improved double Threshold Energy detector , with normal energy detector , double threshold Energy detector with SNR=10dB

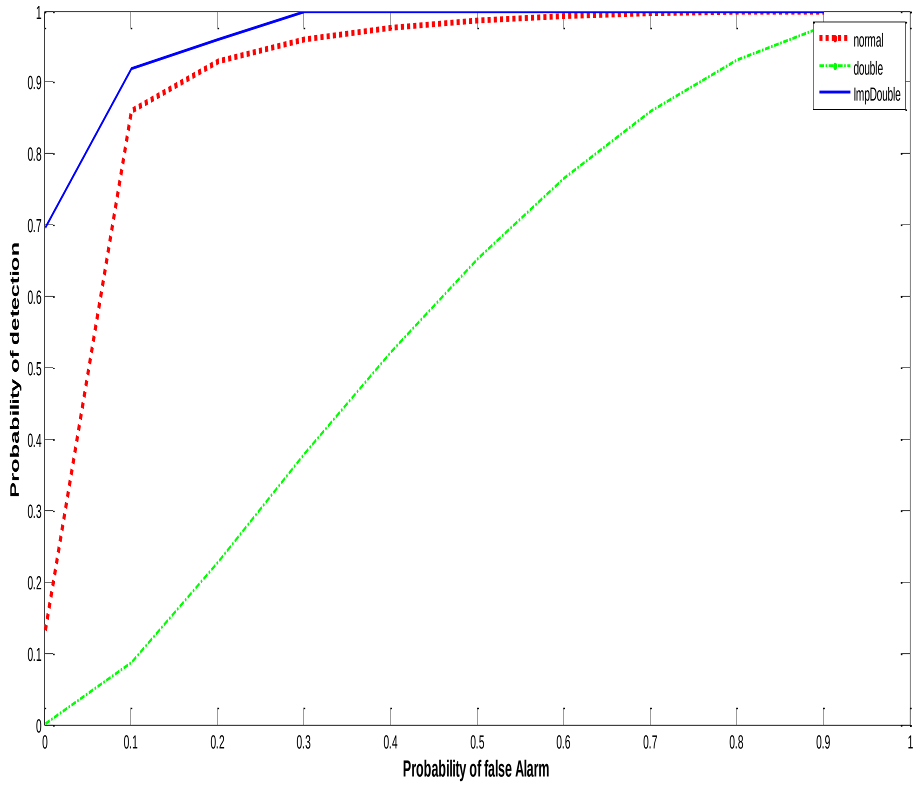

Figure.4.17: ROC plot for Improved-Double threshold Energy detector, with normal, Double threshold energy detector

P_f	P_d (Normal)	P_d(Double)	P_d (Improved double)	Improvement
0.101	0.131	$3.5*10^{-7}$	0.696	0.81 times
0.201	0.86	0.087	0.919	0.06 times
0.301	0.929	0.228	0.959	0.03 times
0.401	0.96	0.37	0.99994	0.04 times
0.501	0.97	0.526	0.99999	0.02 times

Table 4.6: Performance comparison using Probability of detection

From the plot shown above for SNR=10dB , we can observe that the detection performance of Improved Double Threshold Energy detector is improved compared to Energy detector algorithm and double threshold Energy detection , with this improvement this enhancement of this Hybrid detector is gives better detection. Enhancement in the detection Performance of proposed method can be understood clearly by using bellow table 4.6.

From the analysis from Table 4.6, one can observe the better Detection Performance in achieved in Improved Double threshold Energy detector compared with other Energy detector methods.

Probability of collision vs probability of false alarm for Improved double Threshold Energy detector , with normal energy detector , double threshold Energy detector with SNR=10dB :

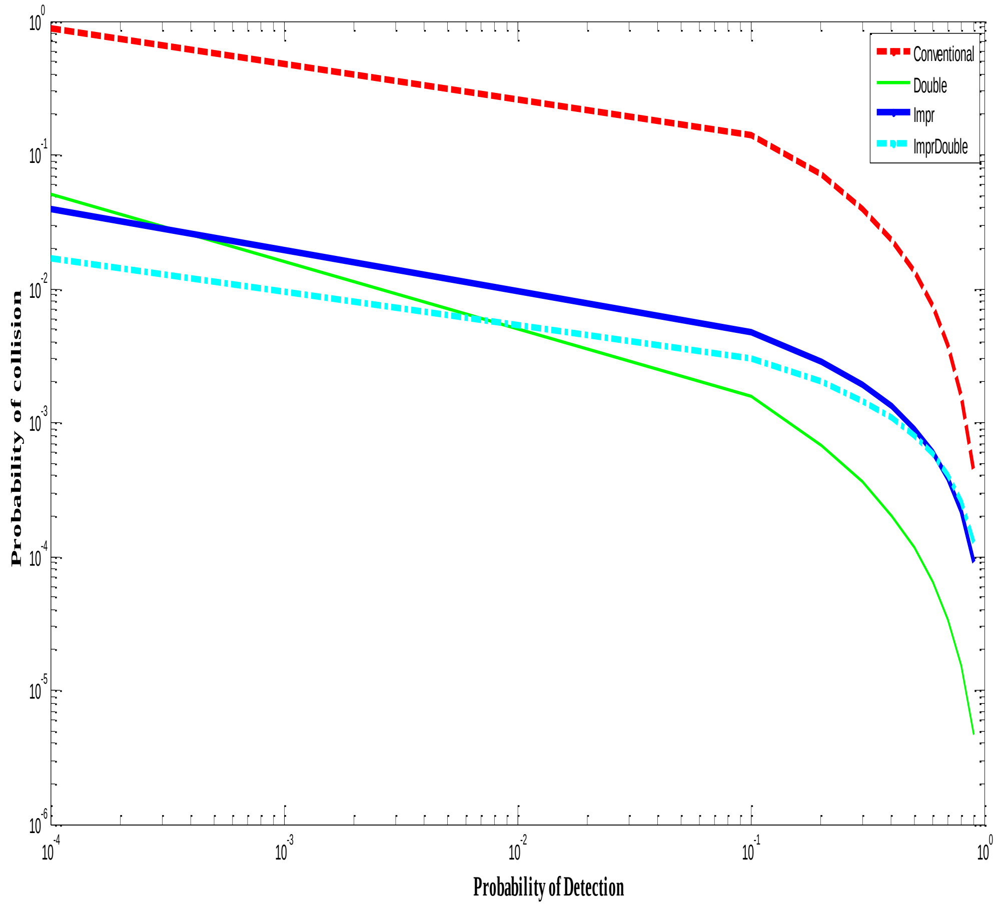

Figure. 4.18. ROC plot for conventional, double-threshold, improved, Improved-double threshold energy detector

From the simulation results shown above in Figure.4.18 i.e., ROC plot (Probability of False Alarm , Probability of Collision) , it is shown that Probability of collision is Reduced in Improved Double Threshold Energy Detector . Its value is almost nearer to probability of collision for Improved Energy Detector .So from the plot we can observe that collisions between primary, secondary users, gives better performance.

P_f	P_c (Improved double)	P_c (Improved)	P_c(Double)
0.001	0.016	0.038	0.05
0.201	0.03	0.0047	0.0015
0.301	0.02	0.0028	0.0006
0.401	0.014	0.0018	0.0003

Table4.7: Performance comparison using Collision Probability

From the above result shown, in Improved Double threshold Energy detector probability of collision is reduced , i.e. By fixing the Probability of false alarm value in between 0.001 to 1 in steps of 0.1 to find the threshold value corresponding to find the collision probability every time . Here Pc of Improved Double threshold energy detector values are almost approaches to Pc value of Double Threshold energy detector. Here we can observe the better performance improvement in the Proposed Method.

Chapter-5

CONCLUSION AND FUTURE SCOPE

Conclusion:

Cognitive Radio is new technology that can utilize the spectrum holes of the licensed bands efficiently. Spectrum Sensing is used in Cognitive Radio Systems to detect the Spectrum holes accurately and quickly. In this thesis, we discuss about different Spectrum Sensing method in Energy Detector and their advantages and disadvantages in both cooperative, non-coopeartive sensing methods. In order later we discuss about hidden terminal problem occurred commonly in Cognitive Radio networks. To address this problem we discuss about Co-operative spectrum sensing. Later we discuss about performance improvement in Improved Energy detector, Double threshold Energy detector . Finally by the proposed Improve Double Threshold Energy detection method ,we improve the performance efficiency of Energy detector.

Future scope:

- With the proposed Improved Double threshold Energy detector, we need to implement this concept in co-operative spectrum sensing for better performance.
- Hybrid Spectrum Sensing techniques like any two combinations of spectrum sensing techniques such as Energy detector and Matched detector (or) Cyclostationary detector ,with Improved Double threshold Energy detection in both Cooperative , non-cooperative sensing needed for better detection performance.
- With the assumption that the signal from all users is sensed at a particular value of SNR only. However by varying the SNR value of different users gives a practical scenario of the cognitive radio model. This makes use of the new Evolutionary techniques which suits for user’s requirement.

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