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INSTITUTE OF ENGINEERING
CENTRAL CAMPUS

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PERFORMANCE COMPARISON OF ENERGY DETECTOR USING VARIOUS
ALGORITHMS FOR COGNITIVE RADIO NETWORKS

by

Nirajan Koirala

A THESIS

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The undersigned certify that they have read and recommended to the Department of Electronics and Computer Engineering for acceptance, a thesis entitled “**Performance Comparison of Energy Detector Using Various Algorithms for Cognitive Radio Networks**”, submitted by **Nirajan Koirala** in partial fulfillment of the requirement for the award of the degree of “**Master of Science in Information and Communication Engineering**”.

Supervisor: Dr. Ram Krishna Maharjan

Electronics and Computer Department

Institute of Engineering

Central Campus

External Examiner: Shiva Raj Baral

Head

Electronics and Computer Department

Kathmandu Engineering College

Committee Chairperson: Dr. Dibakar Raj Panta

Head

Electronics and Computer Department

Institute of Engineering

Central Campus

Date

DEPARTMENTAL ACCEPTANCE

The thesis entitled “**Performance Comparison Of Energy Detector Using Various Algorithms For Cognitive Radio Networks**”, submitted by Nirajan Koirala in partial fulfillment of the requirement for the award of the degree of “**Master of Science in Information and Communication Engineering**” has been accepted as a bonafide record of work independently carried out by him in the department.

Dr. Dibakar Raj Panta

Head of the Department

Department of Electronics and Computer Engineering

Central Campus, Tribhuvan University, Nepal

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ABSTRACT

Spectrum sensing is very important technique in cognitive radio network. Selection of appropriate threshold for spectrum sensing defines the performance of the cognitive radio. Conventional method of threshold selection suffers from the signal and noise fluctuations. So more flexible spectrum sensing algorithms are used which adapt to changing signal and noise power. This work focusses on energy detection based spectrum sensing algorithm as it is simple and does not require prior information. Collision between cognitive users and the primary users determine the detection performance. Performance of adaptive spectrum sensing algorithm and adaptive double threshold algorithm are compared with the conventional double threshold algorithm for the AWGN channel, Rayleigh and Nakagami fading channels. Theoretical analysis and simulation result showed that interference level to primary users is reduced and detection performance is significantly improved using adaptive double threshold algorithm.

Index Terms: — *Double threshold algorithm, adaptive spectrum sensing and adaptive double threshold algorithm*

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LIST OF ABBREVIATIONS

AWGN	Additive white Gaussian noise
BPF	Band Pass Filter
CR	Cognitive Radio
CDR	Constant detection rate
CFAR	Constant false alarm rate
CFD	Cyclostationary feature detection
DSA	Dynamic Spectrum Access
DTFD	double threshold feature detector
ETSI	European Telecommunication Standards Institute
FCC	Federal Communication Commission
NGN	Next Generation Network
PU	Primary User
QPSK	Quadrature phase shift keying
ROC	Receiver operating characteristics curves
SDR	Software Defined Radio
SLC	square-law combining
SLS	Square-law selection
SNR	signal-to-noise ratio
SU	Secondary User

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CHAPTER ONE: INTRODUCTION

1.1 Background

The popularity of various wireless technologies and fixed spectrum allocation strategy, spectrum is becoming a major bottleneck, due to the fact that the most of the available spectrum has been allocated.

The increasing demand for new wireless services, especially multimedia applications, together with the growing number of wireless users and demand of high quality of services have resulted in overcrowding of the allocated spectrum bands, leading to significantly reduced levels of user satisfaction. Particularly, spectrum congestion is a serious problem in communication-intensive situations such as after a ball-game or in a massive emergency. According to Federal Communication Commission (FCC), some spectrum band remains unused at a given time and location, indicating that a more flexible allocation strategy could solve the spectrum scarcity problem. For example, cellular network bands are overloaded in most parts of the world but television broadcasting, amateur radio and paging have been found to be grossly underutilized [1]. Figure 1.1 shows the spectrum usage showing frequency holes. The unused spectrums are called spectrum holes or white spaces.

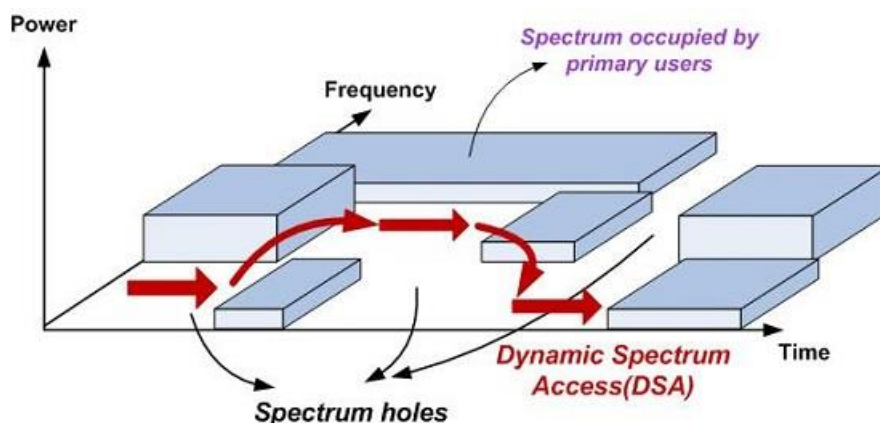


Figure 1.1: Spectrum Usage showing frequency holes [2]

Spectrum scarcity motivates a new paradigm of either through opportunistic spectrum sharing or through spectrum sharing for exploiting the spectrum resources in a dynamic way. Cognitive radio (CR) allows the secondary users (SUs) (lower priority) to share the licensed spectrum originally allocated to the primary users (PUs) (higher

priority). In opportunistic spectrum access, the SU needs to sense the radio environment and identify the temporally vacant spectrum. This sensing-based technology realizes the spectrum reuse based on the temporal characteristic of the radio environment, i.e., the SU and PU will not operate on the same spectrum simultaneously [1] [2].

Spectrum utilization chart showed that large portion of the assigned spectrum is used sporadically and geographical variations in the utilization of assigned spectrum ranges from 15% to 85% with a high variance in time. The sporadic usage of spectrum is illustrated in figure 1.2:

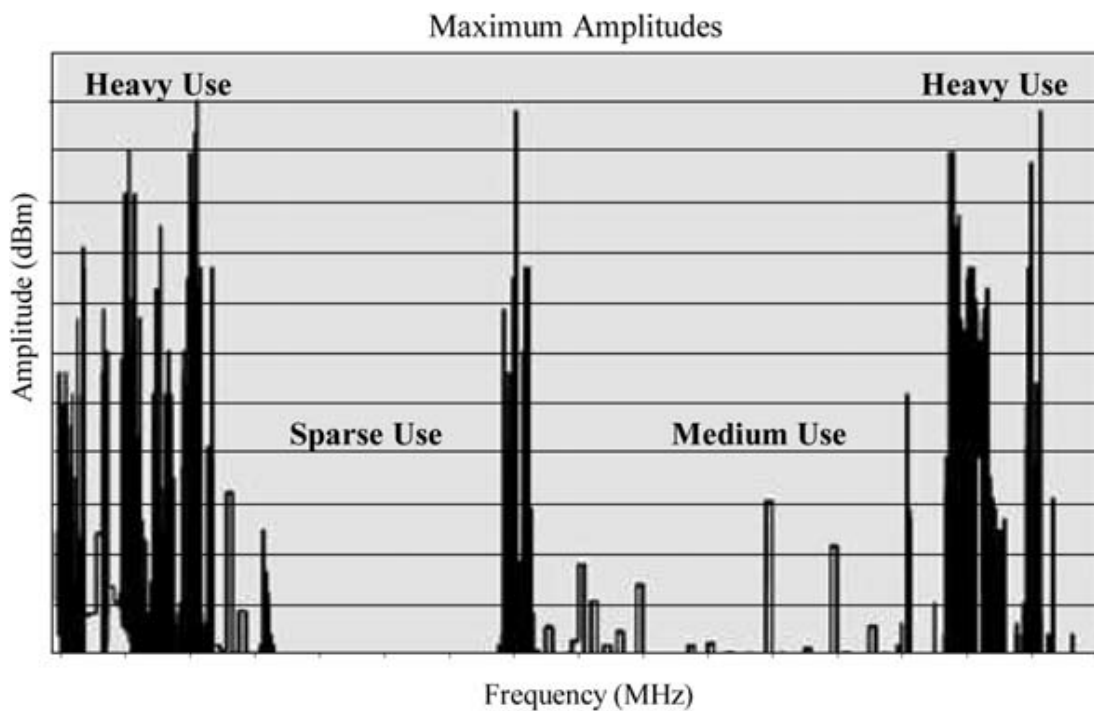


Figure 1.2: Spectrum Utilization chart [3]

used whereas certain frequencies are medium in usage and some frequencies are not used or sparse in usage [3]. The unused spectrums are called spectrum holes or white spaces. Further, the result released by FCC indicates that for 90% of the time many licensed frequency band remain unused. For example, the average utilization of the licensed spectrum for television (TV) broadcast was found to be 14% in 2004, and this number keeps decreasing every year because of the commencement of cable TV and satellite TV. This suggests that it is not an actual spectral shortage but rather the inefficient spectral usage. As demand on the number of users and their data rates steadily increase, it is important to enable efficient access and use of the radio spectrum. The studies of Federal Communications Commission (FCC) spectrum

policy task force has illustrated that in certain licensed bands below 3 GHz, the usage of spectrum is very low at any given location and time. This study group suggested that TV bands operating in UHF/VHF are less significantly used and many upcoming mobile applications and wireless applications can be introduced on this band with some technology. The limited available spectrum in the sense that they are already licensed but not efficiently used, therefore; new applications are competing for the very little spectrum that is left unlicensed or in some cases are not getting spectrum. This scenario defines a new communication paradigm. This new paradigm should allow users to exploit the existing wireless spectrum in a shared manner.

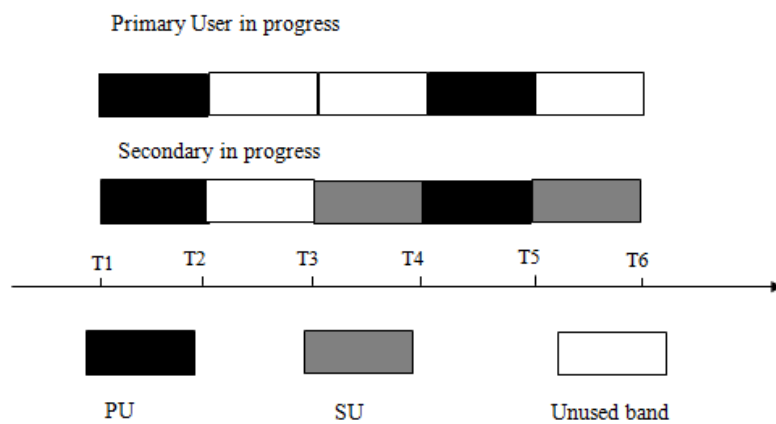


Figure 1.3: Concept of Cognitive radio

The spectrum regulatory bodies in different regions are facing challenges to accommodate the upcoming wireless communication users and applications within the limited electromagnetic spectrum. Besides these, there are data networks in local and personal area, which are called WLAN and WPAN, respectively, working in the license free band called industrial scientific medical (ISM) frequency bands. These bands allow multiple wireless applications to coexist in a given shared environment. The most widespread systems in the 2.4 GHz ISM band are IEEE 802.11 and Bluetooth. Thus, with the proliferation of new wireless technologies and the increasing bandwidth demands, unlicensed ISM spectrums for exclusive use to some extent by increasing infrastructures has become possible. These bands are already crowded with the introduction of increased utilization of wireless technologies operating in this frequency band such as Cordless Phones, Wireless personal area network, HIPERLAN, microwave ovens, wireless video camera, wireless game controller, Zigbee, wiMAX. The co-channel and adjacent channel interference to some extent and the interferences from other non 802.11 applications cause

significant loss of throughput of 802.11. In some countries, the numbers of smart phones are more than their population. Then, it is likely that huge interference among those users is intended. For example, in a given country, there are ten users using fixed frequency bandwidth and there is no more frequency slot left. The new wireless devices manufactures or service providers want to use the frequency for their devices. Since, there are no frequencies left, they cannot operate their devices. As explained earlier, not all the frequency users simultaneously occupy the fixed spectrum. It is logical that those unused licensed spectrum can be used by other service providers under the condition when licensed users are not using the bands. Dynamic spectrum access (DSA) defines such a scenario. The DSA therefore is a new paradigm capable of using the electromagnetic spectrum dynamically by pooling up the frequency. This new paradigm is also referred to as Next Generation Networks.

DSA can be best viewed with the help of the Figure 1.2. It can be seen that the band is used for time intervals: t_1 to t_2 , t_3 to t_4 and t_4 to t_5 by primary user. The band is observed vacant for time intervals: t_2 to t_3 and t_5 to t_6 . The secondary may make use of it for those vacant intervals. Again the SU has to evacuate the channel when the primary wanted to use it. The secondary user should be intelligent enough that it should vacate the spectrum when the primary users want to use its usual frequency spectrum. However, the electronic radio chip used in the traditional communication devices are quite dumb in the sense that they do only things according to the hardware circuits of the chip designed for the purpose. The new paradigm shift in wireless communication, especially in the radio technology with the use of software defined radios, enables intelligence to be embedded such that the radios can think and act accordingly. This provides a development platform to a new wireless technology known as cognitive radios. The cognitive radios are defined by the specific functionalities in order to think and act, learning the radio environment and gathering intelligence with the corresponding decision making processes. The embedded intelligence in the radios is then used to perform efficient communications by optimizing the usage of the scarce radio resources, such as the radio spectrum.

The overview concept of cognitive radio has been given by Mitola through cognitive radio cycle. The cognitive radio cycle proposed by Mitola is depicted in the Figure 1.4. According to the cognitive radio cycle a cognitive radio monitors spectrum bands, captures their information, and then detect the spectrum spaces or spectrum holes or white spaces. The characteristics of the spectrum holes that are detected

through spectrum sensing are estimated. The appropriate spectrum holes are chosen according to the user's requirement. Once the best bands are determined, the communication can be performed over this spectrum bands. This concept was then adopted by Haykin by defining the respective physical layer communications and signal processing associated with it. This then lead to in depth treatment of cognitive radio research around the world, giving a huge number of research papers and the articles produced on the very same topic.

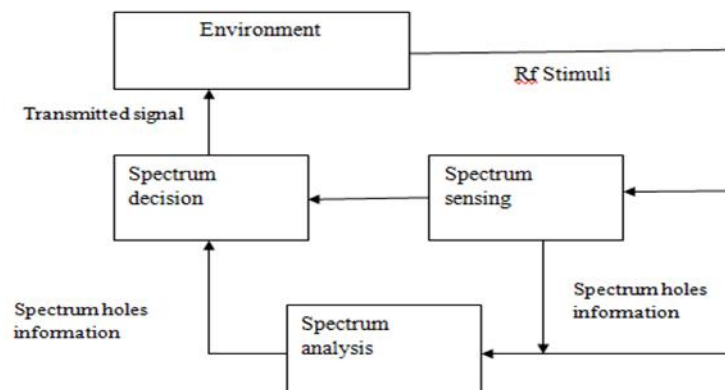


Figure 1.4: Cognitive radio cycle

There has been no globally adopted official/formal definition for cognitive radios as yet; however different definitions are presented in the literature as well as by the radio regulatory authorities around the world. Some of the known definitions of cognitive radio are summarized as follows:

“ A really smart radio that would be self RF and user aware, and that would include language technology and machine vision along with a lot of high fidelity knowledge of the radio environment .” (Mitola)

“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 strategy) in real time, with two primary objectives in mind: Highly reliable communications whenever and wherever needed; Efficient utilization of the radio spectrum [4].” (Simon Haykin)

“Cognitive radio system (CRS): A radio system employing technology that allows the system to obtain knowledge of its operation and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained.” (ITU – R)

Different peoples and organizations defined CR in different ways. All of them pointed to the same core idea- bringing intelligence to radios or embedding intelligence into radios that could then learn, adopt and react accordingly. The licensed allotted/legitimate user with own fixed spectrum is defined as primary user or incumbent user. The other user is secondary user which uses the vacant bands or white spaces in an opportunistic manner without interfering on the communication of the primary user. It means the secondary user adjusts its carrier frequency; transmit power, modulation scheme, coding etc. to make best use of the white spaces with good quality of service. As soon as the primary comes for its service, the secondary either goes away or masks itself without causing any interference to the primary user. Therefore, the secondary needs to know whether the primary is present or not before using that spectrum; which makes the spectrum sensing a challenge in the implementation of cognitive radio. Spectrum sensing is the ability to be aware about the underutilized bands both in temporal and spatial domain. These underutilized or fallow bands are referred to as spectrum holes or white space. The performance of the CR depends on the degree of detection of vacant bands because the interference can be lowered to negligible amount with good detection.

1.2 Spectrum Sensing

A major challenge in cognitive radio is that the secondary users need to detect the presence of primary users in a licensed spectrum and quit the frequency band as quickly as possible if the primary radio emerges in order to avoid interference to primary users. This technique is called spectrum sensing [5].

Figure 1.5 shows the classification of spectrum sensing techniques. They are broadly classified into three main types, transmitter detection (or non-cooperative sensing), cooperative sensing and interference based sensing.

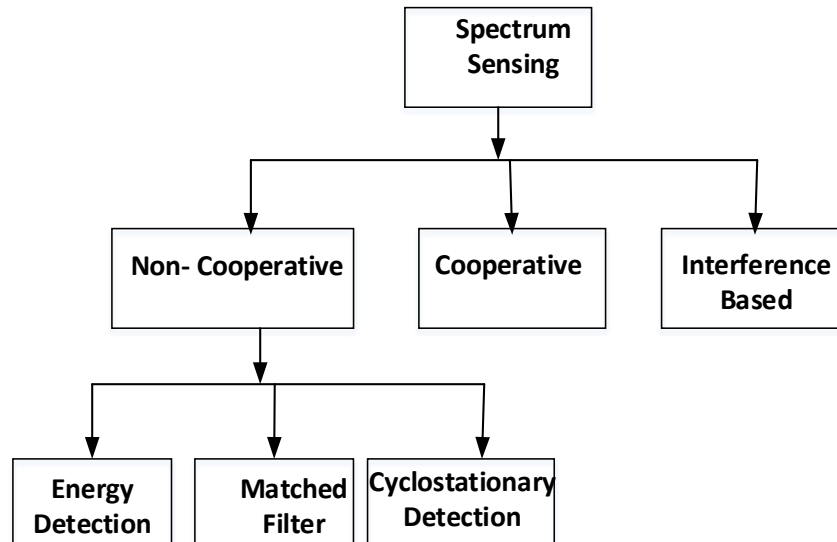


Figure 1.5: Block Diagram showing Spectrum Sensing Techniques

Transmitter detection or non-cooperative technique is further divided into Energy detection, Matched Filter detection and Cyclostationary detection. This work focuses in Energy detection technique. This technique is based on the detection of the weak signal from a primary transmitter. In primary transmitter based detection techniques, a cognitive user determines signal strength generated from the primary user.

1.3 Problem Definition

Spectrum sensing is one of the most important functions in cognitive radio (CR) implementation and use to sense the unused spectrum in an opportunistic manner. The simplest sensing method, often used in cognitive radio application is the energy based detection method. Since the selection of threshold determines the performance of the system. So selection of appropriate threshold based on the noise and signal parameters can increase the system performance. For this purpose, there are various algorithm for setting the threshold such as the Single threshold algorithm, Double threshold algorithm, Adaptive threshold algorithm and Adaptive double threshold algorithm, each of which has advantage over others in different channel conditions and depending upon many other factors. The performance of the energy detector using

Adaptive threshold algorithm, Double threshold algorithm and Adaptive double threshold algorithm is to be investigated.

1.4 Objectives

Energy detection of primary user's signal over a multipath channel has been a great challenge in cognitive radio system. The objective of this project is to

1. To study and compare the performance of the energy detector using Adaptive threshold algorithm, Double threshold algorithm and Adaptive double threshold algorithm

1.5 Organization of the report

Chapter one includes a brief introduction of cognitive radio and different sensing techniques. Chapter Two provides the literature Review on different papers related to recent trends on cognitive radio related to this thesis. Chapter Three describes the theoretical background. Chapter four covers methodology. It explains the system model, performance metrics, performance measurement tools and flowchart. Chapter five deals with simulation result and discussion and the report is concluded in chapter six.

CHAPTER TWO: LITERATURE REVIEW

The paper on ' On the Energy Detection of Unknown Signals over Fading Channels' addresses the problem of energy detection of an unknown signal over a multipath channel. It starts with the no-diversity case, and presents some alternative closed-form expressions for the probability of detection. Detection capability is boosted by implementing both square-law combining and square-law selection diversity schemes. This paper provides the analytical approach for energy detection of unknown signals and obtains closed-form expressions for the probability of detection over Rayleigh and Nakagami fading channels and more importantly, quantify the improvement in detection capability (specially for relatively low-power applications) when low-complexity diversity schemes such as square-law combining (SLC) and square-law selection (SLS) are implemented. This paper analyses the probability of miss (P_m) and probability of false alarm (P_f) [1].

Today, the creation of new radio access technologies is limited by the shortage of the available radio spectrum. These new technologies are becoming ever more bandwidth demanding due to their higher rate requirements. Cognitive radio networks and spectrum sensing techniques are a natural way to allow these new technologies to be deployed. The key characteristic of CR system is that it senses the electromagnetic environment to adapt their operation and dynamically vary its radio operating parameters. A cognitive radio must detect the presence of primary user to avoid interference. Spectrum sensing helps to detect the spectrum holes (un-utilized bands of the spectrum) providing high spectral resolution capability. The paper on ‘A Survey on Spectrum Sensing Techniques in Cognitive Radio’ discusses about various spectrum sensing techniques [6].

Energy detectors are commonly used to detect the presence of unknown signals. An energy detector measures the energy of the received signal over an observation time window and compares it with a predefined threshold to determine the presence of an information-bearing signal [7]. The paper on ‘Performance Prediction for Energy Detection of Unknown Signals’ analyzes the energy detector that is commonly used to detect the presence of unknown information-bearing signals and the algorithm simply compares the energy (or power) in a sliding window to a threshold. Here the unknown signals are modeled as samples of a random process rather than being deterministic. While the analysis of such a model requires approximations, it is more reasonable in most communication applications since the information bearing signal can take on many possible waveforms, depending on the random data sequence to be transmitted over the observation time window. Therefore this model can also include the effect of the communication channel if its frequency response is known. [8].It develops two equations (approximations) that relate two performance measures to three design parameters. That is, they relate the probability of false detection and the probability of missing detection to window length, detection threshold, and signal-to-noise ratio (SNR).It concludes as the detection variable for energy in a window detector can reasonably be approximated with a Gamma distribution for signal and noise with non-flat spectra, provided that the signal and noise are Gaussian.

Spectrum sensing is used for finding unoccupied frequency bands, called white space or spectrum holes. However, spectrum sensing performance in practice is often

compromised with multipath fading, shadowing and receiver uncertainty issues due to low signal to noise ratio (SNR). Use of double threshold feature detector (DTFD) can detect even very low SNR primary user. So use of double threshold algorithm performs better than conventional threshold algorithm [9] [10].

Estimation of energy threshold is the most important factor that affects the performance of the energy detection technique. Probability of detection depends on the probability of false alarm and SNR. If SNR is small, detection probability decreases. Also, if the detection probability increases, the false alarm probability also increases at a given value of SNR. The increase in false alarm probability means more interference to the primary. So an alternate algorithm called double threshold algorithm can be used [11].

The topic “Performance Comparison of Energy Detector using various Algorithms for Cognitive Radio Networks” was selected after going through various journal papers, textbooks,. In this thesis, the performance of energy detector based on double threshold, adaptive spectrum sensing and adaptive double threshold will be compared for AWGN, Rayleigh and Nakagami Channel.

CHAPTER THREE: THEORETICAL BACKGROUND

One of the most prominent features of cognitive radio networks will be the ability to switch between radio access technologies, transmitting in different portions of the radio spectrum as unused frequency band slots arise. This dynamic spectrum access is one of the fundamental requirements for transmitters to adapt to varying channel quality, network congestion, and interference and service requirements. Cognitive radio networks (from now on called secondary networks) will also need to coexist with primary networks, which have the right to their spectrum slice and thus cannot accept interference [12][4]. The spectrum sensing feature for cognitive radio is for the opportunistic access of licensed spectrum for secondary user with low priority access to spectrum. Three signal processing methods used for spectrum sensing are matched filter, cyclostationary feature extraction, and energy detection. First two are coherent detection techniques with better detection probability than non-coherent energy detection. However, the coherent detectors require a priori information [13].

3.1 Matched filter detection

A matched filter (MF) is a linear filter designed to maximize the output signal-to-noise ratio for a given input signal. The block diagram of matched filter is shown in figure 3.1. With this scheme, secondary users (SU) require complete knowledge of the PU transmitted signal. The main advantage of matched filtering is the short time to achieve a certain probability of false alarm or probability of miss-detection. Filtering 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 equivalent to convolving the unknown signal with a time reversed version of the template. The significant disadvantage of the MF is that it would require a dedicated sensing receiver for all PU signal types. It has implementation complexity. It consumes large power as various algorithm need to be executed for detection.

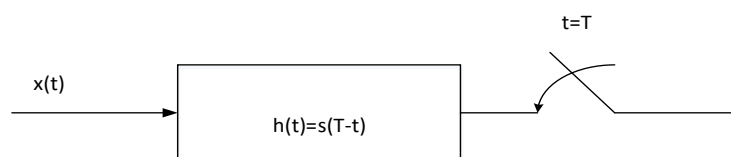


Figure 3.1: Matched Filter

3.2 Cyclostationary Feature Detection

When signals exhibit statistical attributes (like mean, autocorrelation etc.) that change periodically with time, they are termed cyclostationary features. Usually, wireless transmissions present cyclostationarity features depending on their data rate, modulation type, and carrier frequency. Most communication signals can be modeled as cyclostationary, since they exhibit underlying periodicities in their signal structures. Cyclostationary feature detection (CFD) is a method that applies cyclostationary features to detect a signal. Since it can differentiate primary users' signals from noise, it is more robust than energy detector when SNR is low or noise is uncertain [7].

3.3 Waveform-Based Sensing

It depends upon the known patterns such as preambles, midambles, regularly transmitted pilot patterns, spreading sequences etc. In the presence of known patterns, sensing can be performed by correlating the received signal with a known copy of itself. It is proved to outperform the energy detector as far as reliability and convergence time is concerned. Its performance can be enhanced with increasing the length of the known signal patterns. It requires short measurement time but it is equally susceptible to synchronization error.

3.4 Energy Detector-based sensing

Energy detection is mostly used sensing technique. This is because as a non-coherent detection technique energy detection does not require any prior information about the transmitted signal. As a result, energy detection is not only simple in implementation but also robust in various operating environments. In energy detection method, the energy of the received signal is measured and compared with a predefined threshold to determine the presence or absence of primary user's signal. Moreover, energy detector is mainly used in ultra wideband communication to borrow an idle channel from licensed user. Figure 3.2 shows the block diagram of energy detector.

For implementing the energy detector, the received signal $x(t)$ will be filtered by a band pass filter (BPF), followed by a square law device. The band pass filter serves to reduce the noise bandwidth. Hence, noise at the input to the squaring device has a band-limited, at spectral density. The output of the integrator will be the energy of the

input to the squaring device over the time interval T. Next, the output signal from the integrator (the decision statistic), Y, will be compared with a threshold to decide whether a primary (licensed) user is present or not. Decision regarding the usage of the band will be made by comparing the detection statistic to a threshold [5][7].

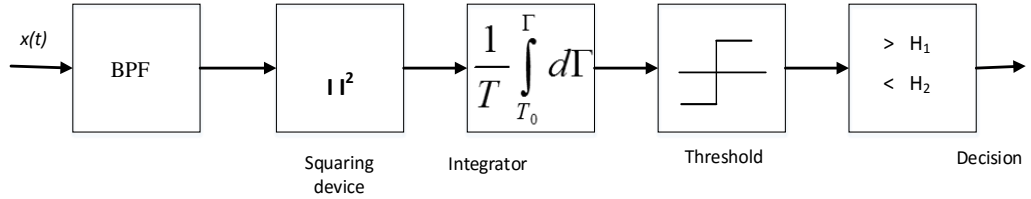


Figure 3.2: Block diagram of Energy detector

The probability of detection is the main concern as it gives the probability of correctly sensing for the presence of PUs in the frequency band. The probability of miss detection is just the complement of probability of detection as shown by figure 3.3. The aim of the sensing schemes should be to maximize the probability of detection for small value of probability of false alarm as possible.

3.3.1 Conventional single-threshold energy detection algorithm

In this algorithm, there is a single detection threshold. When the received signal energy V is greater than the detection threshold V_{th} , the detector concludes that the primary is present in the band of interest and depicted as H_1 . On contrary, absence the primary user is depicted as H_0 [7]. The detection probability, false alarm probability and miss probability respectively can be calculated as:

$$P_D = Pr\{V > V_{th}|H_1\} = Q_u(\sqrt{2\gamma}, \sqrt{V_{th}}) \dots \dots \dots (3.1)$$

$$P_{FA} = Pr\{V > V_{th}|H_0\} = \frac{\Gamma(u, V_{th}/2)}{\Gamma(u)} \dots \dots \dots (3.2)$$

$$P_M = Pr\{V \leq V_{th}|H_1\} \dots \dots \dots (3.3)$$

where γ is the Signal-Noise Ratio (SNR) received by cognitive user, V_{th} is the detection threshold, $Q_u(a, b)$ is normalized Marcum function of order u, a monotonically increasing function with u and monotonically decreasing with b;

$\Gamma(a, b)$ is a non-complete gamma function, monotonically decreasing with b and $\Gamma(a)$ is complete gamma function, H_0 represents absence of signal and H_1 represents presence of signal

From (3.2): $P_{FA} \cdot \Gamma(u) = \Gamma\left(u, V_{th}/2\right)$

Based on the definition of non-complete and complete gamma function:

$$\begin{aligned} \Gamma\left(u, V_{th}/2\right) &= \int_{V_{th}/2}^{\infty} t^{u-1} * e^{-t} dt \\ &= \int_{V_{th}/2}^0 t^{u-1} * e^{-t} dt + \int_0^{\infty} t^{u-1} * e^{-t} dt \\ &= \Gamma(u) - \int_0^{V_{th}/2} t^{u-1} * e^{-t} dt \end{aligned}$$

Again $\int_0^{V_{th}/2} t^{u-1} * e^{-t} dt = \Gamma(u)p(u, V_{th}/2)$ where $z = p(u, x) = \frac{1}{\Gamma(u)}$ is low order non-complete gamma function, and monotone decreasing with x , moreover, $x = p^{-1}(u, z)$ is monotone increasing function with z [1].

So, $P_{FA} \cdot \Gamma(u) = \Gamma(u) - \Gamma(u) \cdot p(u, V_{th}/2)$

or, $P_{FA} = 1 - \Gamma(u) \cdot p(u, V_{th}/2)$

or, $V_{th} = 2p^{-1}(u, 1 - P_{FA})$

On substituting V_{th} into equation (3.1) and (3.3),

$P_D = Q_u(\sqrt{2\gamma}, \sqrt{V_{th}}) = Q_u\left(\sqrt{2\gamma}, \sqrt{(2p^{-1}(u, 1 - P_{FA}))}\right) \dots \dots \dots (3.4)$

$P_M = 1 - P_D = 1 - Q_u\left(\sqrt{2\gamma}, \sqrt{(2p^{-1}(u, 1 - P_{FA}))}\right) \dots \dots \dots (3.5)$

From above analysis, the single-threshold energy detection algorithm may cause serious interference to the primary user. Probability of detection depends on the probability of false alarm and SNR. If SNR is small, detection probability decreases. Also, if the detection probability increase and at the same rate the false alarm probability also increases at a given good value of SNR. The increase in false alarm probability means more interference to the primary [14]. In order to alleviate them, a double - threshold energy detection algorithm has been proposed.

3.3.2 Double threshold energy detector

In this algorithm, another detection threshold is added within the conventional single-threshold energy detection algorithm. The two thresholds are defined as V_{th0} and V_{th1} . The primary user will be detected if and only if $V > V_{th1}$, and will not be present if and only if $V < V_{th0}$. The decisions correspond to H_1 and H_0 respectively. There is high possibility of taking decision if and only if V lies in anywhere in between the thresholds i.e. V is in $(V_{th0}, V_{th1}]$. For the better performance of the detector, it needs re-detection. Based on the conventional single-threshold energy detection algorithm, the performance indicator of the double threshold energy detection algorithm such as the detection probability, false alarm probability and missing probability can be calculated [14], [15]. They can be calculated as:

$$P'_D = P_r(V' > V_{th1}|H_1) = Q'_u(\sqrt{2\gamma}, \sqrt{V_{th1}}) \dots \dots \dots (3.6)$$

$$P'_{FA} = P_r(V' > V_{th1}|H_0) = \frac{\Gamma(u', V_{th1}/2)}{\Gamma(u')} \dots \dots \dots (3.7)$$

$$P'_M = P_r(V' \leq V_{th1}|H_1) = 1 - P_D \dots \dots \dots (3.8)$$

Where P'_D is the correct detection probability when the primary user is present. P'_{FA} is the probability of the primary user detected presently, given, it is not present. P'_M is the probability of primary user perhaps may not be detected, given, it is present. In double threshold energy detection algorithm, two more performance indicators have been introduced for analysis. They are probability of collision between the cognitive user and the primary user, and the probability of spectrum unavailable to the cognitive user. These two parameters are defined and calculated as follows: The probability of collision between the cognitive user and the primary user: $p_c = p\{V' < V_{th0}|H_1\}$. 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 users and the cognitive user is, the more serious the interference of cognitive user to the primary user is, on the contrary, there is less interference. The probability of restricting the cognitive user to the spectrum, that is, the spectrum unavailable probability: $p_{na} = p\{V' > V_{th0}|H_0\}$. It is the probability of 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 interferences to 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 contrary, the spectrum is allocated efficiently. Generally, it has $V_{th0} < V_{th} < V_{th1}$ because of adding detection threshold. Form equations (3.1) and (3.6), it is seen that $Q'_u(\sqrt{2\gamma'}, \sqrt{V_{th1}}) < Q_u(\sqrt{2\gamma}, \sqrt{V_{th}})$ i.e. $P'_D < P_D$. Similarly $P'_M > P_M$ and $P'_{FA} < P_{FA}$. 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, $P_{na1} = P_{FA}$. From this, the calculation of probability of collision between the cognitive user and the primary user and the spectrum unavailable probability is done as follows:

$$p_{c2} = P_r\{V' < V_{th0}|H_1\} = 1 - P_r\{V' > V_{th0}|H_1\} = 1 - Q_{u'}(\sqrt{2\gamma'}, \sqrt{V_{th0}}) \dots (3.9)$$

This is the expression to calculate the collision probability. The next is the spectrum unavailable probability as:

$$p_{na2} = P_r\{V' > V_{th0}|H_0\} = \frac{\Gamma(u', V_{th0}/2)}{\Gamma(u')} \dots \dots \dots (3.10)$$

On comparing equations (3.3) and (3.9), it is seen that, $V_{th0} < V_{th}$ and this implies

$$Q_u(\sqrt{2\gamma}, \sqrt{V_{th}}) < Q_{u'}(\sqrt{2\gamma'}, \sqrt{V_{th0}})$$

And $p_{c2} < p_{c1}$. Similarly, $p_{n1} < p_{n2}$. 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 used spectrum efficiency. In other words, there is still a possibility to improve the spectrums' used efficiency. The detection algorithm is best described by figure 3.3.

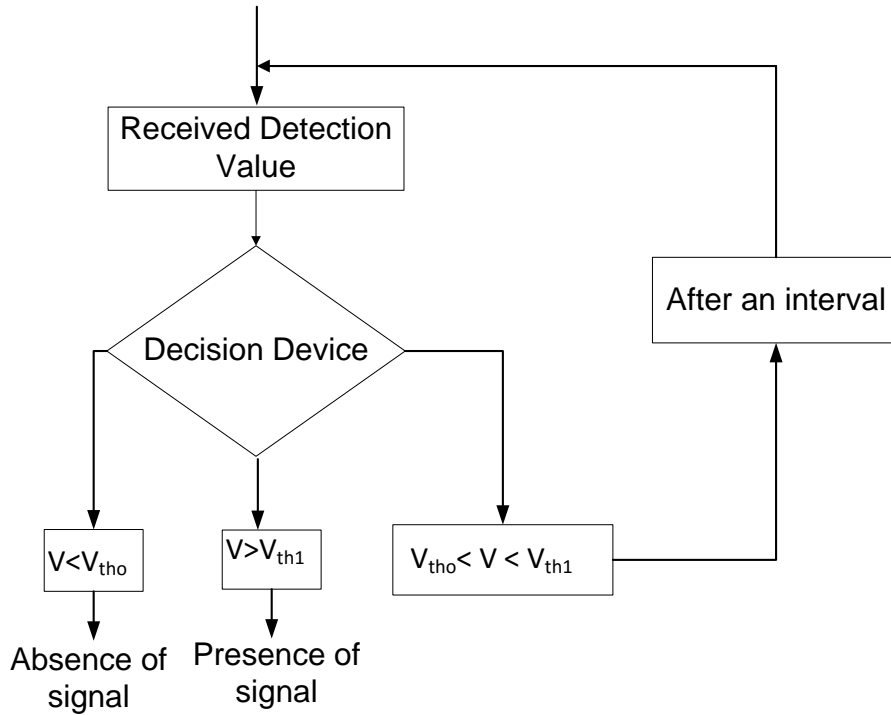


Figure 3.3: Flowchart of double threshold energy detection algorithm

3.4 Cooperative spectrum sensing

In cooperative detection, multiple SUs collaborate in a centralized or decentralized manner to sense spectrum holes for opportunistic access. Each cooperating node employs locally, any of the sensing methods previously described, while sharing the raw sensing information with other nodes. This concept of collaboration is considered since effects of shadowing, multipath fading and receiver uncertainty pose severe challenges to single user transmitter detection approach in spectrum sensing [7].

3.4.1 Conventional cooperative spectrum sensing

As it is known that the prime goal of spectrum sensing is to distinguish between the two hypotheses. In many papers, it is often assume that there are N secondary users and a fusion center in cognitive radio networks, each secondary user experiences independent and identically distributed fading and shadowing with the same average SNR, and each user has the same threshold value λ . The fusion center receives the information of each secondary user and makes a final decision whether the primary is presence or not. In conventional fusion method, OR-rule is used [16]. For example, if one secondary user observes the primary user, then the fusion center determines that it

really exists. Probabilities of detection, missing and false alarm for this cooperative sensing method are as follows,

$$Q_d = 1 - \prod_{i=1}^N (1 - P_{d,i}) \dots \dots \dots (3.11)$$

$$Q_m = \prod_{i=1}^N P_{m,i} \dots \dots \dots (3.12)$$

$$Q_f = 1 - \prod_{i=1}^N (1 - P_{f,i}) \dots \dots \dots (3.13)$$

The individual probabilities are calculated as given by the relations in equations (3.1), (3.2), and (3.3) respectively. Also, Q_d , Q_m and Q_f denote the cooperative probabilities of detection, missing and false alarm respectively, and $P_{d,i}$, $P_{m,i}$, and $P_{f,i}$ are the detection probability, missing probability and false alarm probability of the i th secondary user respectively.

3.4.2 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 predefined threshold as illustrated in figure 3.5. Here in double threshold, “Region of Uncertainty” represented as $O_i = (V_{th0}, V_{th1})$ indicates the collected energy value of the i th secondary user. Two thresholds V_{th0} and V_{th1} is introduced in this algorithm. If the detected energy is greater than V_{th1} , then the user reports H_1 and when detected energy is less than V_{th0} , the user reports H_0 . If the energy value lies in the “Region of Uncertainty” then each primary users reports their observational value. So in this model, the fusion center receives two kinds of information: local decisions and observational values of the secondary users, that is, local energy values [10], [17].

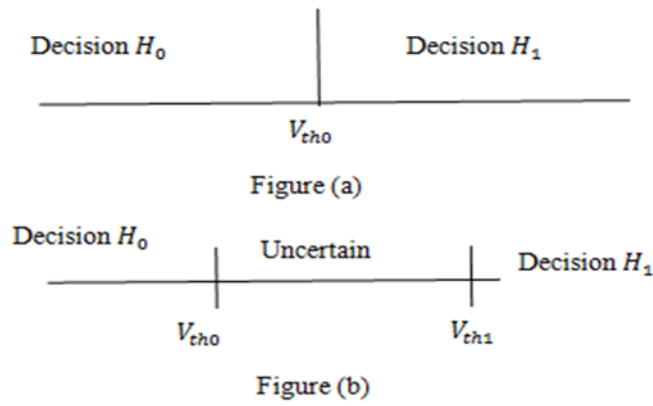


Figure 3.4: Energy detection decision

$$R_i = \begin{cases} O_i & V_{th0} < O_i < V_{th1} \\ L_i & \text{otherwise} \end{cases} \dots \dots \dots (3.14)$$

$$L_i = \begin{cases} 0 & 0 \leq O_i \leq V_{th0} \\ 1 & O_i > V_{th1} \end{cases} \dots \dots \dots (3.15)$$

Where

R_i denotes the information that the fusion center receives from the i^{th} secondary user
 L_i denotes the local decision.

Here, it is assumed that the fusion center receives K local decisions and $N-K$ energy detection values among N secondary users. Then the fusion center makes an upper decision according to $N-K$ energy detection values, which is given by

$$D = \begin{cases} 0 & 0 \leq \sum_{i=1}^{N-K} O_i \leq V_{th} \\ 1 & \sum_{i=1}^{N-K} O_i > V_{th} \end{cases} \dots \dots \dots (3.16)$$

Where, V_{th} is the energy detection threshold value at the fusion center. It shows that these $N-K$ secondary users could not distinguish between the absence and the presence of the primary user, so the fusion center collects their observational values and makes an upper decision instead of the local decision of them [18][19]. The probabilities of misdetection, false alarm and detection are calculated by the following relations:

$$\begin{aligned} Q_m &= \sum_{k=0}^{N-1} \binom{N}{K} \prod_{i=1}^K P_{m,j} \prod_{i=K+1}^N \Delta_{1,i} [1 - Q_{(N-K)u}(\sqrt{2\gamma}, \sqrt{V_{th}})] \\ &+ \prod_{i=1}^N P_{m,i} \dots \dots \dots (3.17) \end{aligned}$$

$$\begin{aligned} Q_f &= 1 - \prod_{i=1}^N (1 - \Delta_{0,i} - P_{f,i}) \\ &= - \sum_{k=0}^{N-1} \binom{N}{K} \prod_{i=1}^K (1 - \Delta_{0,i} - P_{f,i}) \prod_{i=K+1}^N \Delta_{0,i} \left[1 - \frac{\Gamma[(N-K)u, V_{th}/2]}{\Gamma[(N-K)u]} \right] \dots \dots \dots (3.18) \end{aligned}$$

$$Q_d = 1 - Q_m \dots \dots \dots (3.19)$$

Based on the above relations showed that the performance of double threshold outwit that of the conventional cooperative spectrum sensing methods. But, the detection performance gain was achieved by the increase of communication burdens introduced by the local energy values.

3.5 Adaptive Single-Threshold Energy detection Algorithm

For the large number of samples, the probability is detection and the probability of false alarm is given by:

$$P_D = P_r\{D(Y) > \lambda|H_1\} \text{ and } P_{FA} = P_r\{D(Y) > \lambda|H_0\}$$

For the energy decision threshold (λ), an adaptive decision threshold was set. It is decided by the noise power and signal power, which is to adapt noise fluctuation. The probability of detection and the probability of false alarm are given by

$$P_{d1} = Q\left(\frac{\lambda - (\sigma_n^2 + \sigma_s^2)}{(\sigma_n^2 + \sigma_s^2) / \sqrt{N/2}}\right) \dots \dots \dots (3.20)$$

$$P_{f1} = Q\left(\frac{\lambda - \sigma_n^2}{\sigma_n^2 / \sqrt{N/2}}\right) \dots \dots \dots (3.21)$$

Where, σ_n^2 is the noise power and σ_s^2 is the signal power. The optimal threshold λ is decided by the noise power and signal power, which is to adapt noise fluctuation. The smaller λ is, the higher P_{d1} and P_{f1} are. The higher P_{d1} means less interference to PU, but the higher P_{f1} means the less chances of the channel can be reused when it is available and usable. As a result, the achievable throughput for the secondary network is lower. Therefore, there is a tradeoff between P_{d1} and P_{f1} . How to set the decision threshold λ in a robust manner to signal and noise power variation is the key issue of spectrum sensing. If the λ is smaller than the noise power σ_n^2 , many samples of the noise would be detected as PU signal, then the probability of false alarm would be very high. Also, if the decision threshold λ is larger than the signal power σ_s^2 , many samples of the PU signal would be miss detected, and the probability of detection would be very low. Therefore, the decision threshold λ follows,

$$\sigma_n^2 \leq \lambda \leq \sigma_s^2 \dots \dots \dots (3.22)$$

Here the weighted tradeoff principle is used for the well-known two main parameters associated with spectrums sensing performance, i.e., tradeoff between probability of detection and the probability of false alarm. Usually, the design of spectrum detector follows the constant false alarm rate (CFAR) criteria or constant detection rate (CDR) criteria. Generally, it is difficult to achieve the optimal tradeoff between these two probabilities when CFAR principle or CDR principle is applied. This necessitates the weighted tradeoff principle. Let α denote the weight factor of P_{f_1} and $1 - \alpha$ denote the weight factor of P_{d_1} . The weighted probability of miss detection P_{m_1} is defined as:

$$P_{m_1}(\lambda) = \alpha P_{f_1} + (1 - \alpha) P_{d_1} = \alpha Q \left(\frac{\lambda - \sigma_n^2}{\sigma_n^2 / \sqrt{N/2}} \right) + (1 - \alpha) Q \left(\frac{\lambda - (\sigma_n^2 + \sigma_s^2)}{(\sigma_n^2 + \sigma_s^2) / \sqrt{N/2}} \right) \dots \dots \dots (3.23)$$

If the bracketed terms are replaced by x_1 and x_2 respectively, then

$$\begin{aligned} P_{m_1}(\lambda) &= \alpha Q(x_1) + (1 - \alpha) Q(x_2) \\ &= \alpha \cdot \frac{1}{2} \operatorname{erfc} \left(\frac{x_1}{\sqrt{2}} \right) + (1 - \alpha) \left[1 - \frac{1}{2} \operatorname{erfc} \left(\frac{x_2}{\sqrt{2}} \right) \right] \\ &= \frac{\alpha}{\sqrt{\pi}} \int_{x_1/\sqrt{2}}^{\infty} e^{-z^2} dz - \frac{1-\alpha}{\sqrt{\pi}} \int_{x_2/\sqrt{2}}^{\infty} e^{-z^2} dz + (1 - \alpha) \dots \dots \dots (3.24) \end{aligned}$$

For a given value of α , the weighted probability miss detection is strictly a convex function of λ , so the optimal threshold is given by

$$\lambda^* = \frac{1 + \sqrt{1 + \frac{4(2\sigma_n^2 + \sigma_s^2)}{N\sigma_s^2} \ln \left[\frac{\alpha(\sigma_n^2 + \sigma_s^2)}{(1-\alpha)\sigma_n^2} \right]}}{\frac{2\sigma_n^2 + \sigma_s^2}{\sigma_n^2(\sigma_n^2 + \sigma_s^2)}} \dots \dots \dots (3.25)$$

If the noise power and the signal power or the SNR of the received signal is known, the optimal decision threshold can be easily calculated. With this threshold good detection decision is made so that the best performance is obtained.

3.6 Adaptive Double-threshold Energy detection Algorithm

Double threshold energy detection algorithm and adaptive single threshold algorithm are discussed so far. Based on these two algorithms, the idea of double-threshold adaptive spectrum sensing algorithm was introduced. As the name suggest, this algorithm has two thresholds (λ_1, λ_2) and they are based on the adaptive threshold which is obtained by estimating the noise power and the signal power. The energy detection process is shown in figure 3.6. The PU will be detected if the received signal power denoted as $D(Y)$ is greater than the upper threshold denoted by λ_2 . It will not be detected if $D(Y) < \lambda_1$, where λ_1 is lower threshold. When the received signal power is in $(\lambda_1, \lambda_2]$, it is prone to mistaken. It needs detection again. This region is called UNCERTAIN REGION [20], [21], [22]. The optimal detection threshold is obtained as that before as given in the Equation (3.22) by the relation:

$$\lambda' = \frac{1 + \sqrt{1 + \frac{4(2\sigma_n^2 + \sigma_s^2)}{N\sigma_s^2} \ln \left[\frac{\alpha(\sigma_n^2 + \sigma_s^2)}{(1-\alpha)\sigma_n^2} \right]}}{\frac{2\sigma_n^2 + \sigma_s^2}{\sigma_n^2(\sigma_n^2 + \sigma_s^2)}} \dots \dots \dots (3.26)$$

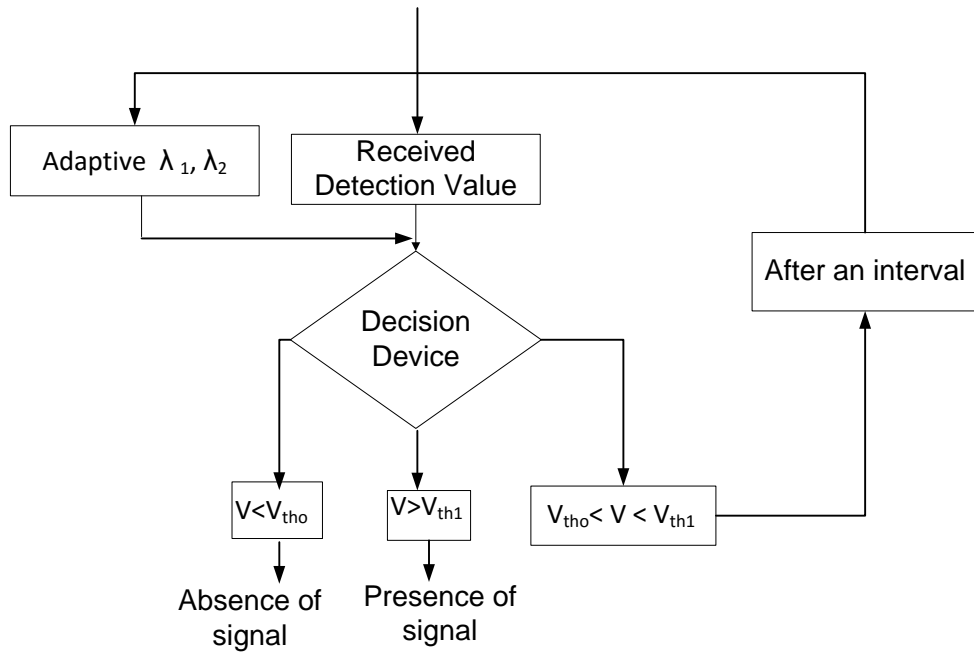


Figure 3.5: Flow chart of adaptive double threshold detection algorithm

Now, the issue is to choose the double threshold. The double threshold λ_1 and λ_2 can be set according to the noise fluctuation based on the optimal threshold. Generally, the double threshold λ_1 and λ_2 are set by

$$\lambda_1 = \alpha\lambda' \dots \dots \dots (3.27)$$

$$\lambda_2 = \beta\lambda' \dots \dots \dots (3.28)$$

Where, α and β are given constant. The received power $D(Y)$, and the SNR is γ is assumed, then the probability of detection P_D and the probability of false alarm P_{FA} are given by:

$$P_D = P\{D(Y) > \lambda_2 | H_1\} = Q_u(\sqrt{2\gamma}, \sqrt{\lambda_2}) \dots \dots \dots (3.29)$$

$$P_{FA} = P\{D(Y) > \lambda_2 | H_0\} = \frac{\Gamma(u, \lambda_2/2)}{\Gamma(u)} \dots \dots \dots (3.30)$$

Where, $\text{SNR} = \frac{\sigma_s^2}{\sigma_n^2}$. Δ_0 and Δ_1 is used to represent the probability of $\lambda_1 \leq D(Y) \leq \lambda_2$ for every cognitive user under hypothesis H_0 and H_1 respectively. Thus, Δ_0 and Δ_1 are given by:

$$\Delta_0 = P\{\lambda_1 \leq D(Y) \leq \lambda_2 | H_0\} = \frac{\Gamma(u, \lambda_1/2)}{\Gamma(u)} - \frac{\Gamma(u, \lambda_2/2)}{\Gamma(u)} \dots \dots \dots (3.31)$$

$$\Delta_1 = P\{\lambda_1 \leq D(Y) \leq \lambda_2 | H_1\} = Q_u(\sqrt{2\gamma}, \sqrt{\lambda_1}) - Q_u(\sqrt{2\gamma}, \sqrt{\lambda_2}) \dots \dots (3.32)$$

And probability of miss detection P_M is given by

$$P_M = P\{D(Y) < \lambda_1 | H_1\} = 1 - \Delta_1 - P_D = 1 - Q_u(\sqrt{2\gamma}, \sqrt{\lambda_1}) \dots \dots \dots (3.33)$$

The performance analysis of this algorithm can be described as: since the lower value of the double thresholds λ_1 is lower than the single threshold λ' , the probability of miss detection P_M would be lower than P'_M as given by Equation (3.33). On the other hand, the probability of detection can be improved in Equation (3.29). From these two facts, it is concluded that the probability of collision can be decreased between the PU and the cognitive user, which can improve the spectrum utilization efficiency.

CHAPTER FOUR: METHODOLOGY

4.1 System Description

The system model is developed based on the three algorithm discussed in previous chapter. The system model is shown in the figure 4.1.

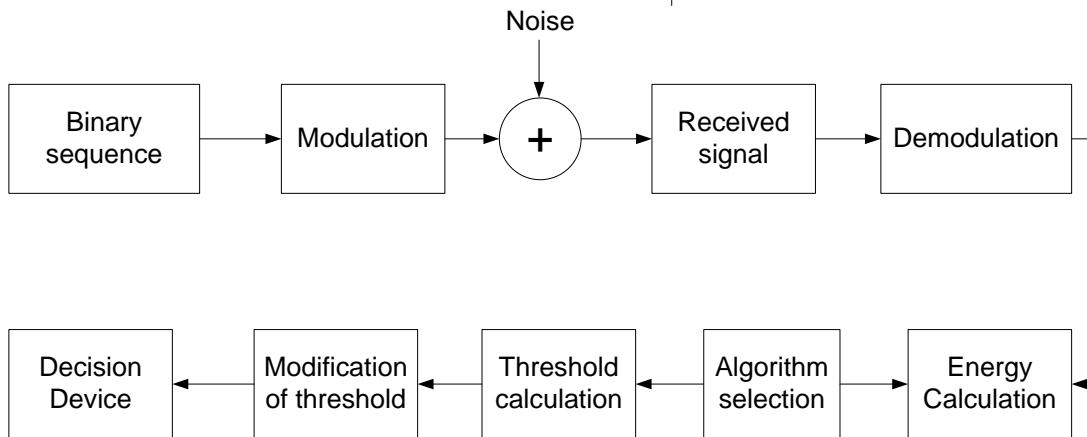


Figure 4.1: System Model

The system model is considered the simple digital communication with QPSK modulation. This QPSK modulated signal is considered as primary signal which is then transmitted through the channel and received at the secondary receiver after QPSK demodulation. The received signal is then fed into the energy detector which implemented the three different algorithms described earlier. The energy of the received signal is calculated after filtering and averaged over the suitably chosen sample size. The algorithms and their threshold are calculated as per their relationships. Certain modification is done on the calculated threshold for getting its optimal version depending upon the algorithms chosen. At last, the decision device decides for and against the primary user.

4.2 Performance Metrics

The correctness of the spectral availability information is defined using sensing quality parameters. This feature makes up the performance metrics. Sensing the performance of the energy detector is specified by the following general metrics:

1. The probability of detection, (P_D)
2. The probability of false alarm, (P_f)

3. The probability of missed detection, (P_m).
4. Collision probability
5. Spectrum unavailable probability

The probability of detection specifies that a detector makes a correct decision that a channel is occupied. The (P_D) is an indicator of the level of interference protection provided to the primary user. Hence, a large P_D denotes exact sensing; which translate to small chance(s) of interference.

A false alarm event occurs when the detector assumes the channel is occupied, when the right decision is the channel is vacant. The probability of this occurrence is specified as a probability of false alarm. When a false alarm event occurs, the SU would not exploit the free spectrum, thus missing a chance to utilize the free channel. P_f should be kept as small as possible in order to prevent underutilization of transmission opportunities.

The probability of declaring the spectrum space vacant, when it is indeed occupied is referred to as the probability of missed detection (P_m). A high PM implies an increase in the chance of interference between the PU and the SU. If the detection fails or a 'miss detection" occurs, the SU initiates a transmission, resulting in interference with the PU signal violating the opportunistic access concept.

The probability of collision between the cognitive user and the primary user is the probability of the primary user which is not detected, but in fact it is existed, and the 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.

Spectrum unavailable probability is the probability of 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 interferences to the primary user. It indicates the efficiency of the spectrum usage

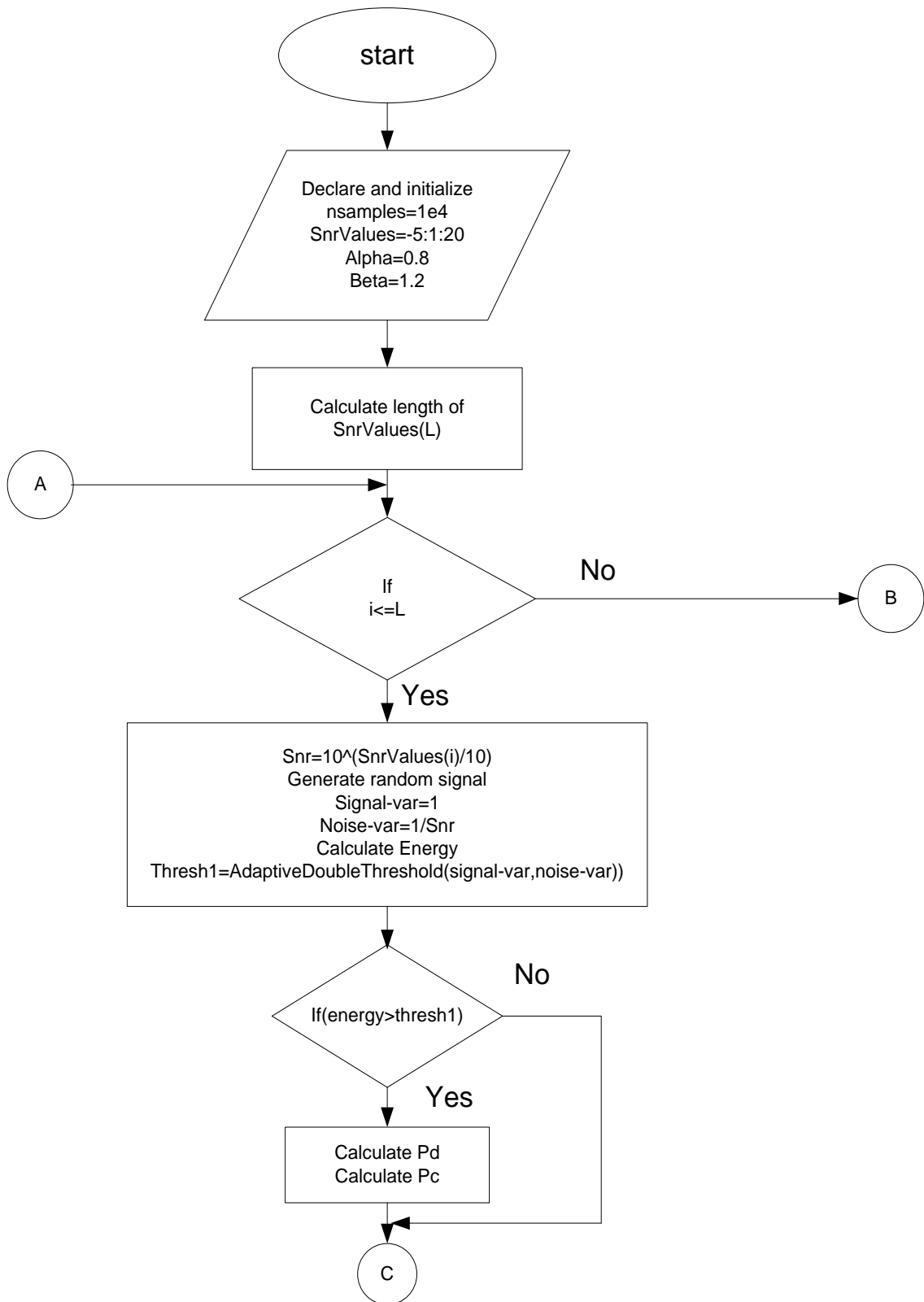
In order to verify the performance predicted by the analytical framework discussed in the chapter three, different parameters such as probability of detection, probability of false alarm, collision probability and spectrum unavailable probability at different conditions are simulated. In particular, each simulation run is carried out according to the following steps:

1. Decision thresholds (λ_1, λ_2) are generated with respect to constant false alarm rate criteria in case of double threshold algorithm. The optimum threshold is generated in the case when the noise is uncertain (particularly in low SNR) for implementing adaptive spectrum sensing algorithm as given in the Equation (3.24). The two thresholds (λ_1, λ_2) are generated based on optimum threshold as given by the relation Equations (3.26) and (3.27) respectively in implementing adaptive double threshold algorithm.
2. The received signal from the primary transmitter $y(t) = s(t) + n(t)$ is generated under Additive White Gaussian (AWGN) channel, Rayleigh and Nakagami fading channel.
3. Next, the received energy i.e. square of $y(t)$ of step 3, at the CR receiver is compared with the respective threshold voltage and respective hypothesis.
4. Steps 1 to 4 are repeated a large number of times (particularly 10000) to reliably estimate the results.

In the later part, SNR is considered and simulate the model as follows

5. Steps 1 to 2 are repeated.
6. CR sensor SNR is generated.
7. The received signal of CR receiver is generated.
8. Step 4 is repeated.
9. Steps 5 to 8 are repeated a large number of times to reliably estimate the probability of detection(P_D) and collision probability (P_C)
10. The plot of these parameters versus SNR is generated.

4.3 Flowchart of Simulation



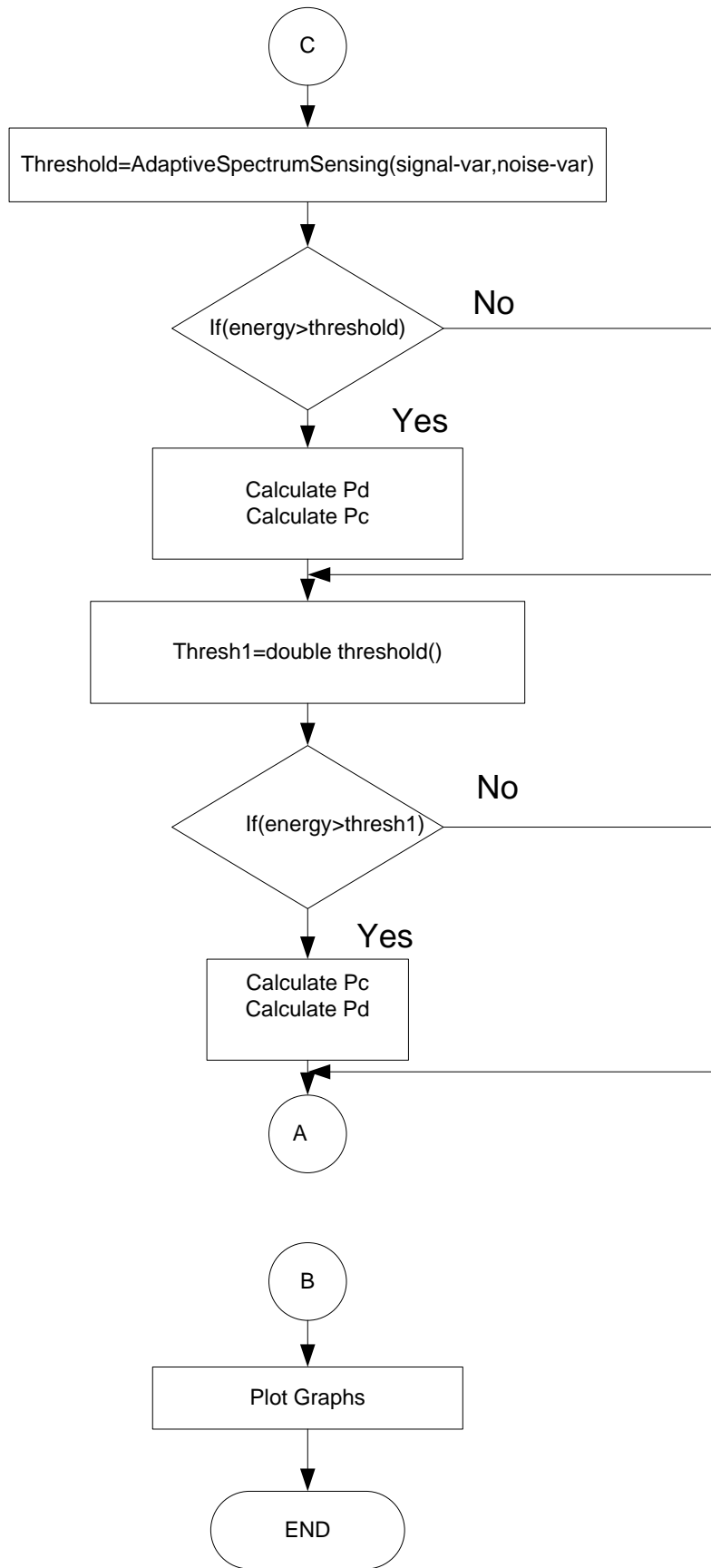


Figure 4.2: Flowchart for Simulation

Figure 4.2 shows the flowchart for this thesis. At first, declaration and initialization of the variables like nsamples, SnrValues, alpha, beta, M was done. The second step is to calculate the length of SNR values. Now in the next step, a condition: $i \leq L$ was tested. If it is true the statements within the loop are executed. The next step is to convert the SNR in log scale into linear scale, generate a random signal for given SNR and calculate the signal energy. Now here, the probability of collision and probability of detection was calculated for double threshold algorithm, adaptive spectrum sensing and adaptive double threshold algorithm if energy is greater than the threshold defined. The threshold is obtained from the user-defined function. The loop runs for L^{th} iterations and then finally graph is plotted. This process is carried out for AWGN, Rayleigh and Nakagami fading channel.

CHAPTER FIVE: SIMULATION RESULT AND DISCUSSION

The performance of energy detector based on double threshold, adaptive spectrum sensing and adaptive double threshold is analyzed in this section. The parameters used to quantify the performances are as follows:

- i) Probability of missed detection, P_M
- ii) Probability of detection, P_D
- iii) Probability of false alarm, P_{FA}
- iv) Probability of collision, P_C
- v) Probability of spectrum unavailability, P_{na}

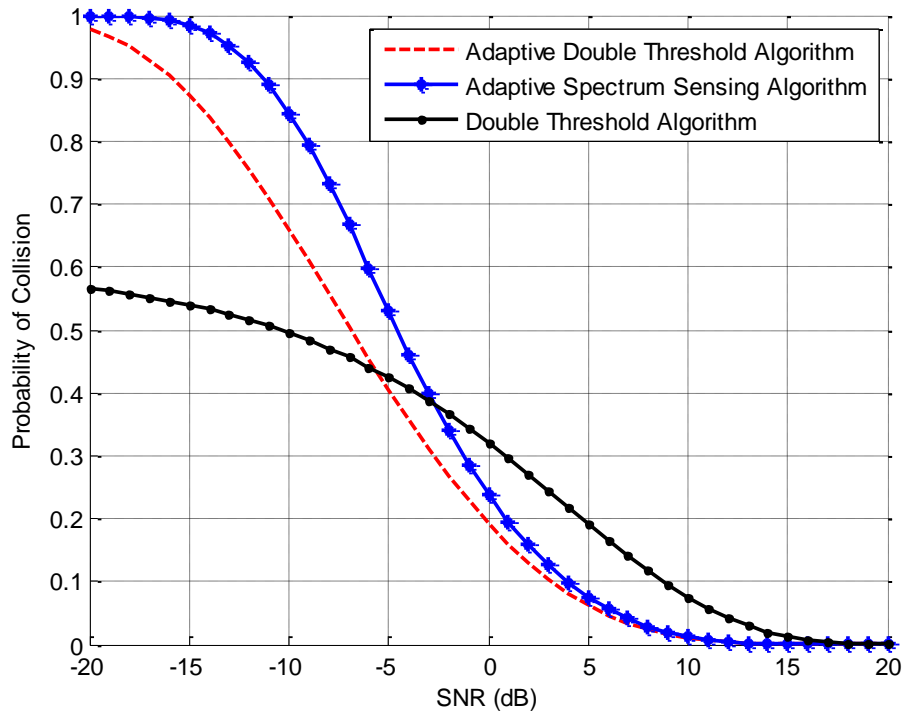


Figure 5.1: Collision Probability Vs. SNR for AWGN Channel

For the simulation, values of alpha and beta are assumed to be 0.8 and 1.2 respectively. The signal variance is considered as 1 and the noise variance is given by $\frac{1}{SNR}$. The modulation scheme used is QPSK. This modulated signal is then passed through the different channel before reaching to the receiver. The sample size taken is 10000. The simulation is done for 20000 times or above for better result.

Figure 5.1 shows the plot of probability of collision versus different value of SNR under the AWGN channel. The probability of collision between the cognitive user and the primary user is the probability of the primary user which is not detected, but in fact it is existed, and the 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. So the probability of collision should be kept low in order to provide protection to the primary users. The plot above shows that the probability of collision decreases with the value of SNR increasing. Among the three algorithm used, double adaptive spectrum sensing performs the best followed by adaptive spectrum sensing and double threshold spectrum sensing. But for SNR below -5dB collision probability for double threshold algorithm is least as it cannot adapt to changing signal and noise variations. For the SNR of 5dB, the probability of collision is reduced from around 20% (double threshold algorithm) to around 6% using adaptive double threshold algorithm. Beyond the SNR of 15 dB, probability of collision for all the algorithms are almost similar.

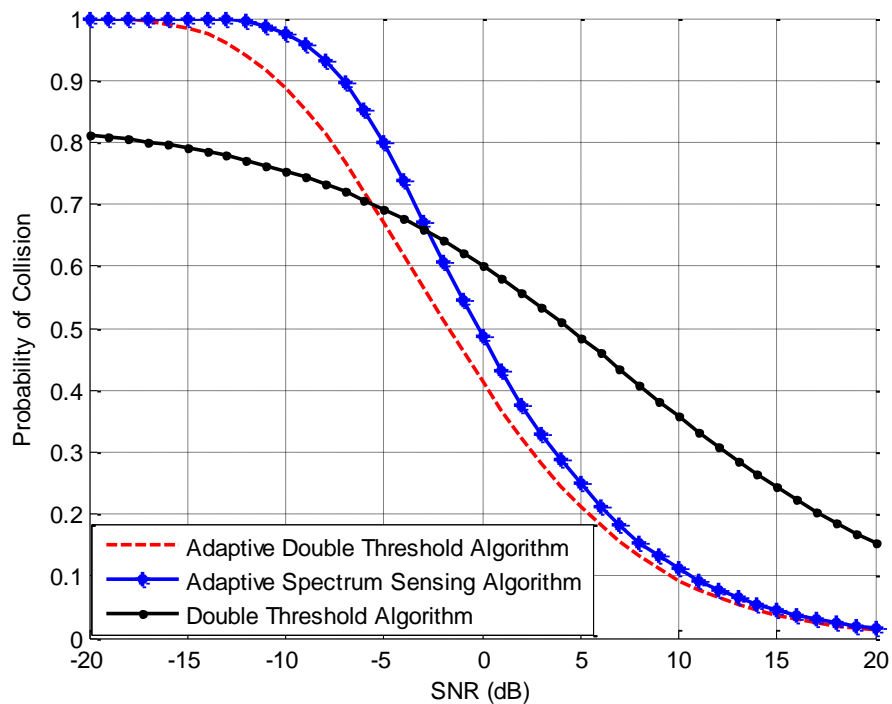


Figure 5.2: Probability of Collision vs. SNR for Rayleigh

Figure 5.2 is the plot of probability of collision versus different values of SNR for the Rayleigh fading channel. It was observed that the probability of collision is greater

than that was observed in the figure 5.2 which was the case of AWGN channel. The AWGN channels considers only the effect of additive white Gaussian noise while the Rayleigh channels considers the fading effects during the course of propagation through the channel. In case of Rayleigh channel for 5dB SNR, the probability of collision is reduced from around 48% (Double threshold) to around 20% using double adaptive threshold algorithm. In case of AWGN channel, it was observed that beyond 15dB SNR, all the algorithm showed almost same probability of collision but in Rayleigh fading channel the scenario was different. For the adaptive and double threshold adaptive, the probability of collision was similar beyond 15dB SNR but the double threshold differ from those by wide margin.

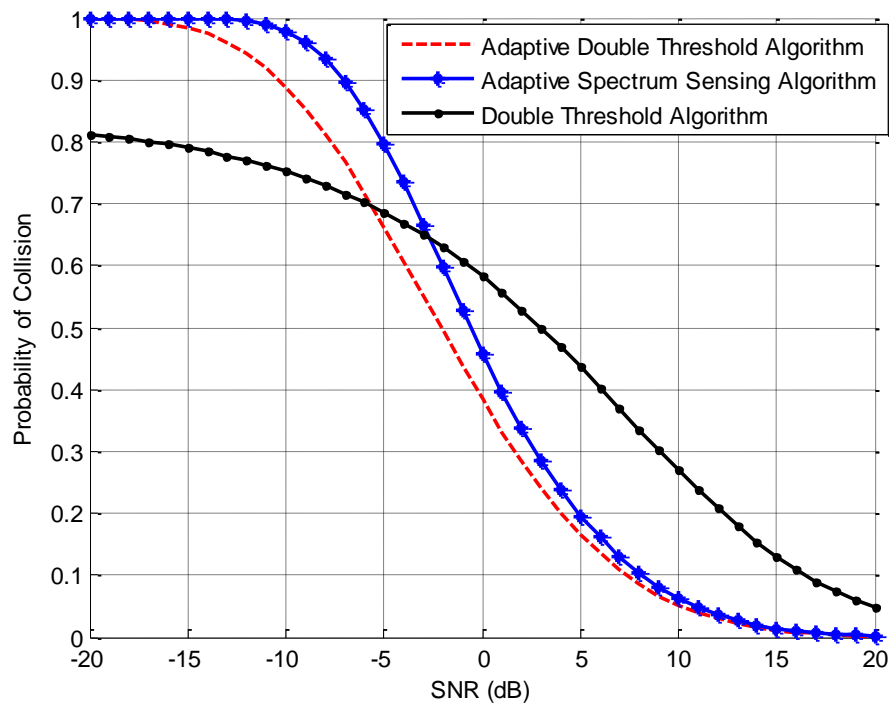


Figure 5.3: Probability of Collision vs. SNR for Nakagami Channel

Figure 5.3 shows the plot of probability of collision versus different values of SNR for Nakagami fading channel. It has performed slightly better than Rayleigh fading channel as it also considers the signal that are in line of sight. For 5 dB SNR, probability is reduced from around 43% to around 17% i.e. from double threshold to adaptive double threshold algorithm .

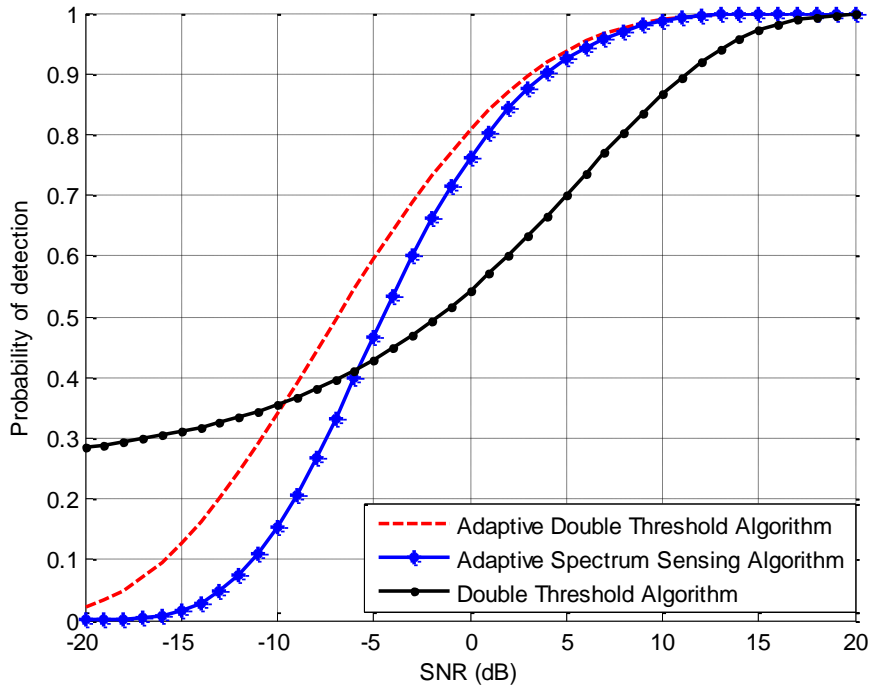


Figure 5.4: Probability of Detection vs. SNR for AWGN

Figure 5.4 shows the plot of probability of detection versus different values of SNR. The probability of detection specifies that a detector makes a correct decision that a channel is occupied (H_1). The (P_D) is an indicator of the level of interference protection provided to the primary user. Hence, a large P_D denotes exact sensing; which translate to small chance(s) of interference. From the figure 5.4, it is seen that the probability of detection is largest in the case of adaptive double threshold algorithm followed by the adaptive threshold spectrum sensing algorithm and double threshold algorithm in the order of high to low. It was also observed that the probability of detection for adaptive double threshold and adaptive spectrum sensing have similar response in the SNR range of 5-20dB. For the 5dB SNR, the probability of detection for adaptive double threshold, adaptive spectrum sensing algorithm and double threshold algorithm is around 94%, 92% and 70% while for SNR of -5dB it was found to be around 59%, 48% and 43% respectively.

Figure 5.5 is also the plot of probability of detection versus different values of SNR but for different channel conditions. It considers the Rayleigh fading channel. Comparing the figure 5.4 and figure 5.5, it is observed that the probability of

detection is less in the case of Rayleigh fading channel in comparison to the AWGN channel. For the 5dB SNR, the probability of detection for adaptive double threshold, adaptive spectrum sensing algorithm and double threshold algorithm is around 94%, 92% and 70% respectively in AWGN channel. The scenario here is different. For the

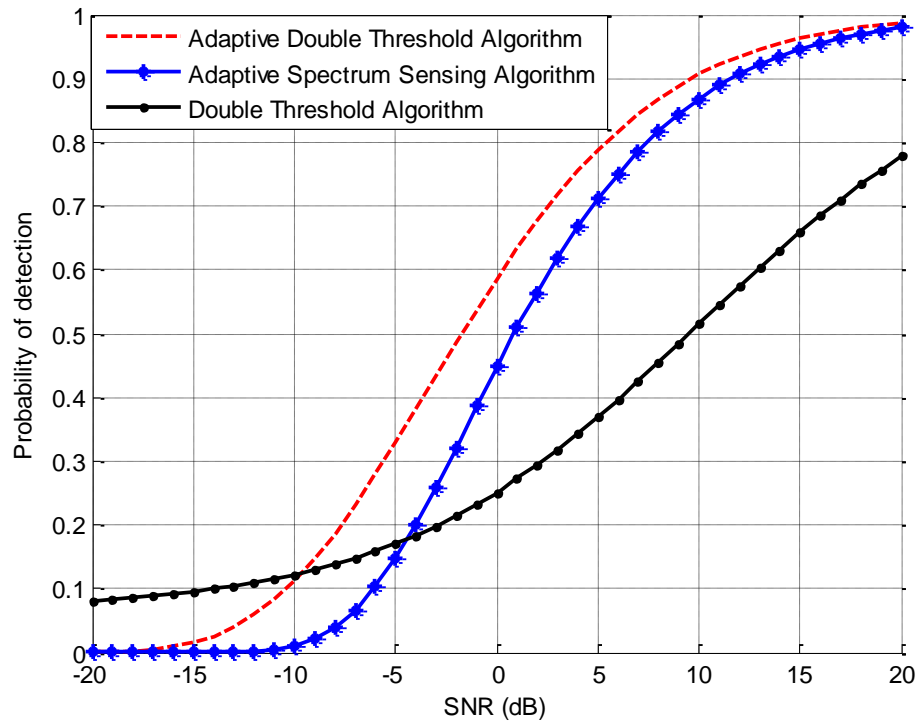


Figure 5.5: Probability of detection Vs. SNR for Rayleigh

same 5dB SNR in Rayleigh fading channel, the probability of detection for adaptive double threshold, adaptive spectrum sensing algorithm and double threshold algorithm is around 82%, 75% and 40% respectively. From the figure 5.4, it is also seen that the adaptive double threshold performs the best detection performance.

Figure 5.6 shows the plot of probability of detection versus SNR for Nakagami fading channel. Here the probability of detection is more than the Rayleigh fading channel and is less than the AWGN channel. Here also the adaptive double threshold performs the best. For 20dB, the probability of detection achieves 100% while it is around 97% in the case of Rayleigh channel. For the SNR below -15dB, the probability of collision for Adaptive double threshold and adaptive spectrum sensing are almost zero but the double threshold algorithm shows better results.

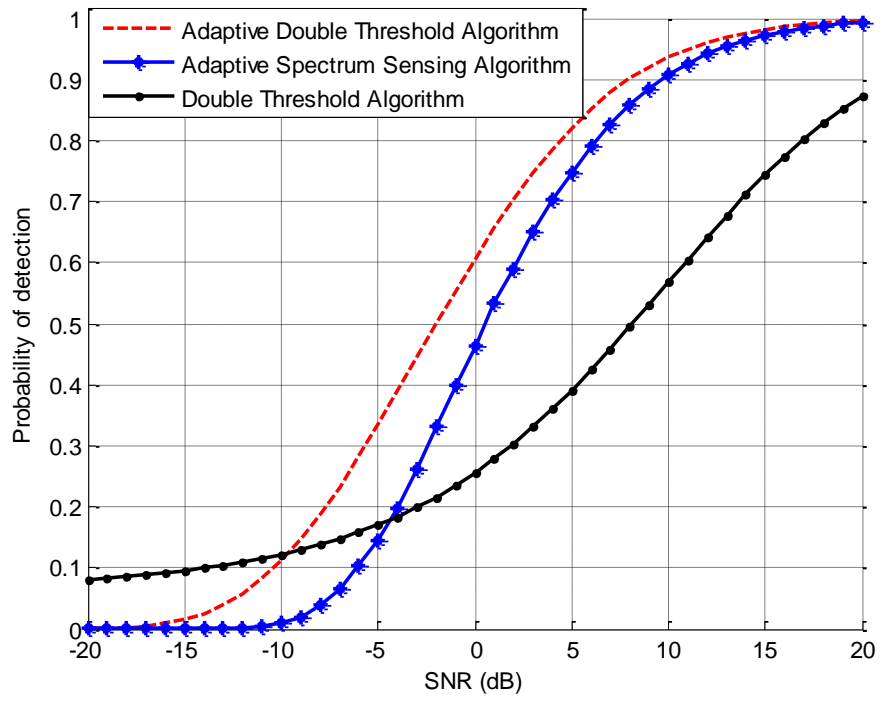


Figure 5.6: Probability of detection Vs. SNR for Nakagami channel

CHAPTER SIX: CONCLUSION AND LIMITATION

6.1 Conclusion

In this study, the performance of the energy detector is compared using Double threshold algorithm, Adaptive spectrum sensing algorithm and Adaptive double threshold algorithm for Additive White Gaussian Noise (AWGN) channel, Rayleigh fading channel and Nakagami fading channel. Double threshold energy detection performs poor based on probability of detection and collision probability. The adaptive spectrum sensing algorithm optimizes the detection threshold of the energy detector. An adaptive double threshold spectrum sensing algorithm is better in performance than adaptive spectrum sensing algorithm. Use of Adaptive double threshold algorithm increases the probability of detection and decreases the probability of collision compared to the adaptive spectrum sensing algorithm and double threshold algorithm. Double threshold algorithm performs poor result as it is based on conventional threshold which do not adapt to changing signal and noise parameters. For different channel similar result was obtained. AWGN channel performs the best result followed by Nakagami and Rayleigh fading channel respectively.

6.2 Limitation

The Adaptive Double Threshold energy detector proved itself the efficient in most of the cases. But, its performance at low values of SNR falls below the performance of Double threshold algorithm. The limitation of this work is

- I. Performance of adaptive double threshold and adaptive spectrum sensing at low values of SNR fall below that of double threshold algorithm.

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