“A TWO STAGE SPECTRUM SENSING IN COGNITIVE RADIO”

A DISSERTATION

Submitted in partial fulfilment of the requirements for the award of the degree of

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IN

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Under the supervision of

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DECLARATION

I hereby declare that the work reported in the M-Tech thesis entitled **"Two Stage Spectrum Sensing in Cognitive Radio"** submitted at **Jaypee University of Information Technology, Waknaghat, India,** is an authentic record of my work carried out under the supervision of **Prof. Ghanshyam Singh.** I have not submitted this work elsewhere for any other degree or diploma.

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CERTIFICATE

This is to certify that the work entitled, "Two Stage Spectrum Sensing in Cognitive Radio" submitted by **Anshu Thakur** in partial fulfilment for the award of degree of **Master of Technology in Electronics and Communication Engineering, Jaypee University of Information Technology, Solan,** has been carried out under my supervision. This work has not been submitted partially or wholly to any other University or Institute for the award of this or any other degree or diploma.

Prof. Ghanshyan Singh

(Supervisor)

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A dissertation cannot be completed without the help of many people who contribute directly or indirectly through there constructive criticism in the evolution and preparation of this work. It would not be fair on my part, if I do not say a word of thanks to all those whose sincere advice made this period a real educative, enlightening, pleasurable and memorable one.

First and foremost, I would like to express my deepest appreciation to my project supervisor, **Professor Ghanshyam Singh** for their gracious efforts and keep pursuits, which has remained as a valuable assets for the successful instrument in keeping my spirit high .His flawless and forthright suggestions blended with an innate intelligent application have crowned my task a success.

Finally, I am very much thankful to **God** for the shower of warm blessings and **my parents** for their moral support and continuous encouragement while carrying out this study.

25-5-2016

Date **Anshu Thakur**

ABBREVIATIONS:

A/D	Analog to Digital Converter
AM	Analog Modulation
AWGN	Additive White Gaussian Noise
CR	Cognitive Radio
CD	Cyclostationary Detection
CRS	Coarse Resolution Sensing
ED	Energy Detection
FCC	Federal Communication Commission
FRS	Fine Resolution Sensing
MAC	Media Access Control
MF	Matched Filter
Pdf	Probability Density Function
PU	Primary User
RF	Radio Frequency
ROC	Receiver Operating Characteristics
TV	Television
UHF	Ultra High Frequency
VHF	Very High Frequency
SU	Secondary Users

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Abstract

In past few years the need for high data rate wireless communication has experienced a tremendous growth indicating a huge commercial potential. The growing demand of wireless devices is restricted by the spectrum access policy of radio regulatory regime. Large part of the spectrum is allocated for exclusive use by the licensed users and only a small portion of the spectrum is given for open access. The commercial success of the unlicensed spectrum has encouraged FCC to frame policies towards more flexible and open spectrum access.

Most of the licensed bands suffer from under-utilization and less spectral occupancy of spectrum. The exclusive usage criteria in the licensed spectrum have resulted in wastage of limited and precious spectrum. The so called ‘spectrum scarcity’ and ‘limited radio spectrum’ is a result of the way the spectrum is being regulated.

Cognitive radio has emerged as a solution to the problem of low spectral occupancy and inefficient utilization of the licensed radio spectrum. It enables the unlicensed users to access the licensed band without violating the exclusive usage facility for the licensed user. It identifies the unused portions of the licensed spectrum known as spectrum holes and makes them available for unlicensed or secondary users.

Spectrum sensing is a technique in which the surrounding radio environment is sensed in order to determine the presence or absence of the licensed user in the licensed band. It enables the CR to get an overview on the radio environment usage and in determining the spectrum holes.

The two-stage spectrum sensing method having the two sensing blocks one is coarse resolution sensing and other is fine resolution sensing. The different techniques are present for finding the PU in the spectrum. It can be done with one stage spectrum sensing but random search took place in this case, so, we head towards the two stage spectrum sensing. In this case of sensing serial searching of the spectrum is done. Cognitive Radio is one of the advance search in the field of wireless communication

Chapter -1

Introduction

In the previous few years a tremendous increase is seen in the Wireless Communication, which is due to boom in the electronics appliances and use of the high-data-rate networks. Wireless standards and technologies which depend on the electronics devices will keep on increasing in future, and this increase in the usage will lead to spectrum scarcity in wireless communication.

The responsible authority for regulation of interstate telecommunication, management and licensing of electromagnetic spectrum is Federal Communication Commission (FCC) within the United States and it fulfills the requirements on inter station interference in all radio frequency bands [1]. The report of Federal Communication Commission (FCC) has shown that the lack in the spectrum is mostly due to not utilizing the spectrum of licensed user properly. About 90-95% of the licensed radio spectrum user is not in use at any location at any given time[2]. The non-utilization of these spectrum which are licensed has led to the problem of artificial spectrum scarcity. It has been seen that the allocated spectrum is not completely utilized because of the fixed allocation of the spectrum. Also, the conventional approach is very infeasible in case of spectral management in the sense that each wireless operator is assigned an exclusive frequency to operate in a certain frequency band. And, with already allocation of the useful radio spectrum, it is not feasible to find vacant bands to either develop new services or to improve the existing ones. In order to solve this situation, we need to develop the solution for improved and smart idea for the use of the spectrum. The issue of not utilizing the spectrum in cellular and wireless communication can be handled in a very improved way using Cognitive radio (CR) technology. Cognitive radios are developed to provide highly reliable and effective communication for all users of the network, wherever and whenever needed and to effectively and efficiently utilize the radio spectrum. Cognitive radio has the ability to change its parameters depends on interaction with environment in which it works. Cognitive radio has basic four main functional blocks: spectrum sensing, spectrum management, spectrum sharing and spectrum mobility. The main function of spectrum sensing is to find spectrum availability and the presence of the licensed users (also known as primary users). Spectrum management is to know or guess about the spectrum holes i.e. how long they are likely to remain available for use to the unlicensed users (also called cognitive radio users or secondary users)

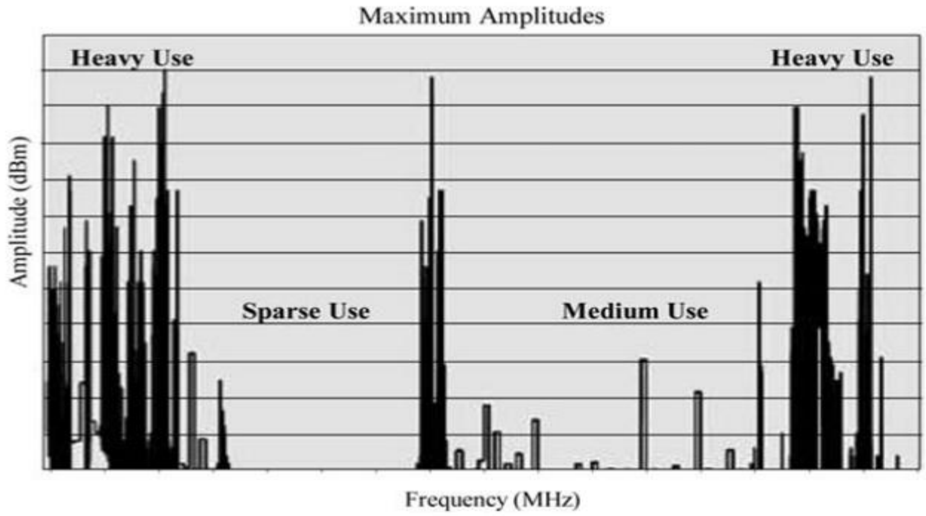

Figure 1.1 Spectrum Utilization [2]

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Spectrum sharing is to distribute the spectrum holes fairly among the secondary users depending on the usage cost. Spectrum mobility is to maintain seamless communication requirements during the transition to better spectrum.

From all given functions given above, Spectrum sensing is considered as the most difficult task to establish cognitive radio networks. The different spectrum sensing techniques have primary transmitter detection, cooperative detection and interference detection. These are discussed and compared in detail in upcoming sections.

1.1 Spectrum Holes:

These are also known as the spectrum opportunities. Spectrum Holes are known as the frequency bands which are assigned to the primary users, but at a point of time they are not used by the primary users and could be accessed by the licensed user.

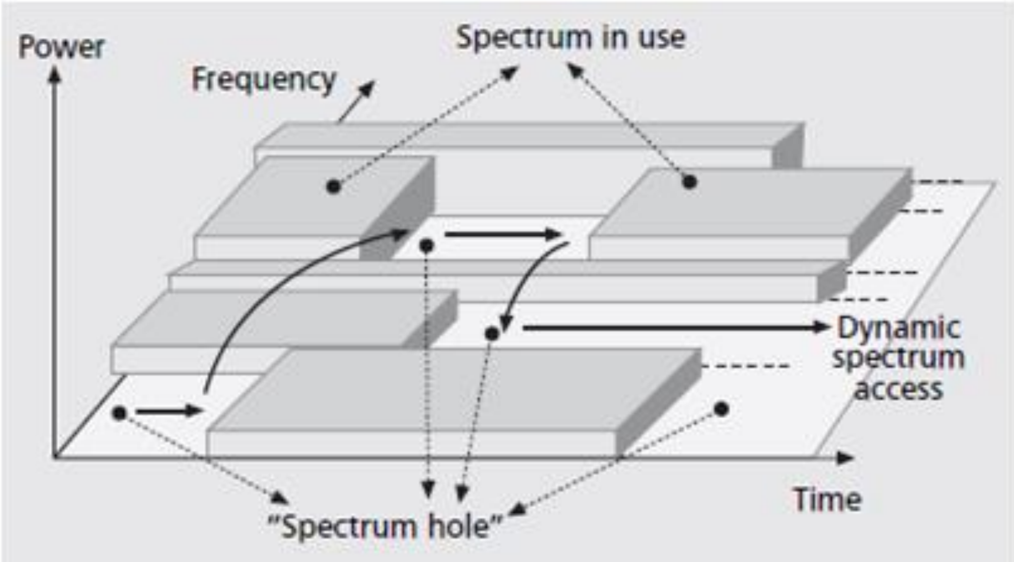

Figure 1.2 Spectrum holes (or Spectrum opportunity) [2]

The limitations in spectrum access due to the fixed type of spectrum licensing scheme are as:

- In the present spectrum licensing scheme, the use of the spectrum cannot be changed weather the needs may be changed. For example, analog TV cannot be used by digital TV broadcast or broadband wireless access technologies. However, this band which is allocated to TV remain largely unused in many locations.

- When a spectrum is licensed to a particular user or wireless service provider in a large region the wireless service provider may use the spectrum for a good number of subscribers, to gain the highest profit as he invested. Consequently, the assigned frequency spectrum remains unused in other areas, and other users are prohibited from accessing this spectrum

- A service provider is generally given large chunk of radio spectrum (e.g. 50MHz). For a service provider, it may not be possible to find the users who need that spectrum for a short period .In present scheme, only a licensed user can access the corresponding radio spectrum and secondary users are not allowed to access the spectrum even though it is not used by the licensed users at that interval of time.

In order to improve the effectiveness, efficiency and utilization of the available spectrum, these limitations should be removed or modified by the spectrum licensing scheme. Among the different steps taken by the authorities worldwide, for better usage of spectrum is the introduction of secondary markets (secondary users). Besides the introduction of secondary markets, we are currently focusing on evolutions of software defined radio (SDR) techniques

1.2 Software-defined radio

A software-defined radio (SDR) wireless communication system which is reconfigurable and the parameters like operating frequency band, modulation mode, and protocol can be controlled dynamically [3]. SDR is one of the major component to implementing cognitive radios.

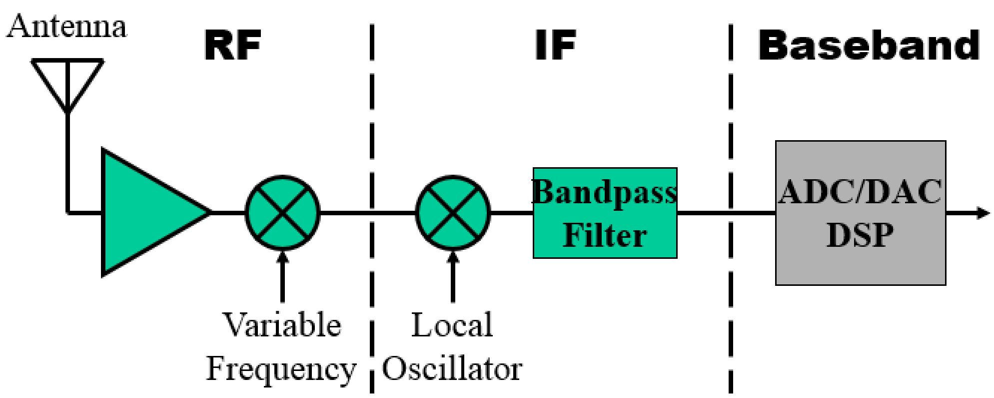

Figure1.3 Software Defined Radio [3]

Some of the functions of the SDR are as follows-

•SDR allows wireless data transmissions over a different frequency spectrum used by different wireless access systems.

• SDR is designed to support different standards like GSM, WCDMA, cdma2000, WiMAX, Wi-Fi.

•SDR has the ability to support multiple types of services, e.g. cellular services or broadband wireless Internet access.

• SDR can transmit or receive on multiple frequency bands simultaneously.

1.3 Characteristics of Cognitive Radio

CR is known as the intelligent radio system which analyse, observe and learn about the condition and make the system friendly to these changes .CR has the following characteristics which are important-

1.3.1 Flexibility:

As CR is an intelligent network so it should be able to change its parameter like data rate, modulation, frequency etc. in order to utilize the spectrum holes present in different frequency bands.

1.3.2. Agility:

These type of Radio should be able to operate in different spectrum bands in order to utilize white spaces observed in different frequency bands. For example a cell phone can operate in two or more different frequencies i.e., GSM 900 and GSM 1900.

1.3.3. Sensing:

CR should be able to sense it's surrounding of the RF and working parameters that are working with in itself in order to get the information about the existence of spectrum holes and to provide information of the radio spectrum utilization.

1.3.4. Networking:

CR should be able to know about the communication between different points of the wireless system to bring synergy in using the radio resources. Sharing of information and cooperatively passing decisions on the radio resources.

1.3.5 Cognitive Capability

Cognitive capability is known as the ability of radio to sense the information from the environment and will perform real time interaction with it. The capability of the cognitive Radio can be explained with the help of three characteristics; Spectrum Sensing, Spectrum Analysis and Spectrum Decision. The task of monitoring is performed by the spectrum sensing and also the detection of spectrum holes is also performed. The spectrum hole is detected with the help of the spectrum analyzer. In case of the spectrum decision, the spectrum which is selected is used to determine the parameters like data rate, transmission mode etc.

1.3.6 Re -configurability

Re-configurability is the ability of radio which allows the cognitive radio to adjust its Parameters like operating frequency, modulation, link and transmission power at real time without any changes in the hardware components. In other words Re-configurability of CR is known as SDR.

1.4 Operation of Cognitive Radio

The network architecture of cognitive radio varies gernally depend on the desired applications. Cognitive Radio can be centralized where a central node co-ordinates for the spectrum sensing in the given system, allocation of all serviced nodes. On the other hand, nodes in a distributed cognitive radio network communicate with each other in an ad-hoc manner to co-ordinate cognitive tasks. Typically, a centralized network simplifies the communication and computation load of each end node, but requires more infrastructure and costs [4]. On the other hand, distributed network is more structurally flexible and requires little infrastructure at the expense of increased complexity.

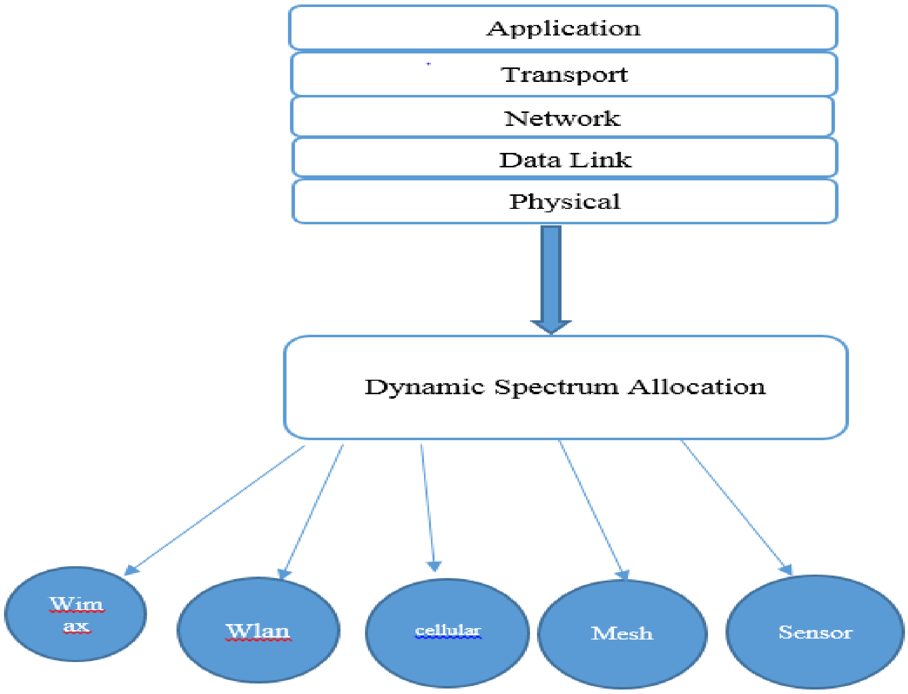

Figure 1.4 Dynamic changes in all layers

Else then the architecture of the, cognitive radio must be flexible in detecting changes in PU activity, hence the cognitive tasks must be performed periodically. Collectively, the cognitive tasks forms a 'cognitive cycle' to ensure the integrity of cognitive radio. It is part of the cognitive cycle that focuses on the spectrum sensing and cognitive intelligence aspect of cognitive radio. While cognitive tasks may vary between implementation and applications, the cognitive cycle consist of four core operations: ***spectrum sensing***, ***spectrum analysis***, ***spectrum decision*** **and** ***data transmission***.

1.4.1 Spectrum Sensing

It is the task where the SU senses the spectrum to detect the presence of PU signals and identify empty spectrum spaces. Sensing can be performed ***in-band*** to detect PU on the spectral channel currently used by the SU, or ***out-of-band*** to identify other possible spectrum spaces beside the channel currently in use [5]. Out of band sensing is beneficial in locating possible back-up channels in case in-band sensing failed, or assisting other SU in detecting a usable channel. Sequential search senses single channels iteratively while parallel search senses multiple channels simultaneously.Spectrum sensing is the main focus of this resean in-depth review will be discussed in the following chapter. Once spectrum spaces are detected, the SU enters the next task of spectrum analysis.

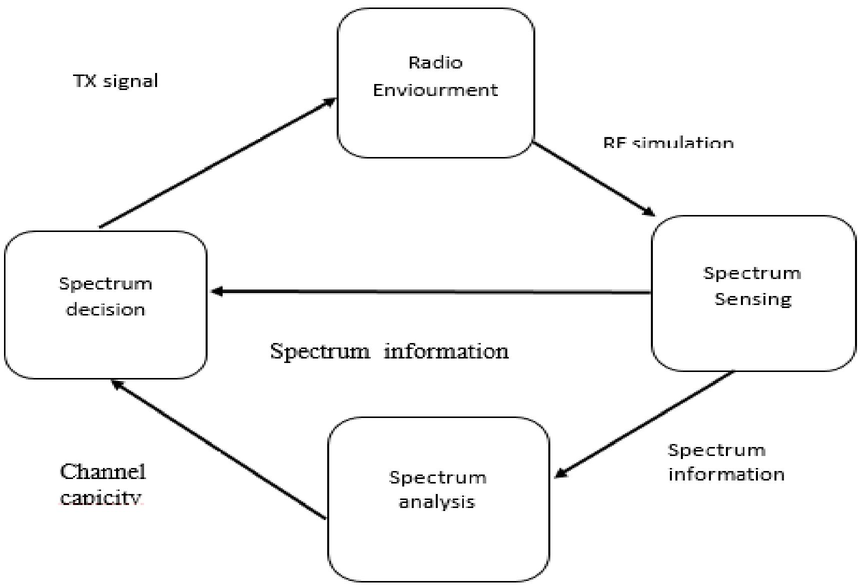

Figure 1-5-Cognitive cycle

1.4.2 Spectrum analysis

It is the task where the SU analyses the detected spectrum space and determine whether these spaces are suitable for the desired SU operation. Depending on the spectrum frequency, transmission and propagation characteristics of certain channels may be unable to support the desired operation, such as unsatisfactory quality of service, insufficient coverage, etc. Furthermore, if PU traffic model has been established, it is possible that PU for particular spectrum spaces are more likely to return in the near future and is best avoided. Once the SU has analysed which spectrum spaces are more suitable, it then must decide on a space to use.

1.4.3 Spectrum decision

It is used to decide on which spectrum space to continue communication and will affect all nodes within the SU network. The decision may instruct the nodes to remain on the current channel if PU is not detected, or immediately relocate to the next backup channel if PU is present. If the SU network is changing to a different channel, then all SU nodes must know which channel to change to. If particular nodes cannot be serviced after the channel change, they must also know which back-up service to switch to. Spectrum decision is best performed by combining spectrum analysis results from all nodes within the SU network. The decision collaboration can be either through decision fusion or data fusion. For decision fusion, SU nodes provide a hard decision on which channel they detected to be empty. For data fusion, SU nodes provide a soft metric, such as the test statistic of the sensing detector, to be collaboratively analyzed.

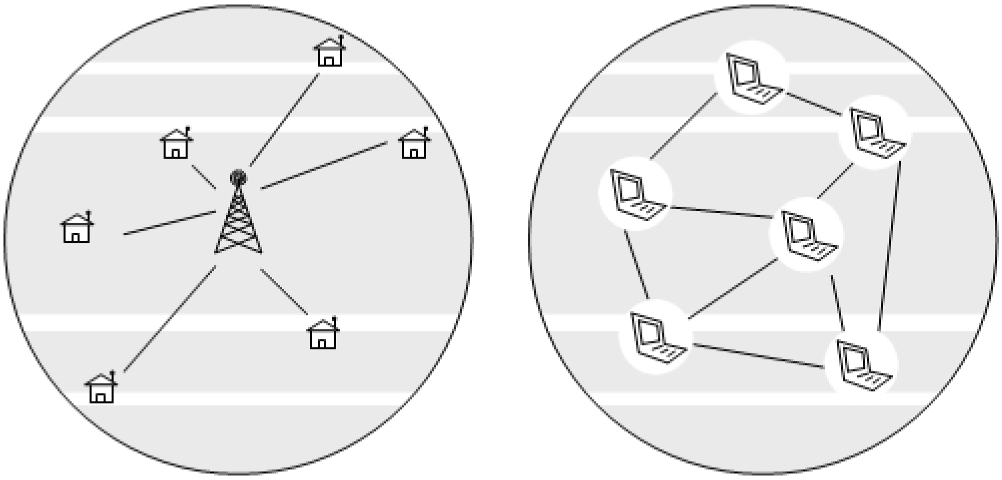

Figure1.6 Architecture of centralized vs. distributed cognitive radio network. [5]

Fusion and decision can be made at the coordinating node of a centralized network, or by individual nodes in a distributed network. Once all nodes within the networks agree on an operating channel, they can then begin or continue data transmission.

1.4.4 Data Transmission

Data transmission is where the SU [6] transmits the communication data. The SU must adapt its transmission parameters such as radio hardware and software algorithms to suit the propagation characteristics of different PU channels. Longer data transmission period increases the overall throughput of the SU network and the spectrum utilization is more efficient. Furthermore, achieving greater bandwidth can maintain higher QoS [7]. SU nodes are typically monetarily charged based on the duration or amount of data transfer. Therefore as the network operator, it is important to maximize data transmission while maintaining the efficiency of SU network and protecting PU activity.

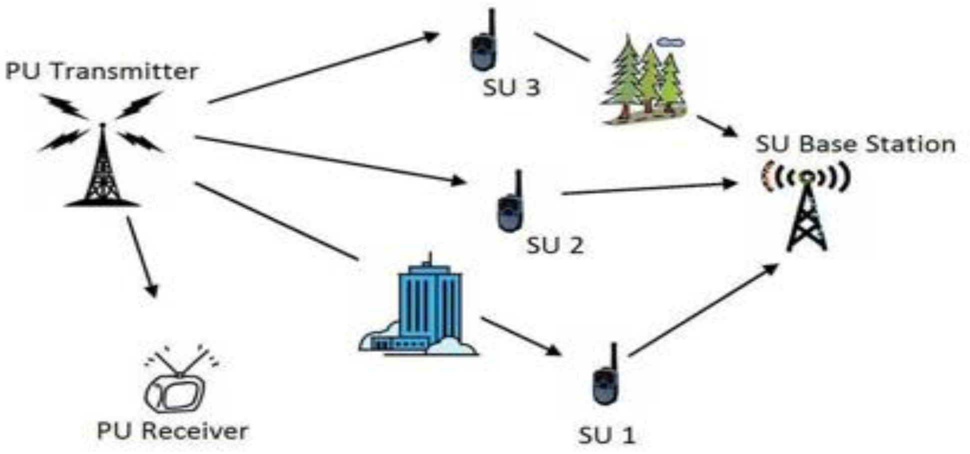

Figure 1.7-Cooperative spectrum sensing to improve global sensing performance [7]

1.5 Terms of Cognitive Radio Network

Some of the important terms related to cognitive radio network are as follows:

1.5.1 Primary user-

A primary user is the one who is having the right to access the frequency band .The other name of the primary user is licensed user.

1.5.2 Secondary user-

If the user has no rights to utilize the licensed spectrum than it is known as the secondary user. It is also known as CR user. It senses the radio spectrum and searches for the Un-utilized portions of the radio spectrum [8]. The main aim of the secondary user is to transmit the signals without affecting the primary user.

1.5.3. White spaces-

Un-used part of the licensed spectrum is known as white space. CR technology helps the unlicensed user to access the spectrum when it is free. The fundamental motive of the CR is to search for white spaces[9]. The other term used for this is spectrum holes.

1.6 Standard for Cognitive Radio

The major issue that arises due to the band regulation is the scarcity of the band. According to the report of the FCC as the demand of the spectrum is keep on increased day by day which leads to the problem of spectrum scarcity. The success of commercialized unlicensed bands has forced the FCC to provide more unlicensed spectrum. To increase the spectrum utilization of bands, FCC has allowed unlicensed users to access the licensed bands without affecting the PU. The standard which gives the opportunity of utilizing the unoccupied TV bands for CR users are IEEE 802.22[8] .It does not cause any significant interference to the licensed user. The other name of the given standard is the WRAN standard. It main area for concern in this case is VHF/UHF TV bands as they are highly favorable propagation characteristics and internationally they move from analog to digital TV and creates a spectrum opportunities which are known as "White Spaces"[9].

IEEE 802.22 focuses mainly on the rural areas, where wireless is a viable source of communication. It works on PHY layer and MAC layer specification for different methods.

These devices mainly sense TV signals and Wireless Microphone signal for the detection of white spaces in the VHF/UHF band.

1.7 Motivation:

In CR spectrum sensing is one of the major issue as it is the major component for establishment of the CR. For CR to fulfill the requirement of the user it offers to solve the spectrum underutilization problem and do so in a reliable and computationally feasible manner.

To make this possible we require a spectrum method that can help to detect the spectrum holes with a minimum time and identifies the unknown directions of interfering signals. Spectrum sensing is the key method for finding the spectrum holes in the licensed bands. There are some already known methods like energy detection, matched filter and cyclostationary detection method used for the spectrum sensing [10]. A huge amount of research is going on in the spectrum sensing area to increase the probability of detection and reduce the probability of false alarm for the detection scheme. As the work in the single stage spectrum sensing is going on the disadvantages of this is that it takes more time and miss detection is also there which leads us to the two stage spectrum sensing.

1.8 Objective of the Work

In this dissertation a two-stage spectrum sensing method for detection of PU is implemented. The objective for the implementation of the two stage spectrum sensing can be summarized as follows

The objective is to decide the threshold at which level or after what particular value we are going to find out the licensed user. And after that filtering of the user is done to find the unused frequency spectrum by the users.

Multiple users, both licensed and unlicensed, may share the radio spectrum in a network. Also, multiple networks can coexist for which transmissions in one network may interfere with transmissions in other networks. So, to decide which frequency spectrum is occupied by which user it's important to sense the spectrum.

In spectrum sensing, the longer the observation period, the more accurate will be the spectrum sensing result. So it's important to decide the time period for how long we are going to sense the given frequency spectrum [10]. If the observation time period is high then the accuracy of the system is low and if the accuracy of spectrum sensing is low, collision and interference to the transmissions by licensed users could occur to degrade the performances of both licensed and unlicensed users. So the time period is one of the important factor in this case.

Sensing in large channel network would be typical in a cognitive radio If, the number of available channels are larger than the number of available interfaces at the radio transceiver then only a fraction of the available channels are sensed simultaneously. So we tried to overcome this problem by the concept of the two stage spectral

1.9 Dissertation Organization

The Dissertation has been organized into five chapters. The present chapter gives the

Chapter-1 Brief Introduction to the concept of CR, its operation, characteristics and need. It also gives a overview of IEEE 802.22 standard. The motivation and the objective present an essence of the dissertation.

Chapter 2 In this chapter gives the brief introduction of the spectrum sensing, the different method of detection for the sensing, introduction about the hypothesis model, the complete discussion about the different detection method, type of the sensing, comparison between the different detection methods, discussion about the region of convergence and issues related to the spectrum sensing.

Chapter-3 In this chapter there is a discussion about the posteriori energy detection method, process of the detection method, encoding of the energy detection method, detection of the signal in this case, finding the relation between the SNR and detection.

Chapter-4 In the given chapter there is a discussion about the two stage spectrum sensing, coarse resolution sensing and fine resolution sensing, mean detection time and overall detection time in the given case, analysis of the false alarm in the two stage spectrum sensing, settling time in the two stage.

Chapter -5 In the given chapter the conclusion of the given dissertation is present and also the future possibilities of the research work is present.

Chapter-2

Spectrum Sensing In Cognitive Radio

One of the main tasks of Cognitive radio is to sense the radio environment and search for white spaces in it. Spectrum sensing is one of the important sections in CR cycle. It enables the CR to observe its surrounding environment and to utilize the radio environment by determining spectrum holes, without causing interference to the primary network. The objective of spectrum sensing is to detect the presence of transmissions from licensed users. There are three major types of spectrum sensing, namely, non-cooperative sensing, cooperative sensing, and interference-based sensing. These will be described as follows:

2.1 Types of Spectrum Sensing

Spectrum sensing can be classified in three groups. They are:

- Non-cooperative sensing
- Co-operative detection
- Interference-based sensing

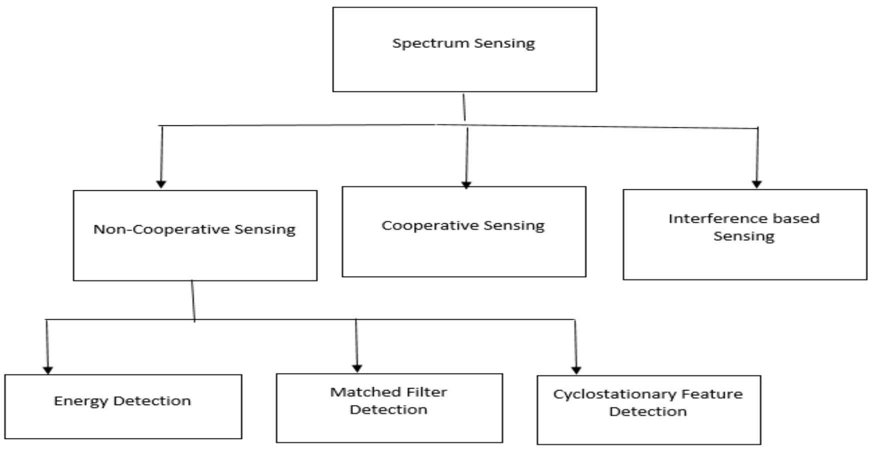

Figure-2.1 Different type of Spectrum Sensing

These spectrum sensing types are described in the following sections

2.1.1 Non-cooperative sensing

In this detection method, CR users sense the radio environment in order to detect the presence of PU signal. Since the CR users have no prior information regarding the PU signal type and characteristics so, it has to distinguish between the noise and the PU signal. It is the most widely used method since it directly gives an idea regarding the usage pattern of a given radio spectrum. CR uses binary hypothesis problem formulation for detecting the PU signal against the noise. The binary hypothesis problem is described in details in subsequent section.

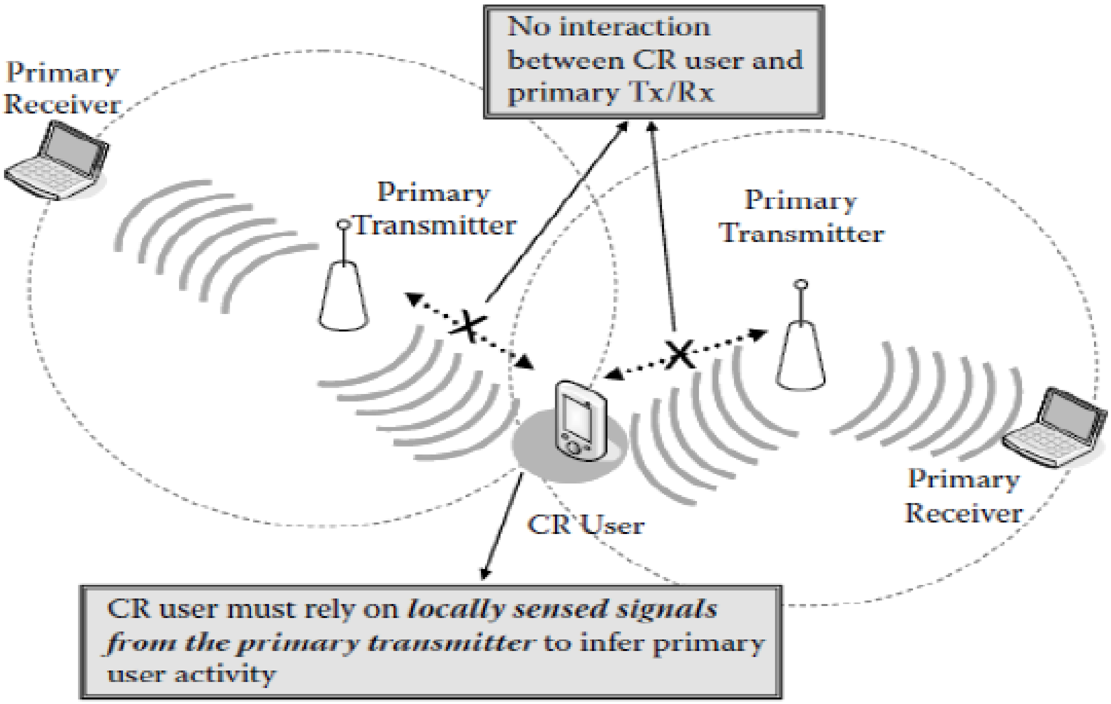

Fig 2.2- Primary Transmitter Detection [10]

The primary detection can be performed by various methods, out of which there are three popular methods, (a) Energy detection method, (b) Matched Filter detection method and (c) Feature based Detection method. These methods are described in details in the following section.

2.1.1.1 Energy Detection Method [11]

It is a blind detection scheme and optimal detection method when the primary user signal is unknown. It is the most widely used method for the detection of PU signal since, it doesn't require any *a priori* information [12]. In this method, the energy of the received signal is calculated which is compared against some given threshold to determine the presence or absence of PU signal. For the calculation of energy of the received signal, firstly the samples are squared and integrated over the observation interval and the output of the integrator is then compared against the threshold. If the output of the integrator exceeds the threshold then it is assumed that the given radio spectrum[12]-[13] is occupied otherwise it is treated as vacant. The detection problem can be written as

Ho, if $\boldsymbol{x(t)} = \boldsymbol{n(t)}$ (2.1)

H_1, if $\boldsymbol{x(t)} = \boldsymbol{h} * \boldsymbol{s(t)} + \boldsymbol{n(t)}$ (2.2)

Where x (t) is the received signal of an unlicensed user, s (t) is the transmitted signal of the licensed user, n (t) is the additive white Gaussian noise (AWGN), and H is the channel gain. Here, H_o and H_1 are defined as the hypotheses of not having a signal from a licensed user [14] in the target frequency band, respectively. Energy detection method can be performed both in frequency domain and time domain. It requires$O(1/_{SNR^2})$ number of Samples for the calculation of decision statistics. It is the simplest and easier to implement among all the three methods, but it suffers from some drawbacks. Firstly, the threshold is highly susceptible to receiver noise uncertainty. Secondly, it cannot discriminate among the PU signal and noise and performs poor in low SNR [15]-[16] environment.

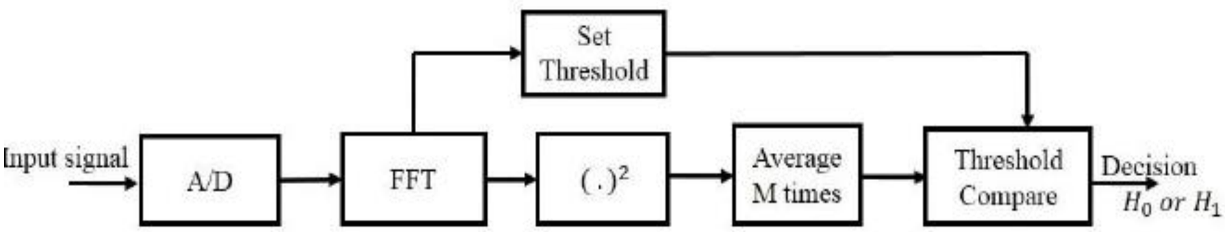

Figure-2.3 Energy Detection Method.

The performance of a spectrum sensing technique [17] is generally measured in terms of the probability of correct detection (P_d), the probability of false alarm (P_f), and the probability of miss (P_m).

Mathematically, P_d = Prob {decision = $H_1|H_1$},

Pf = Prob{decision = $H_1|H_0$},

and Pm = Prob {decision = $H_0|H_1$}.

2.1.1.2Matched filter detection or coherent detection:

Matched filter detection is basically used to detect a signal by the comparison of a known signal (i.e. a template) with the input signal. The main operation of a matched filter is to maximize the received SNR[17] to measure the signal. Therefore, if the information about the licensed user's signal is known (e.g. Modulation and packet format), a matched filter is an optimal detector in stationary Gaussian noise. A matched filter needs only a small amount of time to operate. However, if this information is not available or is incorrect, the performance of spectrum sensing keeps on decreasing significantly. Matched filter detection [18] is suitable when the transmission of a licensed user has pilot, preambles, synchronization word or spreading codes, which can be used to construct the template for spectrum sensing. In the case of the CR user requires some *a **priori*** information like pilot carriers[19], modulation type etc. regarding the PU. Matched filter is used to correlation between unknown signals with the known signal. The output of the MF is then compared against the threshold to decide the presence or absence of PU signal in the specified band. The detection problem for this scheme can be written as

$$H_0 = \boldsymbol{if}\ \sum_{\boldsymbol{n=1}}^{\boldsymbol{N}} \boldsymbol{Y}[\boldsymbol{n}] * \boldsymbol{x}[\boldsymbol{n}] \leq \boldsymbol{\lambda} \qquad (2.3)$$

H_1 Otherwise

Where y[n] is known as the received signal in the CR receiver, x[n] in this case is the known signal, λ is denoted as threshold, H_0 is noise only hypothesis and H_1 is signal plus noise hypothesis[20].

This method is the best among all the three methods but unfortunately widely in use in CR scenario. The drawback that lies is the prior knowledge requirement for its implementation. CR has limited information regarding the signal structure of the PU. In licensed spectrums the pilot carrier information of PU is available with the CR. It requires only *O (1/SNR)* number of samples for the calculation of decision statistics. It performs very poor when no information or incorrect information is available with the CR user. Its main advantage is it needs less number of samples for detection. The main disadvantage that comes is in demodulation process which requires the timing to be perfect modulation, carrier synchronization, etc. for which the requirement is a dedicated receiver for different PU signals[21] to increase the complexity of the system.

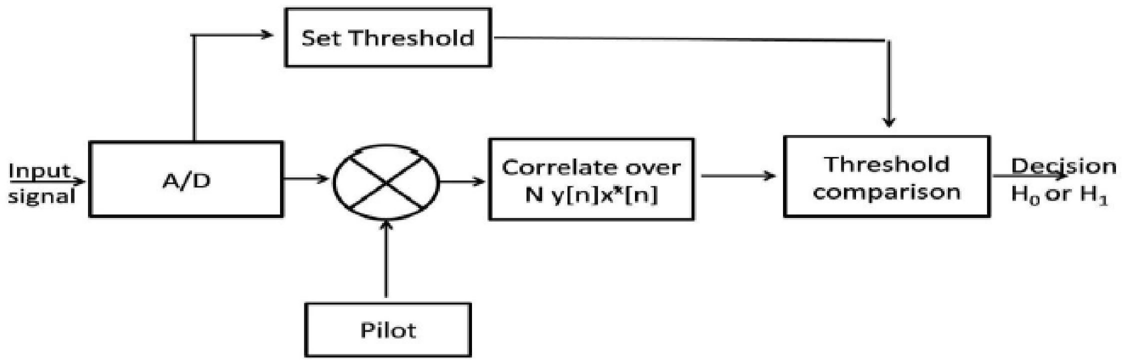

Figure-2.4 Pilot based Matched Filter Detection

2.1.1.3 Cyclostationary feature detection:

The signal that is transmitted from a licensed user commonly has a periodic pattern. The pattern which is periodic is referred to as cyclostationarity, and is also used to detect the presence of a licensed user. A signal is cyclostationary (in the wide sense) if the autocorrelation of the signal is a is a periodic function. Then the transmitted signal from a licensed user can be distinguished from noise, which is a wide-sense stationary signal without correlation. In general, this type of detection can provide a more accurate sensing result and it is robust to variations in noise power. However, the detection is complex and requires long observation periods to obtain the sensing result. A scheme that is based on the pattern recognition a neural network can be used to implement cyclostationary feature detection for spectrum sensing. To improve the overall performance of spectrum sensing [21], multiple detection methods can be integrated in a single unlicensed system. For example, for a quick scan of a wide range of spectrum bands the cyclostationary energy [22] method can be used- . In the spectrum bands with high energy densities same method is used. It performs better than the energy detection scheme in low SNR condition [23]. The cyclostationary property is also capable of differentiating signal on the basis of its type. Its main drawback is its large computationally complexity and longer observation interval. It cannot utilize the short duration spectrum holes effectively.

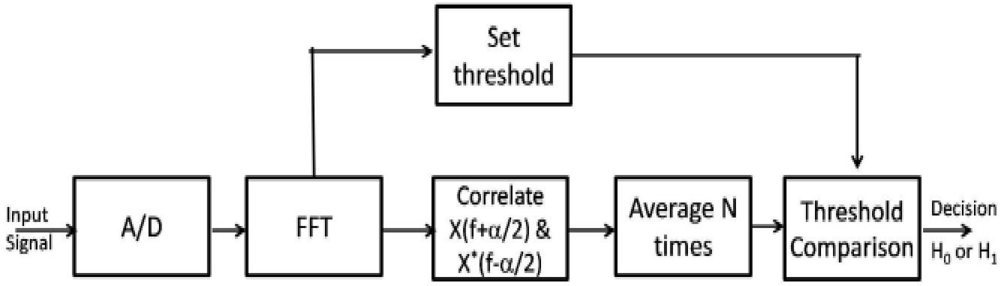

Figure-2.5 Cyclostationary feature based detection.

The advantages and disadvantages for the above mentioned detection scheme is presented in.

Spectrum Sensing	***Advantages***	***Disadvantages***
Energy Spectrum	• Does not need any priori information. • Low computational cost	• Poor performance at low SNR. • Can't distinguish the users sharing the same channel.
Matched Filter Detection	• Optimal filter detection • Low computational cost	• Require the prior knowledge about the PU. • Design of the each kind of the primary user signal.
Cyclostationary Based Detection	• Robust in low SNR. • Robust in interference.	• Require partial information about primary user. • High computational cost.

Table 2-1 Comparison between different Detection Methods.

2.1.2 Cooperative Sensing

The secondary user transmitter may not always be able to detect the signal from a primary transmitter which is due to the geographic separation and channel fading[25]. For example as given in the figure below the transmitter and receiver of the unlicensed user cannot detect the signal from the transmitter of the primary user as they are out-of-range

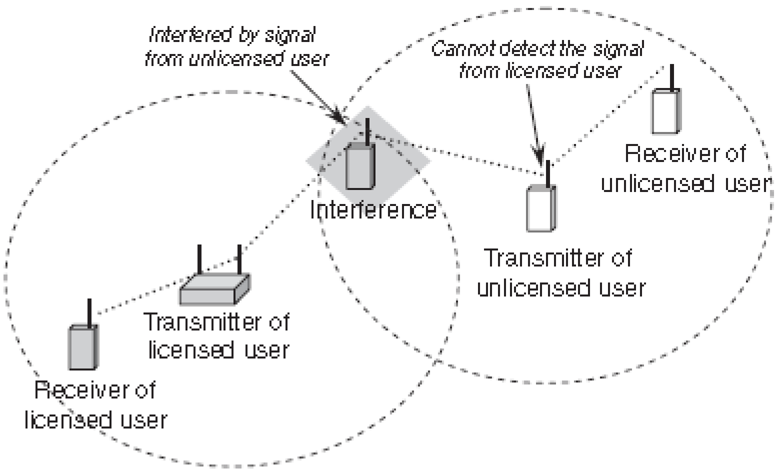

Figure 2.6-Hidden Node Problem.

in the given case. This is known as the hidden node problem. In the given case, when the transmitter of the secondary user transmit the signal, it sometimes interfere with signal of the primary user. To solve the hidden node problem of the non-cooperative transmitter sensing, cooperative spectrum sensing technique can be used. In the given case of the spectrum sensing technique, the information of the spectrum sensing from multiple secondary users [26] are exchanged with respect to the each other to detect the presence of primary users. The architecture of the cooperative spectrum sensing [27] can be either centralized or distributed. The hidden node problem can be solved by the cooperative spectrum sensing and the probability of the detection can be significantly improved in a heavily shadowed environment. For cooperative sensing, two different networks i.e. a sensor network and an operational network can be deployed to perform spectrum access [28] and sensing, respectively.

2.1.3 Interference Based Sensing

Interference-based sensing was firstly proposed by the FCC. In this case, the sensing Algorithm will measure the noise/interference level from all sources of signals at the receiver of the PU. This information that is provided by the PU is used by an SU to control the spectrum access without any destruction to the interference temperature limit [29]. Alternatively, the SU transmitter can also observe the feedback signal from a licensed receiver to gain knowledge on the interference level. The interference is measured with the help of interference temperature. The main drawback of this method is the difficulty in measuring or estimating the interference temperature.

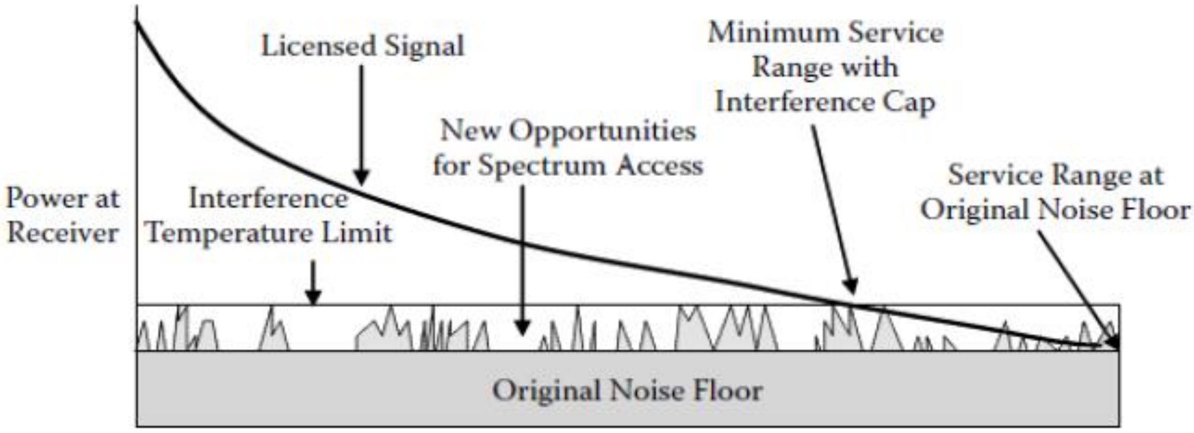

Figure 2.7-Interfarence Temperature Management [30]

2.2 Binary Hypothesis Testing

The major task of spectrum sensing is to determine whether the PU signal is present or not in the specified spectrum band. The CR detection problem can be considered as *binary hypothesis testing problem.* In this, CR has to distinguish between the PU signal and noise signal. The binary hypothesis testing model can be described as

$$y(t) = \begin{cases} n(t); \\ n(t) + x(t) \end{cases} \quad (2.4)$$

where, *y(t)* = received signal by the CR user

x(t) = transmitted signal of the primary user

n(t) = zero-mean additive white Gaussian noise (AWGN)

H_0 = null hypothesis, which indicates the absence of PU signal

H_1 = alternative hypothesis, which indicates the presence of PU signal

$$Y = \begin{cases} T \le \lambda \\ T \ge \lambda \end{cases} \quad (2.5)$$

Where *Y* = Decision made by the CR user

T =Test statistics

λ= Predetermined threshold

In this two parameters are of great importance, they are defined as

It is defined as the probability of deciding H_1 when $H_1 \backslash H_1$ is true

$$\mathrm{Pr} = \{\mathrm{T} > \lambda \backslash H1\} \quad (2.6)$$

(ii) Probability of false alarm $\boldsymbol{Pfa}$

It is defined as the probability of deciding H_1 when H_0 is true

$$P_{fa}=P_r\{T>\lambda|H_0\} \quad (2.7)$$

2.3 Receiver Operating Characteristics (ROC)

It is one of the important tool in analysing performance of a detector. It is mostly used in binary hypothesis testing problem. ROC [31] curves provide graphical representation of the performance of binary classifier system. A ROC curve is generated by plotting **the *probability of detection*** **(P_d) versus *probability of false alarm*** **(P_{fa}).**

In a binary classification problem, there are two possible outcomes, positive (P) and negative (N) where, P denotes the presence of PU signal and N denotes its absence. There are four possible conditions in binary classification system. They are as follows:

(i) True positive (TP)

In this condition, the PU [32] signal is present and the detector also decides the H_1 hypothesis [33] i.e. presence of PU signal.

.

(ii) False positive (FP)

In this condition, the PU signal is present but the detector decides the Ho hypothesis [33] i.e. absence of PU signal.

(iii) True negative (TN)

In this condition, there is no PU signal and the detector also decides the Ho hypothesis i.e. absence of PU signal.

(iv) False negative (FN)

In this condition, the PU signal is absent but the detector decides the H1 hypothesis i.e. presence of PU signal.

The above mentioned conditions in binary classification system can be presented in form of 2×2 matrix known as contingency or confusion matrix given in the given table.

	Condition Positive (P)	Condition Negative (N)
Detector output Positive (P)	True Positive (Sensitivity)	False Positive (Type I Error)
Detector output Negative (N)	False Negative (Type II Error)	True Negative (Specificity)

Table 2-2 Confusion matrix or Contingency Table

From the above mentioned conditions four important parameters can be calculated. They are as follows

(i) Sensitivity

It is also known as true positive rate (TPR) or probability of Detection (Pd) [34]. It determines the number of times the detector has correctly detected the PU signal.

$$Sensivity\ or\ TRP = \frac{TP}{P}$$

(ii) Specificity

It is also known as true negative rate (TNR). It determines the number of times the detector has

Correctly decided that the band is unoccupied or vacant.

$$Specificity\ orTNR = \frac{TN}{N} = \frac{TN}{TN + FP}$$

(iii) Type I error

It is also known as false positive rate (FPR) or probability of false alarm (Pfa) [35]. It determines the number of times the detector has incorrectly decided that the band is occupied.

$$Probability\ of\ false\ alarm(FPR) = \frac{FP}{N} = \frac{FP}{TN + FP}$$

(iv) Type II error

It is also known as false negative rate (FNR) or probability of Missed Detection (Pmd). It determines the number of times the detector has incorrectly decided that the band is vacant.

$$Probability\ of\ miss\ detection\ or\ (FPR) = \frac{FN}{P} = \frac{FN}{TP + FN}$$

The probability of False alarm and probability of detection lies in the range of 0 to 1. The point [0, 1] in the ROC curve represents perfect classification. The upper left portion of the ROC curve is of prime interest for the CR. The upper left portion denotes high probability of detection and low probability of false alarm, which provides security to the PU from the secondary users and increases the spectrum holes utilization by the CR users.

2.4 Research challenges in cognitive radio

2.4.1 Issues in spectrum sensing

Spectrum sensing gives rise to several physical and MAC layer research issues. While the physical layer issues are mostly related to signal processing, the MAC layer issues are related to optimization of spectrum sensing.

2.4.2 Optimizing the period of spectrum sensing

In spectrum sensing, the accuracy of the spectrum [36] is dependent on the observation period. However, during sensing, a single-radio wireless transceiver is unable to transmit in the same frequency band. Consequently, if the observation period is increased than it will result in the lower system throughput.

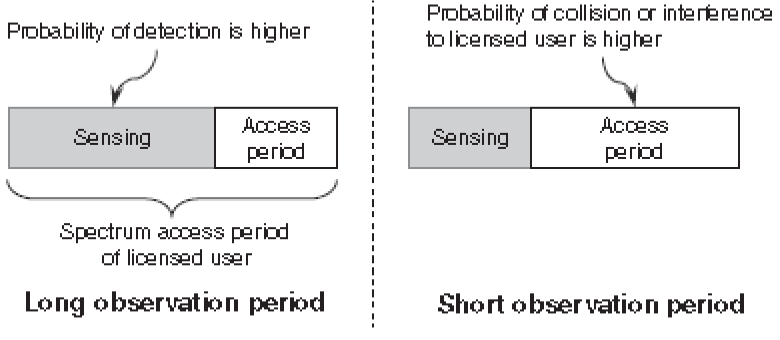

Figure 2.8- Trade-off between spectrum sensing time and user throughput.[15]

To achieve an optimal spectrum sensing solution performance Trade-off is used. If the accuracy of spectrum sensing is low, then in that situation interference and collision to the transmissions by PU [37] could occur which leads to the degradation of the performances of both licensed and unlicensed users.

2.4.3 Spectrum sensing in multichannel networks

The example of multichannel transmission is OFDM-based transmission [38] and it will be typical in a CR network. However, the number of channels that are available in this case would be larger than the number of available interfaces at the radio transceiver. Therefore, only a fraction of the available channels can be sensed simultaneously. Selection of the channels (among all available channels) to be sensed will affect the performance of the system. For spectrum sensing, a channel which is mostly occupied by the licensed user(s) should be less preferred to a channel which is occasionally occupied. In a multichannel environment, selection of the channels should be optimized [39] for spectrum sensing to achieve the optimal system performance under hardware constraints at the cognitive radio [40] transceiver.

Chapter-3

Energy Detection in Spectrum Sensing

Energy detector is based on the transmitter detection to deduce whether there is a signal from primary transmitter which is present in a spectrum or not. As we mentioned earlier, the energy detector simplifies the matched filter to perform non-coherent detection [41]. It detects the received signals energy to compare with the threshold and then deduce the status of the primary signals. It has low computational and execution complexities, so it is the most widely used techniques in spectrum sensing. But it also has some disadvantages. Energy detector [42] cannot distinguish between modulated signals, noise and interference. Furthermore, a threshold we used will be easily influenced by unknown or changing nose levels, so the energy detector will be confused by the presence of any in-band interference. Thirdly, CR [43] users cannot perform the sensing tasks and transmission at the same time. Thus, according to the hardware limitation, a new sensing structure where observation period and transmission period will be separated is necessary for CR users

3.1Maximum a Posteriori Energy Detection for Spectrum Sensing

The maximum a posteriori (MAP) detector is known to be optimal in CR networks. When CR users start the spectrum sensing to detect the primary users‟ status, the received signal *r (t)*, can be expressed as:

$$r(t) = \begin{cases} n(t) & H_0 \\ n(t) + s(t) & H_1 \end{cases} \tag{3.1}$$

Where H_0 stands for ‘no signal transmitted’, and H_1 stands for ‘transmitted signal’, s(t) is the signal waveform and the n(t) is a zero mean AWGN.The detection probability P_d and the Probability of false alarm P_{fa} can be detected as:

$$P_d(\lambda) = P_r\left[y > \frac{\lambda}{H_1}\right] \tag{3.2}$$

$$P_{fa}(\lambda) = [Y > \lambda/H_0] \tag{3.3}$$

λ is known as the decision threshold of MAP detection. The value of the P_f should be kept as small as possible this is to bypass the underutilization of transmission opportunities, on another hand,P_f for the same reasons should be kept very large.

For getting the energy from the device, the output signal of A/D converter and band pass filter with bandwidth *W* is squared and integrated over the sensing time. So we can get the output of the integrator, *Y*, compared with the threshold to determine the absence or the presence of the primary user.

In the MAP detection, the output of the integrator is known as the Chi-square distribution. If the number of samples is large, with the central limit theorem, we can assume that the Chi-square distribution is approximate as Gaussian distribution.

$$y \approx \begin{cases} N(n\sigma_n^2, 2n\sigma_n^4) & H_o \\ N(n(\sigma_n^2 + \sigma_s^2 , 2n(\sigma_n^2 + \sigma_s^2)^2) & H_1 \end{cases} \tag{3.4}$$

Where *n* is the number of the samples, σ_n^2 is the variance of the noise, σ_s^2 the is the variance of the received signal *s(t)*, as we know, the minimum sampling rate should be 2*W* from the Nyquist sampling theorem, so n can be represented as 2 *W*, where is the observation time and *W* is the bandwidth of the spectrum. From the above given equations the false alarm probability P_f can be derived in terms of the *Q* function.

$$P_f(w, t_s) = Q(\frac{\lambda - 2t_s W\sigma_n^2}{4t_s W\sigma_n^4}) \tag{3.5}$$

From the given equation we can get that the false alarm probabilities varies with the *W* and the observation time t_s . We can get the threshold λ as:

$$\lambda = \sqrt{4t_s W\sigma_n^4}\, Q^{-1}(P_f) + 2t_s W\sigma_n^2 \tag{3.6}$$

The parameters like the false alarm probability and the threshold are the important parameters in CR networks, the false alarm probability should be kept as small as possible to avoid underutilization of transmission opportunities, and we will test the detections if it is reasonable under the false alarm probability the threshold is used to compared with detected signal's energy to determine the status of the primary users.

3.2 Process of the Energy Detection

In the process of the experiment, we encoded the signal in matlab to simulate the output signal from the integrator. It consists of the energy values of each samples signal. Then design an energy detector to detect the energy of different samples from the simulated signal we get. Comparing the energy we detected with the threshold, which we mentioned in Section 3.1 we can determine the presence or the absence of the primary users in the given energy detector.

The minimum SNR is the least signal level needed to decode the received signals. So, we change the SNR to see the relationship between the SNR and the final detections.

As we know that CR promises the secondary users access the spectrum which is allocated to a primary user, so avoiding interference to potential primary users is a basic requirement. Therefore we should detect the primary user status through the continuous spectrum sensing.

When CR users start spectrum sensing to detect the status of the primary user, they will get the received signal expressed which we mentioned in Section 3.1. Then the received signal *r* (*t*) will goes into the A/D converter select by the band pass filter where we will get a threshold according to the noise floor. To measure the energy of the signal, the bandwidth *W* of the signal will be squared and integrated. At last the output signal of integrator is the signal we simulated.

We use matlab to encode the output signal from the integrator with zero-mean AWGN. The output signal is in Chi-square distribution, but in section 3.1, we assume the Chi-square distribution as Gaussian distribution when samples are large, so we can encode the output signal from the integrator as:

Then we set the values of the parameters to simulate the signal:

SNR = -10 dB (we take an example); the bandwidth W = 1 ; the observes time t_s= 1 s; samples N = 2*t_s *W; the variance of the noise σ_n^2= 1 ; the variance of the received signal =$\sigma_s^2 = (\sigma_n \times 10^{-1})^2$ b (SNR= -10 dB);

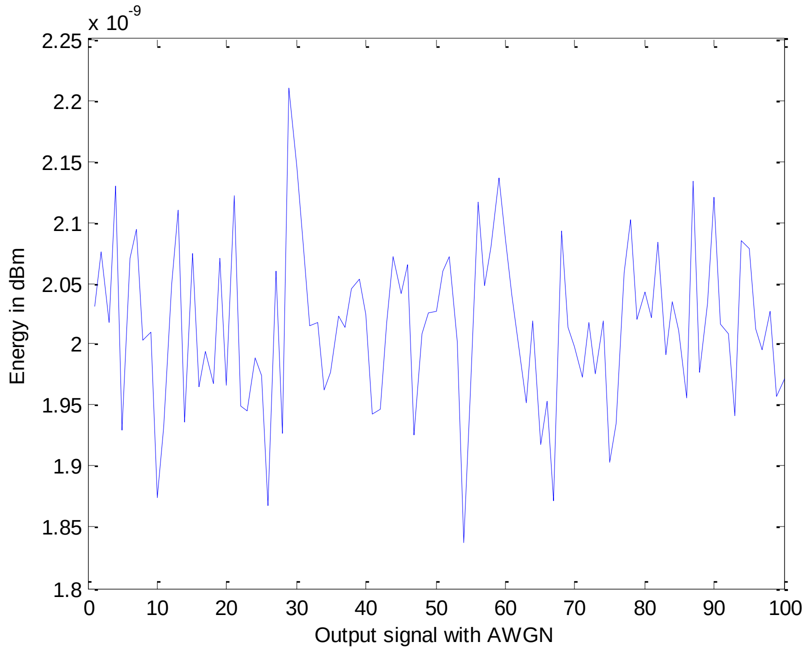

Figure 3.1- The different energy signals at different samples.

3.3 Encoding of the Energy Detector

The idea of the energy detector is to detect the energy of the different signal samples and then comparing the energy with the threshold to see if there is primary user or not. We can get the false alarm probability

$$P_f(w,t_s) = Q(\frac{\lambda - 2t_s W \sigma_n^2}{4t_s W \sigma_n^4}) \qquad (3.7)$$

Which is in terms of the Q-function, inverse the Q-function we can get the threshold So we can encode the threshold (lambda) as lambda =

$$\lambda = \sqrt{4t_s W \sigma_n^4}\, Q^{-1}(P_f) + 2t_s W \sigma_n^2 \qquad (3.8)$$

Then compare the with each samples energy *E*:

If $E > \lambda$, it means the spectrum is occupied by primary users and we get 1 detection.

If $E < \lambda$, it means the spectrum is idle and we get 0 detection. (We ignore the possibility of $E = \lambda$).

In this experiment, we take the SNR =- 10 dB, the false alarm probability = 0.01 and take 100 samples from the simulated output signal to calculate their energy compared with the threshold respectively to determine whether a licensed user is present or not, and sum all the samples which are detected. Through the detection we get the each samples‟ energy and the threshold lambda = 0.2147. Comparing with the detections, there are three samples‟ energy larger than threshold so there are 3 spectrums occupied and there 3 detections.

3.4 SNR and Detection of the Signal

In CR networks, to determine the spectrum availability, CR user need statistical information on the received primary signals, so the minimum SNR is the least signal level needed to decode the received signals. In the previous section we take the value=- 10 dB but as the value of the SNR keep on increasing the probability of the detection keep on increasing in the given case. with the increasing of the SNR (from 10 dB to 0) the detections we get also increased and within -7 dB and -5 dB, the increasing slope is the largest. So the SNR influences the detections. It indicates that with the increasing of the SNR, the more spectrums which are occupied we can detect.

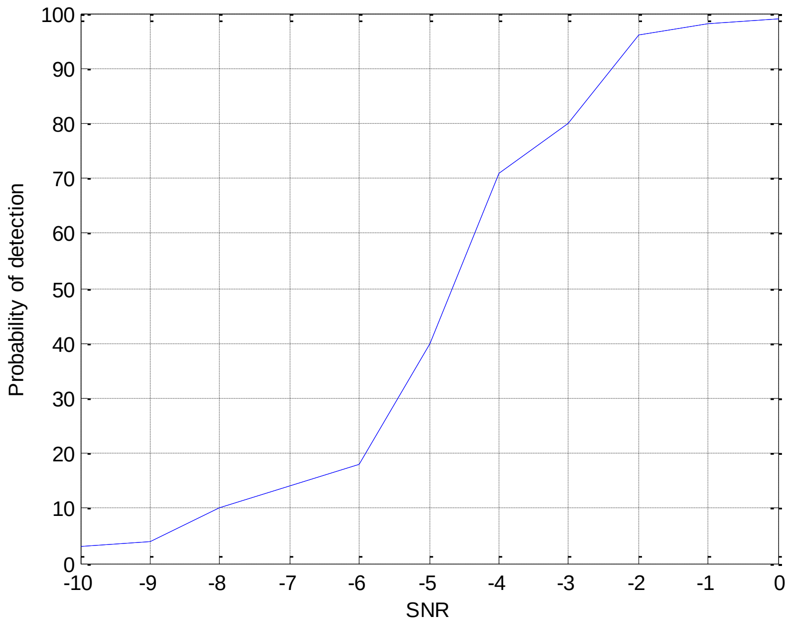

Figure 3.2-Graph between SNR and Probability of Detection

The value of the detection got effected with the increase in the value of the SNR.So, here we will compare the theoretical value and simulation value for SNR as we change the value of SNR keeps on increasing from -10 to 1 then probability of false alarm keep on decreasing.

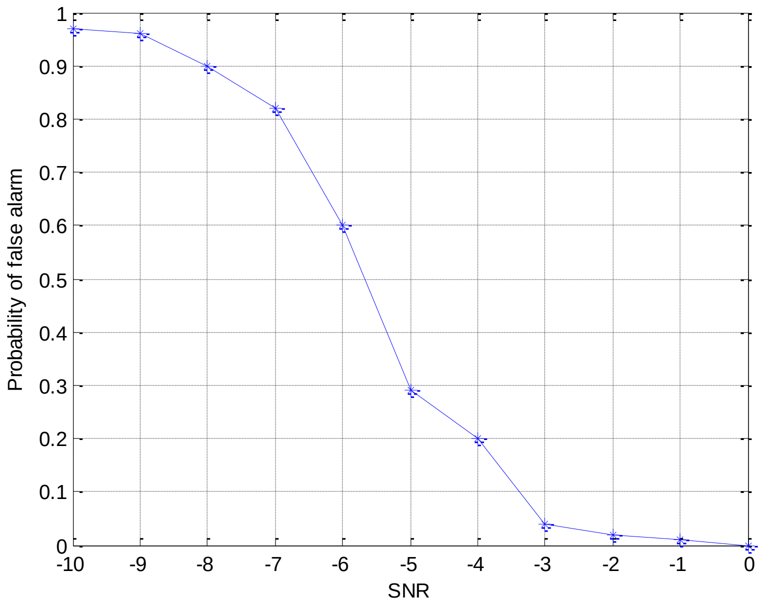

Figure 3.3-Probability of False Alarm and SNR

Here we succeed in getting the energy of 100 samples and calculate the false alarm probability. It is different from the theory value we take. So the SNR can be considered as an important factor to influence the detections. By changing the value of the SNR, we get the relationship between the SNR and the detections, from the diagram, we can see from 2 dB to 0, SNR makes the energy detector performs best. We choose a proper value of SNR and repeat the simulation for 10 times, we can the false alarm probability = 0.017, it matches the theory value = 0.01 within acceptable errors. Therefore, the results are satisfactory and the energy detector works success in the simulation.

Chapter-4

Two Stage Spectrum Sensing

From the old day, the licenced users are designed to work only in their particular set of the radio frequency but with the advancement in the technologies present, and increase in the wireless technology approach, the sub-10GHz i.e the Radio Band assigned for licenced users is quickly becoming saturated. From the various well-known studies of spectrum utilization, it has been found that licensed and spectrum that are allocated is used inefficiently; for example, more than 50% of the spectrum utilization in the Washington area are unused, which is known as 'white spaces' in the spectrum. Dynamic spectrum access (DSA) nowadays is one of the major approach to improve spectral efficiency by making the spectrum to be used by the secondary user for a non-interfering basis with primary users. This idea gain the attraction of the regulatory bodies as well as evidenced by the recent ruling of the FCC to open up a frequency band of 700 MHZ band for use on a dynamic basis. The two basic approach for the DSA are centralized and distributed. In a centralized spectrum sharing protocol, In case of the coordinating spectrum sharing a group of links are used for the sharing between the different networks. By knowing the gain of the link in the network, the server of the spectrum organizes schedule and this schedule is optimal which maximizes the average throughput of the network. In the other system i.e. distributed system. An idle channel must found out in both Transmitter and receiver by which they can communicate. Different studies in the given field have that overall throughput of the network can be increased by varying the level of the cooperation.

One of the basic requirement of both approaches is the effective and fast detection of idle primary channels by secondary users are determined by the mean detection time. The average time required to sense an available channel successfully will depends on the search algorithm, which can be broadly classified as either random or deterministic. The performance of the sensing channel is fundamental to many other sensing aspects for cognitive radios. The detector design of the spectrum sensing is further enhanced by the impact of its operating characteristic these operating characteristics are determined by the probabilities of correct detection, P_d, and false alarm, P_{fa}, respectively.

The sensing algorithm used in the given case the performance of the system also depends on the sensing architecture; thee work in this thesis basically concentrated on the DSA approach that consist basically of coarse resolution sensing (CRS) followed by fine resolution sensing (FRS). The entire spectrum in the given case is first partitioned into several coarse sensing blocks (CSB) and these blocks are having the equal bandwidth; each is denoted as either CSBW with or CSBN and in this spectrum there is no idle channel is present. FRS is then performed on a CSBW to find out the idle number of the spectrum. If FRS is unsuccessful to find the idle spectrum, the search algorithm returns to the CRS stage. In the given thesis analytical and simulation results for the mean detection time are developed for the two-stage DSA scheme.

The CSB bandwidth, mean detection time, integration duration, and power dissipation are also explored.

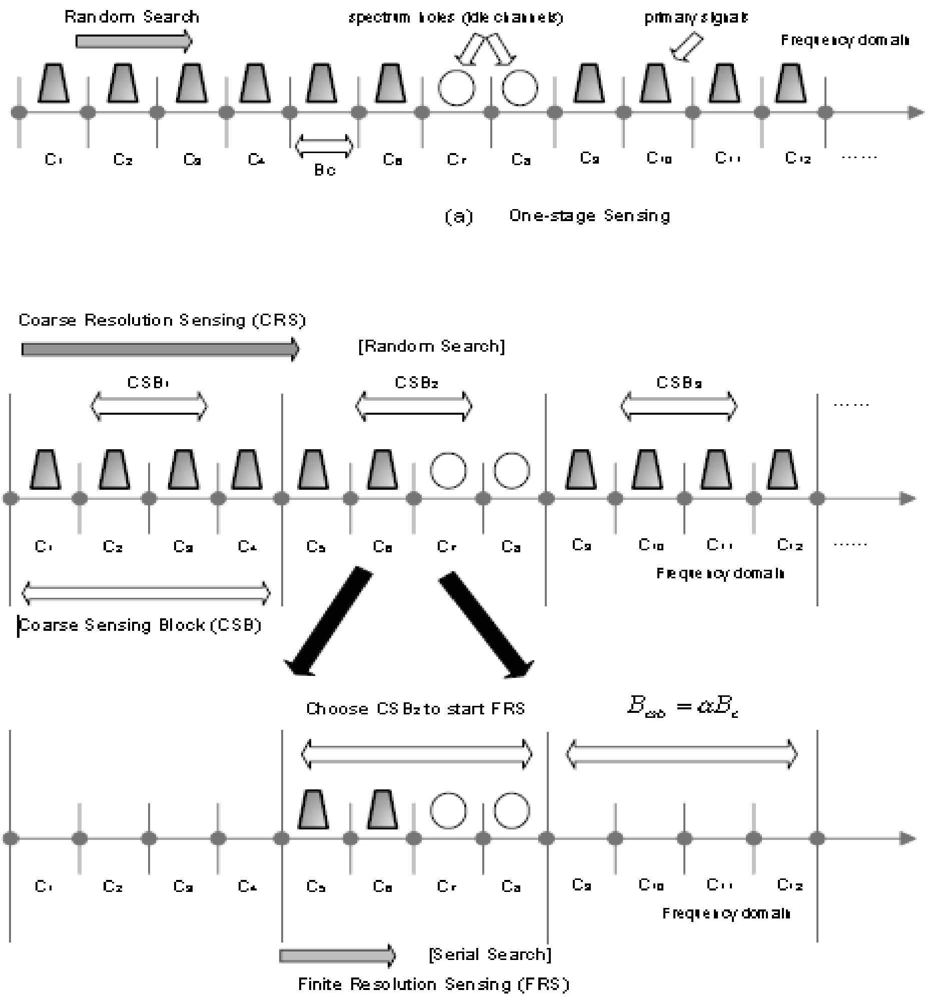

Figure-4.1 Two Stage Spectrum Sensing [20]

4.1 System Description

4.1.1 System Model:

In the given case we assume that the frequency band having N set of contiguous discrete frequency domain channels each having a bandwidth, *Bc*, and is also used to represent the bandwidth of a primary signal of interest. Let the idle number of channel in the given case is L .These are the channels which are unoccupied by primary users where typically $L/N \leq 1$. Another assumption in this case is that the *L* idle channels are randomly distributed over the *N*-set. The binary variable, O_k, K^{th} channel status is found with the help of this, where O_k= 0(1) which refers to weather the channel is busy (idle). Hence,

$$P\ (O_k = 1) = \frac{L}{N}\ ,\ k = 1\ ...\ \mathrm{N} \qquad (4.1)$$

All channels are considered to have additive white Gaussian noise (AWGN) with normalized amplitude gains of unity. Moreover, non-coherent energy detection scheme is used which is worldwide used, where in the signal samples that are observed in this case are filtered to detect the bandwidth, B_{sense} passed through a square-law detector after that it is integrated over a sensing period of time ,after that it is compared to a decision threshold, D_t.

P_n and P_{sig} are the noise and primary signal powers which are studied by the secondary users.

$$P_n = KTB_{sense} \qquad (4.2)$$

$$P_{sig} = \overline{\gamma} P_n \qquad (4.3)$$

where *k* is known as the Boltzmann's constant (1.38 × 1023 J/°K), *T* is the temperature of the given system (e.g., 300 °K), and $\overline{\gamma}$ is the average signal to-noise ratio (*SNR*).

4.1.2 Sensing of the Channel

The random search scheme that is used previously is widely used in all type of the channel sensing. If the channel are randomly selected by the secondary user and it is found to be busy then another channel is randomly chosen; the process keeps on repeating itself until an idle channel is found. On the other hand in case of serial search scheme, the secondary user searches sequentially beginning with an initial channel until an idle channel is discovered. Both random and serial searches are one-stage sensing schemes. However, it has been shown that for L/N≤1 the detection Performance of both one-stage schemes is not satisfactory because in this case long mean times to detection are required; hence, there is a need for the new approach. For example, nodes are used with multiple antennas allow parallel multi resolution scanning of disjoint frequency bands to improve the mean time to detection. In our work, we adapt the Concept of simultaneous scanning with multiple antennas to nodes with a single antenna by using *multiple (two) stage* scanning to achieve similar improvements. The bandwidth spectrum is divided into coarse sensing blocks having value β , out of which α channels having equal bandwidth Bc ($\alpha = N/\beta, Bcsb = \alpha Bc$).As described earlier, the sensing algorithm comprises two stages: coarse resolution sensing followed by fine resolution sensing.

In CRS, the first CSBW is located; thereafter, FRS is used to detect an idle channel in it. A random search is used in CRS and the bandwidth is equal to that of the CSB; i.e., $Bsense = Bcsb$. In the given case random search provides a better way to find a potential free channel, it does not matter whether it is at the beginning or end of the channel sequence. Random search leads to the un-necessary dead locks, FRS in the given case used with a serial search the $Bsense = Bc$. Due to the use of the FRS the dead locks are easily avoided in this case because the evaluation in this case is done only once. If there is no detection of the idle channel during FRS,then the device returns to the CRS mode as If a false alarm (detecting a busy channel as idle) occurs during FRS, a penalty equal to J integration periods is incurred for recovery from the error before scanning is resumed.

4.1.3 Settling Time and Energy Consumption

In case of the two stage spectral sensing frequency should fast shift from one channel to the channel as CRS and FRS both are scanned with the help of the maximum frequency hop. Such a frequency hopping require settling time and it is provided by the phase lock loop(PLL).It is used to generate the carrier frequency of the channel It is well known that a conventional PLL designed with a wider bandwidth achieves a faster settling time.

In the below diagram typical type -2 third order PLL, It consist of main five components: the reference oscillator, the phase-frequency detector (PFD) and it associated charge pump (CP), the low-pass loop filter (LPF),the voltage-controlled oscillator (VCO) and the feedback $\div N$ digital divider. The reference frequency, f_{ref}, is typically derived from a fixed low-frequency oscillator (e.g., a crystal oscillator). The PFD/CP consist of +the bi-directional

current with magnitude of the system is proportional to the phase error, $\varphi_e = \varphi_{in} - \varphi_{out}$. The charge pump output is filtered by the LPF to find out the VCO control voltage. The VCO is used to find out the output of a frequency, f_{out}, and this frequency is proportional to control voltage. By getting the negative feedback action of the PLL, the reference frequency is multiplied by *N* to produce the desired channel carrier frequency. The PLL in this case is requires to generate a large number of the frequencies required for the spectrum sensing in cognitive radio.

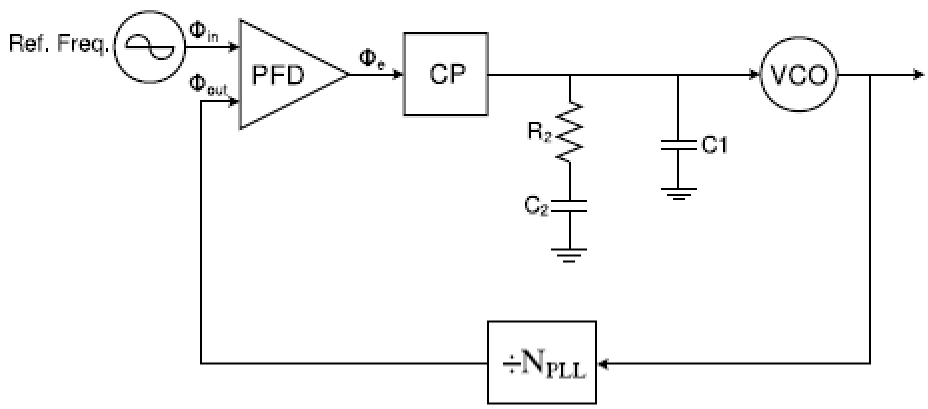

Figure 4.2-Block Diagram of Phase Lock loop[21]

Settling Time (T_s))(microsecond)	Power (P) (mill watts)
0.009	124
0.15	57.6
20	20
70	11.4
120	42

Table 4-1 Measured settling time and Power for the different PLL [2]

The total energy consumed in the given case is E_{total} which is determined as

$$\mathrm{E_{total}} = \mathrm{T_s} \times \mathrm{P} \qquad (4.4)$$

4.2 Analysis of Detection and False Alarm Probabilities in the Two Stage Spectrum Sensing

4.2.1 Detection and False Alarm in FRS

IN case of the FRS stage, the channel bandwidth of the device become equal to the sensing bandwidth; i.e.,$B_{sense} = B_c$. The decision is taken from H_1 and H_0 which are known as the hypothesis denotes as signal and noise and only noise, respectively. The output is given by the Gaussian probability density functions.

$$f(x/H_1) = \frac{1}{\sqrt{2\pi}\sigma_n} \exp\left(-\frac{x^2}{2\sigma_n^2}\right) \qquad (4.5)$$

$$f(x/H_0) = \frac{1}{\sqrt{2\pi}\sigma_n} \exp\left(-\frac{(x - \sqrt{P_{sig}})^2}{2\sigma_n^2}\right) \qquad (4.6)$$

Where σ_n=$\sqrt{P_n/2} = \sqrt{KTB_c/2}$

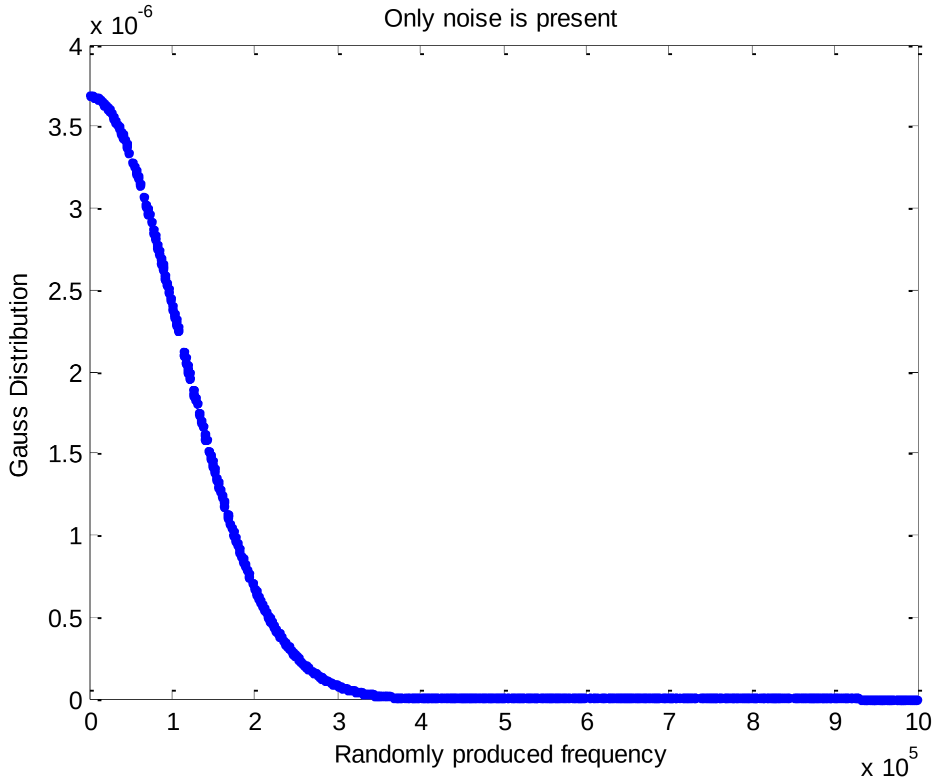

Figure 4.3-Hypothesis model when only noise is present

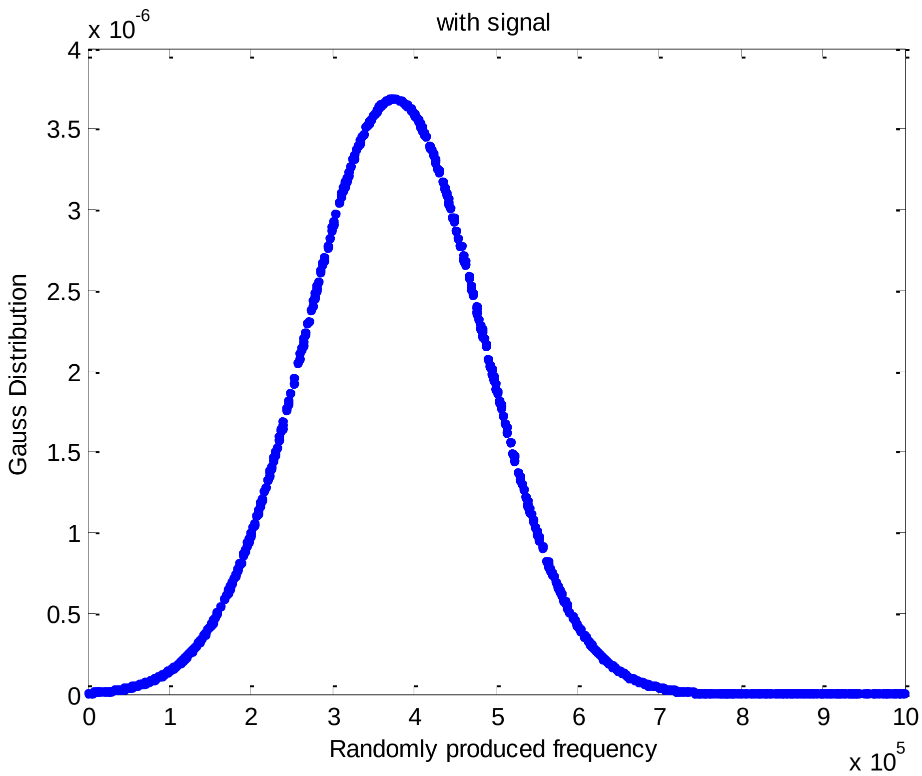

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Figure 4.4-Hypothesis model when signal and noise both are present.

Let Z denote the final decision variable after time integration;

i.e., $Z = \sum_{i=1}^{M_f} x_i^2$ (4.7)

where $M_f = \lfloor B_c T_i^f \rfloor$ where $\lfloor x. \rfloor$is the largest integer contained in the x. T_i^f is the integration time during the non-coherent detection in the FRS. Z in the given case consist of the Chi-square distribution under the null hypothesis H_1 and non-central chi-distribution under H_0 both with a M_f degree of equation.

$$f(z/H_1) = \frac{1/2M_f}{\Gamma(M_f)} \; Z^{M_f-1} e^{-z/2} \quad (4.8)$$

$$f(z/H_0) = \frac{1}{2} e^{\frac{-x+\lambda}{2}} \; (^Z/_\lambda)^{(M_f-1)/2} \, IM_f - 1(\sqrt{Z/\lambda} \quad (4.9)$$

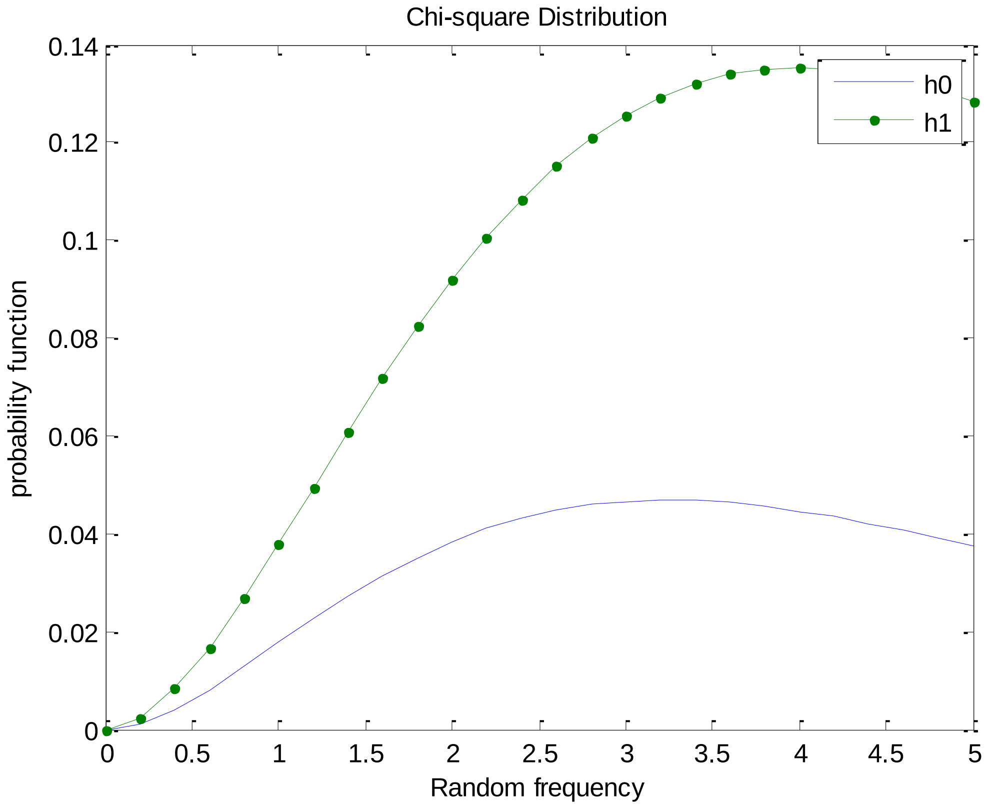

Figure 4.5- Hypothesis model in case of the FRS for the detection of signal

During the FRS stage the detection (P_d^f) and false alarm P_{fa} probabilities correspond to the successful detection by the secondary user of an idle channel under H_1 with no primary signal

H_1present under . Hence, probability of detection and false alarm in non coherent detection in FRS is

$$P_d^f = f_{\frac{z}{H_1}}\left(\frac{D_t}{\sigma_n^2}\right) = \frac{\bar{\gamma}(M_{f,}{}^{D_t}/_{2\sigma_n^2})}{\Gamma(M_f)} \qquad (4.10)$$

$$P_f = f_{\frac{z}{H_0}}\left(\frac{D_t}{\sigma_n^2}\right) = (1 - QM_f)(\sqrt{2\bar{\gamma}}M_f, \frac{D_t}{\sigma_n^2}) \qquad (4.11)$$

Where $\bar{\gamma}$ the lower incomplete Gamma is function $\bar{\gamma}(a,x) = \int_0^\infty t^{a-1}e^{-t}\,dt$ and Q_m is the Marcum Q- function

$$Q_M(\alpha,\beta) = \frac{1}{\alpha^{M-1}}\int_\beta^\infty x^M e^{-(x^2+\alpha^2)/2} I_{M-1}(\alpha x)\,dx. \qquad (4.12)$$

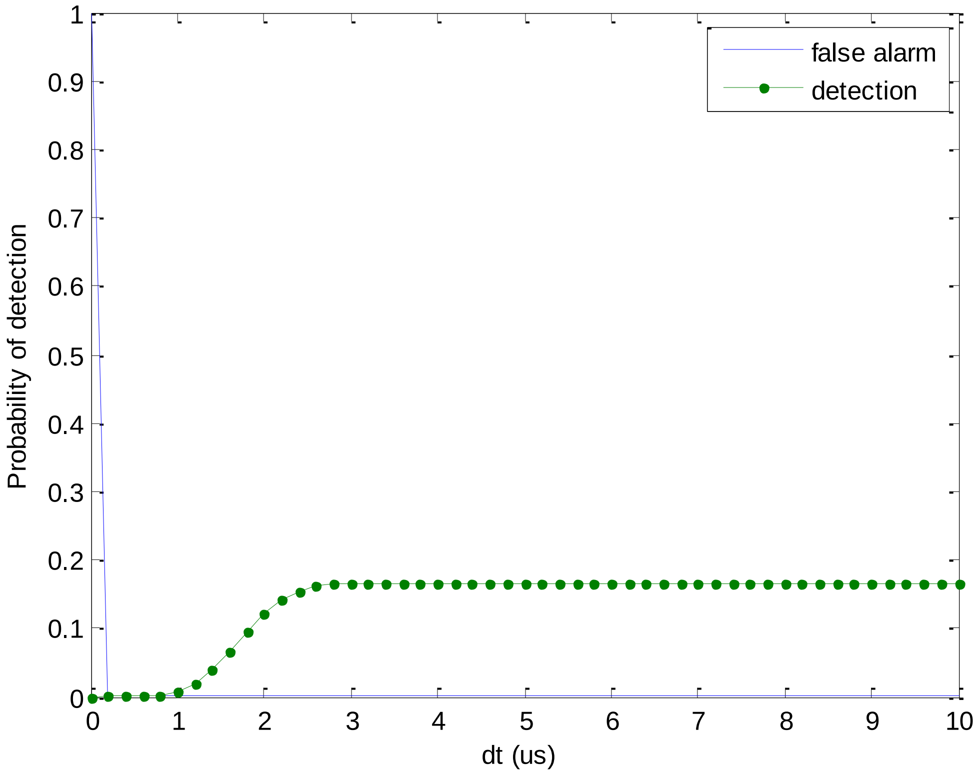

Figure 4.6-Probability of signal wrt to time (micro sec)

4.2.2 Detection and False Alarm in CRS

The analysis of the CRS sensing stage is more complex however the decision process again chooses between one of two hypotheses: H_1 when there exists at least one idle channel in the CSB and *H*0 when there is none. If hypothesis H_1 is true, the FRS stage is invoked to identify an idle channel contained in the CSB. In the independent identically distributed (*i.i.d*) model, the *L* idle channels are randomly scattered over the *N*-set of channels and a primary signaloccupies a specific channel with probability (1 − L/N). Therefore, the number of idle channels, n, in a coarse sense block follows a binomial distribution; i.e., n ∼ B(α,L/N).As a sub-hypothesis of H_1, $H_{(1K)}$ denotes the event that there are CSB assuming α ≤ L; hence, The probability density functions of the measurements, y, that are inputs to the CRS detector, conditional on the two hypotheses, are thus given by

$$f\left(y/H'_{1(k)}\right) = \frac{1}{\sqrt{2\pi}\sigma'_n} \exp\left(-\frac{(x-(a-K)\sqrt{P_{sig}})^2}{2\sigma_n'^2}\right) \quad (4.13)$$

$$f(y/H'_0) = \frac{1}{\sqrt{2\pi}\sigma'_n} \exp\left(-\frac{(x-a\sqrt{P_{sig}})^2}{2\sigma_n'^2}\right) \quad (4.14)$$

For the non-coherent detector during the coarse resolution stage, the noise power at the detector input is $\sigma n = \sqrt{P'_n}/2 = \sqrt{aP_n/2}$.Hence, the noise power is amplified by the factor α relative to that in the FRS scenario whereas the signal power remains the same. Assuming the detector uses *Mc* samples, the decision. In most practical cases, the number of available channels is no less than the number of channels in a CSB ($\alpha \leq L$). However, there might be just few a available channels through the whole spectrum, causing $L < \alpha$; hence, in this extreme.

4.3 Mean Detection Time

Each channel scanning period comprises two sub intervals:T_s and T_i. T_s is the settling time of the PLL used in the frequency synthesizer, which depends on its type and order as well as other circuit details. T_i is the integration time required for the non-coherent detector to reach a decision on the status of the channel (i.e., busy or idle); it is a function of the detector configuration and the desired value of $P_d - P_{fa}$, which is a measure of accuracy. The overall mean detection time, T_{det}, required for a secondary user to successfully identify an idle channel is a function of the two subintervals mentioned above; i.e.,

$$T_{det} = S_{det}(T_s + T_i)$$

where S_{det} is the average number of steps required for acquisition. Each channel scanning period comprises two subintervals: T_s and T_i. T_s is the settling time of the PLL used in the frequency synthesizer, which depends on its type and order as well as other circuit details. T_i is the integration time required for the non-coherent detector to reach a decision on the status of the channel (i.e., busy or idle); it is a function of the detector configuration and the desired value of $P_d - P_{fa}$, which is a measure of accuracy. The overall mean detection time, T_{det}, required for a secondary user to successfully identify an idle channel is a function of the two subintervals mentioned above; i.e.,

$$T_{det} = S_{det}(T_s + T_i) \tag{4.15}$$

$$P_r H'_{1,(k)} = P_r(n = k) = \binom{a}{K}\left(\frac{L}{N}\right)^k \left((1 - \frac{L}{N})^{a-k}\right) \tag{4.16}$$

$$P_r H'_1 = 1 - P_r(n = 0) = 1 - \left(\frac{N - L}{N}\right)^a \tag{4.17}$$

$$P_r H'_{1,(k)}/H'_1 = \frac{P_r(n = k)}{P_r H'_1} = \binom{a}{K}\left(\frac{L^k N - L^{a-k}}{N^a - (N - L)^a}\right) \tag{4.18}$$

$$\begin{aligned}
P_d^c &= F_{z|H_1'}(D_t'/\sigma_n'^2) = \sum_{k=1}^{\alpha} F_{z|H'_{(k)}}(D_t'/\sigma_n'^2)\, Pr(H'_{(k)}|H'_1)| \\
&= \sum_{k=1}^{\alpha} Pr(H'_{1,(k)}|H'_1)\left[1 - Q_{M_c}\left(\sqrt{2\frac{\alpha - k}{\alpha}\overline{\gamma} M_c}, \sqrt{\frac{D'_t}{\alpha\sigma_n^2}}\right)\right] \\
P_{fa}^c &= F_{z|H_0'}(D_t'/\sigma_n'^2) = 1 - Q_{M_c}\left(\sqrt{2\overline{\gamma} M_c}, \sqrt{D'_t/\alpha\sigma_n^2}\right)
\end{aligned} \tag{4.19}$$

$$Pr(H_1^{\prime}) = \sum_{i=1}^{L} Pr(H_{1,(i)}^{\prime}) = \sum_{i=1}^{L} \binom{\alpha}{i} \left(\frac{L}{N}\right)^{i} \left(1-\frac{L}{N}\right)^{\alpha-i} \quad (4.20)$$

$$Pr(H_{1,(k)}^{\prime}|H_1^{\prime}) = \frac{Pr(n=k)}{Pr(H_1^{\prime})} = \binom{\alpha}{k} \left(\frac{L}{N}\right)^{k} \left(1-\frac{L}{N}\right)^{\alpha-k} / Pr(H_1^{\prime}) \quad (4.21)$$

$$P_{cd}^{\prime} = \sum_{k=1}^{L} Pr(H_{1,(k)}^{\prime}|H_1^{\prime}) \left[1 - Q_{M_c}\left(\sqrt{2\frac{\alpha-k}{\alpha}\overline{\gamma} M_c}, \sqrt{\frac{D_t^{\prime}}{\alpha\sigma_n^2}}\right)\right] \quad \textbf{(}4.22)$$

The mean number of detection steps required for conventional random are

$$\overline{S}_{ran} = \frac{(N-L)J * P_{fa}^{f} + N}{P_d^{f} L} = \frac{(1-\frac{L}{N})J * P_{fa}^{f} + 1}{P_d^{f}\frac{L}{N}} \quad (4.23)$$

$$\overline{S}_{ser} = \frac{(N-L)J * P_{fa}^{f} + N}{P_d^{f}(L+1)} \quad \textbf{(4.24)}$$

In the ideal scenario where $P_d = 1$ and $P_{fa} = 0$, (4.23) and (4.24) simplify to

$$\overline{S}_{ran,ideal} = \frac{N}{L} \quad (4.25)$$

$$\overline{S}_{ser,ideal} = \frac{N}{(L+1)} \quad (4,26)$$

The average number of detection steps required for **two stage spectrum sensing** is next

4.3.1 Analysis of Two Stage Spectrum Sensing

The mean number of total detection steps in the coarse plus fine resolution stages is

$$Sdet = Scrs + Sfrs \quad (4.27)$$

In the i.i.d model, each CSB has the same probability, $P_r(H_1)$, of containing a white space. Hence, similar to the analysis of the conventional random search, the mean number of steps required during the CRS stage to successfully detect an idle channel in a coarse sensing block is

$$\overline{S}_{crs,det} = \frac{1}{Pr(H_1^{\prime})P_d^c} \tag{4.28}$$

However, if no idle channels are found during an FRS stage, the CRS stage is re-initialized, which occurs with probability

$$\begin{aligned} P_{miss} &= \sum_{k=1}^{\alpha} Pr(H_{(k)}^{\prime}|H_1^{\prime})(1-P_d^f)^k \\ &= \sum_{k=1}^{\alpha} \binom{\alpha}{k} \frac{L^k(N-L)^{\alpha-k}}{N^\alpha-(N-L)^\alpha}(1-P_d^f)^k \end{aligned} \tag{4.29}$$

The number of steps for such missed detection follows a geometric distribution with an expected value of 1/(1*Pmiss*).Thus, the average total number of steps during the CRS stages given by

$$\begin{aligned} \overline{S}_{crs} &= \overline{S}_{crs,det}/(1-P_{miss}) \\ &= \frac{1/[(1-(\frac{N-L}{N})^\alpha)P_d^c]}{1-\sum_{k=1}^{\alpha}\binom{\alpha}{k}\frac{L^k(N-L)^{\alpha-k}}{N^\alpha-(N-L)^\alpha}(1-P_d^f)^k} \end{aligned} \tag{4.30}$$

The analysis of the FRS stage is divided into two conditional events: (a) after correct detection, and (b) after false alarm in the CRS stage to yield $S_{frs,col}$ and$S_{frs,fal}$respectively. Assuming that exactly *i* idle channels exist in a CSB (i.e., *n* = *i)*

$$\overline{S}_{frs,cor} = E[S_{frs,cor}|n=i] = \sum_{i=1}^{\alpha}\binom{\alpha}{i}\frac{L^i(N-L)^{\alpha-i}}{N^\alpha-(N-L)^\alpha}\frac{(\alpha-i)J*P_{fa}^f+\alpha}{P_d^f\cdot i}$$

. (4.31)

For each false alarm during a CRS stage, the subsequent FRS stage uses $a(1+JP_{Fa}^{f})$ more steps on average before discovery. Because the probability of a CSB with at least one idle channel is $P_r(H_1)$, the mean number of steps caused by false alarm in CRS is

$$\overline{S}_{frs,fal} = (1 - Pr(H_1^{\prime}))P_{fa}^{c}\overline{S}_{crs,det}(1 + J * P_{fa}^{f})\alpha$$

$$= \frac{P_{fa}^{c}\alpha(1 + J * P_{fa}^{f})(N-L)^{k}}{P_{d}^{c}(N^{k} - (N-L)^{k})} \tag{4.32}$$

Hence, the expected number of steps for FRS sensing, S_{frs} is given by [Eq.4. 33] In the ideal scenario with $P_d^f = P_d^c = 1$ and $P_{fa}^f = P_{fa}^d = 0$, the overall mean number of detection steps simplifies to

$$\overline{S}_{det} = \sum_{i=1}^{\alpha} \binom{\alpha}{i} \frac{L^{i}(N-L)^{\alpha-i}}{N^{\alpha} - (N-L)^{\alpha}} \cdot \frac{\alpha}{i} + \frac{1}{1 - (\frac{N-L}{N})^{\alpha}} \tag{4.33}$$

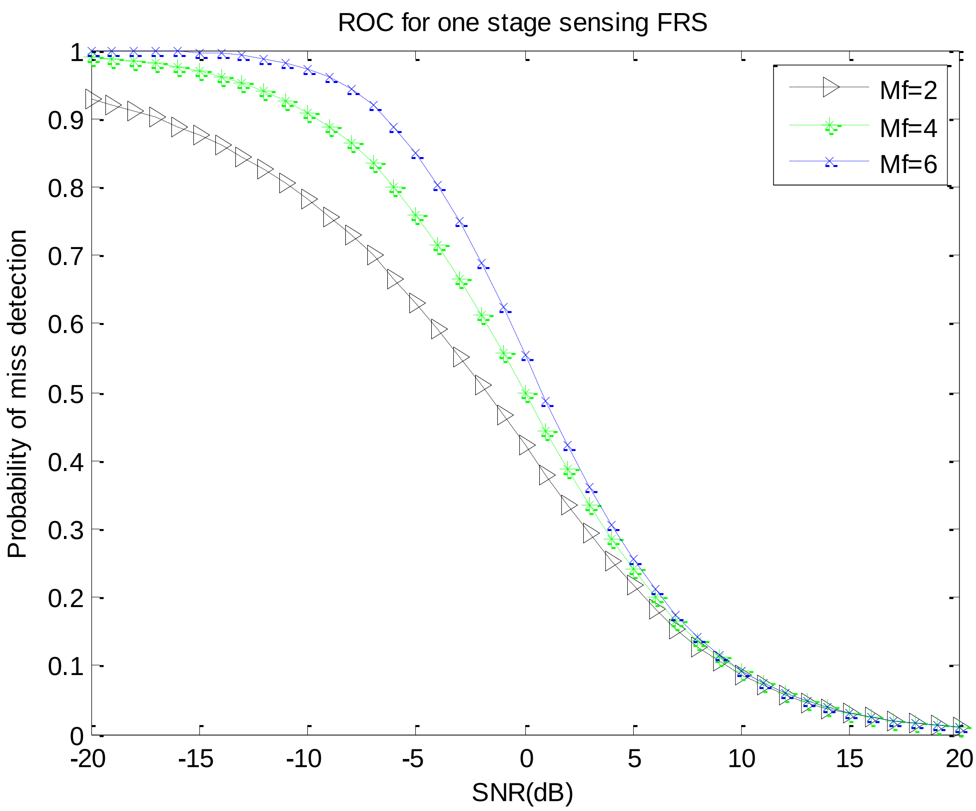

Figure -4.7 Probability of Detection wrt SNR in case of one stage spectrum sensing

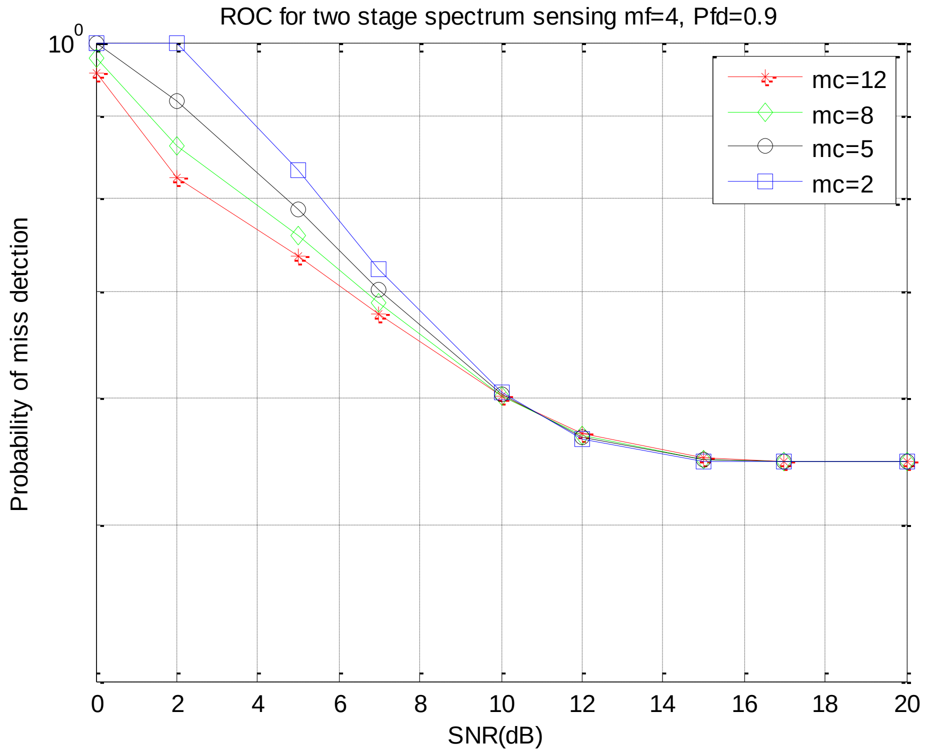

Figure 4.8-Probability of miss detection in case of two stage spectrum sensing wrt SNR.

4.3.2 Overall mean detection time

At each sensing stage, an increased number of samples(pre-detection integration) results in a more reliable outcomes determined by higher detection and lower false alarm probabilities, which in turn leads to fewer steps required on average for detecting an available idle channel. Let Mc and M_f denote the number of sensing samples in the CRS and FRS stages, respectively.

Then the corresponding mean detection time (T_{det}) is expressed in terms of T_i^c and T_i^f, the integration periods for CRS and FRS, respectively:

$$\overline{T_{det}} = \overline{S_{frs}}(T_s + T_i^f) + \overline{S_{crs}}(T_s + T_i^c) \qquad (4.34)$$

Where

$$T_i^c = \frac{M_c}{\alpha B_c} \qquad (4.35)$$

$$T_i^f = \frac{M_f}{B_c} \qquad (4.36)$$

4.3.3 Overall $P_d - P_{fa}$

In two-stage sensing, the overall accuracy of the system (i.e., $(P_d - P_{fa})$ depends on the decision thresholds for the two stages:

$$P_d = P_d^c P_d^f \qquad (4.37)$$

$$p_{fa} = 1 - (1 - P_{fa}^c)(1 - P_{fa}^f) \qquad (4.38)$$

The FRS stage having the receiver operating characteristics (ROC) as in one-stage sensing, because both operate under the same conditions using the same approach. To gain additional insight into the operation of the two stage sensing scheme, the ROC is held constant during the FRS stage (P_d^f = 0.9,M_f = 4, and γ = 6*dB* (the per sample *SNR* at the front-end of the detector)), while the parameter of the CRS stage are varied to determine the effects on the

Overall $(P_d - P_{fa})$ plot the Pm vs. p_{fa} performances ($Pm = (1 - P_d)$) of the non-coherent energy detector for different values of *Mc*, α and *L/N*. It is observed that a wider CSB bandwidth results in decreased $(P_{fa} - P_m)$ performance due to the increased noise power. Although $(P_{fa} - P_m)$ performance always improves by integrating over more sensing samples, a significantly larger number were required to achieve the desired $(P_{fa} - P_m)$ performance.

Moreover, the performance of the system benefits from thesmaller values of *Pm* associated with the larger values of *L/N*.In a typical TV spectrum, the total system bandwidth is *Bsys* = 1.2 GHz and the channel bandwidth is *Bc* = 6 MHz; hence, the number of channels is *N* = *Bsys/Bc* = 200. Considering different average values of *SNR* (γ) at the input to the non-coherent detector, the integration durations needed during the CRS stage to achieve P_{fa} = 0.9, P_{fa}^f = 0.05, P_d^c = 0.8,and P_{fa}^c = 0.15

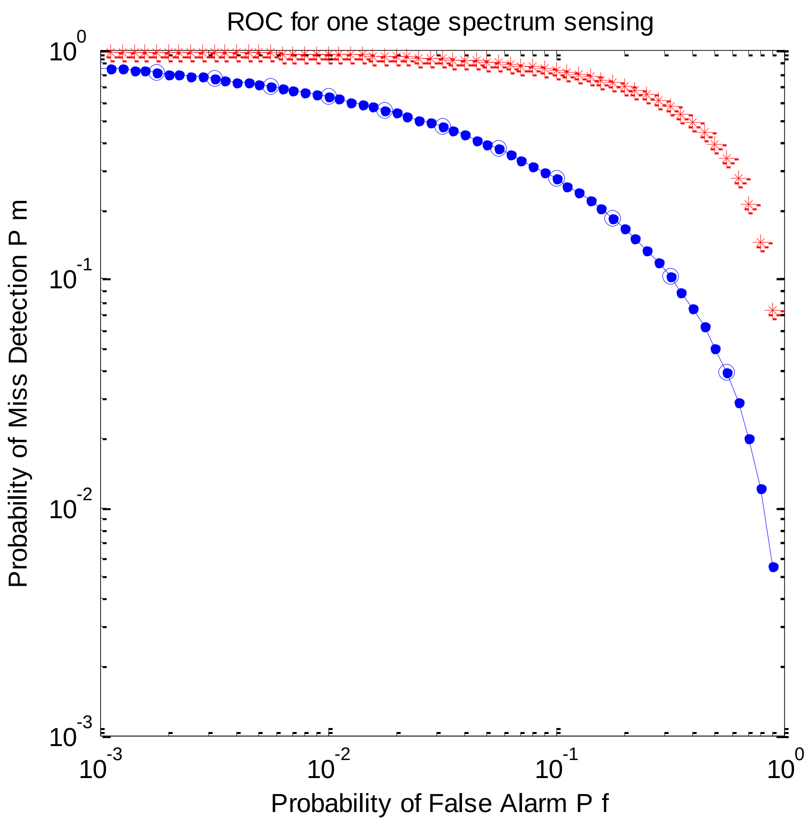

Figure 4.8- Relationship between the Probability of Miss Detection and False Alarm

Chapter-5

Conclusion and Future Work

5.1 Conclusion

As the demand of radio spectrum increases in past few years and licensed bands are used inefficiently, improvement in the existing spectrum access policy is expected. Dynamic spectrum access is imagine to resolve the spectrum shortage by allowing unlicensed users to dynamically utilize spectrum holes across the licensed spectrum on noninterfering basis. This research was aimed towards the detection and classification of primary user's spectrum in cognitive radio networks. The primary requirement of a spectrum sensing system is its real time processing and decision making.

We discussed about the one dimension spectrum sensing but it is not a complete solution for the scarcity of the spectrum so we discussed about the two stage spectrum sensing .The time period required in this case for the sensing of the spectrum is less as there are serial search took place in this case and this sensing is divided into the two parts i.e. coarse resolution sensing and fine resolution sensing. The two-stage sensing with a small bandwidth coarse sensing block outperforms the traditional one stage sensing scheme in terms of lower mean detection time.

5.1 Future Work

The two-stage spectrum sensing method urge to achieve better spectrum sensing for cognitive radio at a cost of high computational complexity in low SNR environment. The future work can be derived from this demerit and the computational complexity of the two-stage spectrum sensing method can be reduced by applying some optimization techniques. The future works in the area of two-stage spectrum sensing can be described as follows

- Optimization techniques can be applied on the number of samples to be passed from first stage to second stage in order to obtain the desired detection results.
- Implementation of optimization technique to determine the number of samples to be used as input to the two-stage spectrum sensing method.

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