COOPERATIVE SPECTRUM SENSING IN COGNITIVE RADIO NETWORKS

By

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ABSTRACT

Cognitive Radios is a promising technology for the opportunistic use of under-utilized spectrum since they are able to sense the spectrum and use frequency bands. For this purpose several spectrum sensing techniques are employed like Energy Detector, Matched Filter and Cyclo-Stationary feature detector. The performance of these Spectrum Sensing techniques for cognitive radios is limited by the received signal's strength which may be severely degraded due to pathloss. In such a scenario cooperative sensing may alleviate the problem of detecting the primary user by reducing the probability of interference to a primary user. The cooperative sensing relies on the variability of signal strength at various locations. It is expected that a network of cognitive radios with sensing information exchanged between neighbors will have a better chance of detecting the primary user compared to the individual sensing. This thesis demonstrates that single node detection is not sufficiently reliable in a lossy environment and how cooperative spectrum sensing can be improved. Moreover cooperative and non cooperative spectrum sensing schemes have been compared on the basis of reliability and performance. All simulations have been carried out in MATLAB.

DEDICATION

I would like to dedicate this thesis to my family, teachers and friends.

ACKNOWLEDGMENTS

First of all, I am thankful to almighty Allah who has given me the strength and courage to work on the thesis. My special thanks to my supervisor Dr. Shoab Ahmed Khan for his guidance and technical support in the development of the project. It has been a pleasure to work with and learn from him.

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Najam ul Hasan

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Chapter 1

INTRODUCTION

1.1 Introduction

The growing progress in the wireless technology has place a question in front of spectrum regulatory bodies to find new ways for the spectrum management. As most people belief that with the advancement in the wireless technology the requirement of wireless spectrum would also increases that will become impossible to satisfy with the current spectrum management policy. Secondly if we look towards the spectrum usage pattern of existing wireless technology it is come to known that most of the allocated spectrum is under utilization. Spectrum usage measurements obtained by the FCC's spectrum shown in Figure 1.1 shows that most of the time much of the available spectrum lies idle. These measurements show that this shortage of usable spectrum is due to drawbacks in the spectrum management policies rather than any physical shortage. The underutilization of the spectrum has forced the engineering, economics and regulation communities to go for a better spectrum management policies and techniques.

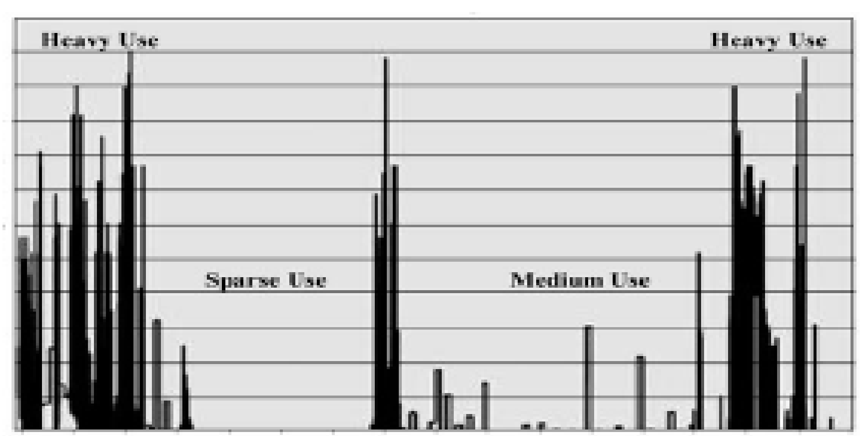


Figure 1.1 Spectrum Utilization [1]

In usual spectrum management policy each operator is assigned fixed frequency band. As most of the spectrum is already allocated to different service provider it is difficult to provide the frequency bands to new service providers or to extend the existing one [3].

As already mentioned the licensed spectrum is not utilized optimally. Based on this observation regulatory bodies' moves their intention to find new ways for the effective utilization of existing spectrum. They come up with new approach for the spectrum utilization named as dynamic spectrum access. In this approach a secondary (unlicensed) user is allowed to access the licensed band of primary user in an opportunistic manner. Federal Communication Commission (FCC) particularly shows its interest in the use of the spectrum of licensed user whenever it is available. IEEE 802.22 has emerged as a new standard to work on this idea[3]. Figure 1.2 shows a more elaborative view of IEEE 802.22.

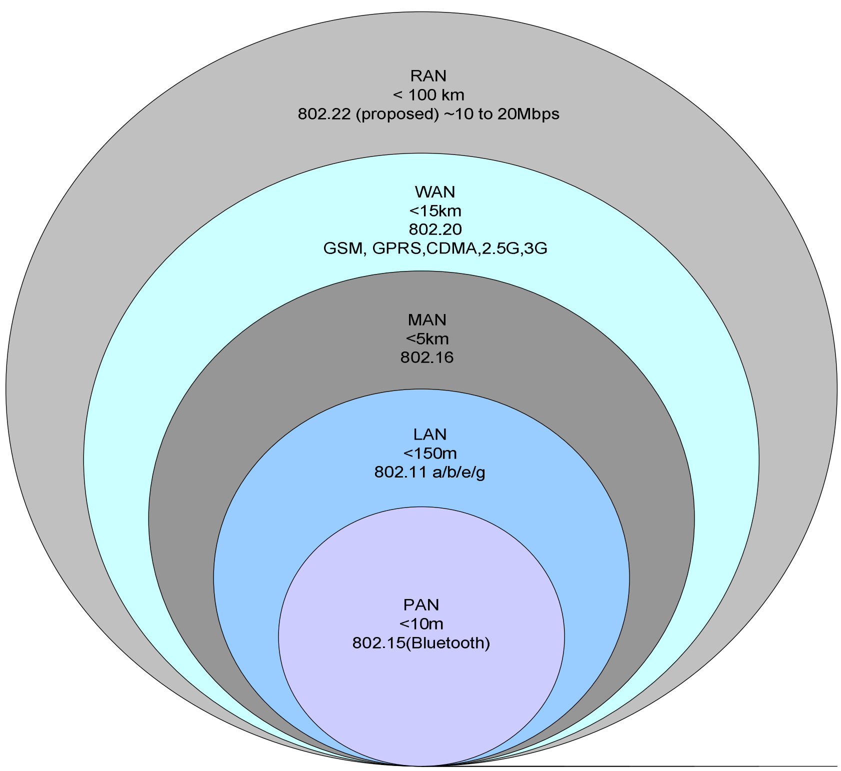


Figure 1.2 Spectrum Utilization [5]

As the secondary user starts communication in the frequency band of the licensed users so there might be a chance that it will cause interference to primary user. To protect the primary user from the interference of secondary user's robust spectrum sensing techniques can play a key role. Table1 list the approaches employed for this purpose.

	Infrastructure cost	Legacy compatibility	Transceiver Complexity	Continuous Monitoring
Database Registry	High	No	Low	No
Beacon signals	High	No	Low	No
Spectrum Sensing	Low	Yes	High	Yes

Table 1.1 Classification of white spaces identification methods [3]

The first two approaches listed in Table 1.1 have urged the licensed users to inform the secondary user about the current status of spectrum utilization. This activity can be accomplished either by the use of central server are by acknowledgment to all secondary users but it requires some modifications in the existing structures of the primary network which is seems to be incompatible with the structures of the primary network so spectrum sensing techniques is seems to be a promising approach in this context [3]. The cognitive radio technology can be good choice for this particular idea that will also incorporate the spectrum sensing issues.

1.2 Characteristics of Cognitive Radios

Cognitive radio is a radio that is capable of finding the spectrum holes and then dynamically adjusts its architecture according to the available spectrum. The evolution to cognitive radio spread over three generations of communication, Fixed Radios Adaptive radios and Fully Adaptive Radios. Figure 1.3 clearly illustrate the characteristics of these types of radios

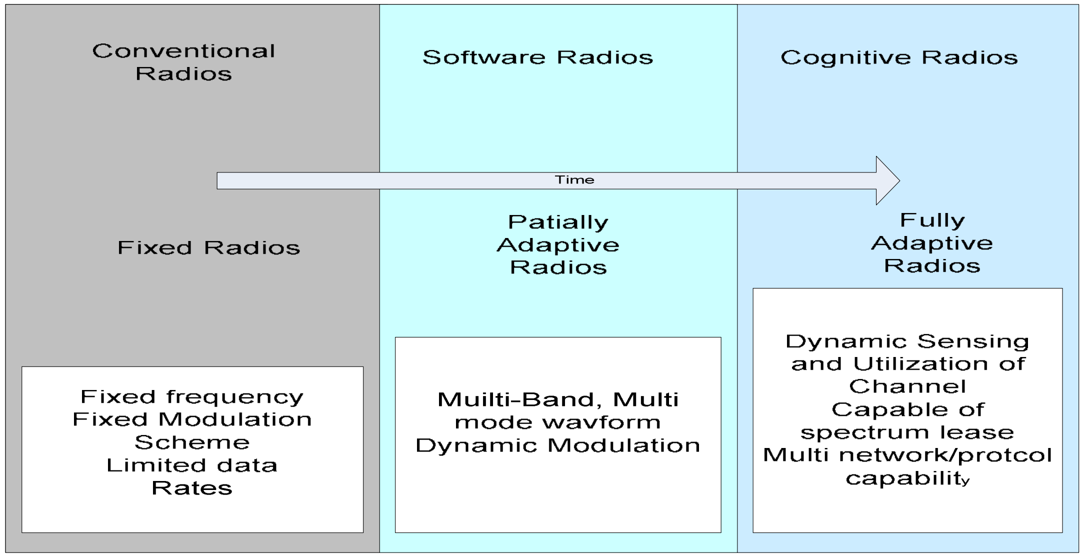


Figure 1.3 Generation of Radios [9]

The main features that distinct the cognitive radio from other radios are cognitive capability and reconfigurability. A cognitive radio can sense the radio environment (cognitive capability), analyze and learn sensed information and change its parameters according to the environment (reconfigurability).

1.2.1 Cognitive Capability

Following are the main parts of cognitive capabilities.

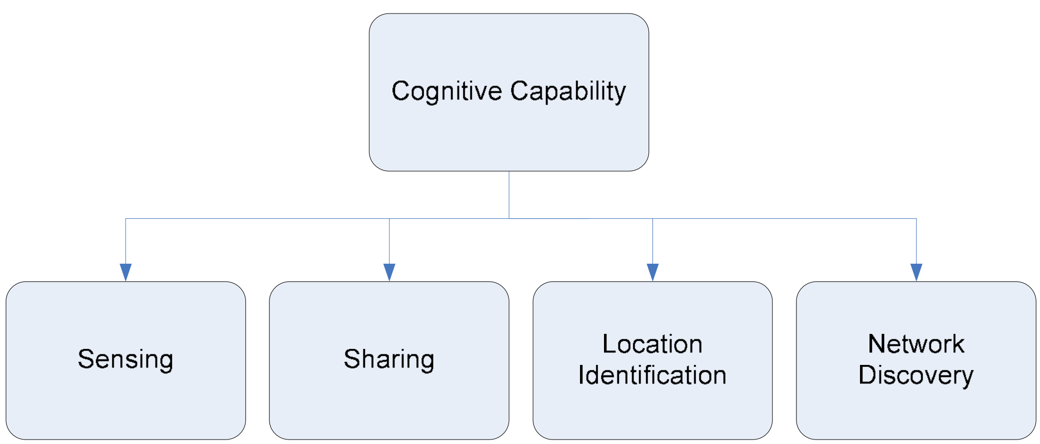


Figure 1.4 Cognitive Capability components

The cognitive radio is in search of that part of the licensed user's spectrum which is available at particular time. The Spectrum Sensing is necessary step for the operation of cognitive radios. In order to use the spectrum of licensed user there is a need of efficient spectrum sharing scheme that results in the optimal utilization of the sensed spectrum. The location identification is needed to allow the cognitive radio to adjust its parameters like power and frequency according to the location of other users. The cognitive radio should be able to use the facility provided by any network at any instant of time [6].

1.2.2 Reconfigurable Capability

Main parts of cognitive reconfigurability are shown in Figure 1.5. The frequency agility component allows the CR to work on any available frequency. The CR should have the capability to support multiple types of modulation schemes for switching between different types of networks. The CR should have to support multiple power levels. It also has the ability to work on low power in order to increase the data rate. The CR should also support multiple network access mechanisms [6].

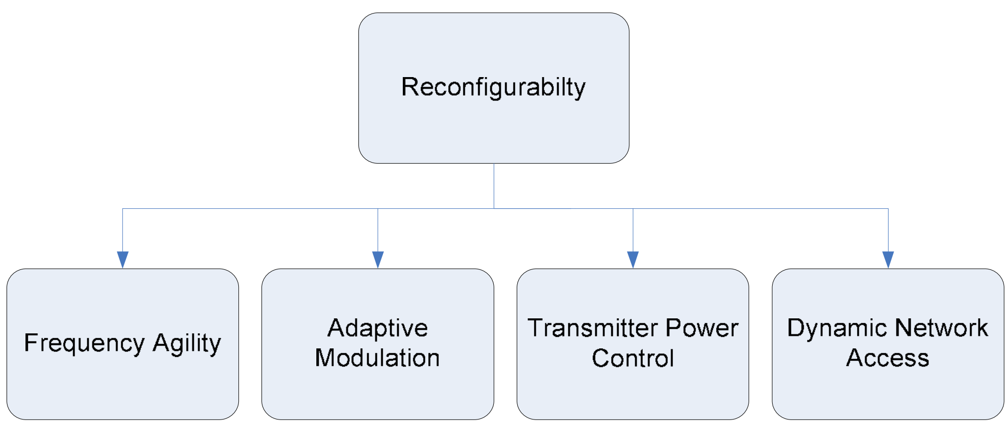


Figure 1.5 Reconfigurability Components

In order to perform the functionalities described above the CR must has to modify all its layers according to the environment as illustrated in the Figure 1.6.

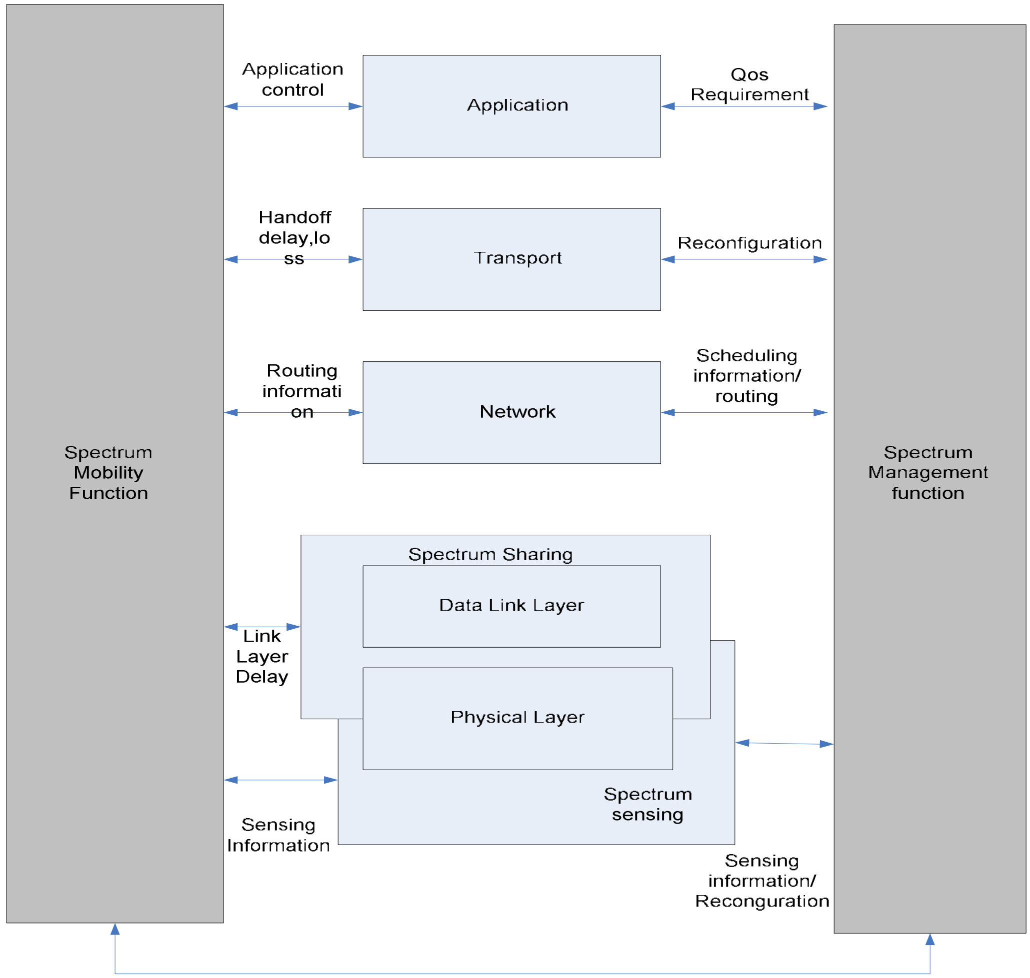


Figure 1.6 Dynamic changes in all Layers [1]

1.3 Spectrum Sensing

The first step in the operation of cognitive radios is the spectrum sensing. The cognitive radio goes across the whole spectrum and finds the area which is not utilized by the primary or licensed users. The real advantage of the cognitive radio technology is possible only if the sensing schemes are reliable. By reliability I mean that it detects the presences of primary user in proficient manner. The success of the transmission of the CR users is directly dependant on the behavior of the sensing schemes. Figure 1.7 illustrates the concept of spectrum holes. The absence of blocks indicates opportunity for the transmitters of secondary users to use that particular spectrum.

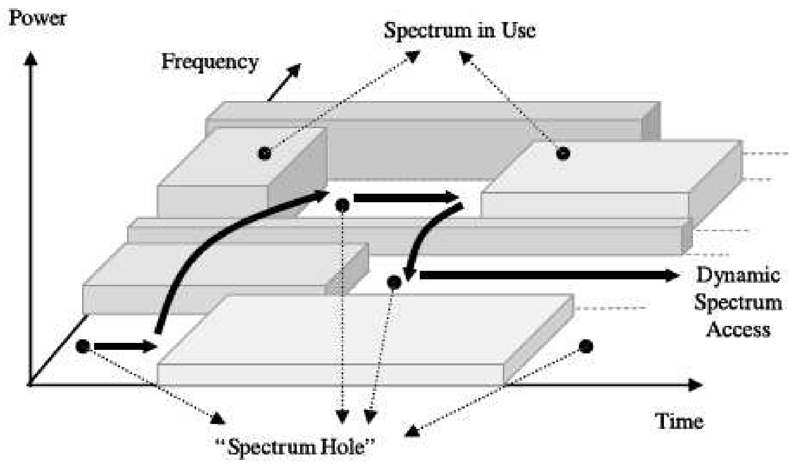


Figure 1.7 Spectrum hole concept [1]

The cognitive capability of a cognitive radio allows the CR users to perform interaction to its environment on real time basis. The tasks required for adaptive operation in open spectrum are shown in Figure 1.6 [1], which is referred to as the cognitive cycle. The three main steps of the cognitive cycle, shown in Figure 1.8, are as follows:

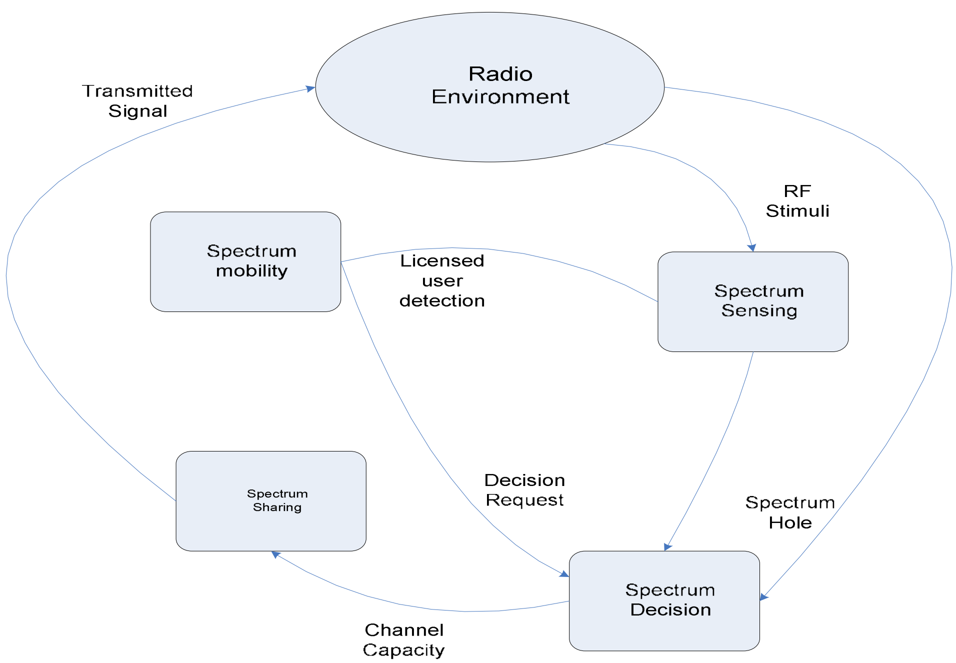


Figure 1.8 Cognitive Cycle [1]

1.3.1 Spectrum Sensing

A cognitive radio goes across the radio environment and senses the presence of the primary users in order to find the transmission opportunity.

1.3.2 Spectrum Analysis

The spectrum band which is not utilized by the primary user is analyzed for their characteristics estimation.

1.3.3 Spectrum Decision

Cognitive radio first determines its own capabilities e.g. the data rate, the transmission mode, and the bandwidth of the transmission. Then, the appropriate spectrum band selection is made from the spectrum holes determined in spectrum sensing. Once the operating spectrum band is determined, the communication can be performed over this spectrum band. However, since the radio environment changes from time to time, the cognitive radio should be aware of the changes of the radio environment.

If some primary user wants to communicate on the spectrum band, which is in the use of cognitive radio then the spectrum mobility function is invoked to provide a seamless transmission. Any environmental change during the transmission such as primary user appearance, user mobility, or traffic variation can activate this adjustment.

1.4 Architecture of Cognitive Radio Network

The cognitive radio networks has the multiple responsibilities in the sense that it not only handles the communication of the cognitive radio users but also have to ménage the interaction with different types of networks hence the cognitive radio networks seems be not a simple alone network it must be a heterogeneous networks. But here, heterogeneity comprise of many factors it is heterogeneous in terms of different wireless access technologies, networks etc. The objective behind cognitive radio network architecture is not only to improve the spectrum utilization but also to improve the entire network. If we look from user's point of view the cognitive radio networks should be able to fulfill the requirements of the users. And from the operators' perspective, they must be able to provide more bandwidth and low interference

1.4.1 Network Architecture

The Cognitive Radio Network can be deployed in any network configuration like network-centric, distributed, adhoc, and mesh architectures. The main components in the architecture of cognitive radio networks are as follow [6].

1.4.1.1 Cognitive Radio mobile Station (MS)

As we know that the Cognitive Radio user will not have any license so some modifications are needed in the architecture of mobile station of cognitive radio users.

1.4.1.2 Cognitive Radio base-station

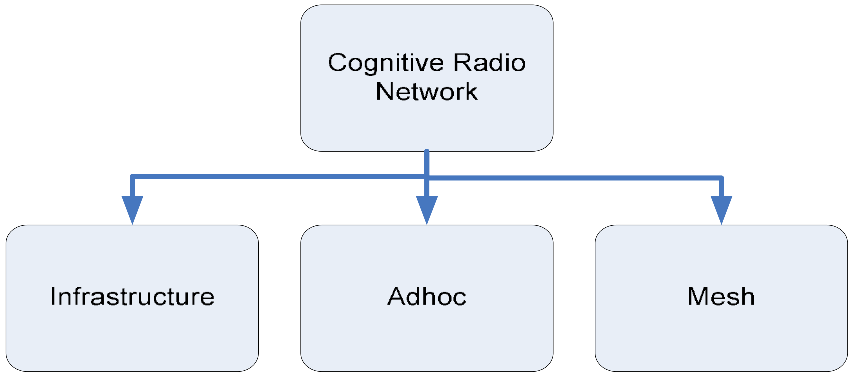
A fixed infrastructure that is responsible to provide single hop connection to unlicensed CR users. CR user can access the other networks with the help of this component.

1.4.1.3 Core networks

The main entity at the backbone or core of the network called Spectrum Broker that is responsible to share the sensed spectrum among the CR users of different CR networks. It is acting like centralized server that has all information about available spectrum to enable coexistence of multiple CR networks [5].

1.4.2 Types of Cognitive Radio Networks

There CR networks can be characterized by the following three types of networks.



1.4.2.1 Infrastructure Architecture

In the Infrastructure architecture mode a CR base station is responsible for all the communication among the CR users of different network in terms of on hop. Different base stations are connected through backbone called Spectrum broker [1].

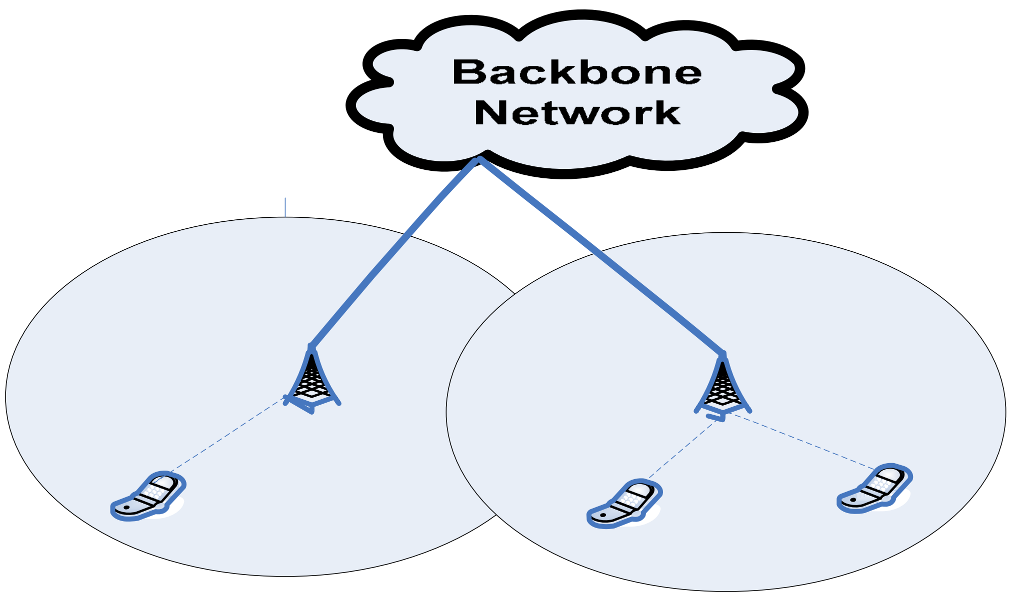


Figure 1.9 Infrastructure Network [6]

1.4.2.2 Ad-hoc Architecture

This architecture is also known as infrastructure less mode. In this mode all CR users communicate each other by exchanging control information in order to share the spectrum sensed through spectrum sensing process.

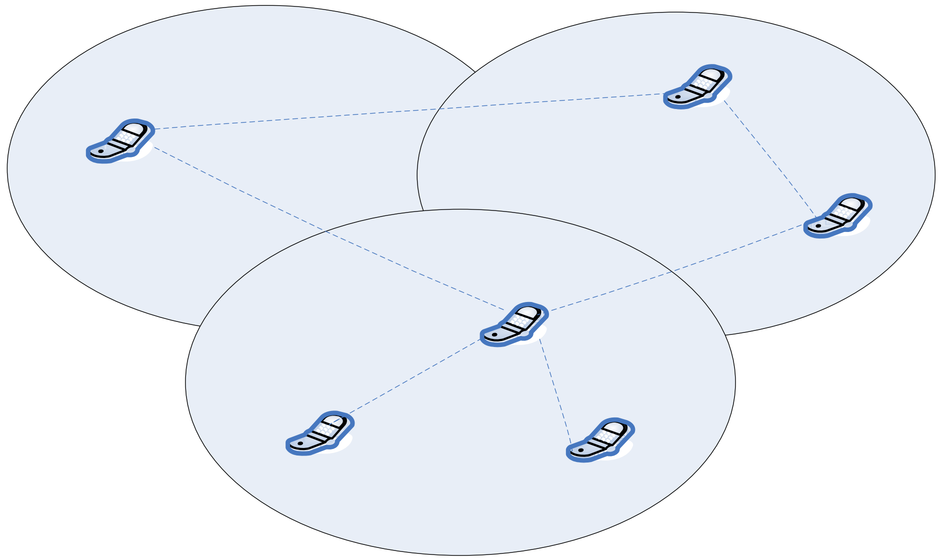


Figure 1.10 Adhoc Network [6]

1.4.2.3 Mesh Architecture

The combination of Infrastructure and Ad Hoc architectures is known as mesh network. The CR base stations act as routers and form wireless backbones.

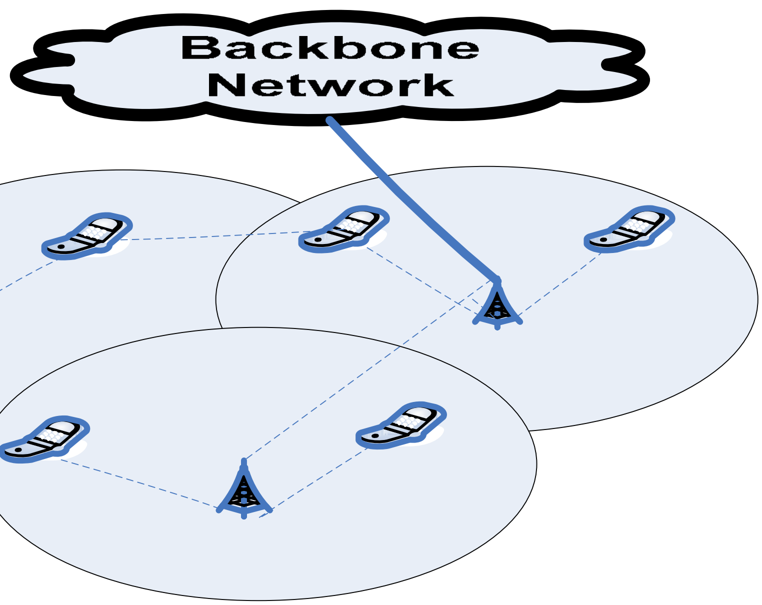


Figure 1.11 Mesh Network [6]

1.5 Applications of Cognitive Radios

Cognitive Radio Networks can be applied to the following cases:

1.5.1 Leased network

The main application of CR networks is that it can work as leased network. The CR network can utilize the spectrum of licensed user on leased basis with the promise that it will not harm the communication of primary users.

1.5.2 Cognitive mesh network

The main objective of mesh networks is to provide broadband connectivity [10]. Since the cognitive radio technology enables the access to larger amount of spectrum, therefore cognitive radio networks will be a good choice to meet the requirements of mesh networks.

1.5.3 Emergency network

The CR network can be utilized at the place of primary network in case of natural disasters [11].

CR networks can communicate on available spectrum band in ad hoc mode without the need for an infrastructure and by maintaining communication priority and response time.

1.5.4 Military network

In [12] authors proposed that the CR networks can be used in military radio environment. CR networks can enable the military radios to choose arbitrary intermediate frequency (IF) bandwidth, modulation schemes, and coding schemes, adapting to the variable radio environment of battlefield.

1.6 Problem Statement

The purpose of the research is to improve reliability in the identification of spectrum holes by employing the cooperative techniques among the CR users. To see how much we can gain by employing cooperative spectrum sensing, how cognitive users cooperate in a cognitive radio network and what is the overhead associated with cooperation.

1.7 Objectives

The primary objective of this thesis is to conduct a comprehensive appraisal of the contemporary techniques used for non cooperative and cooperative spectrum sensing in cognitive radio networks and to provide implementation of suitable cooperative spectrum sensing techniques. The secondary objective includes identification of the areas for improvement of the results and the resolution of the identified deficiencies.

1.8 Thesis Organization

The rest of the research is organized as follows. Chapter 2 gives a review of the techniques that have been used for non cooperative and cooperative spectrum sensing. Chapter 3 gives the formal definition and provides a framework for the solution of the problem in hand. It also lists the assumptions and conditions that define the scope of the work. Chapter 4 illustrates the detailed design of different cooperative spectrum sensing techniques. It also further explains how these modules are finally integrated to form a complete test program. Chapter 5 gives an in depth analysis of the results obtained during the experimentation and comparison of cooperative and non cooperation based spectrum sensing techniques. Lastly, chapter 6 concludes the research and highlights the future work, which can be done to carry forward this effort.

1.9 Summary

This Chapter covers the broader aspects of the research topic. It presents the motivation behind the selection of this subject as final thesis. It has highlighted the basic aspects of Cognitive Radio Networks. The problem statement is given to clarify the scope of the project. At the end an organization of the rest of the document is provided.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

This chapter includes the detailed description of various Spectrum Sensing approaches used to detect the spectrum holes in the CR network. The chapter encompasses the background work on both the Cooperative and Non Cooperative Spectrum Sensing techniques.

2.2 Classification of Techniques

The first step toward the functional implementation of CR networks is the spectrum sensing. In spectrum sensing there is a need to find spectrum holes that are not utilized by the licensed users. However direct measurement of channel between primary transmitter and receiver seems to be difficult [1].

For CR simultaneously transmission and detection is a problem thus, we need such robust spectrum sensing techniques that is efficient in term detection time and reliability. In literature the spectrum sensing techniques have been classified in the following three categories [1].

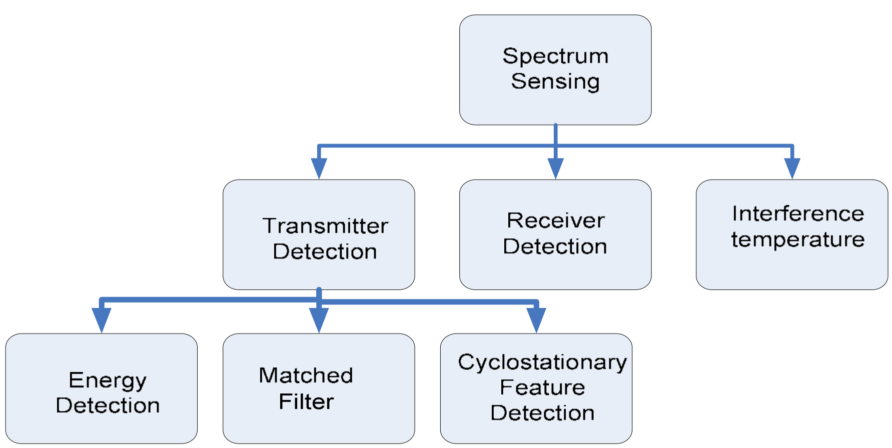


Figure 2.1 Classification of Spectrum Sensing Techniques [1]

2.2.1 Transmitter Detection

The main objective in the transmission detection schemes is to detect the presence of the primary transmitter that is transmitting at a particular time.

The hypothesis model that is presented for the detection of primary transmitter in [13] is, the signal received by the CR user is

$$x(t) = \{n(t)H_0 \qquad (2.1)$$

$$x(t) = \{hs(t) + n(t)H_1$$

Where x (t) is the signal received by CR, s (t) is the transmitted signal of primary user, n (t) is the Additive white Gaussian noise (AWGN) and h is the amplitude gain of the channel. There are three transmitter detection techniques base don this hypothesis model [14]: Energy Detection, Matched Filter Detection and Cyclostationary Feature Detection.

Now in the following section we will discuss each of the transmitter detection technique their pros and their cons.

2.2.1.1 Matched Filter Detection

The matched filter is used to provide maximum signal-to noise ratio at its output for a given transmitted waveform [11]. Figure 2.2 depicts the block diagram of matched filter. The signal received by CR is input to matched filter which is r (t) = s (t) + n (t). The matched filter convolves the r (t) with h (t) where h (t) = s (T-t + τ). Finally the output of matched filter is compared with a threshold λ to decide whether the primary user is present or not.

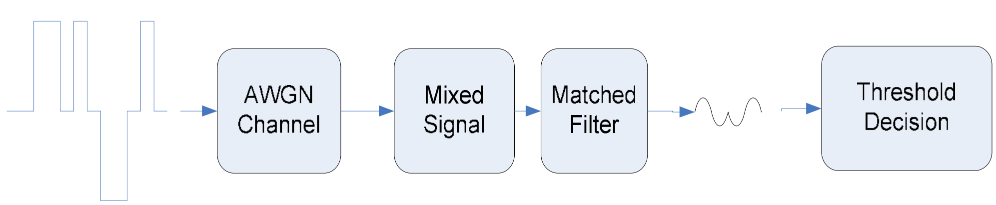


Figure 2.2 Block Diagram of Matched Filter

If the wave from of the primary transmitter is already known to CR then the matched filter is the optimal scheme for the detection of primary transmitter. This requires some background about the waveform of primary user such as modulation type, the pulse shape and the packet format which is very difficult to ménage so if CR doesn't have this type of prior information then it's difficult to detect the primary user. This scheme can still be utilized due to its simple and the fact that the prior knowledge ca be provided by introducing pilots or spreading codes in the waveform of primary users. But still there are certain limitations in matched filter like, each CR should have the information of all the primary users present in the radio environment. Advantage of matched filter is that it takes less time for detection. However it requires a dedicated receiver for every primary user class which is difficult to meet [14].

2.2.1.2 Energy Detection

The matched filter technique is the optimal choice if CR has sufficient information about primary user's transmitter. However if CR unable to get all this information but it has the knowledge about the power of the random Gaussian noise, then Energy Detector is the better choice in this case[1].

In [13] the authors proposed the basic components of energy detector which is shown in Figure 2.3. The signal received by the CR is passed through the band pass filter of center frequency fs and bandwidth of interest W. The filter is followed by a squaring device to measure the received energy then the integrator determines the observation interval, T. Finally the output of the integrator, Y is compared with a threshold, λ to decide whether primary user is present or not.

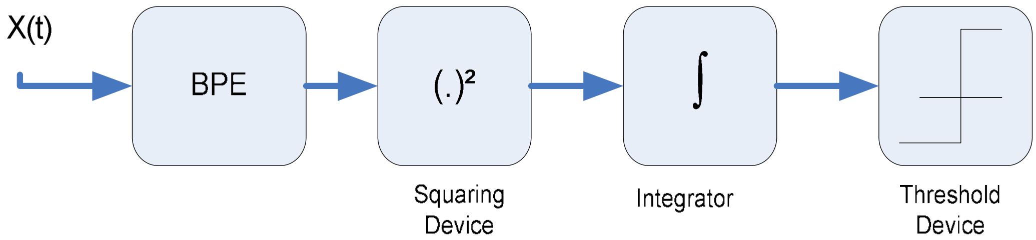


Figure 2.3 Block Diagram of Energy Detector

2.2.1.3 Cyclostationary Feature Detection

The coupling of modulated signals is usually done with the use of sine wave carriers, pulse trains and other parameters that brings built-in periodicity [14]. Even though the data is stationary random process, these modulated signals are characterized as Cyclostationary, since their statistics, mean and autocorrelation, exhibits periodicity. These features are detected by analyzing a spectral correlation function. The periodicity is provided for signal format so that receiver can use it for parameter estimation like pulse timing, carrier phase etc. This periodicity can be used in the detection of random signals with a particular type of modulation with the noise and other modulated signals.

Recent research efforts show that the Cyclostationary feature detection scheme can be utilized for the classification purpose and its classification is robust in terms of reliability than the simple energy detection and match filter detection scheme. As discussed, a matched filter as requires a prior knowledge which is difficult to provide. Energy detector, although doesn't require prior knowledge and simple to implement still it is prone to interference and noise levels [13] and it is unable to differentiate between signal power and noise power.

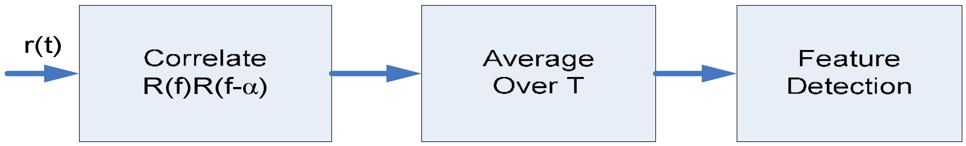


Figure 2.4 Block Diagram of Cyclostationary Feature Detector

The block diagram of Cyclostationary feature detection is shown in Figure 2.4. The detected features may the number of signals, their modulation types, symbol rates and presence of interferers. The correlation factor greater than the threshold indicates the presence of primary user in radio environment. Although the performance of this scheme is better than energy detector but it is computationally very expensive thus requires more processing time, which is bottleneck of Cognitive radio.

2.3 Regulatory Constraints

The opportunistic access technique of CR is dependent on satisfactory protection of the primary users from harmful interference. The performance of sensing technique has to follow certain regulatory constraints, which are characterized in the following manner.

2.3.1 Sensing Periodicity

The CR technology operates on the band of primary users with the promise that it will not create any sort of interference for the primary users. In order to avoid the interference with the primary user while utilizing a white space, the CR should need to periodically sense the band on regular basis (e.g. every Tp). Where the sensing period Tp, indicates the duration of time during which the CR user will be aware of the arrival of primary user. Therefore, the sensing period determines the delay, and thus indicates lower bound on the quality of service (QoS) when the primary user regains its license band. Since it is not possible to sense and transmit simultaneously, so sensing has to be interleaved with the data transmission

2.3.2 Detection Sensitivity

The interference due to the CR user is extremely harmful for the primary user if it causes the signal-to-interference ratio (SIR) at any primary receiver to fall below a certain threshold, specify by regulatory bodies. This threshold depends on the fact that how robust the receive is towards the interference and variations in the used spectrum bands.

Considering these parameters into account the detection sensitivity, r_{min} as the minimum SNR at which the primary signal may still be accurately (e.g. with a probability of 0.99) detected by the cognitive radio, this regulatory requirement may be expressed as

$$r_{\min} = \frac{P_p L(D+R)}{N} \qquad (2.2)$$

Where Pp denotes the transmitted power of the primary user, L denotes the total pathloss (including shadowing and multipath) at a distance d from the transmitter, D is the interference range of the secondary user, R is the maximum distance between a primary transmitter and the corresponding receiver and N is the noise power [3]. In order to determine the detection sensitivity Pp and R showed be provided by the regulator or the corresponding primary system. The interference range of a cognitive user is depicted in Figure 2.5.

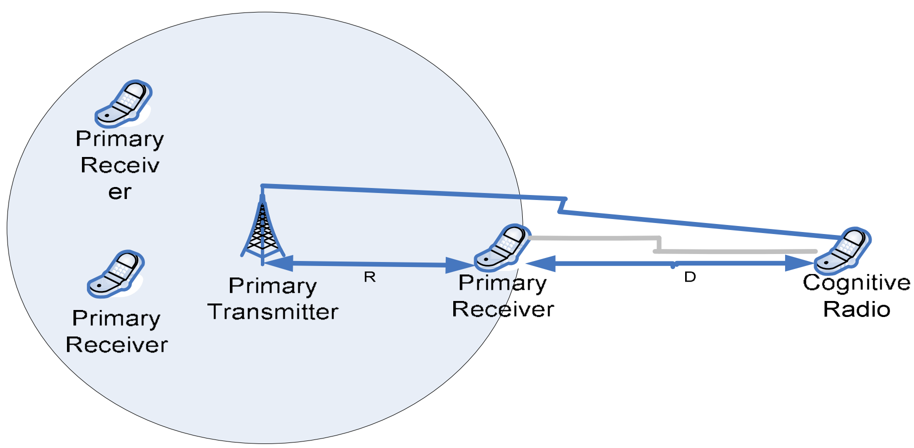


Figure 2.5 Interference range of a cognitive radio [3]

From the preceding paragraph it can be concluded that there is a strong relationship between the detection sensitivity of a cognitive radio and the maximum power it is allowed to transmit in a certain licensed band. This notion can be extended to generalized cognitive radio networks. Intuitively, a network with more users and/or higher transmitted powers impacts primary systems that are far away from each other. Therefore, a spectrum management body should manage the total interference according to the detection sensitivity.

2.4 Spectrum Sensing Challenges

Spectrum Sensing in cognitive radio networks has several challenges like sources of uncertainty in channel, device and network. Since spectrum sensing should perform robustly even under worst case conditions, such uncertainties usually have implications in terms of the required detection sensitivity, as discussed below.

2.4.1 Channel Uncertainty

Under channel fading or shadowing , a low received signal strength does not necessarily imply that the primary system is located out of the secondary user's interference range, as the primary user may be experiencing a deep fade or being heavily shadowed by obstacles. Therefore spectrum sensing is challenged by such channel uncertainty since cognitive radio has to be more sensitive to distinguish a faded or shadowed primary signal from white spaces. Eq.2.2 shows that any uncertainty in the received signal power of the primary signal translates into a higher detection sensitivity requirement.

Under severe fading, a single cognitive radio relying on local sensing may be unable to achieve this increased sensitivity since the required sensing time may exceed the sensing period, T_p .As this report will illustrate later, this issue may be tackled by having a group of cognitive radios share their local measurements and collectively decide on the occupancy state of a licensed band.

2.4.2 Noise Uncertainty

In order to calculate the required detection sensitivity in Eq.2.2, the noise power has to be known. Such a priori knowledge, however, is not available in practice, and N has to be estimated by the receiver. Unfortunately, calibration errors as well as changes in thermal noise caused by temperature variations limit the accuracy with which noise power can be estimated. Since a cognitive radio may violate the sensitivity requirement due to an underestimate of N, rmin should be calculated with the worst case noise assumption, thereby necessitating a more sensitive detector.

Spectrum sensing is further challenged by noise uncertainty when energy detection is used as the underlying sensing technique. More specifically, a very weak primary signal will be indistinguishable from noise if its SNR falls below a certain threshold determined by the level of noise uncertainty. Feature detectors, on the other hand, are not susceptible to this limitation due to their ability to differentiate between signal and noise.

2.4.3 Hidden Node Problem

Figure 2.6 illustrates the problem of hidden node it is shown that User A and B cannot hear user C, so they are trying to utilize the spectrum band of user C. But they do not know that they are going to create interference to User C at the intended receiver. The solution to this problem is the cooperative spectrum sensing.

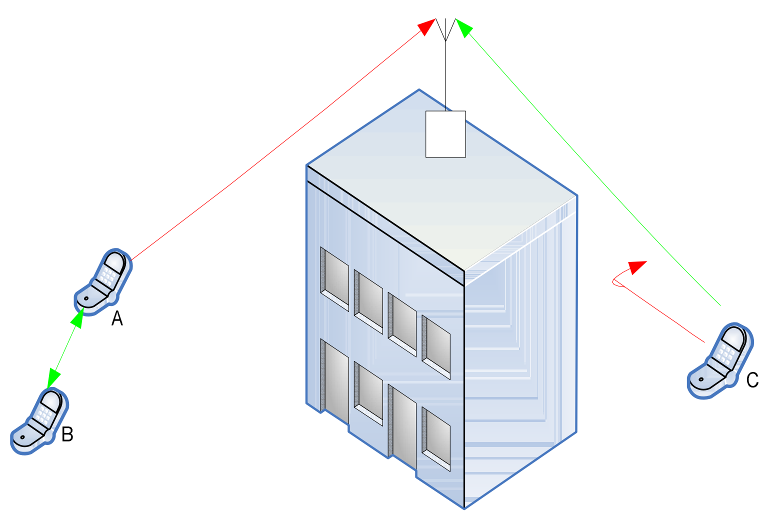


Figure 2.6 Hidden Node Problem

2.4.4 Aggregate-Interference Uncertainty

A CR network grows with the advancements in the network technology there will be a chance that multiple cognitive radio networks try to operate over the same available spectrum. As a result, spectrum sensing will be complicated by uncertainty in aggregated interference may turn out to be harmful. This uncertainty requires of most sensitive detectors for CR to detect the harmful interference to primary users. As illustrated in Figure 2.7 three networks cognitive radio network A, B and C are operating Cognitive Radio A is forcing B to move to another spectrum band. Even the interference of Cognitive Radio network A and Cognitive radio C can still be harmful.

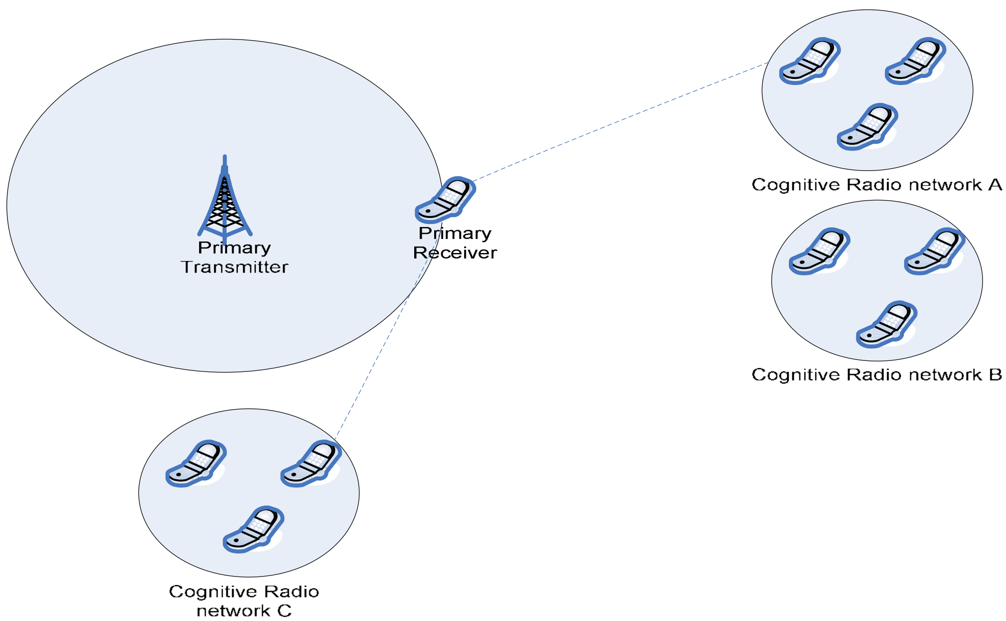


Figure 2.7 The operation of network A forces network B to move to another band; However the aggregate Interference of networks A and C may still be harmful [3]

2.5 Cooperation in cognitive radio

The detection of primary user by the CR is the key point in a cognitive radio networks. However this seems to be difficult due to the fast occurring changes in the in wireless environment. There will be a chance that CR user experience losses due to multipath fading, shadowing, and building penetration which would result misperception about the primary user, which would in turn cause interference to the primary. This phenomenon demands from the CR to be highly robust to channel losses and detection of extremely low power signals. These stringent requirements pose a lot of challenges in front of CR networks. These requirements can be maximally satisfied if multiple CR users cooperate in sensing matter.

2.5.1 Cooperative topologies in cognitive networks

The Cooperative techniques that have been presented in the literature can be broadly classified into three categories according to their level of cooperation.

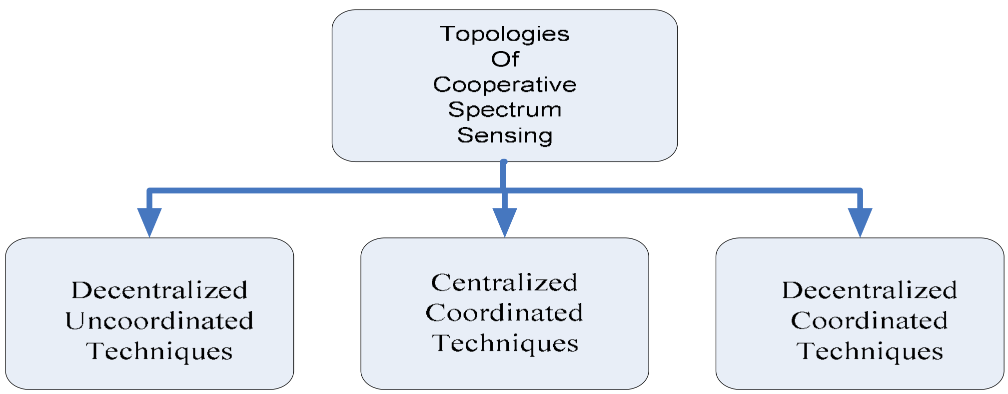


Figure 2.8 Classification of Cooperative Techniques [7]

2.5.1.1 *Decentralized Uncoordinated Techniques*

In this approach the CR user does not show any sort of cooperation and they work independently. Each CR user will independently detect spectrum holes for transmission and in case of the arrival of primary user it would leave the channel without informing the other CR users. The uncoordinated techniques are prone to many types of problems as compared to coordinated techniques. This is clear from the Figure 2.9 that the CR users experience wrong prediction about the shadowed regions and detects the channel incorrectly thereby causing interference at the primary receiver.

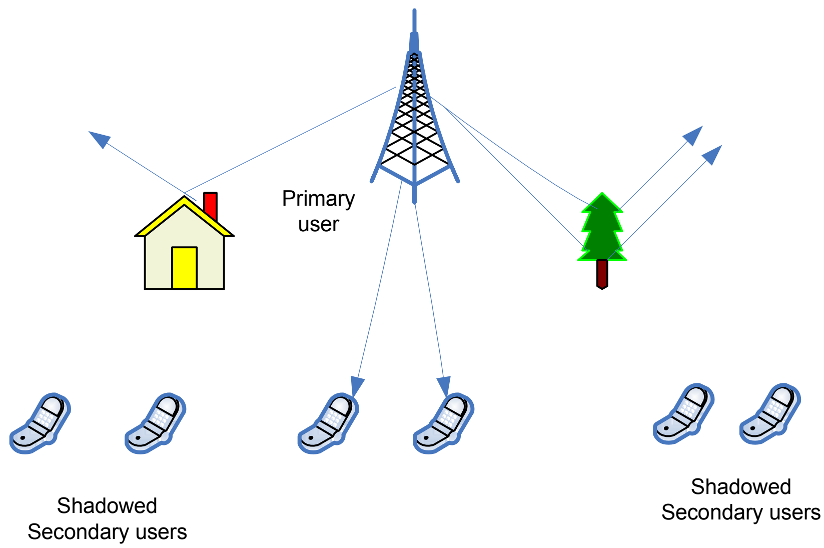


Figure 2.9 Decentralized Uncooperative Detection Technique [7]

2.5.1.2 Centralized Coordinated Techniques

In this approach of cooperation there is need of an infrastructure deployment as shown in Figure 2.10. The CR user that detects the presence of a primary transmitter or receiver must have to forward this information to central entity called CR controller. The CR controller can be thought of as device or it may be another CR user. The main responsibility of CR controller is to notify all the CR users in its range about the presence of primary user through a control message. The Centralized schemes can be further classified according to their level of cooperation into Partially Cooperative and Totally Cooperative Schemes. In partially cooperative scheme CR show cooperation during the sensing of the channel only. CR users independently detect the channel and in case of presence of primary user it will inform the CR controller which then notifies all the CR users while in Totally Cooperative Schemes CR cooperate in exchanging the detective information among each others in addition to cooperation in sensing the spectrum.

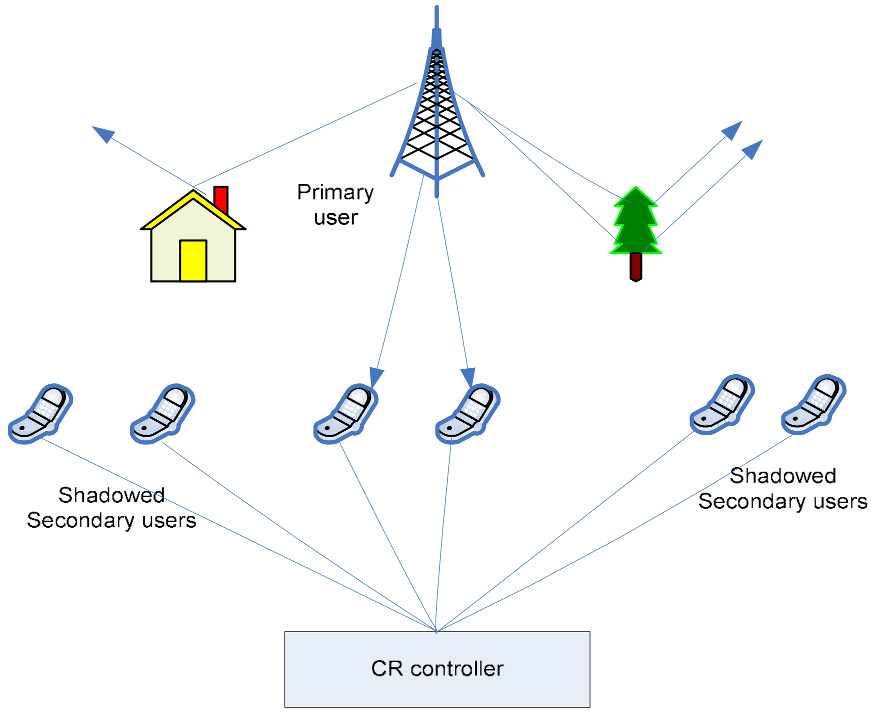


Figure 2.10 Centralized cooperative Detection Technique [7]

2.5.1.3 Decentralized Coordinated Techniques

A decentralized algorithm named gossiping has been proposed which performs the cooperation spectrum sensing task at much lower cost. Clustering schemes have also been proposed by where cognitive users form in to clusters and these clusters coordinate amongst themselves. This kind of cluster formation is similar to clustering algorithms in sensor network topologies. The main aim of these clustering schemes is to reduce transmission overhead.

2.6 Receiver Detection

Now we need such spectrum sensing techniques which are able to remove the problems in transmitter detection. To remove receiver's uncertainty, we have to design techniques which we have some information about primary receiver. The makers of transmitter detection techniques state that we have available the information of primary receiver. The detection of weak signals from primary transmitter where it was shown [15] that the problems becomes very difficult when there is uncertainty in the receiver noise variance. Then new spectrum sensing techniques are introduced in which we will get information about receiver from its own architecture.

2.6.1 Local Oscillator Leakage

Modern day radio receivers are based on super heterodyne receiver architecture invented by Edwin Armstrong in 1918. This architecture is shown in Figure 2.11.

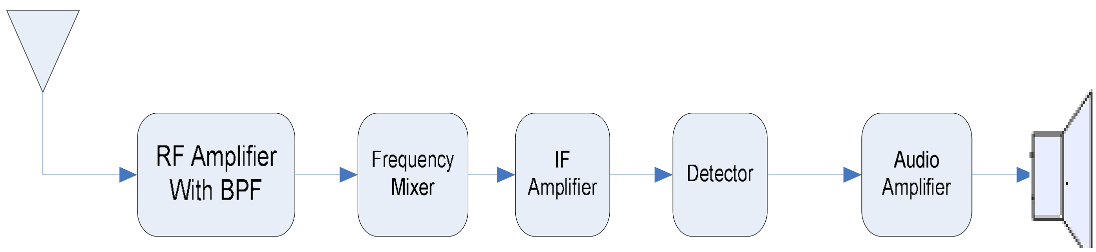


Figure 2.11 Architecture of Super heterodyne Receiver

This type of receiver architecture converts Radio frequency (RF) into fixed low intermediate frequency (IF). In order to convert RF to IF, frequency mixer is used which consists of local oscillator (LO). Local oscillator is tuned on a frequency such that when mixed with incoming RF signal, it converts it into fixed low IF band. In all of these receivers, there is inevitable reverse leakage, and therefore some of the local oscillator power actually couples back through the input port and radiates out of the antenna [16]. If we are able to measure this LO leakage then problem of receiver uncertainty is solved.

But things are never this simple. In the past decade, some improvements have been made to the receiver's architecture, resulting in reduced LO leakage power. Figure 2.11 tells the leakage of television receiver versus years.

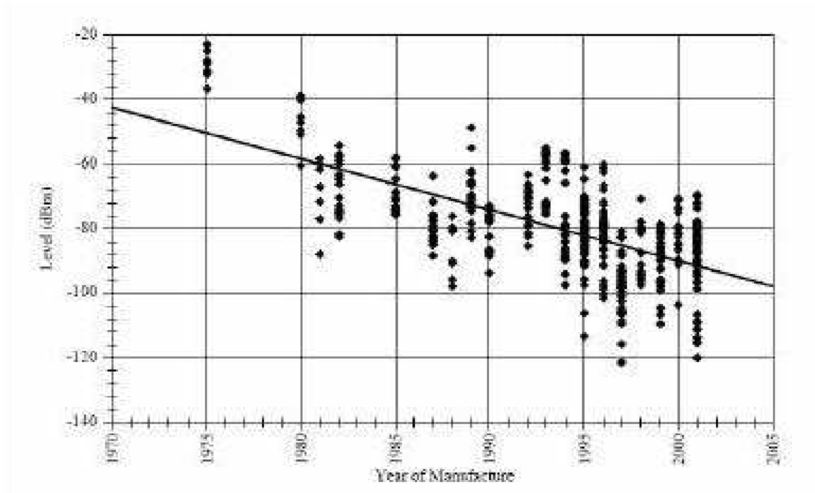


Figure 2.12 TV Local Oscillator leakage versus model year [16]

Detecting this leakage power directly with a CR would be impractical for two reasons [17]. First, it would be difficult for the receive circuitry of the CR to detect the LO leakage over larger distances. In [17] they calculate and prove that at a distance of 20m, it would take on order of seconds to detect the LO leakage with a high probability. In section 1 we see that we need sensing time in milliseconds in worst cases. The second reason that it would be impractical to detect the LO leakage directly is that LO leakage power is very variable and depends on the receiver model and year. Currently this method is only feasible in the detection of the TV receivers.

2.6.2 Sensor Nodes for Receiver Detection

In [12] the authors proposed to build tiny, low cost sensor nodes that would be mounted close to the primary receivers. The node would first detect the LO leakage to determine to which channel the receiver was tuned. It would then relay this information to the CR through a separate control channel using a fixed power level. Working of this is shown in Figure 2.13.

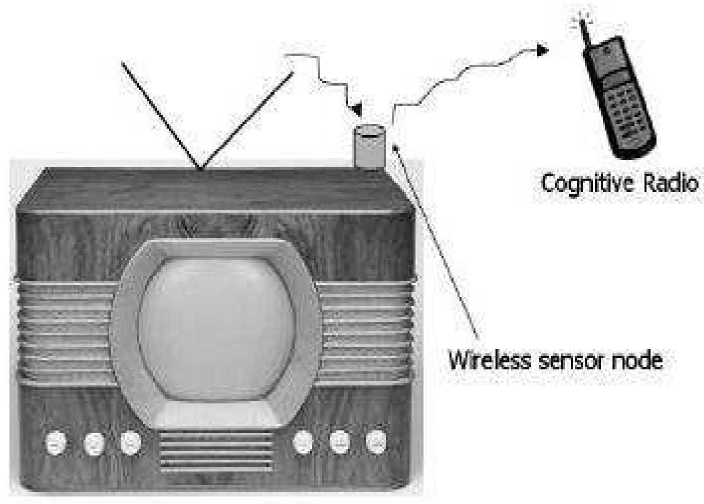


Figure 2.13 Sensor Nodes Notifying Cognitive Radio [12]

2.6.3 Interference Temperature Management

Interference is typically regulated in a transmitter centric way. Interference can be controlled at the transmitter through radiated power, out-of-band emissions, location of individual transmitters and frequencies used by specific type of radio operations. There interference management techniques served well in the past but do not take into account the interference from the receiver point of view, as most of interferences occur at the receiver. Moreover, the dramatic increase in the overall demand for spectrum based services, rapid technical advancements in radio systems; in particular the introduction of new robust modulation techniques demands a new technique that focuses on actual RF environment and interaction between transmitter and receiver.

This demand moves us towards new interference management technique known as Interference Temperature Management. We can define interference temperature as measure of the RF power generated by undesired (CR) emitters plus noise that is present in the receiver system per unit of bandwidth. The emissions from undesired (CR) transmitters could include out of band emission from transmitters operating on adjacent frequencies as well as from transmitters operating on the same frequency as a desired transmitter. In principle, the interference temperature measurements would be taken at various receiver locations and these measurements would be combined to estimate real time condition of RF environment. The interface temperature model shown below explains the signal of a radio designed to operate in a range at which the received power approaches the level of the noise floor. As additional interfering signals appear, the noise floor increases at various points within the service area, as indicated by the peaks above the original noise floor. This model manages the interference at the receiver through the interference temperature limit, which is represented by the amount of new interference that the receiver can tolerate.

2.7 Summary

This Chapter reviews the techniques and algorithms developed and implemented for the Cooperative Spectrum Sensing for cognitive radios. Since the purpose of this work is to analyze the transmitter detection techniques therefore the focus has been kept on the transmitter detection techniques of spectrum sending.

Chapter 3

MODELING PHILOSOPHY

3.1 Introduction

This project is another step towards developing an efficient cooperative spectrum sensing scheme in the cognitive radio environment. Extensive research has been carried out to arrive at the final results which shall be presented later in this thesis report.

3.2 Scope

In spectrum sensing system for Cognitive Radio Networks, the input of the system is the waveform which it will be receiving form licensed/primary user. This signal contains the information that is exchanged among primary users on licensed band. In order to find the spectrum holes we have to sense the radio environment and then have to take decision that whether there is space for cognitive radio or not. Efficient detection of spectrum holes is the major part of this system.

3.3 System model

3.3.1Two users Cognitive Radio Networks

In view of the low reliability of Single secondary user (SU) sensing a cooperative spectrum Sensing is employed as illustrated in Figure 3.1.

Here we assume that there are 2 SUs in the network. Both SU1 and SU2 receive the signal transmitted by Licensed User (LU). As SU2 is far away receives a weak signal SU2 is very far away from LU and thus experiencing deep fading. When it receives signal form LU it started local sensing but as it is far away from LU it will not be able to detect it accurately. Then Signal received by SU1 is amplified and forward to SU2. Now SU2 receives a relatively good signal than previous received signal and starts sensing procedure once again. In short, SU1 is acting as a relay for SU2.

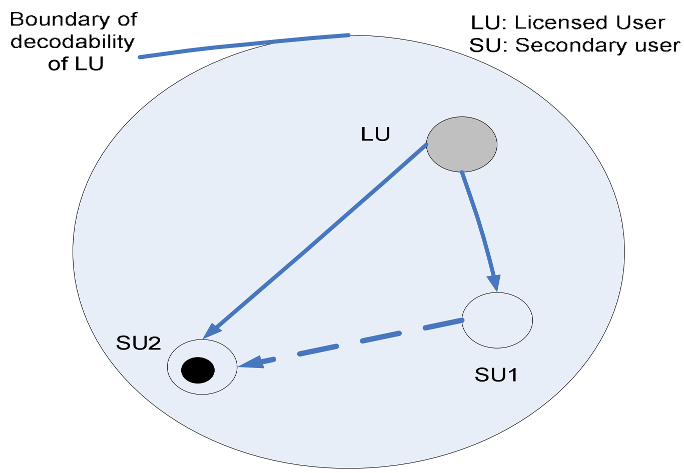


Figure 3.1 Cooperation in Cognitive Radio

3.3.2 Multi-user Cognitive Radio network (Centralized Approach)

In view of the how users cooperate in a multi-user cognitive radio environment, a centralized cooperative spectrum sensing scheme is employed, as illustrated in Figure 3.2.

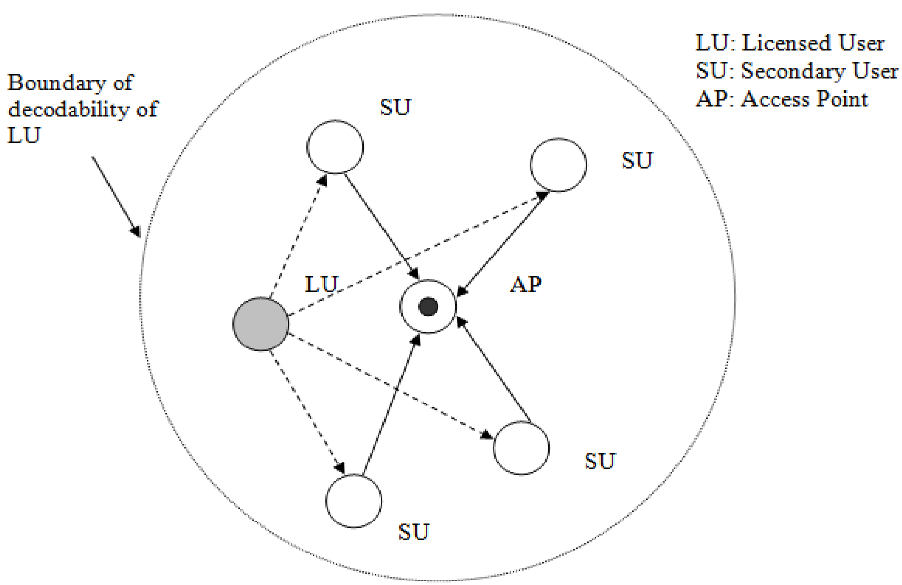


Figure 3.2 Centralized Cooperative Spectrum Scheme

We assume that there are ‘N’ SUs in the network. A training stage is first initiated at the AP to evaluate the credibility of each SU. Credibility of each SU is dependent on its relative distance from LU and the conditions of the radio environment. We can measure credibility by using fuzzy comprehensive evaluation. We assume that the channel condition of each SU is constant and the credibility of each SU can thus be considered to be invariant. After the training phase the sensing procedure is started at each SU by conducting a local sensing scheme, and the decisions of each SU are then transmitted to the AP. Then final sensing decision is made at the AP using fuzzy combination of the results from different SUs local sensing.

To simplify and idealize the problem we only considered into account the pathloss and delay introduced as the signal travel. For introducing pathloss we have used two models: Either free space loss or Hata-okumura model.

3.4 Licensed Users Transmitter

Block diagram of Licensed Users Transmitter is shown in Figure 3.3. The input is any piece of information (a text file, a sampled speech signal, a coded image …) that is converted to sequence of bits. Information bits, b[n] are coded by adding some redundant bits to protect information against channel noise and interference from other users. Data symbols, s[n] are obtained by grouping the bits into symbol. After that, data symbols are passed through pulse shaping filter p_T (t) and modulate the resulting signal to generate an RF (radio frequency) signal for transmission through channel.

At the receiver, all the steps which are mentioned in transmitter are operated with their reverse functionalities to obtain the original input signal.

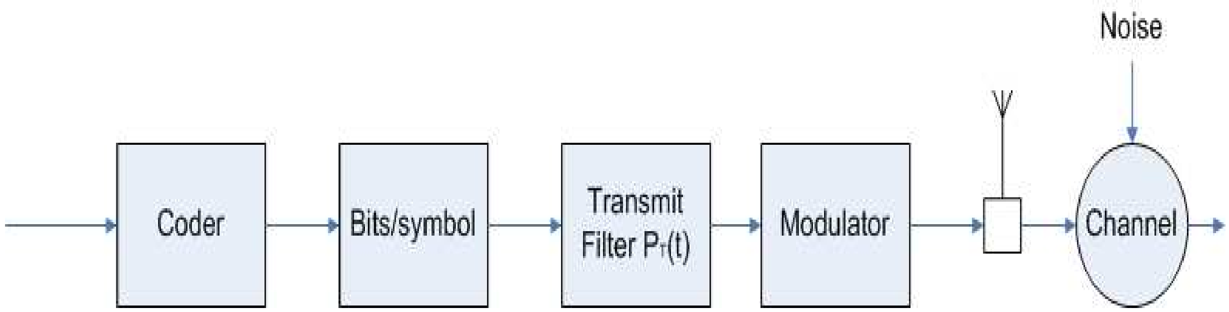


Figure 3.3 Block Diagram of Digital Communication Transmitter

3.5 Channel Model

In the channel modeling method first path loss factor α is computed and then modulated signal is attenuated using α. Path loss models are discussed in Chapter 2 in detail. After that we have to pass this resultant signal form propagation delay model. In which signal is delayed by time‘t’ depending on the distance between sender and receiver. The channel affects the signal by adding noise and distortion into it. There may be interference from other users also present. Block diagram of Channel is shown in Figure 3.4.

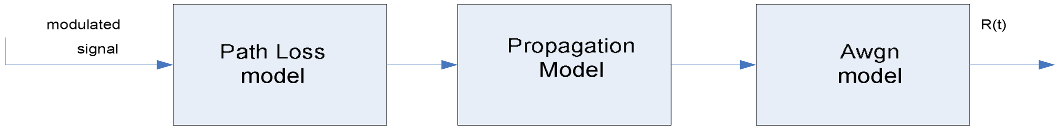


Figure 3.4 Channel model components

3.6 Problem Decomposition into Modules

The system is decomposed in to two modules. The modules are divided into sub modules cooperative and non cooperative spectrum sensing. These modules further include four phases a) Training phase b) Local Sensing c) Fuzzy Logic and d) Decision Modules of the system is illustrated in Figure 3.5.

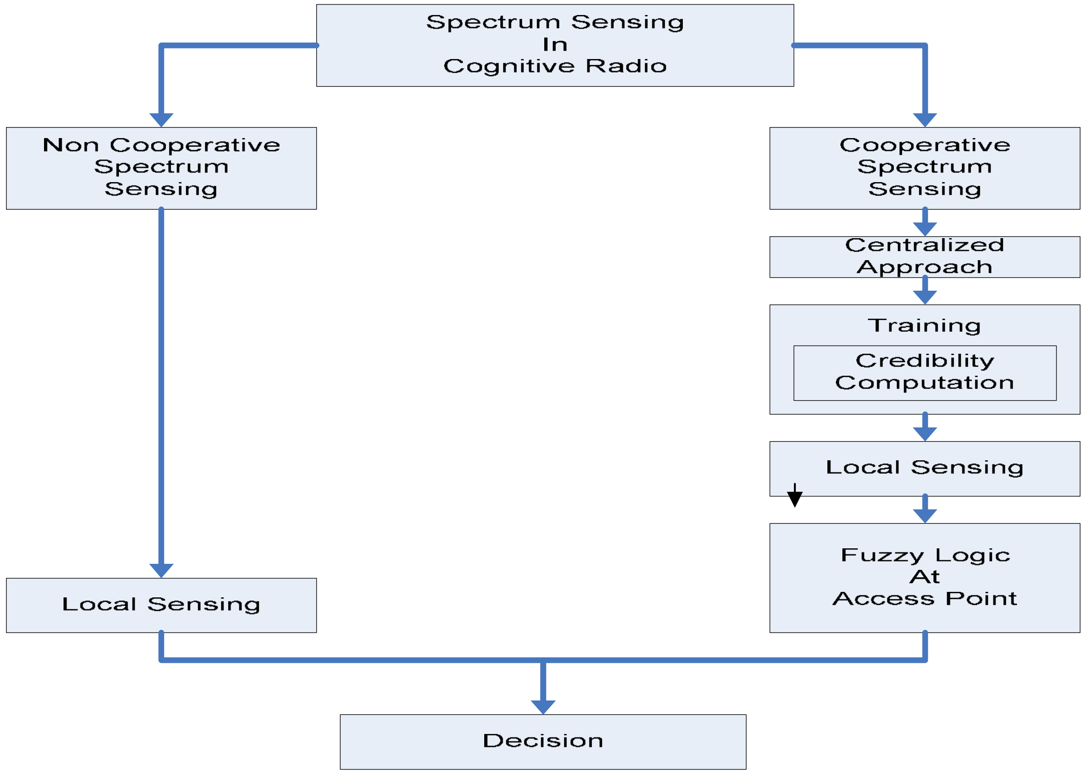


Figure 3.5 System Process Diagram

3.6.1 Centralized Approach

AP is used as central entity in the cognitive radio network as illustrated in Figure 3.2. AP has to decide for the presence and absence of the white spaces. The decision of the AP is based on the combination of the local decision made at SUs. In other words at AP cooperative decision is taken with the help of other SUs.

3.6.2 Training Phase

Consider the centralized multi-user cognitive radio network shown in Figure 3.2 consisting of N nodes (SU). Each SU is provided with different credibility. In training stage we evaluate the credibility of each SU node using comprehensive fuzzy logic for computation of credibility of each SU.

3.6.2.1 Fuzzy Model

The fuzzy model used here contains three sets A, B and C. Set A is a set can be said as evaluation factors basically it is defining the credibility criteria of a particular secondary user, set B can be said as evaluation set and set C is the judgment set that transform the collected data into a number representing the credibility of a particular secondary user.

Set A consist of three factor which are determined the quality of a particular secondary user These three factors are illustrated in Figure 3.6.

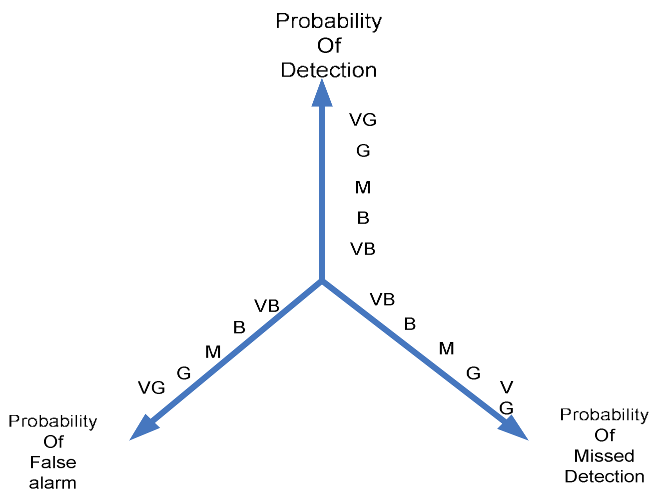


Figure 3.6 Quality attributes of Factor Set A

Under the umbrella of each quality attribute of the Evaluation Factor set there is an evaluation set B. The evaluation set B further contains contain five possibilities as shown in Figure 3.6

Each possibility of evaluation set B is assigned a weight as shown in Table 3.

VG	1
G	0.8
M	0.6
B	0.4
VB	0.2

` Table 3.1 Weight of possibilities of set B

Set C (Judgement Set)

Set C basically is the judgment set that assigns weight to the quality attributes as shown in Table 3.2.

Probability of detection	0.5
Probability of missed of detection	0.3
Probability of false alarm	0.2

Table 3.2 Values of Judgement Set C

3.6.3 Local Spectrum Sensing

At Each SU node local sensing is performed using the following transmitter detection based spectrum sensing techniques a) Energy detection b) Matched Filter and c) Cyclostationary feature detection. For more reliable identification of spectrum holes a fuzzy logic based decision is employed explained later in Section 3.7

3.6.4 Fuzzy Logic at AP

After the evaluation of credibility evaluation and local sensing at each SU node, with the decisions Di, $1\leq i \leq N$, obtained from local sensing at each SU, and the corresponding Ci $1\leq i\leq N$, obtained from the training stage. All the decisions Di and Ci are collected at AP.All the decision are multiplied by the credibility computed for each secondary user and added up.

An arbitrary example is as under

The credibility matrix contains credibility of three users SU1, SU2 and SU3. The decision matrix contains the decision after the local sensing by each of the three secondary users respectively

Credibility= [0.5 0.7 0.4]

Decision= [1 0 0]

Result=0.5*1 +0.7*0 +0.4*0=0.5

3.6.5 Decision

Now AP compares Result with a predetermined threshold. If the decision metric is larger than the predetermined threshold, AP will assert the presence of the LU. Otherwise it will deny the presence of the LU.

3.7 Local Fuzzy Logic Based Hybrid Approach

The fuzzy model used here contains three sets a, b and c. Set a contains the spectrum sensing techniques employed for the spectrum sensing. Set b contains the levels of uncertainties in determination of the presence or absence of a licensed user of a particular technique. Set c contains the weight assigned to each employed spectrum sensing technique. Set a and b can be clearly viewed from the Figure 3.7.

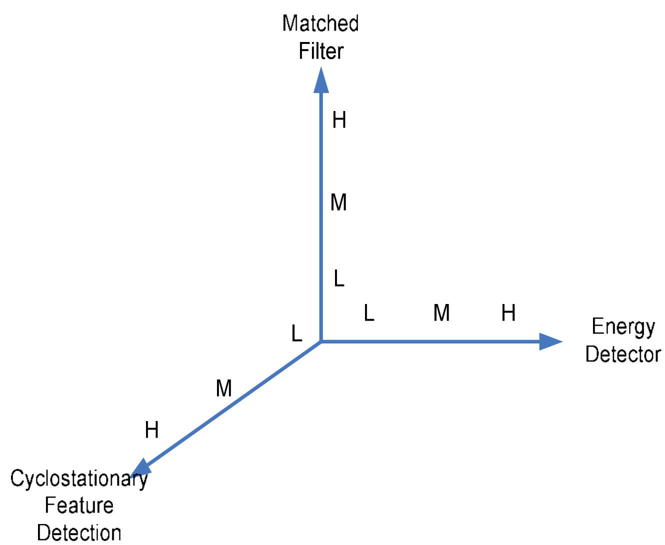


Figure 3.7 Set a and b

Values assigned to set b are shown in Table 3.3.

L	0
M	0.5
H	1

Table 3.3 Values assigned to Set b

Set c contains the values assigned to the elements of set a as shown in Table 3.4

Energy Detection	1
Matched Filter	1
Cyclostationary Feature detection	1

Table 3.4 Values assigned to set A

3.7.1 Decision

Each of the spectrum sensing technique made a decision {0 1 0.5} and the result from all these are added up and compared to a threshold if the result is greater than the threshold than its means user is present. An arbitrary example is as under in Table 3.5

Energy Detector	Matched Filtering	Cyclostationary Feature Detection	Decision
1	0	1	Present
0	0.5	0	Absent

Table 3.5 Fuzzy Logic based decision

3.8 Summary

Chapter 3 sets up the basis of this research. It narrows down the vastness of the topic to the conditions and assumptions under which this work has been done. The chapter breaks down the process into modules and briefly explains the functioning of each individual module.

Chapter 4

IMPLEMENTATION

4.1 Introduction

This chapter demonstrates the implementation of spectrum sensing techniques in cooperative as well as non cooperative radio environment to obtain the simulation results. Further these results are analyzed. First a simplified program structure consisting of two cognitive radio users then centralized spectrum monitor architecture for cognitive radio is explored followed by the algorithms. Lastly the different experiments designed and conducted during the research have been discussed.

4.2 Transmitter of Licensed Users

First of all we need primary user waveform on which we can apply different spectrum sensing techniques. Transmitter can have different transmitting parameters like they can have different operating frequency, different modulation scheme. Block diagram of digital transmitter is shown in Chapter 3. Flow chart of implementation of primary transmitter is shown in Figure 4.1.The following steps is followed in developing transmitter for the licensed user.

Begin

1. *Choose Operating Frequency 'F' , Sampling Frequency 'Fs', Number of samples per symbol 'N' , distance of the secondary users from the licensed users 'd', Signal to noise ratio 'SNR' and channel impulse response 'h'.*
2. *Take input from the user to transmit.*
3. *Convert input signal into waveform using raised cosine filter.*

4. *Modulate the signal using BPSK modulation*

5. *Attenuate the modulated signal using pathloss model*

6. *Introduce propagation delay in the attenuated signal*

7. *Add AWGN noise in the signal*

End

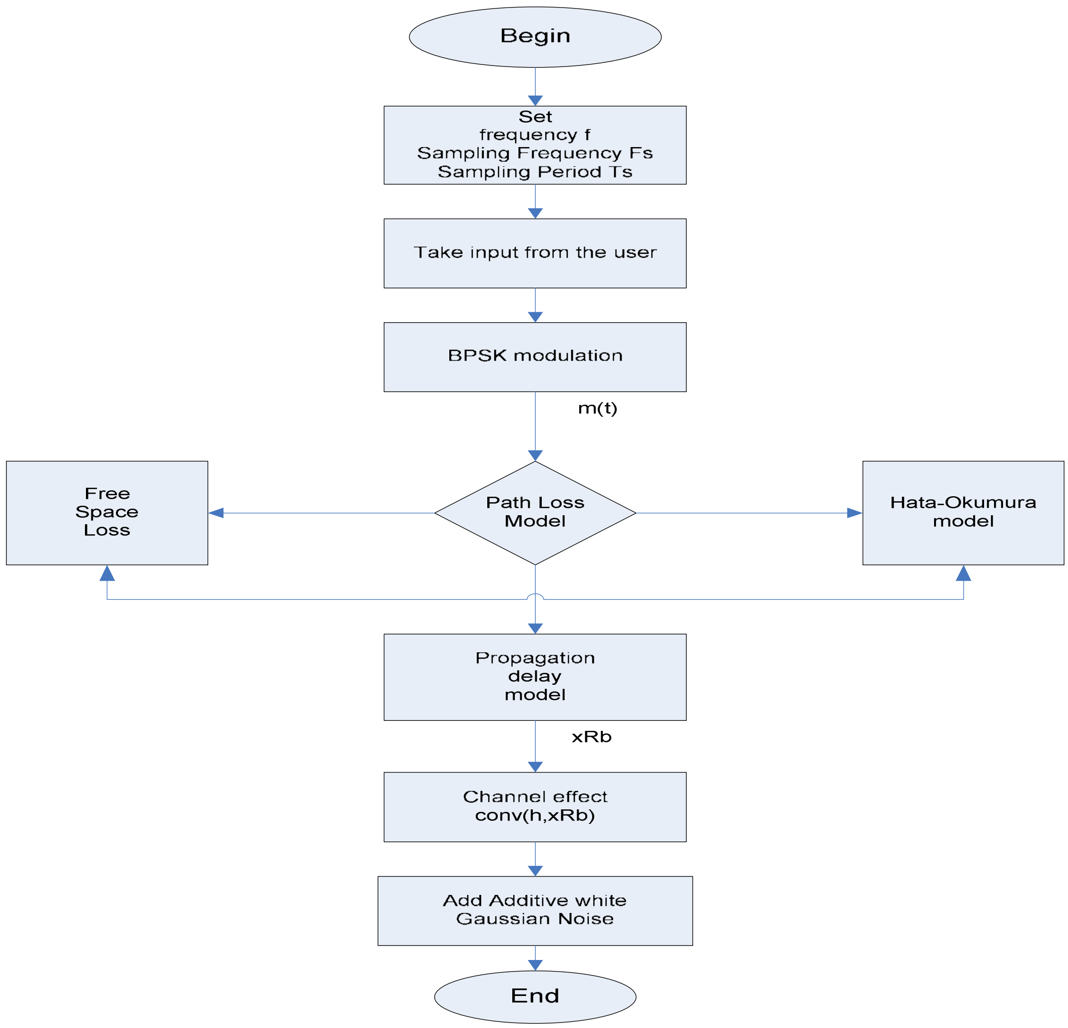


Figure 4.1 Flow chart for Implementation of Primary Transmitter

The MATLAB script ‘transmitter.m’, presented in Annex I, simulates two types of Primary transmitter for Spectrum Sensing in Cognitive Radio Networks, one using BPSK modulation technique and other using QPSK modulation technique. The code is self-explanatory.

4.3 Local Spectrum Sensing Algorithms

At SU Spectrum is scanned using the Spectrum sensing algorithm illustrated in Figure 4.2.

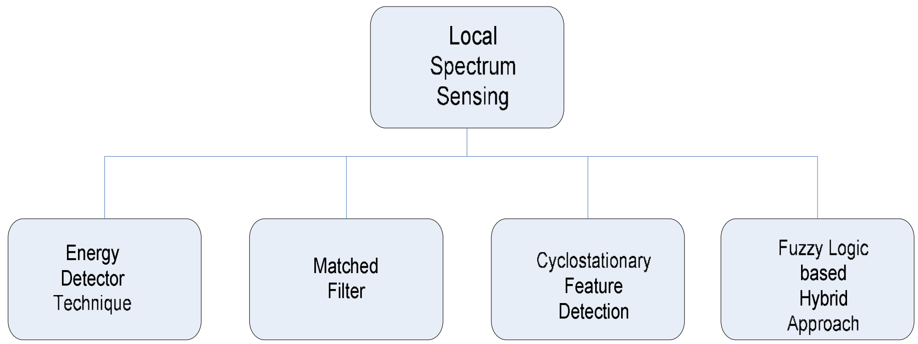


Figure 4.2 Spectrum Sensing algorithms

4.2.1 Energy Detection

The simplest detection technique for spectrum sensing is Energy Detection. As discussed in Chapter 2 energy detector measures the energy received from primary user during the observation interval. If energy is less then certain threshold value then it declares it as spectrum hole. Let r(t) is the received signal which we have to pass from energy detector. The Algorithm of the Energy Detector is as follows.

Algorithm

Begin

1. *Estimate Power Spectral density (psd) of the received signal.*
2. *Compute Avg. Power in the signal over the frequency band.*
3. *Summation of the Avg. Power over every 20 samples.*
4. *Result in step 3 is compared with a threshold* λ
5. *Decide Presence or absence of the Licensed User using comparison in Step 4.*
6. *if Licensed user is Absent*

    if no more sample

Go to step1

Else

Go to step3.

End

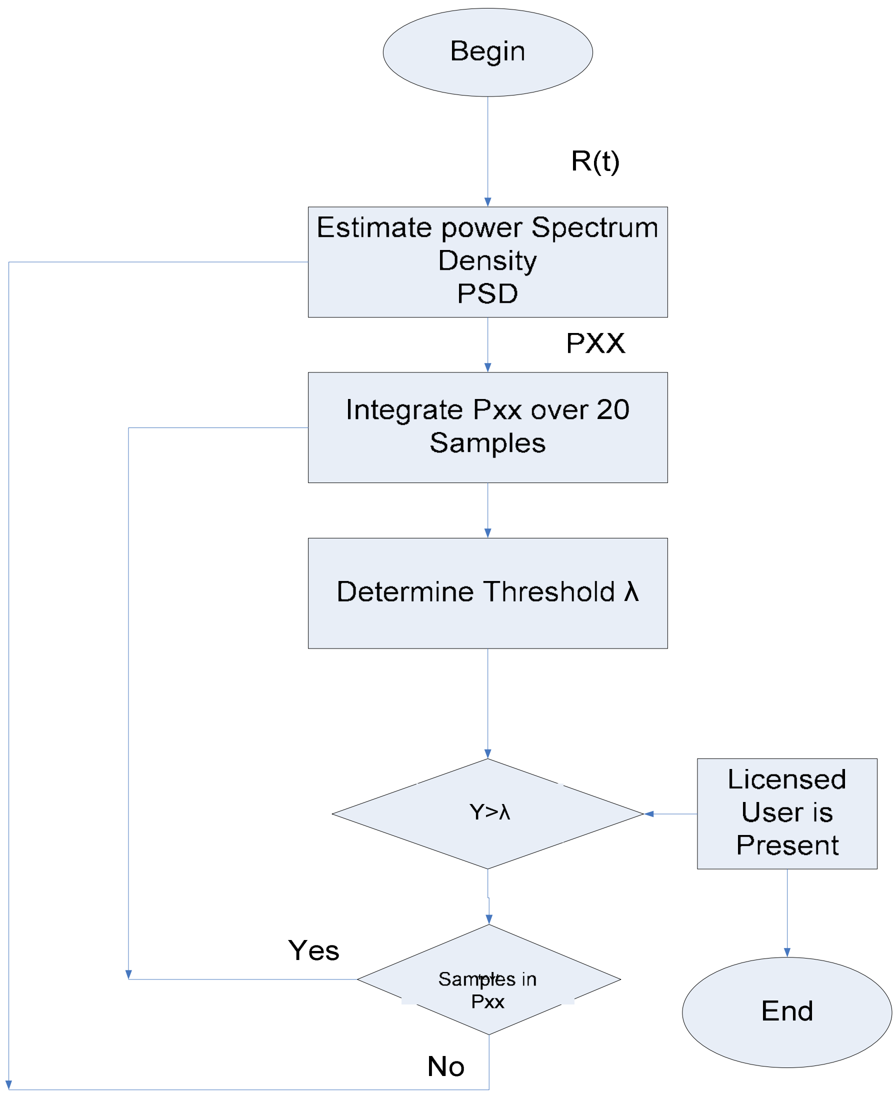


Figure 4.3 Flow chart for Implementation of Energy Detector

Flow chart for the implementation of Energy Detector is shown in Figure 4.2. The MATLAB script 'energydetector.m', presented in Annex I, simulates the Energy Detector for Spectrum Sensing in Cognitive Radio Networks. The code is self explanatory.

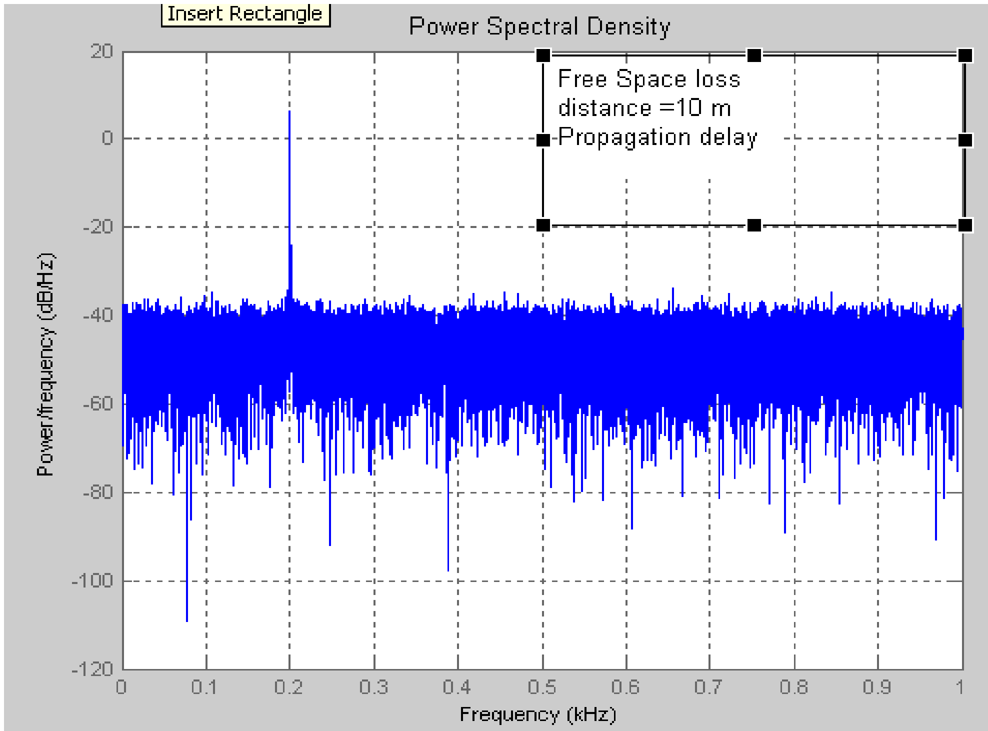


Figure 4.4 Output of Energy Detector when distance is small

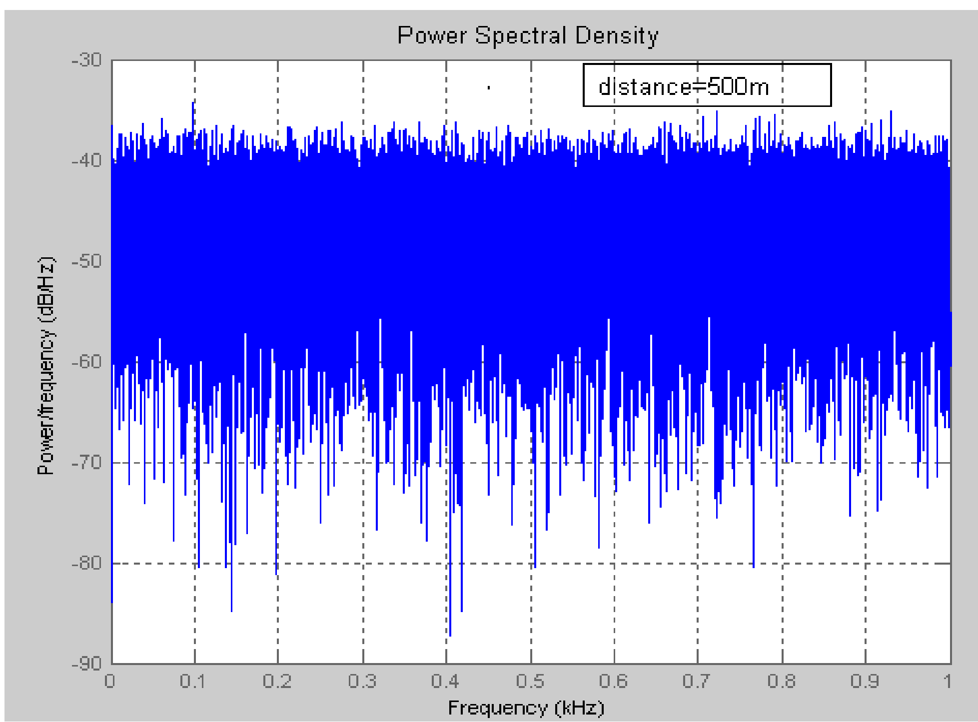


Figure 4.5 Output of Energy Detector when distance is large

4.2.2 Matched Filter

Another technique for spectrum sensing is Matched Filter as discussed in Chapter 2. Matched filter requires prior knowledge about primary user's waveform. Hence, it requires less sensing time for detection. Flow chart of Matched Filter is shown in Figure 4.7. Let r (t) is the received signal which we have to pass from matched filter. The matched filter compares the received signal with the transmitted signal and sees its matching with the transmitted signal. The drawback of matched filter is requirement of the prior knowledge. So to implement a matched filter sensing as a spectrum sensing technique we have to have some modification in the primary transmitter. The procedure of the matched filter is as follows.

Algorithm

Begin

1. *Generate a local Carrier using Local oscillator*
2. *Take 20 samples and correlate the locally generated carrier with the received signal*
3. *Compare the result of step2 with a threshold λ determined on the experimental basis.*
4. *Decide Presence or Absence of Licensed User using comparison in step 3.*
5. *If licensed user is absent or no more samples*

   If no more samples

   Go to step 1

   Else

   Go to step 2

End

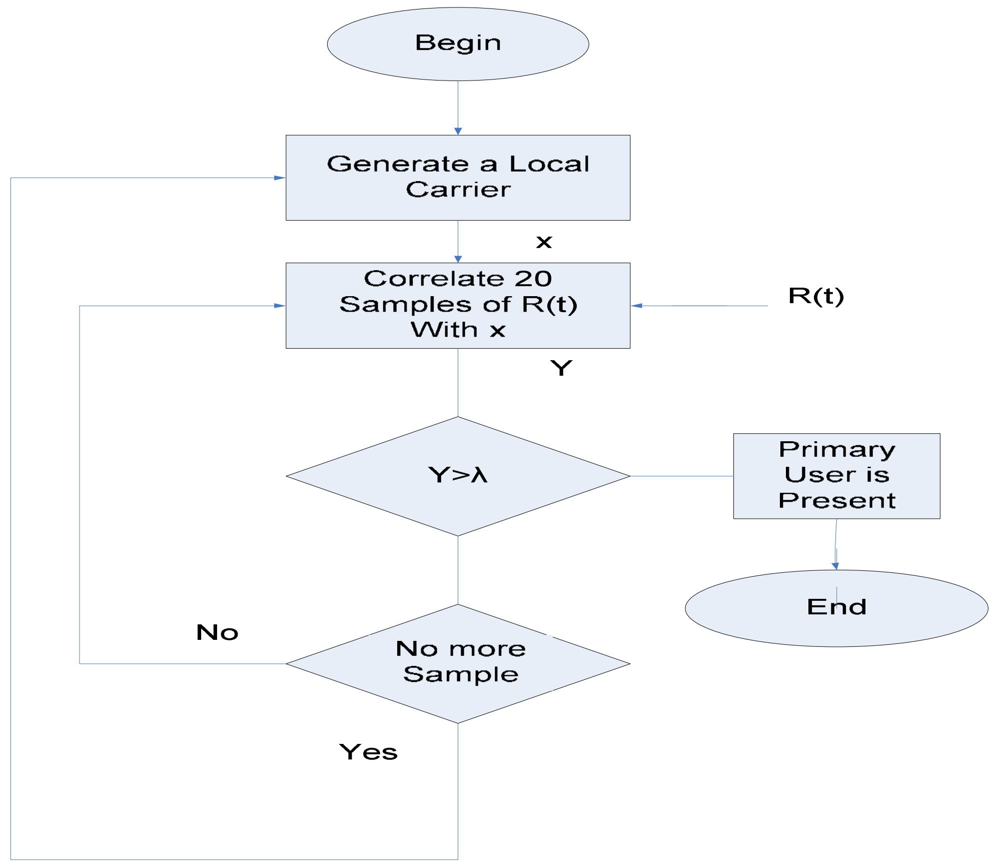


Figure 4.6 Flow chart for Implementation of Matched Filter

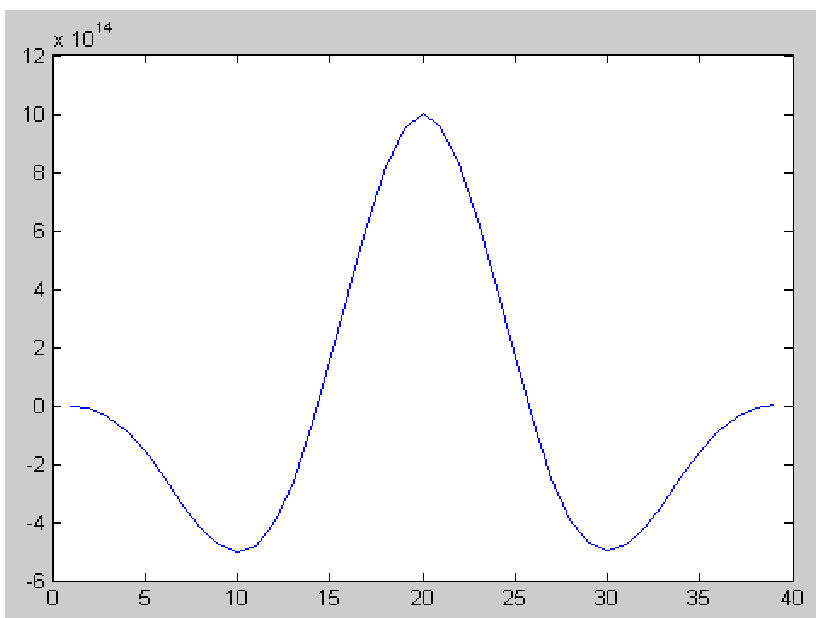


Figure 4.7 Output of Matched Filter when distance is small

4.2.3 Cyclostationary Feature Detection

Cyclostationary Feature Detection as discussed in Chapter 2. It uses inbuilt features in the primary user's waveform for detection. Hence, it is computationally complex detector. Flow chart for the implementation of Cyclostationary Feature Detector is shown in Figure 4.8. Let r(t) is the received signal which we have to pass from Cyclostationary feature detector detector. The procedure of the Cyclostationary Feature Detection is as follows.

Algorithm

Begin

1. *Compute R the Fourier transform of the received signal.*
2. *Compute XT by shifting the received signal in time domain by multiplying it with complex exponential.*
3. *Compute XY by Correlating XT with R.*
4. *Compute pt by averaging XY over time T.*
5. *Compare pt with a threshold determined on experimental basis.*
6. *Decide the presence or absence of licensed user using comparison in Step 5.*
7. *if licensed user is Absent*

    if no more samples

    Go to Step 1

    Else

    Go to Step 4

8. *Determine features of the licensed user like operating frequency and modulation scheme.*

End

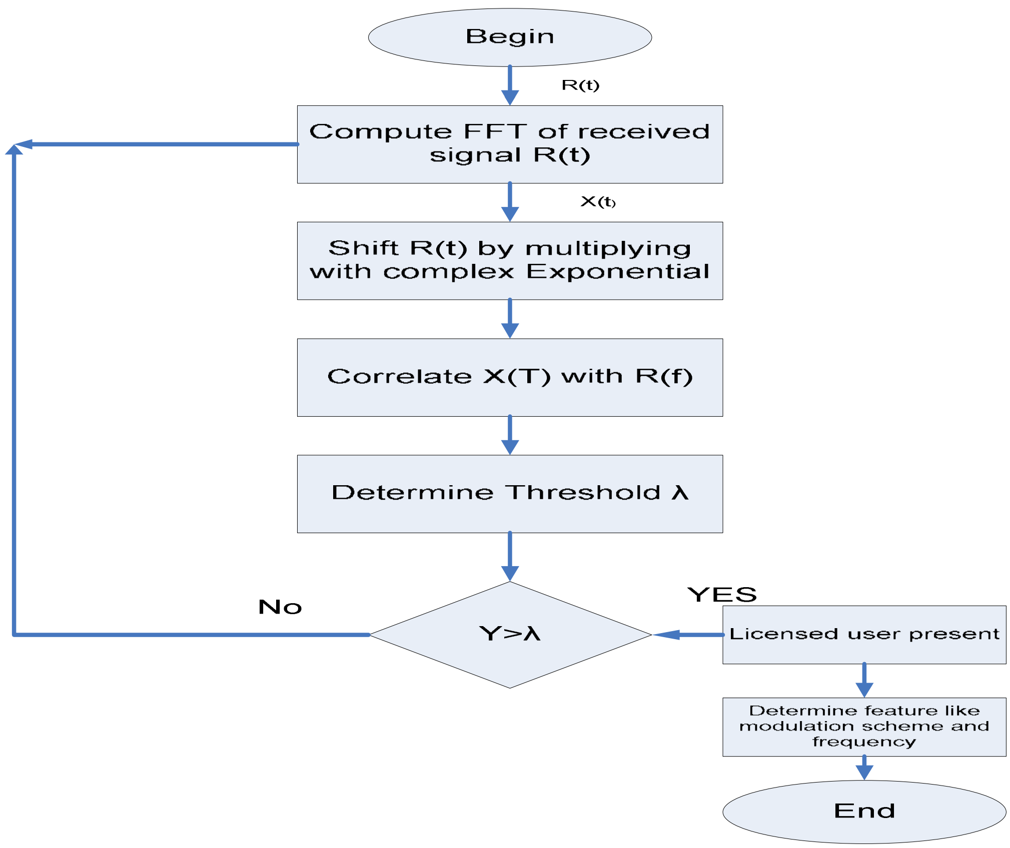


Figure 4.8 Flow chart for the implementation of Cyclostationary Feature Detection

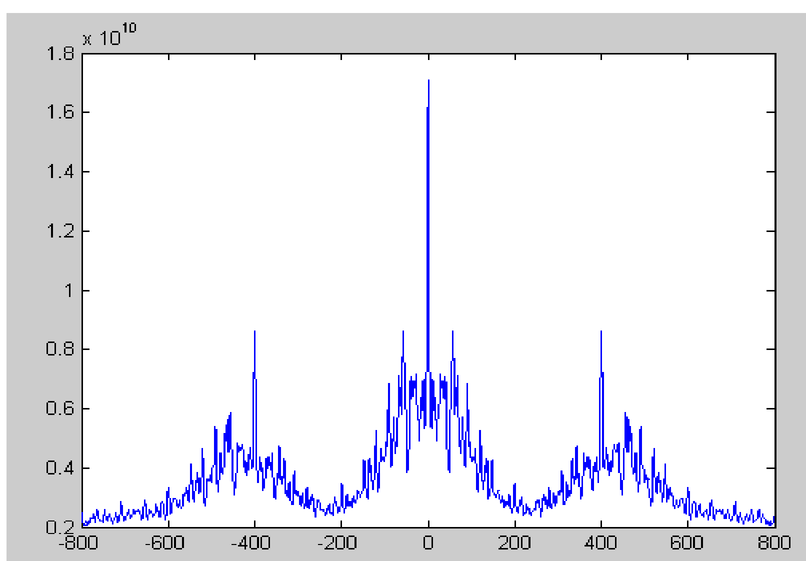


Figure 4.9 Output of Cyclostationary Feature Detection when distance is small

4.2.4 Fuzzy Logic Based –Hybrid approach

Fuzzy logic based hybrid approach block diagram is shown in Figure 4.10. The secondary user receives the signal from the licensed user R(t) .Local sensing using Energy detector, Matched Filter and Cyclostationary Feature detector algorithms are employed and result is computed as {H,M,L} . Y is computed by adding up the result from all the techniques. Y is compared with a threshold. if Y is greater than 1.5 then licensed user is present

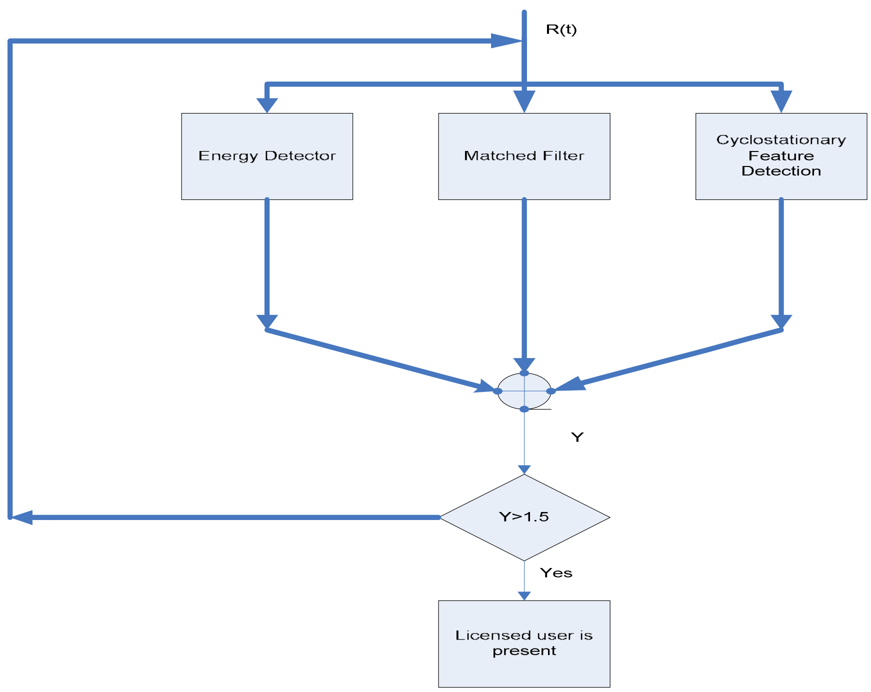


Figure 4.10 Flow chart for the implementation of Fuzzy logic based Hybrid approach

4.3 Credibility of a Secondary User (Centralized Approach)

Block diagram for computing the credibility of a secondary user is shown in Figure 4.10 .R (t) is the received signal from the primary user. Each user run its local sensing algorithm ten times and computes P a matrix containing probability of detection, probability of missed detection and probability of false alarm. An arbitrary P matrix is given as under

$$P = \begin{bmatrix} 0.5 & 0.3 & 0.2 & 0 & 0 \\ 0.4 & 0.4 & 0.2 & 0 & 0 \\ 0.6 & 0.2 & 0.1 & 0.1 & 0 \end{bmatrix}$$

A judgment matrix S is defined as under

$$S = \begin{bmatrix} 0.5 & 0.3 & 0.2 \end{bmatrix}$$

Now a matrix Q is obtained by transforming the matrix P according to matrix S

$$Q=S\ (P) = S \circ P = \begin{bmatrix} 0.5 & 0.2 & 0.2 & 0.1 & 0 \end{bmatrix}$$

Now credibility of a secondary user is obtained as under

$$\text{Credibility} = \begin{bmatrix} 0.5 & 0.2 & 0.2 & 0.1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 0.8 \\ 0.6 \\ 0.4 \\ 0.2 \end{bmatrix} = 0.8$$

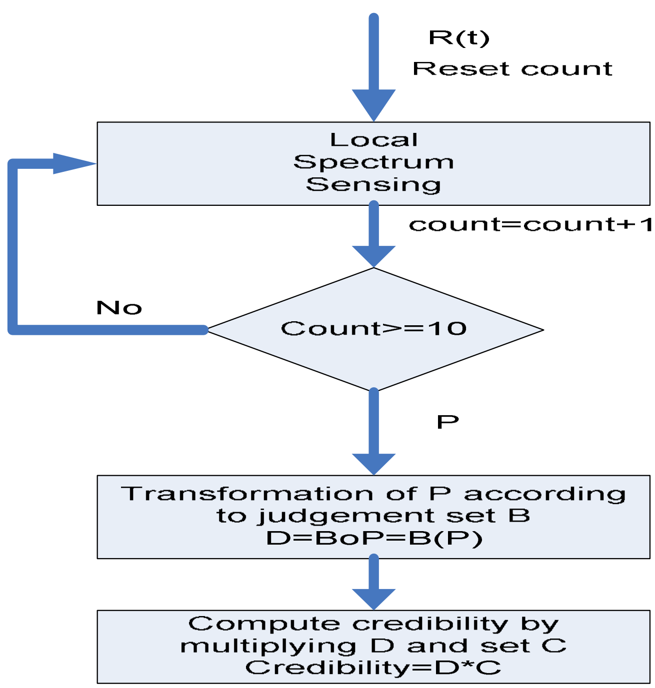


Figure 4.11 Credibility Computation of an Unlicensed User

4.4. Summary

The designed test program is written in MATLAB. The program comprises of three major techniques (i.e. Energy Detector, Matched Filter and Cyclostationary Feature Detection). The program to compute the credibility of secondary user by computing the Probability of detection, Probability of missed detection and Probability of false alarm, and then transform the se computed probabilities into the credibility of the secondary user.

Chapter 5

COMPARISON AND ANALYSIS

5.1 Introduction

In this chapter, the results of the algorithms and techniques, given in Chapter 2, have been presented. For experimentation, primary user's waveforms at different SNR have been identified. A comparison of all transmitter based detection techniques in cooperative and non cooperative environment is done. In the end the results of centralized cooperative spectrum sensing techniques are compared.

5.2 Comparison of Cooperative Vs Non Cooperative

Here comparison of cooperative and non cooperative detection is done on the basis of detection sensitivity. Probability of detection, probability of false alarm and probability of miss detection is found for cooperative and non cooperative detection is measured.

5.2.1 Comparison of cooperative VS Non Cooperative Energy Detection

The major drawback of the energy detector is that it is unable to differentiate between sources of received energy i.e. it cannot distinguish between noise and primary user. So this makes it susceptible technique when there are uncertainties in background noise power, especially at low SNR. Figure 5.1 shows probability of detection in cooperative Vs non cooperative energy detection for the SU2 as discussed in Chapter 3. In Figure primary user is present under different SNRs values which are received by secondary user. Results show that without cooperation SU2 is unable to detect the licensed user at any value of SNR. But with cooperation it will detect licensed user under low SNR values just because of noise power. At high SNR values it is still unable to detect licensed user as the transmitted power of the transmitted signal is same so as the SNR increases means the noise power added to the signal is decreased so the overall power of the received signal decreases sot the secondary user can not detect the licensed user at high values of SNR.

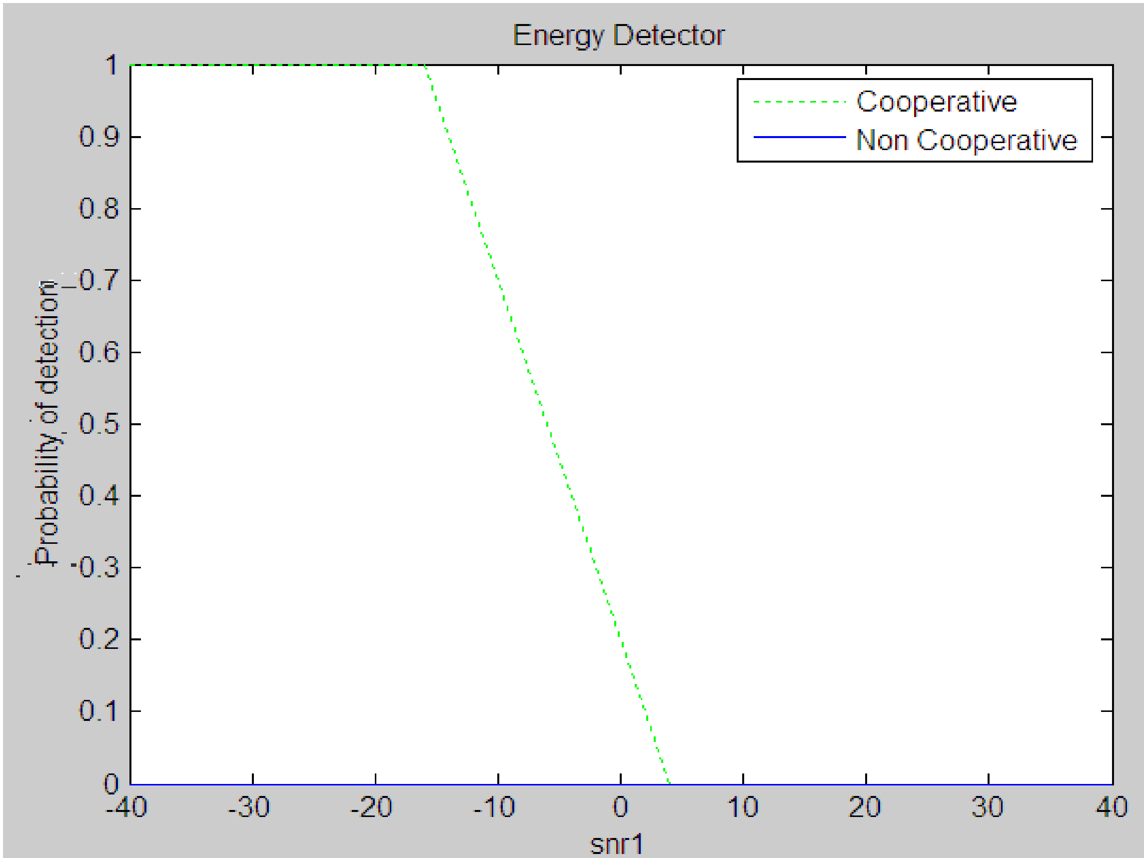


Figure 5.1 Probability of Detection Energy Detector

Figure 5.2 shows probability of misdetection in case of cooperative VS non cooperative. In Figure 5.2 one can clearly see that in cooperative case SU2 miss detects the primary user at high SNR values but correctly detects at low SNR values just because of noise factor. But with non cooperation it will miss detect all the times.

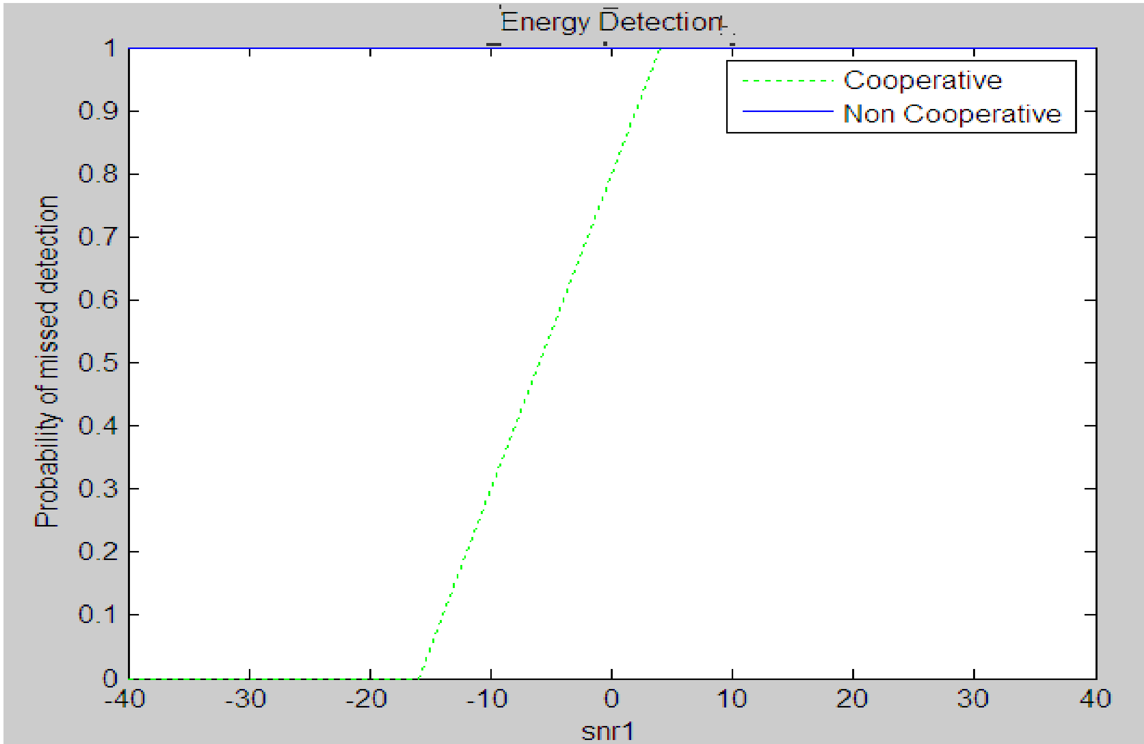


Figure 5.2 Probability of Miss Detection Energy Detector

5.2.2 Comparison of cooperative VS Non Cooperative Matched Filter

As matched filter required prior knowledge about primary user's waveform but in comparison with energy detector it is still better under noisy environment. Figure 5.3 shows probability of detection in cooperative Vs non cooperative matched filter for the SU2 as discussed in Chapter 3. In Figure primary user is present under different SNR values which are received by secondary user. Results show that without cooperation SU2 is able to detect the licensed user at all values of SNR with low probability. But with cooperation it will be able to detect licensed user under high SNR values. At low SNR values it is still unable to detect licensed user. Figure 5.4 shows probability of misdetection in case of cooperative VS non cooperative. In Figure one can clearly see that SU2 miss detects the primary user at low SNR values but correctly detects at high SNR values in case of cooperation.

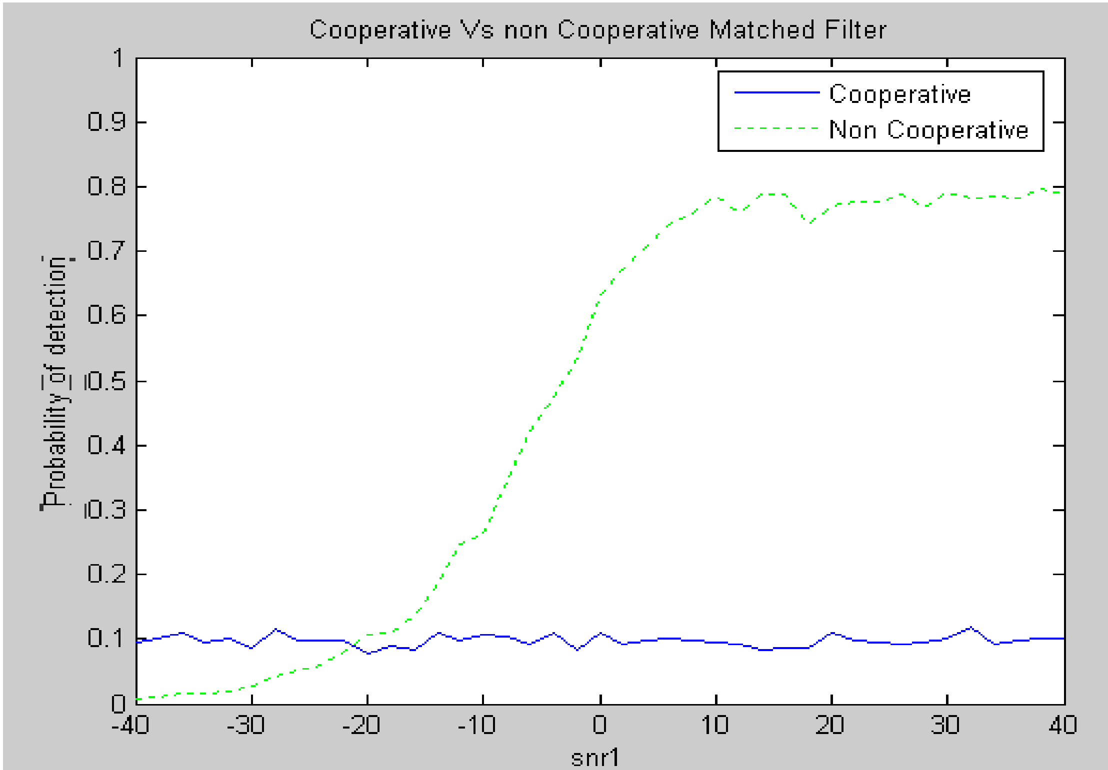


Figure 5.3 Probability of Detection Matched Filter

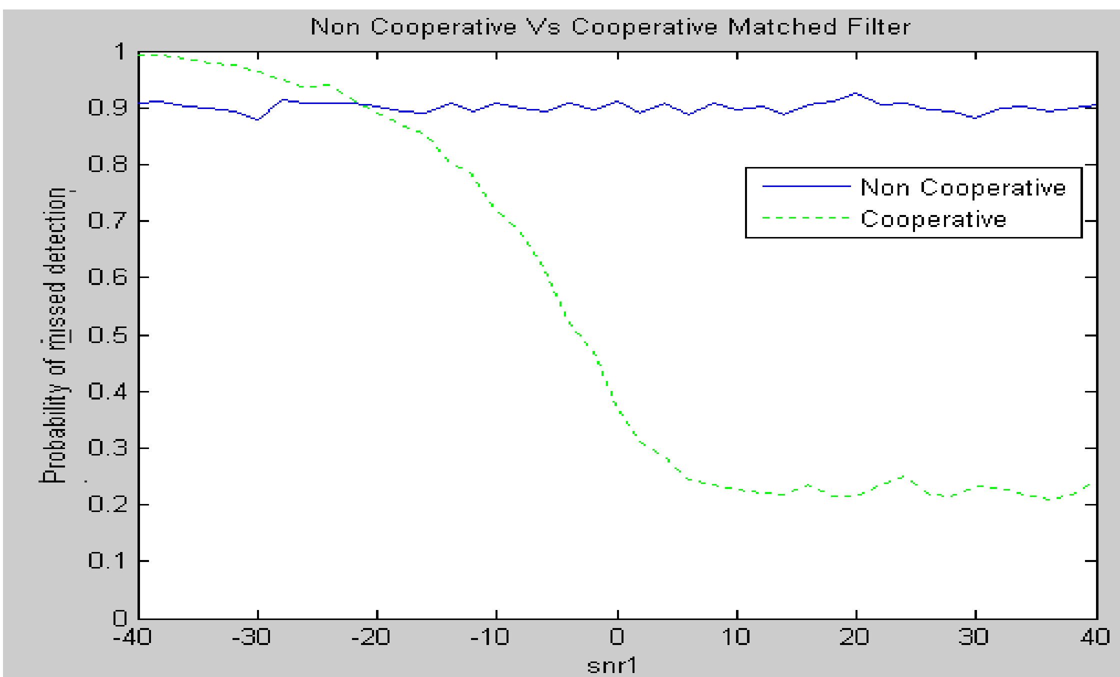


Figure 5.4 Probability of Miss Detection Matched Filter

5.2.3 Comparison of cooperative VS Non Cooperative Cyclostationary Feature Detection

Cyclostationary Feature Detector is good technique under noisy environment as it is able to distinguish between noise energy and signal energy. Figure 5.5 shows probability of detection in cooperative Vs non cooperative Cyclostationary feature detection for the SU2 as discussed in Chapter 3. In figure primary user is present under different SNR values which are received by secondary user. Results show that without cooperation SU2 is able to detect the licensed user at all values of SNR with low probability but have probability higher then matched filter. But with cooperation it will be able to detect licensed user under high SNR values. At low SNR values it is still unable to detect licensed user. Fig 5.6 shows probability of misdetection in case of cooperative VS non cooperative. In case of cooperation figure one can clearly see that SU2 miss detects the primary user at low SNR values but correctly detects at high SNR values.

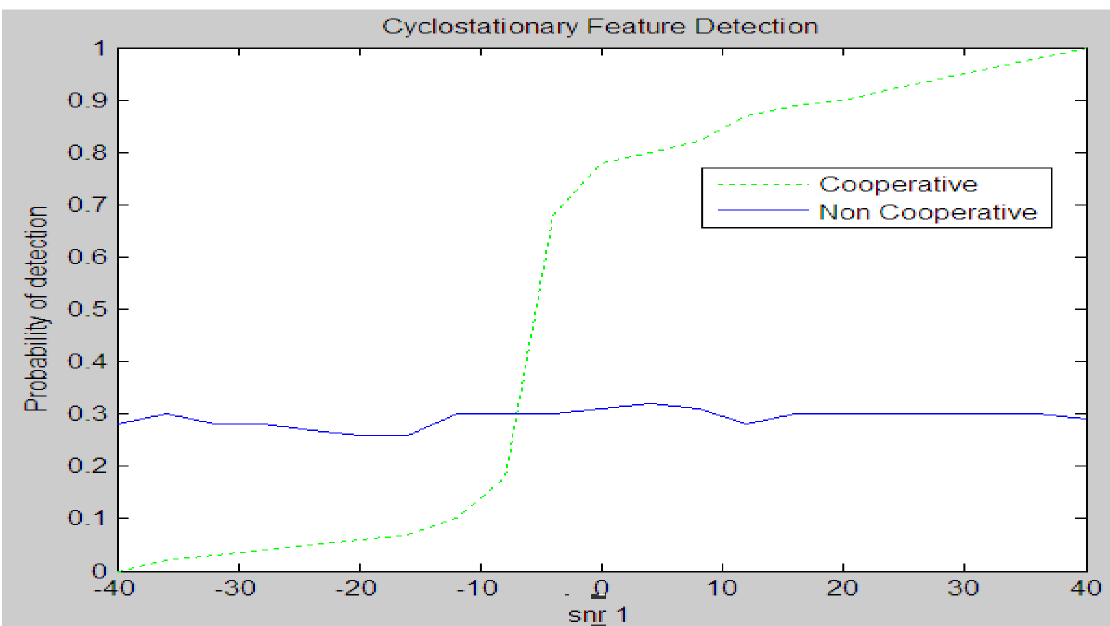


Figure 5.5 Probability of Detection Cyclostationary Feature Detection

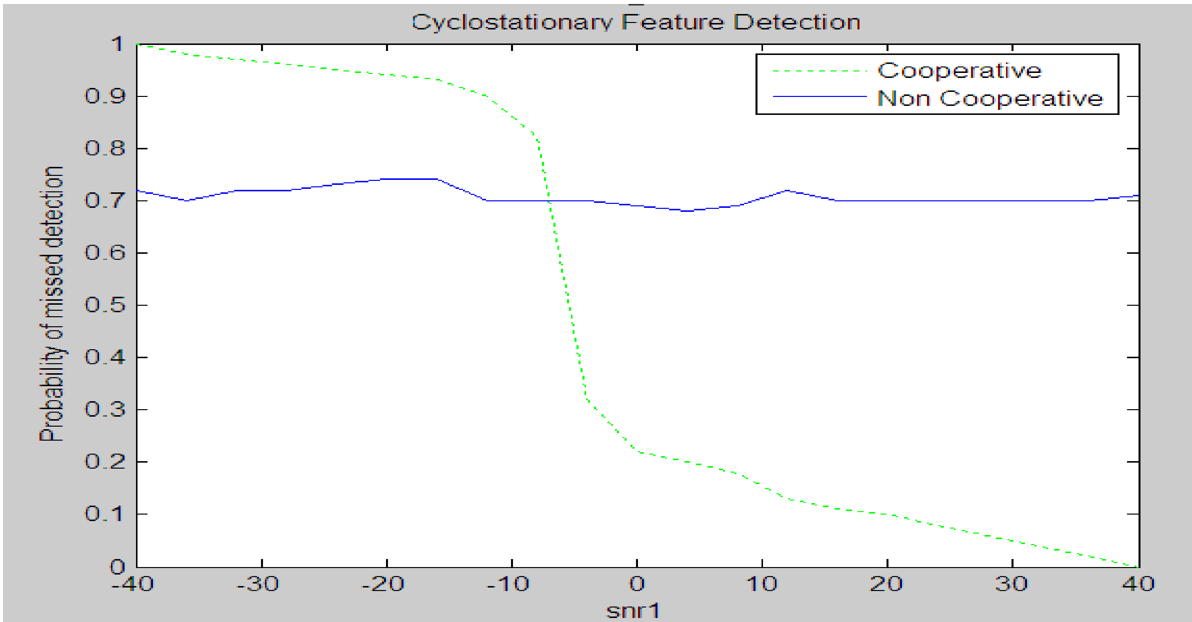


Figure 5.6 Probability of Miss Detection Cyclostationary Feature Detection

5.2.4 Comparison of cooperative VS Non Cooperative Fuzzy logic based sensing

Fuzzy logic based spectrum sensing is a technique which uses the results of all three transmitter detection based techniques. It is a good approach of sensing if sensitivity time is not important. Fig 5.7 shows probability of detection in cooperative Vs non cooperative fuzzy logic based approach for the SU2 as discussed in Chapter 3. In figure primary user is present under different SNR values which are received by secondary user. Results show that without cooperation SU2 is able to detect the licensed user at all values of SNR with low probability. But with cooperation it will be able to detect licensed user under even low values of SNR with low probability and at high SNR values detects licensed used with high probability. Fig 5.8 shows probability of misdetection in case of cooperative VS non cooperative. In case of cooperation figure one can clearly see that SU2 miss detects the primary user at low SNR values but correctly detects at high SNR values.

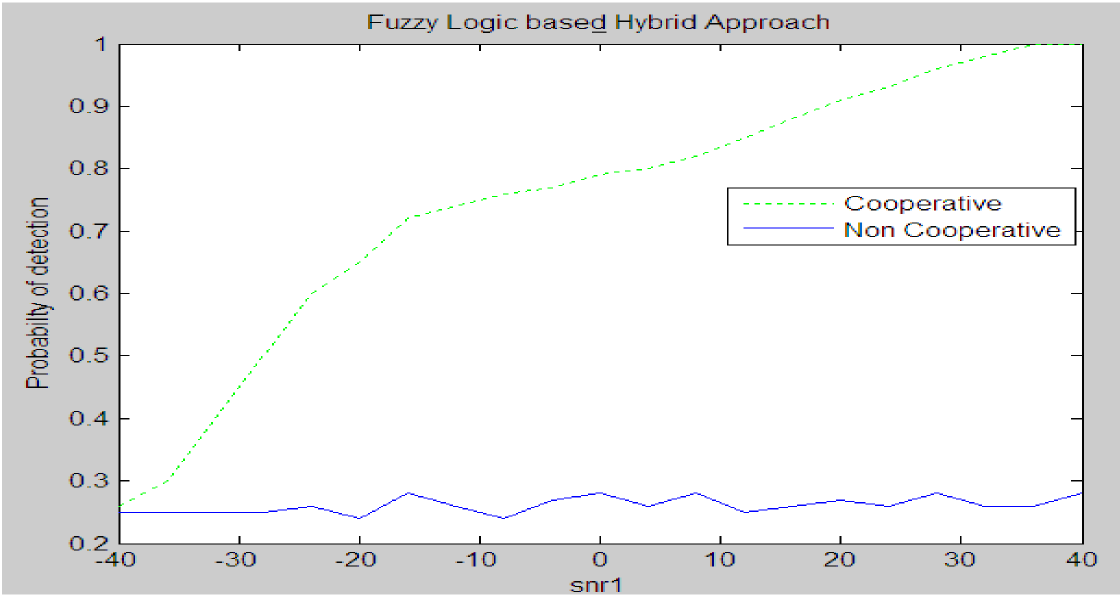


Figure 5.7 Probability of Detection Fuzzy Logic Based Approach

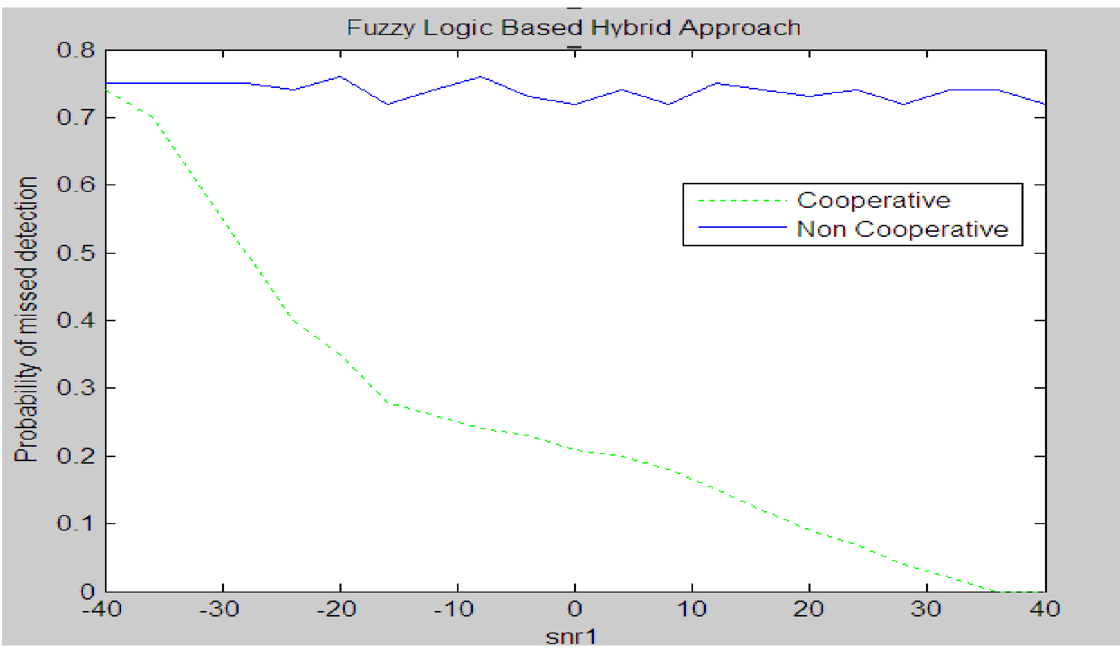


Figure 5.8 Probability of Miss Detection Fuzzy Logic Based Approach

5.3 Comparison of Cooperative Spectrum Sensing Techniques

As matched filter required prior knowledge about primary user's waveform but in comparison with energy detector it is still better under noisy environment. The major drawback of the energy detector is that it is unable to differentiate between sources of received energy i.e. it cannot distinguish between noise and primary user. So this makes it susceptible technique when there are uncertainties in background noise power, especially at low SNR. Cyclostationary Feature Detector is good technique under noisy environment as it is able to distinguish between noise energy and signal energy. Fig 5.9 shows comparison of transmitter detection techniques and fuzzy logic based approach when there is primary user is present under different SNR values. Results shows that at low SNR when primary user is present Cyclostationary and matched filtering are unable to detect primary user but energy detector still detect it. Hence, when we have no prior knowledge about primary user's waveform then best technique is Fuzzy logic based approach.

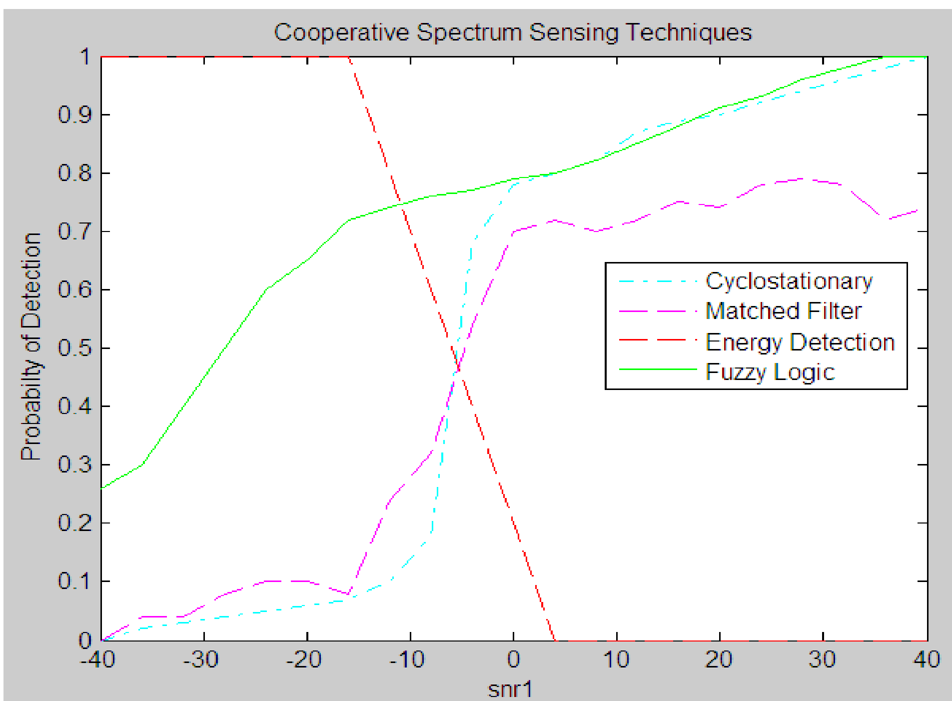


Figure 5.9 Comparison of Probability of Detection using different Techniques

5.4 Centralized Approach

There are four CR users, one licensed user and an access point for final decision. After ten times execution of energy detector under varying SNR each user come up with a credibility of detection. The methodology of computing credibility is defined in Chapter 3. Now the access point has the credibility matrix which has the credibility of each CR user. Now when ever access point received some results from CR users it will decide final results on the basis of credibility matrix as discussed in Chapter 3.

Figure 5.10 shows the credibility matrix and probability of detection for energy detector under different SNR values. In Figure one can see that under low SNR values it will detect accurately just because of high SNR values but at high SNR values it will not be able to detect.

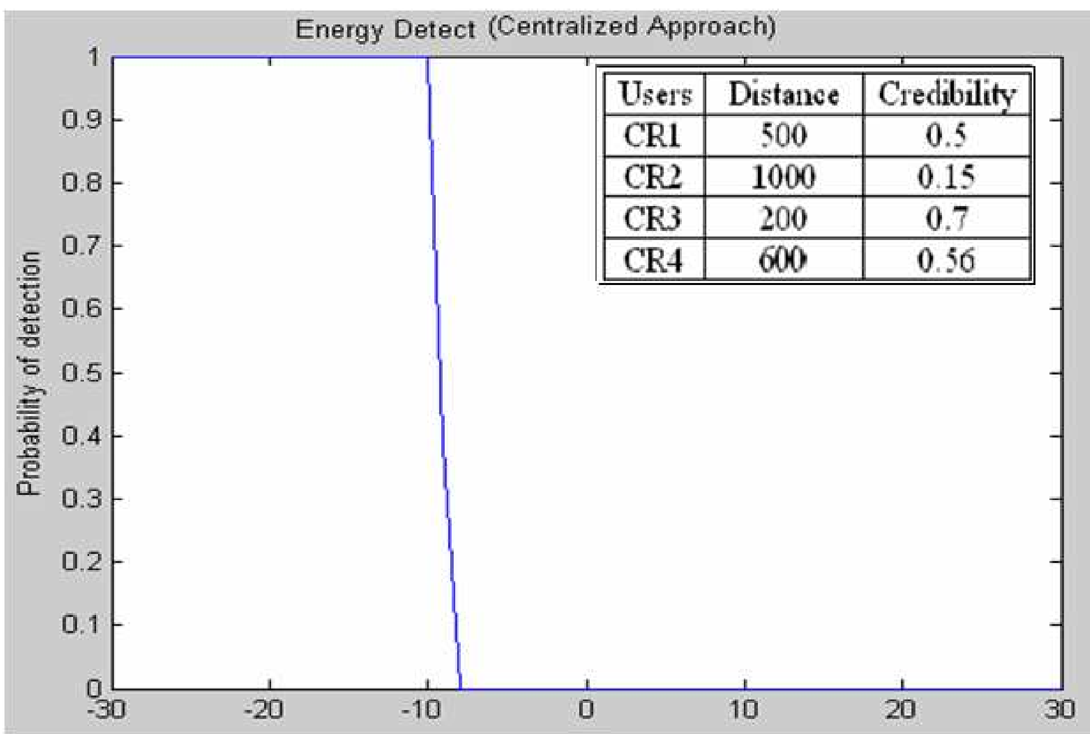


Figure 5.10 Centralized Approach, Energy Detector

Figure 5.11 shows the credibility matrix and probability of detection for matched filter under different SNR values. In Figure one can see that under low SNR values it will not be able to detect accurately but at high SNR values it will detect with quite good probability and achieve a probability level of 1 at SNR=15 dB.

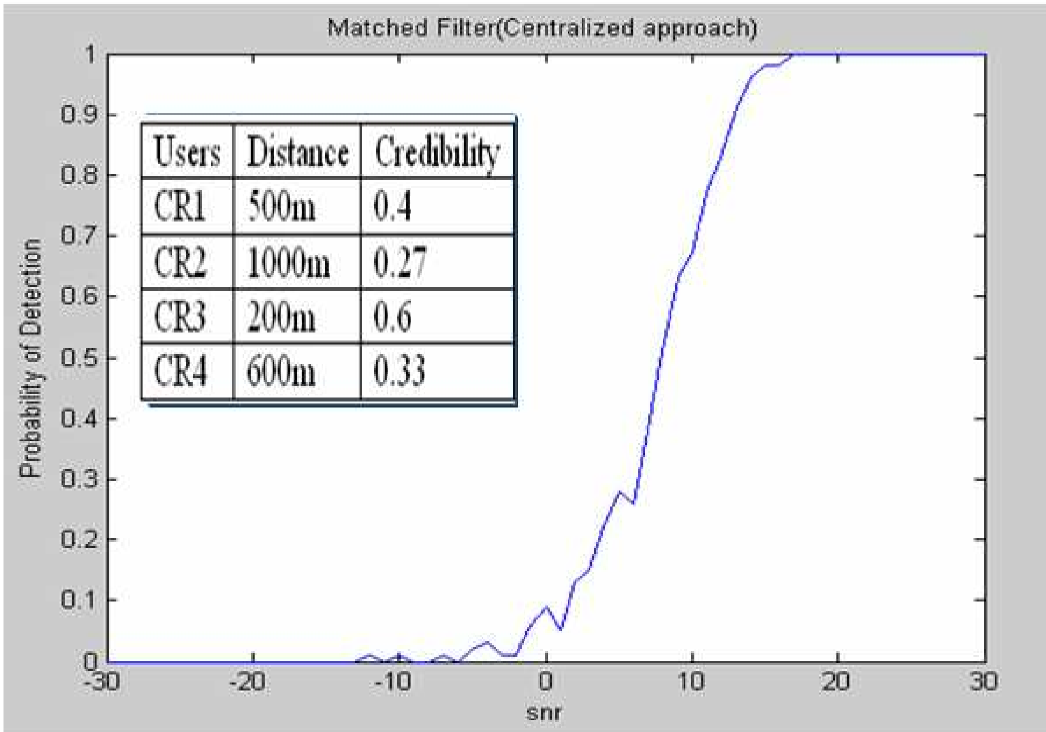


Figure 5.11 Centralized Approach, Matched Filter

Figure 5.12 shows the credibility matrix and probability of detection for Cyclostationary feature detection under different SNR values. In Figure one can see that under low SNR values it will not be able to detect accurately but at high SNR values it will detect with quite good probability which are better then matched filter in Figure 5.11 and achieve a probability level of 1 at SNR=4 dB.

Figure 5.13 shows the credibility matrix and probability of detection for Fuzzy Logic based Hybrid Approach under different SNR values. In Figure one can see that under low SNR values between -20 to 0 dB it will detect primary user with quite good probability achieve a probability level of 1 at SNR=0 dB.

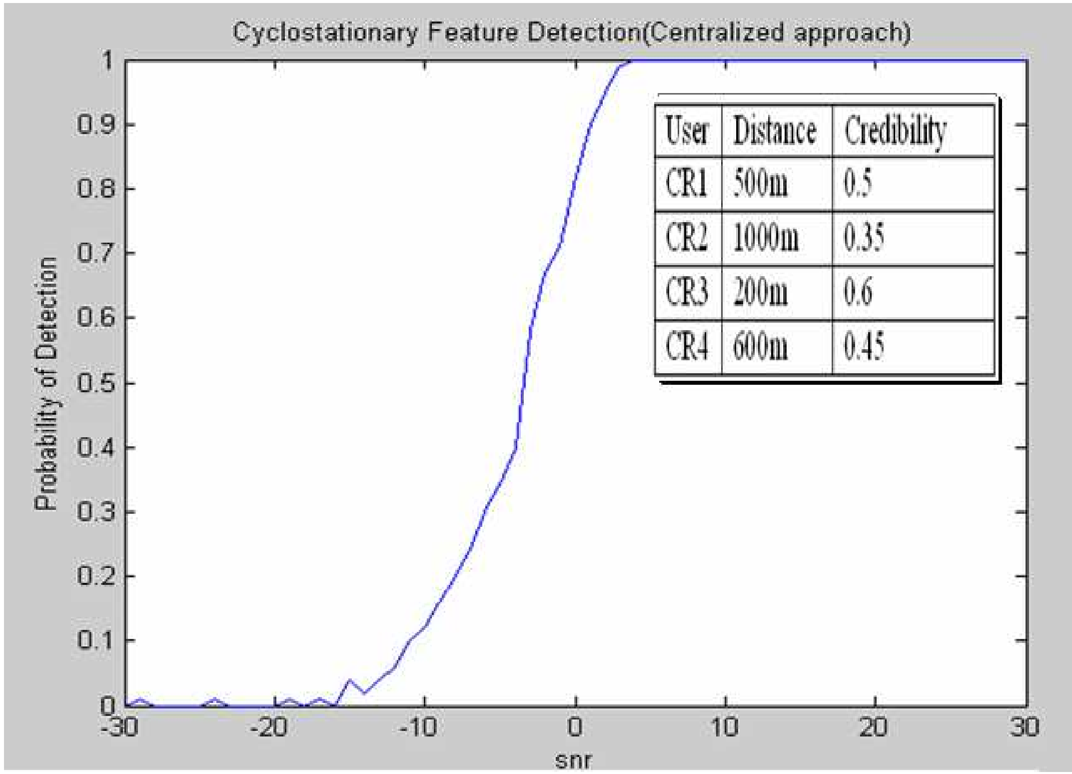


Figure 5.12 Centralized Approach, Cyclostationary Feature Detection

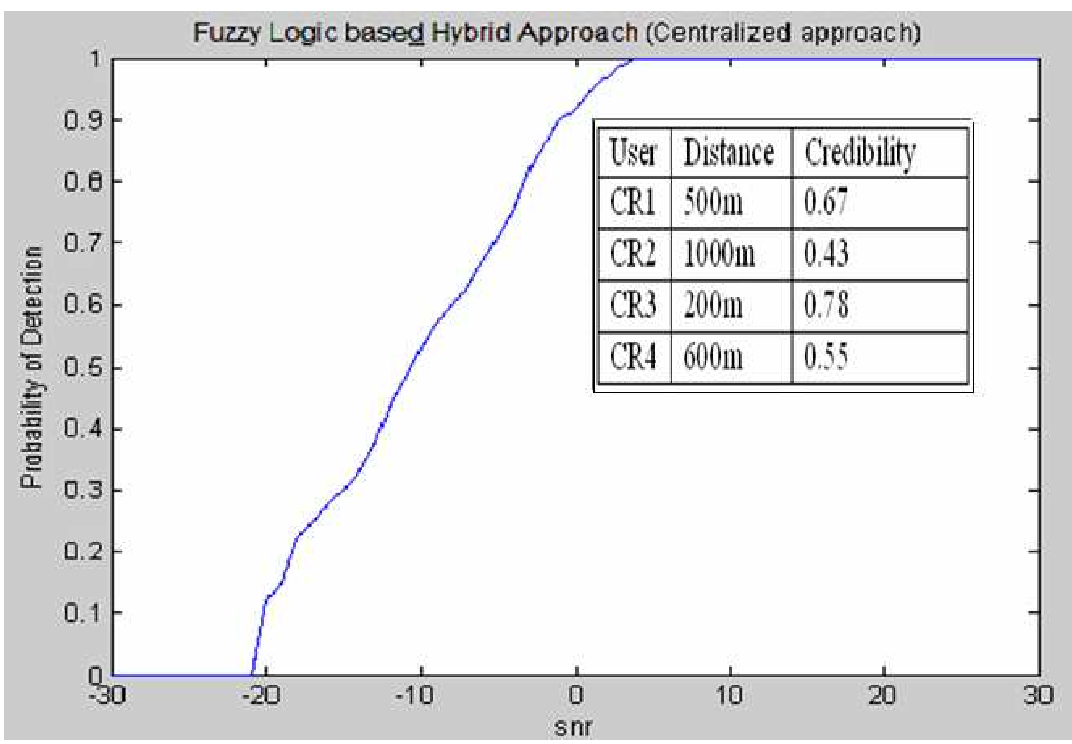


Figure 5.13 Centralized Approach, Fuzzy Logic based Hybrid Approach

5.5 Comparison of SNR walls

Figure 5.14 shows SNR walls comparisons with varying number of cooperative users. From the figure it is clear that as number of cooperative users increases SNR wall decreases. Further comparing the SNR walls for transmitter detection techniques and fuzzy logic based hybrid approach. Fuzzy based hybrid approach can achieve 0 dB SNR wall with 5 cooperative users and its good as compared to other transmitter detection techniques.

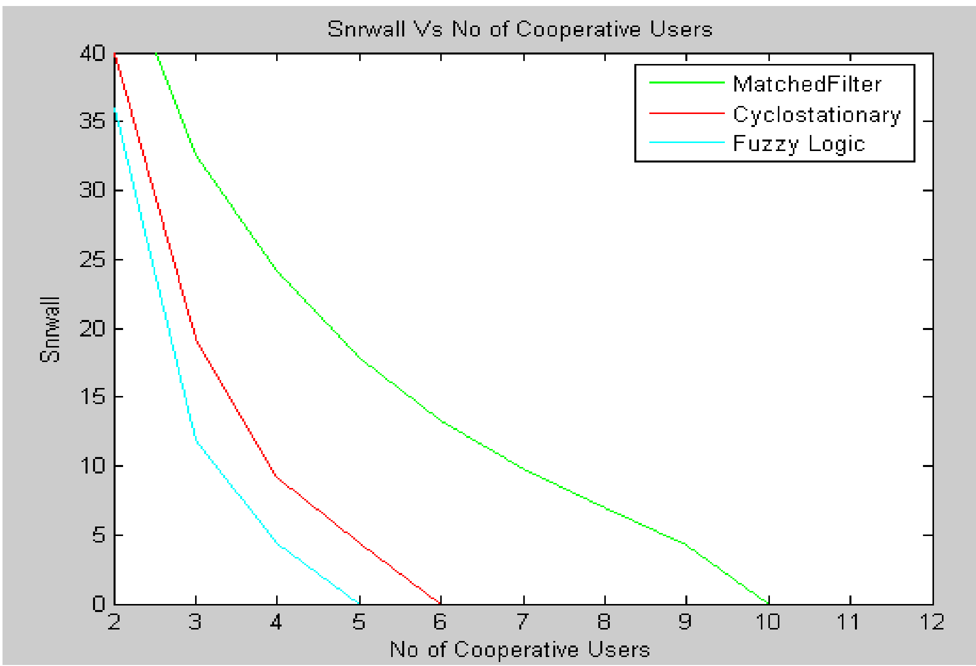


Figure 5.14 Comparison of Probability of Detection using different Techniques

5.6 Comparison of Processing Time

During communication cognitive radio continuously sense the radio environment for spectrum holes and CR can't transmit and sense at the same time. Therefore we need sensing time as small as possible.

Matched Filtering is a good technique for spectrum sensing in cognitive radio networks if we have prior knowledge about primary users waveform. But in most of cases we have no prior knowledge about primary user's waveform which makes it difficult for the use of spectrum sensing. It requires least sensing time to achieve high processing gain due to coherency.

Figure 5.15 shows that Fuzzy Logic based hybrid approach takes highest sensing time as compared with other transmitter detection techniques. Increasing the number of cooperative users will not have a great impact on the sensing time. Matched Filter has least sensing time but it will require prior knowledge of primary user's waveform.

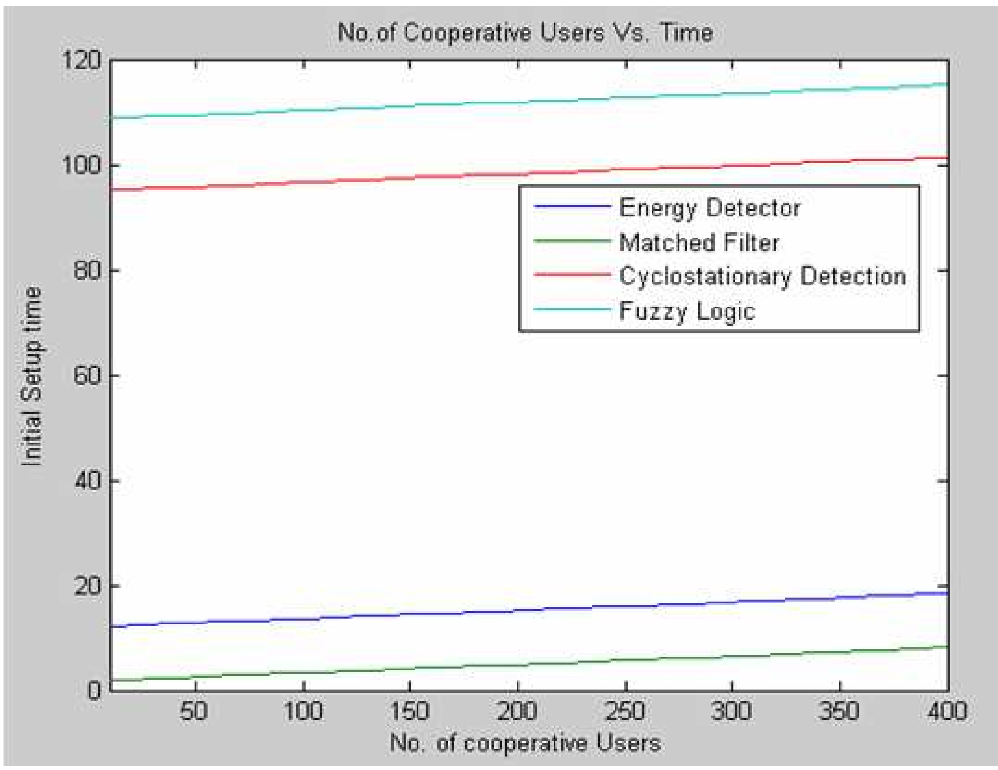


Figure 5.15 Comparison of Probability of Detection using different Techniques

5.4 Summary

This chapter provides the results of the applied technique on various types of primary user's waveforms. The result analysis clearly shows that the algorithm based detection approach has been proved to be highly successful in spectrum sensing for cognitive radio networks. The approach of having used a rule based detector for spectrum sensing using all transmitter detection techniques has made the overall system robust. In the end, the fuzzy based detection is implemented for the spectrum sensing and compared with individual techniques based on the performance.

C h a p t e r 6

CONCLUSION

6.1 Overview

In this thesis we have discussed about cognitive radio and the issues in spectrum sensing that may cause interference to primary users. We have shown some results which can mitigate these issues. The cognitive radios must adjust their power according to their distance from primary receiver protected zone. To detect the signals cognitive receiver must be highly sensitive. Agility improvement by cooperative spectrum sensing helps in vacating the frequency band faster as compared to non cooperative in which one user relays its message to other user there by reducing the detection time. Energy detection has been extensively studied in the past which can not distinguish between the signal power and the noise power so a better approach is employed based on fuzzy logic in a cooperative sensing environment to overcome the hidden terminal and exposed node problem which assumes same environment for transmitters and receivers. The results take care of the environment using path loss and propagation delay models and probability of correct detection, probability of missed detection and probability of false alarm is calculated. An increase in detection probability reduces the chances of interference with primary users. Hence, if we employ all these techniques to sense the signal in cognitive environment, better results could be achieved, thereby making a way towards efficient spectrum utilization.

6.2 Future Work

Most of the research on spectrum sensing is mainly focused on reliable sensing to meet the regulatory requirements. One of the important areas for the research is to focus on user level cooperation among cognitive radios and system level cooperation among different cognitive radio networks to overcome the noise level uncertainties. In this work, the noise level uncertainties are catered by a proper combination of spectrum sensing techniques.

Another area for research is cross layer communication in which spectrum sensing and higher layer functionalities can help in improving quality of service (QoS).

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