APPLICATIONS AND SIMULATION OF FEMTOCELLS IN A COGNITIVE RADIO ENVIRONMENT

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

Bachelor of Technology
In
Electronics and Communication Engineering

Under the guidance of

Prof. Sarat Kumar Patra

by

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Declaration

We hereby declare that this thesis is our own work and effort. Throughout this documentation wherever contributions of others are involved, every endeavor was made to acknowledge this clearly with due reference to literature. This work is being submitted for meeting the partial fulfillment for the degree of Bachelor of Technology in Electronics and Communication Engineering at **National Institute of Technology, Rourkela** for the academic session **2008 – 2012.**

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Certificate

This is to certify that the thesis entitles "**APPLICATIONS AND SIMULATION OF FEMTOCELLS IN A COGNITIVE RADIO ENVIRONMENT**" submitted by **Sumeet Kumar Dandapat (Roll no: 108EC004)** and **Guru Gaurav Ray (Roll no: 108EC034)** in partial fulfillment of the requirements for the award of **Bachelor of Technology** Degree in **Electronics and Communication Engineering** at **National Institute of Technology, Rourkela** is an authentic work carried out by them under my supervision and guidance.

Date: 14th May, 2012

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Abstract

Femtocells are small base stations that provide radio coverage for mobile devices in offices or homes. Throughout our project work we put forth a femtocell based cognitive radio architecture for enabling efficient multi-tiered access in next generation broadband wireless systems. The key requirements for femtocell deployment, its benefits, the usage model, design challenges and market issues will be investigated. This architecture combines the conventional femtocell concept with an infrastructure based overlay of a cognitive network. The merits of using a femtocell is enhanced coverage minimized interference and increased capacity. By incorporating a femtocell in a cognitive radio environment problems such as spectrum underutilization can be solve. This is achieved by allowing secondary users to use the free and available spectrum. We provide experimental results to demonstrate the feasibility of such a model. The advantages and several bottlenecks in administering this concept are also illustrated. The purpose of this project is to explore the use of femtocells in present cellular systems to provide better coverage and deal with resource allocation by employing it in a cognitive radio environment.

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List of Abbreviations

AWGN	-	Additive White Gaussian Noise
BER	-	Bit Error Rate
BPSK	-	Binary Phase Shift Keying
CFBS	-	Cognitive Femto Base Station
CFD	-	Cyclostationary Feature Detection
CP	-	Cyclic Prefix
CR	-	Cognitive Radio
CSI	-	Channel State Information
CSS	-	Cyclostationary Spectrum Sensing
DFT	-	Discrete Fourier Transform
ED	-	Energy Detection
FCC	-	Federal Communications Commission
FFT	-	Fast Fourier Transform
ISI	-	Inter Symbol Interference
P_d	-	Probability of Detection PU - Primary Users
P_f	-	Probability of False Detection
PSD	-	Power Spectral Density
QPSK	-	Quadrature Phase Shift Keying
RKRL	-	Radio Knowledge Representation Language
SCF	-	Spectral Correlation Function
SH	-	Spectrum Holes
SNR	-	Signal to Noise Ratio
SU	-	Secondary Users

Introduction

Unlicensed spectrum is becoming increasingly scarce, especially those under 3 GHz. The Federal Communications Commission (FCC)'s statistics reveal that many frequency bands are being allocated to multiple users, overlapping each other. The two major limitations of wireless communication are range and capacity. The initial cellular systems were designed for a single application, voice, but today with the advent of third-generation (3G) cellular systems, users expect good quality of voice, uninterrupted voice calls, clear video images and faster downloads. Femtocells provide a good solution to overcome indoor coverage problems and also to deal with the traffic within Macro cells. They provide reliable and high quality of service to all customers. Using Femtocells along with cognitive radio architecture leads to efficient use of bandwidth as unused primary channels are allocated to secondary users to evade data traffic. Cognitive Radio (CR) has been highlighted as a possible candidate in improving spectrum utilization by providing opportunistic spectrum access. A cognitive radio can be defined as a radio that is able to sense the spectral environment over a wide frequency, and exploit this information to opportunistically provide wireless links that best meet the user's communication requirements. This project aims to investigate the various spectrum sensing techniques and its application in a Femtocell network. The project layout combines the conventional Femtocell concept with an infrastructure based overlay of a Cognitive Network to unwind limitless possibilities in the field of Opportunistic Spectrum Sensing. By incorporating a Cognitive-Femtocell, spectrum utilization can be optimized along with enhanced coverage, minimized interference, and better spatial correlation between capacity need and infrastructure.

Brief Overview of Femtocells

Chapter 1

1.1 Introduction

A femtocell serves as a small range and consumer installed data access point situated around high user density hotspots serving stationary or low mobility users. Typically the range of a Femtocell is 10-50m. Users transmitting to femtocells experience superior signal reception and lower the transmitting power, consequently prolonging battery life. Femtocells are judiciously placed in traffic hotspots improving network capacity and quality of service (QoS), high user capacity can be ensured by higher re-use through femtocells and interference avoidance by way of antenna sectoring and time hop CDMA to each tier.

Deployment of femtocells proves to be beneficial for operators in the sense that cost gets optimized along with enhanced coverage. The subscriber satisfaction improves due to better spatial correlation between capacity need and infrastructure. Reliability of the microcell gets assured as well.

User advantages include, low power transmission which results in a prolonged battery life. Better indoor reception cheaper services are collateral benefits as well. Overall the bandwidth subscribed for is used more effectively. Initial investment costs may be high as this technology is fairly new. Broadband may get congested due to backhauling. IP security is also an issue which must be paid heed to.

1.2 Femtocell Handoff

The ability to seamlessly switch between the femtocell and the macrocell networks is a key driver for femtocell network deployment. The handover procedures are basically divided into two phases: handover preparation phase (information gathering, handover decision), and handover execution phase. During the information gathering phase, the transceiver collects information about the handover candidates, and authentications are acquired for security reasons. In handover decision phase, the best handover candidate is determined. Finally, after deciding to perform the actual handover, the mobile station (MS) initiates to connect with a new access point.

1.3 Evolution of Wireless Technology

Characteristics	**2G**	**3G**	**4G**
Frequency Band	350-1900 MHz	1.8-2.5 GHz	2-8 GHz
Bandwidth	200KHz	5-20 MHz	5-20 Mhz
Data Rate	56-115 Kbps	Upto 2 Mbps	Upto 20 MBps
Access	TDMA, CDMA	Wideband CDMA	Multi-carrier-CDMA or OFDM

Table 1

1.4 Capacity of a Femtocell by Shannon's Law

$$C = B \log_2 \left(1 + \frac{S}{N}\right)$$

C – Channel Capacity of white band limited Gaussian Channel.

B – Bandwidth of spectrum

S – Signal Strength

N – Additive Noise

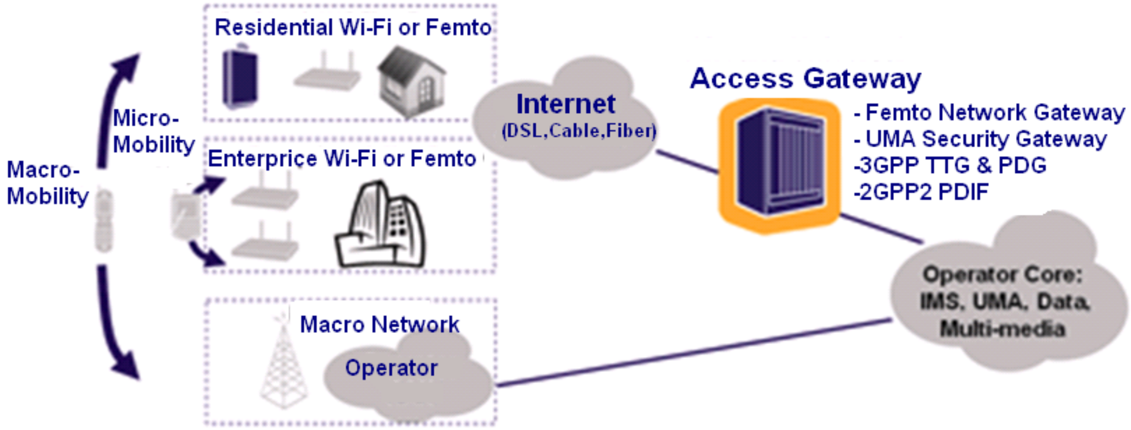

Figure 1: *Implementation of a Femtocell*

1.5 <u>Propagation Models</u>

1.5.a <u>Empirical Model</u>

These are based on statistics and measurements. They do;;t require the knowledge of geometry of surroundings because the reflections and diffractions aren't computed. In this approach only distance between emitter and receiver have to be taken into account, the loss L in dB at a distance d of the emitter can be estimated with

$$L = 10\,\mathrm{n}\log(d) + C$$

Both the constant values C which represents the system losses and the parameter 'n' which is path loss exponent, depend entirely on kind of environment.

1.5.b <u>Semi Empirical Model</u>

Typical values of Attenuation

Main Wall (Concrete)	15 dB
Inner Wall (Plaster)	5 dB
Window (Glass)	1.5 dB
Door (Wool)	0.5 dB

Table 2

2.1 Introduction

The Federal Communications Commission (FCC) is an independent United States governing agency, responsible for regulation of interstate telecommunication, management and licensing of electromagnetic spectrum and it imposes requirements on inter-station interference in all radio frequency bands. They license segments to individual users in specific geographic areas. With the recent boom in wireless technologies like Bluetooth, Wi-Fi, WiMax, ZigBee, and LTE, these unlicensed bands have become crowded. Due to the growing paraphernalia of such emerging technologies, unlicensed spectrum less than 3 GHz is becoming increasingly scarce and therefore Cognitive Radio is a possible candidate in improving opportunistic spectrum allocation.

The term Cognitive Radio was initially coined by Joseph Mitola in the year 1999.He expressed it as – "*The point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs.*" The essential premise of this concept is to let people utilize licensed bands, provided they can ensure interference perceived by the primary license holders will be minimal. It offers a novel way to solving spectrum underutilization problems. It does this by sending the radio environment with a twofold objective – (a) Identifying the sub-bands of the radio spectrum that are underutilized by Primary User (b) Providing means for making those bands available for use by subserviced secondary user.

The primary keywords dealt within this chapter are awareness, intelligence, learning, adaptively, reliability, and efficiency. Cognitive Radio learns from the environment and adapts its performance for each transceiver to statistical variations in the incoming RF stimuli. It controls the communication processes among competing users through the proper allocation of available resources.

IEEE defines a Cognitive Radio as -*"A radio frequency transceiver that is designed to intelligently detect whether a particular segment of the radio spectrum is currently in use and to jump into (and out of as necessary) the temporarily used spectrum very rapidly, without interfering with the transmission of other authorized users."*

In the early days of communication, there were fixed radios in which the transmitter parameters were fixed and set up by their operators. The new age of communication includes Software Defined Radio (SDR). A SDR is a radio that includes a transmitter in which the operating parameters including the frequency range, modulation type or maximum radiated or conducted output power can be altered by making a change in software without making any hardware changes. SDR is used to reduce hardware requirements; it gives user a cheaper and steadfast solution. Cognitive Radio (CR) is newer version of SDR in which all the transmitter parameters change like SDR but it will also change the parameters according to the spectrum availability.

2.2 Terminology

Spectrum Hole (SH):

A spectrum hole is a vacant band of frequencies present in the band assigned to a primary user at a particular time and specific geographic location. Primary Users are those holding licensed channels or primary bands. Depending on the current interference and the interference temperature on the previous iterations all channels can be classified into three types of spectrum holes**- (a)** White Spectrum Holes (Not fully used) **(b)** Grey Spectrum Holes (Partially used) **(c)** Black Spectrum Holes (Fully used)

After the sensing process is completed, the secondary users will be allowed to liberally use the white holes and moderately use the gray holes in a way that will not interfere with the primary user. However they will not be allowed to use the black holes, because these holes are expected to be fully used and any extra use will interfere with the ongoing communication in them.

Reactive Sensing:

This type of sensing is initiated only when the user has data to send, thus it is an on-demand sensing. If no user was found then the user will wait for a predefined period of time and then restart sensing again. This technology reduces overhead but data is delayed until sensing is performed with good accuracy.

Proactive Sensing:

This type of sensing is done periodically even when the user does not intend to send any data. The time between successive sensing operations is called as sensing period. The delay is decreased substantially since users know the holes beforehand. However, a lot of time and effort is utilized in sensing even when it's not needed, thus increasing sensing overhead.

Interference Temperature:

Interference Temperature is the degree of sensed power in a particular frequency band. Two important limits can be obtained - **(a)** Maximum Level where any signal exceeds threshold level and thus that band cannot be used. **(b)**Minimum level where any signal below it can be neglected and thus that certain band can be used.

Primary user:

They are defined as users of primary network who have a license to operate in a certain spectrum band. Hence, they should not be affected by the interference of any unlicensed user or user of any other network. Therefore, primary users do not need any change for coexistence with Cognitive Radio base-stations or secondary users.

Secondary Users:

Cognitive Radio user or secondary user has no spectrum license for its operation so some additional functionality is required to share the licensed spectrum band. A secondary user can access the licensed band if either of the following two constraints is adhered to:

Either **(a)** there is a maximum interference level that the primary system is willing to tolerate and the secondary user must adjust within this limit, hence both primary and secondary users can transmit within the same band simultaneously, or **(b)** secondary users are allowed to opportunistically access the spectrum on the basis of no-interference to the primary (licensed) users. These two paradigms fit into what is commonly known as *hierarchical-access schemes*.

Radio Knowledge Representation Language:

Software Radio is a dynamic technology that provides a platform for flexible radio systems, multi-service, multi-standard, multi-band, reconfigurable and reprogrammable by software for PCS. Cognitive radio extends the software radio with radio-domain model-based reasoning about such radio etiquettes enhancing the diversity of personal services through a Radio Knowledge Representation Language (RKRL).

2.3 Cognitive Radio tasks

The cognition cycle can be divided into three tightly interconnected tasks:

- Radio Scene Analysis
- Channel Identification
- Transmit Power control and dynamic spectrum management

2.3.a Radio Scene Analysis

- Estimation of interference temperature of the radio user
- Detection of Spectrum Holes

2.3.b Channel Identification

This stage encompasses estimation of Channel State Information (CSI) and prediction of channel capacity for use by transmitter. CSI refers to recognizable channel properties of a communication channel. This information describes how a signal propagates from the transmitter to the receiver and represents the collective effect. For example, fading, scattering, and power decay with distance. The CSI makes it possible to adapt transmission to current channel conditions which is decisive for achieving reliable communication with high data rates in multi-antenna systems. CSI needs to be approximated at the receiver end , and is typically quantized and fed back to the transmitter.

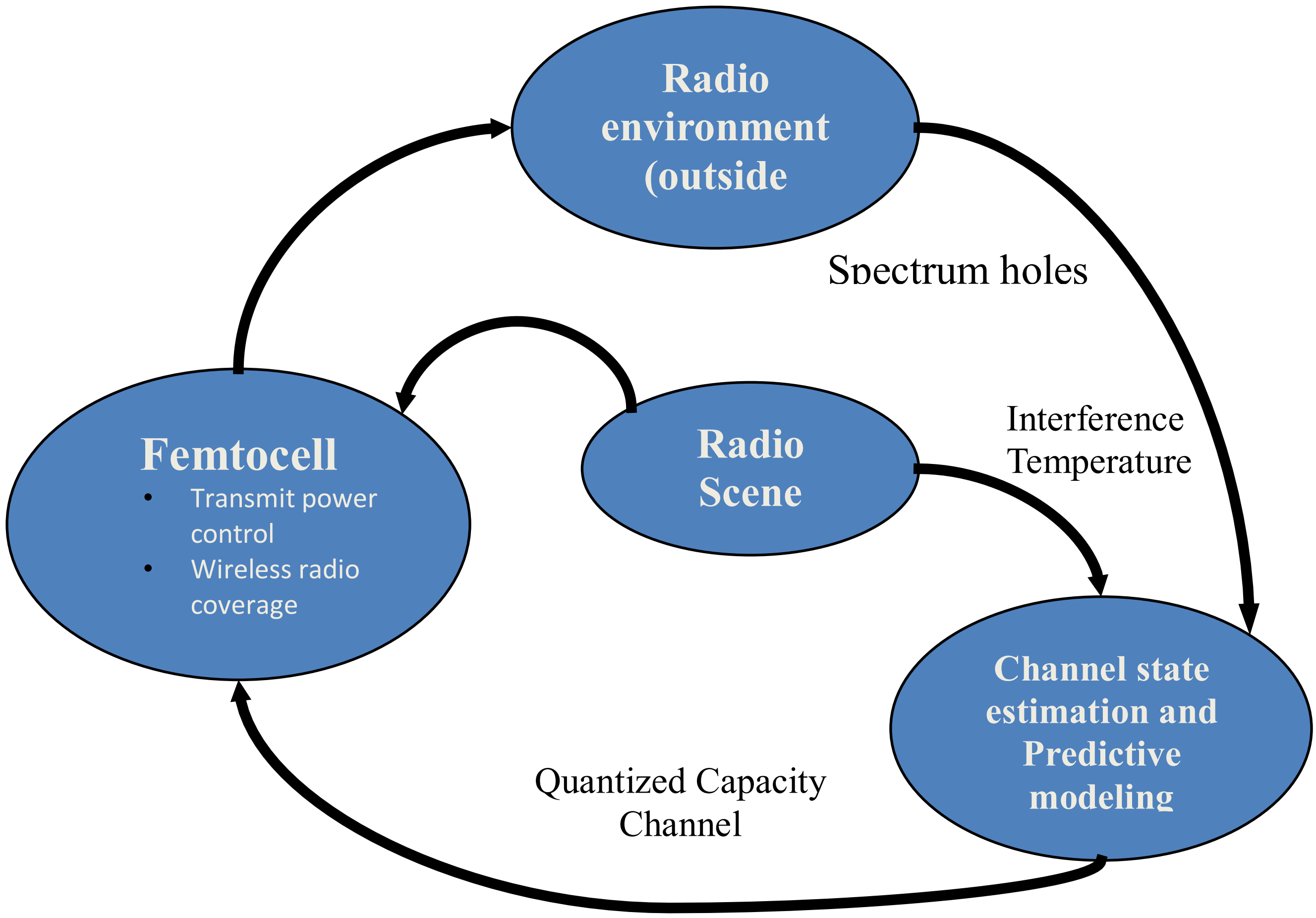

Figure 2.1: *Basic Cognitive Cycle*

2.3.c <u>Transmit Power Control and Dynamic Spectrum Management</u>

During Radio Scene Analysis different radio configurations are probed to estimate interference temperature and to detect spectrum holes. Along with transmit-power control, dynamic spectrum management is performed in the transmitter. These two tasks are closely related to each other. They carry out the role of multiple-access control in the basic cognitive cycle above. The primary purpose of spectrum management is to develop an adaptive strategy for the resourceful and effective deployment of the RF spectrum. Specifically, the spectrum-management algorithm is intended to do the following: Building on the spectrum holes detected by the radio-scene analyzer and the output of transmit-power controller, select a modulation strategy that adapts to the time-varying conditions of the radio environment meanwhile assuring dependable communication across the channel. Communication reliability is guaranteed by choosing the SNR gap large enough as a design parameter.

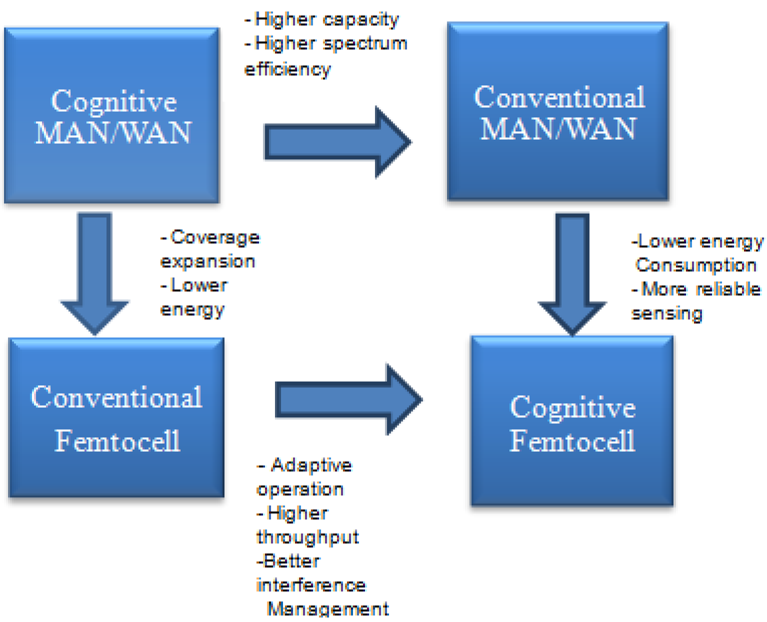

Figure 2.2: *Access modes and Network Matrix*

This architecture allows more advanced machine learning and identity-based spectrum sensing. Since the CFBS manages the traffic backhauling from the PUs and allocation of spectrum resources to the SUs, it can train itself on the traffic pattern of both PUs and SUs. Traffic prediction and modeling is a fundamental ability in order to allocate spectrum resources efficiently. Briefly, if the CFBS had precise knowledge of current and future spectrum usage pattern, it would be trivial to allocate white spaces. SUs would access the spectrum whenever there is no traffic and would vacate the band just before the spectrum band is occupied. Although this exact knowledge is impossible, it can be approximated utilizing accumulated information and applying various prediction methods. For instance, in CR nodes the residual idle and traffic of primary WLAN channels are estimated using the theory of alternating renewal processes. In this model each PU channel is considered to follow up and down periods in a renewal cycle that correspond to busy and idle channel states, respectively. Cognitive Radio systems estimate the call arrival rate and call holding time using an algorithm that exploits the periodicity of the PU traffic process.

3.1 Introduction

In a radio environment there are many primary users present at some particular time. At any one instant different primary user from different technologies can also be there. The ultimate objective of the cognitive radio is to obtain the best available spectrum information through cognitive capability and reconfigurability. Since there is already a shortage of spectrum, the most important challenge is to share the licensed spectrum without interfering with the existing transmission of the licensed users. The cognitive radio enables the usage of temporarily unused spectrum, which is referred to as spectrum hole. If this band is later on used by a licensed user, the cognitive radio moves to another spectrum hole or stays in the same band, altering its transmission power level or modulation scheme to avoid any interference. The cognitive capability of a cognitive radio enables real time interaction with its environment to determine appropriate communication parameters and adapt to the dynamic radio environment. Spectrum Sensing is necessary for knowing whether or not the primary user is present in the channel at a particular instance. Based on this decision a secondary user can be given a vacant spectrum band for temporary use. Detection is mainly concerned with particular features such as modulation type and operating frequency. Primarily there are three primary user detection techniques:

- Matched Filter
- Energy Detection
- Cyclostationary Feature Detection

3.2 Feature Extraction

Once feature detection is applied, certain features are extracted from Primary User waveform for purpose of classification. Information like operating frequency, modulation type, and data rate of each waveform can be obtained.

If the inputs coming from each technique is mapped to these values then if the summation is more than or equal to 1.5 then a primary user is present.

3.2.a Transmitter of Primary Users

First of all we need a primary user waveform on which we can apply different spectrum sensing techniques. Transmitter can have different transmitting parameters like operating frequency and modulation scheme.

Step 1- The system parameters are set up as follows:

- Sampling frequency
- SNR
- Number of samples

Step 2- Input must be given by user i.e. any sequence of bits, text, or default is kept incase user decides not to give input.

Step 3- Here number of sample as ‘L’ is fixed as MATLAB simulation must resemble a real world continuous signal to the nearest.

Step 4- Modulation is done to create the signal ready for transmission through the channel. Here BPSK and QPSK are the two viable options.

Step 5- The channel noise is assumed to be Additive White Gaussian with signal strength 2dB. In MATLAB AWGN function can be directly used for this purpose.

3.2.b Fuzzy Logic Based Confidence Table

The sensing accuracies of the three techniques can be categorized as High = 1; Medium = 0.5; Low = 0.All three methods are used in succession and a confidence table is made for decision regarding presence or absence of primary user. If the inputs coming from each technique is mapped according to these values and the summation is more than or equal to 1.5 then a primary user is present and for all other cases it is absent.

Matched filtering	**Energy detector**	**CFD**	**Decision**	**Matched filtering**	**Energy detector**	**CFD**	**Decision**
0	0	0	Absent	0.5	1	0	Present
0	0	0.5	Absent	0.5	1	0.5	Present
0	0	1	Absent	0.5	1	1	Present
0	0.5	0	Absent	1	0	0	Absent
0	0.5	0.5	Absent	1	0	0.5	Present
0	0.5	1	Present	1	0	1	Present
0	1	0	Absent	1	0.5	0	Present
0	1	0.5	Present	1	0.5	0.5	Present
0	1	1	Present	1	0.5	1	Present
0.5	0	0	Absent	1	1	0	Present
0.5	0	0.5	Absent	1	1	0.5	Present
0.5	0	1	Present	1	1	1	Present
0.5	0.5	0	Absent				
0.5	0.5	0.5	Present				
0.5	0.5	1	Present				

Table 3

3.3 BPSK (Binary Phase Shift Keying)

BPSK is the simplest form of phase shift keying (PSK). It uses two phases which are separated by 180°.This modulation is the most robust of all the PSKs since it takes the highest level of noise or distortion to make the demodulator reach an incorrect decision. It is, however, only able to modulate at 1 bit/symbol. It is simple to realize and a common technique chosen for signal modulation. In most cases a NRZ encoder is used to create a bipolar message signal.

$$s_m(t) = \sqrt{\frac{2E_b}{T_b}}\cos\big(2\pi f_c t + \pi(1-m)\big), m = 0,1$$

This yields two phases, 0 and π. In the specific form, binary data is often conveyed with the following signals:

$$s_0(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t + \pi) = -\sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t)$$

$$s_1(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t)$$

Where, f_c is the frequency of the carrier-wave.

Hence, the signal-space can be represented by the single basis function.

$$\phi(t) = \sqrt{\frac{2}{T_b}}\cos(2\pi f_c t)$$

3.3.a Bit Error Rate

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \text{ or } P_b = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right)$$

The bit error rate (BER) of BPSK in AWGN can be calculated as above. Since BPSK has only one bit per symbol this is also the symbol error rate.

3.4 Energy Detection Method

When information about the presence of Gaussian noise is available, then this is a suitable technique for spectrum detection. Energy Detection is the most widespread way of spectrum sensing because of its minimal computational and implementation complexities. It is a more generic method as the receivers do not require any prior knowledge on the primary user's signal. The input band pass filter selects the center frequency and bandwidth of interest. The filter is followed by a squaring device to measure the received signal energy. Subsequently, the integrator determines the observational interval T. Finally the output of the integrator is compared with a threshold λ to decide whether primary user is present or not. In later parts of this chapter we will deal with how the threshold value is calculated statistically.

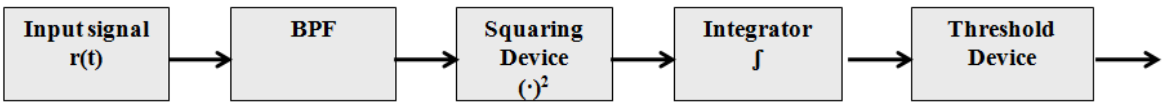

Figure 3.1: *Block Diagram of Energy Detector*

The simplest detection technique for spectrum sensing is Energy Detection. It 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. One of the main problems of energy detection is that performance is susceptible to uncertainty in noise power. It cannot differentiate between signal power and noise power. It just tells us about the presence or absence of a Primary User.

3.4.a SNR Wall Concept

The energy detector system with noise 'N' trying to detect low signals (<< 0 dB SNR) is subject to a fundamental limit under which signals are impossible to detect. It is given as follows:

$$SNR_{wall} = 10\log_{10}\left[10^{(N/10)} - 1\right] dB$$

3.4.b Adaptive Window Technique

A cognitive radio is often 'blind' in the sense that it has no prior knowledge about incumbents. This often means that the window size chosen for energy detector may not be appropriate. As a result energy detector often fails if its signal is narrow compared to the detector window or if only a small fraction of the signal is captured within the window. An energy detector that can selectively sub-divide large windows into finer ones can trade the minimum detectable bandwidth with possible increase in sensing time. The weakness of the conventional energy detector when using narrow or partial signals is demonstrated in the PSD showing frequency bands of 195MHz to 203MHz.

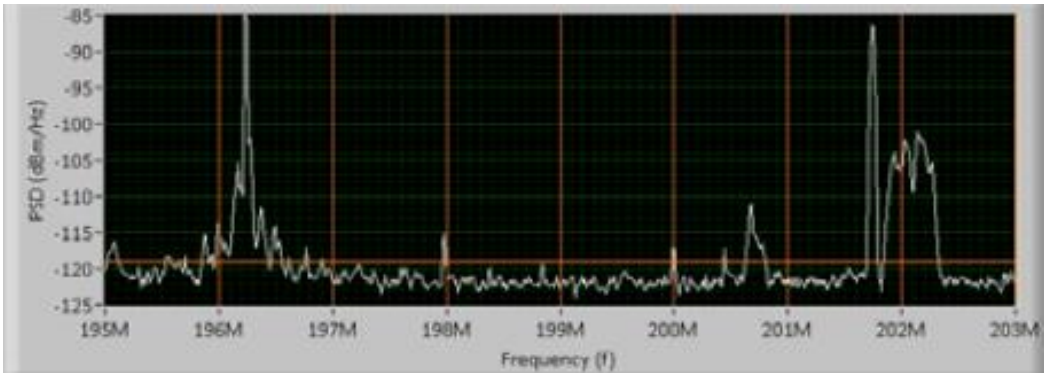

Figure 3.2: *Windowed analysis of a particular detected signal*

Assuming no prior information of the incumbents, the system uses a 1MHz window for energy detection. The window 1,3,4,5 and 6 shown above are free. However, it is evident which windows contain substantial signal strength. While these signals are present, they occupy a band that is narrow compared to the energy detector. The total power in the window is not sufficient to rise above the threshold value.

The three possible methods to alleviate this problem are:

- Lowering the Threshold
- Choosing a window comparable in size to signal under detection
- Narrowing the Detector window

Lowering the threshold increases the P_f (probability of false detection), leading to an unstable radio system. Selecting a window size closer to the signal under detection requires prior knowledge of incumbents, something the CR often doesn't have. Using a narrow detector window combats the problem at the cost of prolonging sensing time.

The adaptive Energy Detector normalizes the threshold to dB/Hz; it performs the preliminary scan of the PSD within the detector window and does a sub-division if necessary. If peaks exist above the normalized threshold and wider than the least detectable bandwidth, then the detector automatically subdivides the current window under observation into N number of sub windows. The minimal detectable signal bandwidth is limited by the frequency resolution (f_r) of the Fast Fourier Transform (FFT).

The number of subdivisions is:

$$N = \frac{B}{f_r}$$

The Energy Detection of each sub-window is completed and the collective result is used in the detection decision criteria

$$D = E_0 \vee E_1 \cdots \vee E_{N-1}$$

Where, D is the decision variable and E_i is the decision of the i^{th} window.

3.4.c <u>Calculation of Threshold Value</u>

The threshold value to be used in the detection decision criteria can be statistically calculated from the distribution density curves of Probability of False Detection and Probability of Missed Detection. Both of these cases need to be considered when spectrum sensing. Using the decision rule described earlier, it is evident that sometimes a signal is erroneously detected even when it is not present.

The Probability of False Alarm is:

$$P_{\varepsilon_0} = \int_{\mu}^{\infty} \frac{1}{\sqrt{2\pi}\sigma} e^{-y^2/2\sigma^2} dy$$

Similarly, the Probability of Missed Detection is:

$$P_{\varepsilon_1} = \int_{-\infty}^{\mu} \frac{1}{\sqrt{2\pi}\sigma} e^{-(y-A)^2/2\sigma^2} dy$$

Letting P_0 and P_1 be the source digit probabilities of zeros and ones. We can define the overall probability of error to be:

$$P_\varepsilon = P_0 P_{\varepsilon_0} + P_1 P_{\varepsilon_1}$$

In the equiprobable case this becomes,

$$P_\varepsilon = \frac{1}{2}\left(P_{\varepsilon_0} + P_{\varepsilon_1}\right)$$

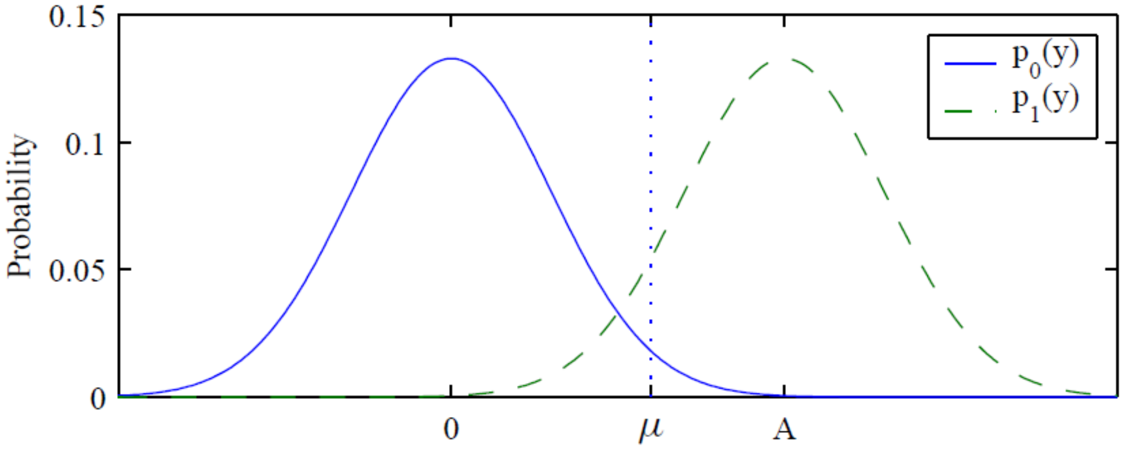

Figure 3.3: *Probability Distribution Curves of P_f and P_{md}*

The sum of these two errors will be minimized for $\mu = A/2$. This sets the threshold for a minimum probability of error for $P_0 = P_1 = 1/2$

Overall Probability of error is:

$$P_\varepsilon = \int_{A/2}^{\infty} \frac{1}{\sqrt{2\pi}\sigma} e^{-y^2/2\sigma^2} dy$$

This may be written in a more useful form by using $S = A^2/2$ and noise power $N = \sigma^2$

$$P_\varepsilon = \mathbf{erfc}\sqrt{\frac{S}{2N}}$$

3.4.d ED Sensing Algorithm

1. Apply FFT to received discrete time samples over a certain observation window.
2. Use FFT to calculate an average Power Spectral Density (PSD) function for ED
3. Use a decision threshold to detect signal and estimate the carrier frequency by finding center frequency of PSD

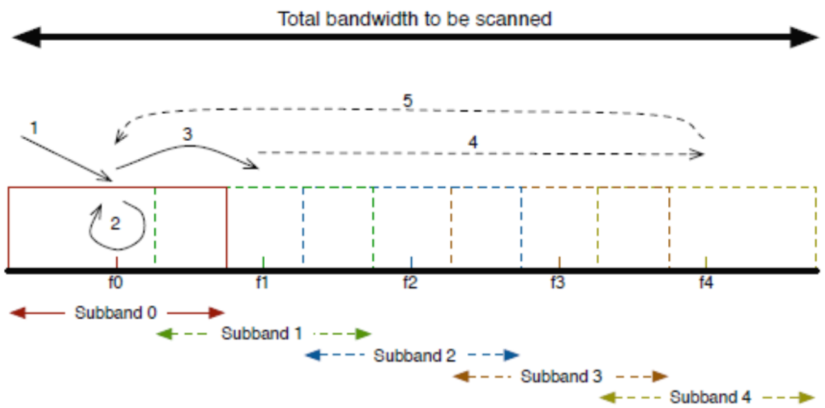

Figure 3.4: *Carrier Frequency Acquisition Mechanism*

The general frequency band of interest is divided into overlapping sub-bands where fi denotes center frequency of i^{th} sub-band. Overlapping sub-bands are employed to prevent misdetection of edges when only part of the signal is received

The receiver searches for the signal to determine the carrier frequency. If a signal is detected then the receiver exploits the above algorithm to estimate carrier frequency. The sub-bands are necessary due to the bandwidth limitation of Radio Frontend. If detection is successful, the receiver periodically checks whether the signal is lost or not.

3.5 <u>Matched Filter Detection</u>

The matched filter method is an optimal approach for spectrum sensing in the perspective that it maximizes the SNR in presence of additive noise. Match Filter technique requires less observation time since the high processing gain can be achieved by coherent detection. The advantage is achieved by correlating the received signal with a template to detect the presence of a known signal in the received signal. However it relies on prior knowledge of the primary user, such as modulation type and packet format. It also requires the cognitive radio to be equipped with carrier synchronization and timing devices. A matched filter is a linear filter designed to provide the maximum signal-to noise ratio at its output for a given transmitted waveform. 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.

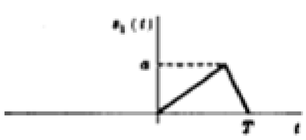

Fig 3.5(a):*Impulse Response h(t)*

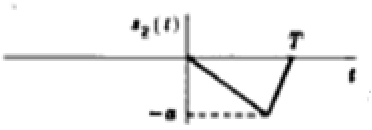

Fig 3.5(b):*Time inverted impulse response h(T-t)*

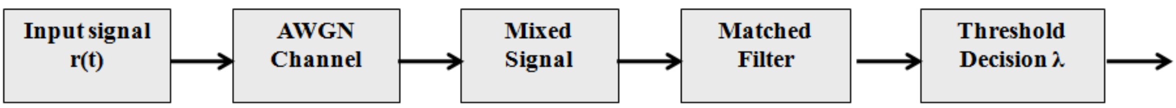

Figure 3.6: *Block Diagram of Matched Filter Detector*

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. When compared with energy detector, Matched Filter is better under noisy environment though.

3.6 Cyclostationary Feature Detection

3.6.a Introduction

It uses inbuilt features in the primary user's waveform for detection. Hence, it is computationally complex detector. It can distinguish between noise and user signal by analyzing its periodicity. In Cyclostationary Feature Detection modulated signals which carry information are usually sine wave, pulse trains, which have some periodicity in them. These signals are named as Cyclostationary because the autocorrelation and the mean are periodic.

Spectral Correlation Function (SCF) is used to distinguish between noise and signal because noise is wide sense stationary which has no periodicity. At first stage, BPF is used to measure energy around related band and the FFT is calculated of the signal received from BPF. The band pass is purely stationary because we would like to detect the pilot tone and then perform a D time decimation to reduce the sampling rate in order to reduce computational complexity.

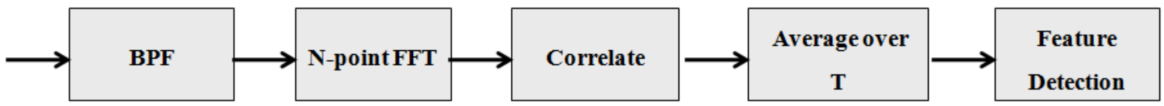

Figure 3.7: *Block Diagram of Cyclostationary Feature Detection*

3.6.b Mathematical Analysis

Assume a signal for a primary user is described as:

$$x(t) = s(t) + n(t) = \alpha e^{j(2\pi f_0 t + \theta)} + n(t)$$

Where,

s (t) = primary user's transmit signal

n (t) = noise signal (AWGN)

f_o = carrier frequency

The periodicity of mean and autocorrelation function can be expressed respectively as:

$$M_x(t) = E[x(t)] = \alpha e^{j(2\pi f_0 t + \theta)} = M_x(t + T_0)$$

$$R_x(t,\tau) = E\left[x\left(t+\frac{\tau}{2}\right)x\left(t-\frac{\tau}{2}\right)\right] = R_x(t+T_0,\tau+T_0)$$

Where, $T_0 = 1/f_0$, ,

Using Fourier series the autocorrelation function can be expanded as:

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

Where, α is called cycle frequency $\alpha = mf_0$ and m is an integer.

$$R_x^{\alpha}(\tau) = \lim_{T\to\infty}\frac{1}{T}\int_{-T/2}^{T/2} R_x^{\alpha}(t,\tau)e^{-j2\pi\alpha t}dt$$

Taking Fourier Transform of Cyclical autocorrelation, we get spectral correlation function.

$$S_x^{\alpha}(f) = \int_{-\infty}^{\infty} R_x^{\propto}(\tau)e^{-j2\pi f\tau}d\tau$$

Assume the interval is T as the spectral correlation needs to be estimated in finite time samples. i.e. from t-T/2 to t+T/2.

$$X_T(t,f) = \int_{-T/2}^{T/2} x(u)e^{-j2\pi fu}du$$

The spectral correlation function is:

$$S_x^{\propto}(f) = \lim_{\Delta f\to 0}\lim_{T\to 0} S_{X_T}^{\alpha}(t,f)_{\Delta f}$$

This is a 2-D transform having two variables, the cyclic frequency α, and the spectral frequency f. Using autocorrelation function for a signal it can detect weak wireless signals buried in noise.

4.1 Semi-Empirical Path Loss

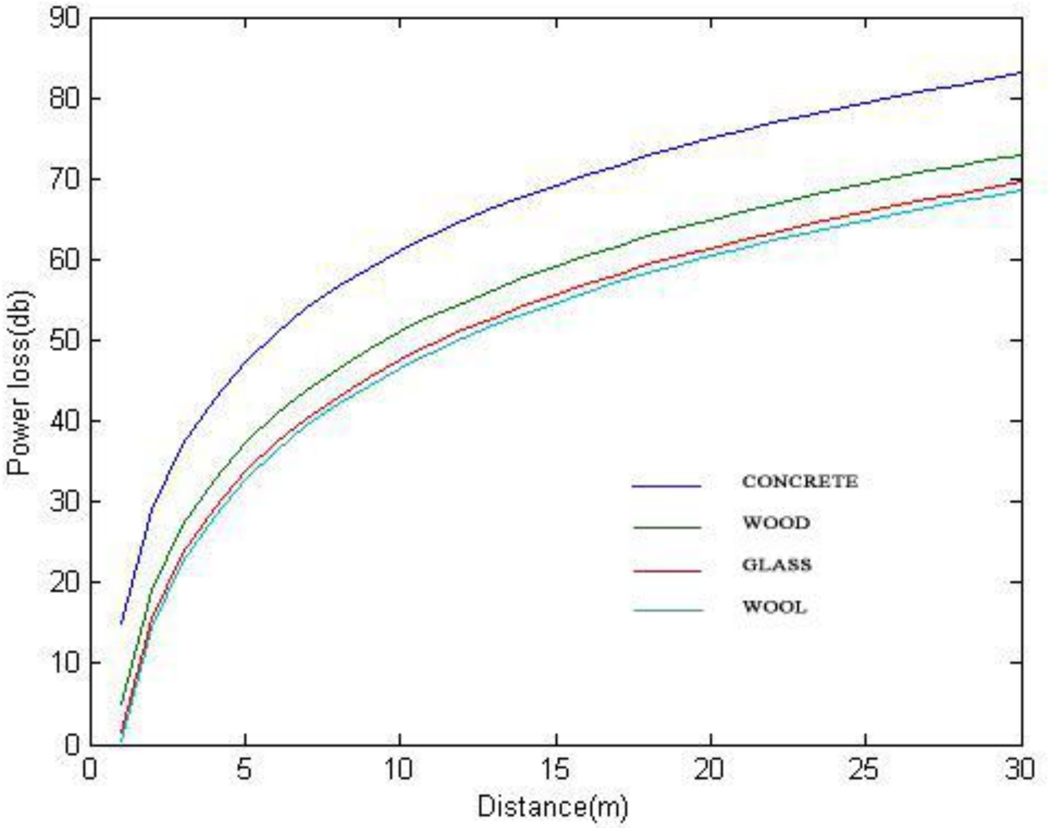

Figure 4.1: *Propagation loss vs. Transmitter-Receiver Distance*

4.1.a Inference

The signal power loss increases substantially with increase in density of material in between emitter and receiver. When the distance between emitter and base station increases it gradually saturates and becomes steady. The slope during smaller distances is high.

4.2 BPSK Modulated Primary Waveform

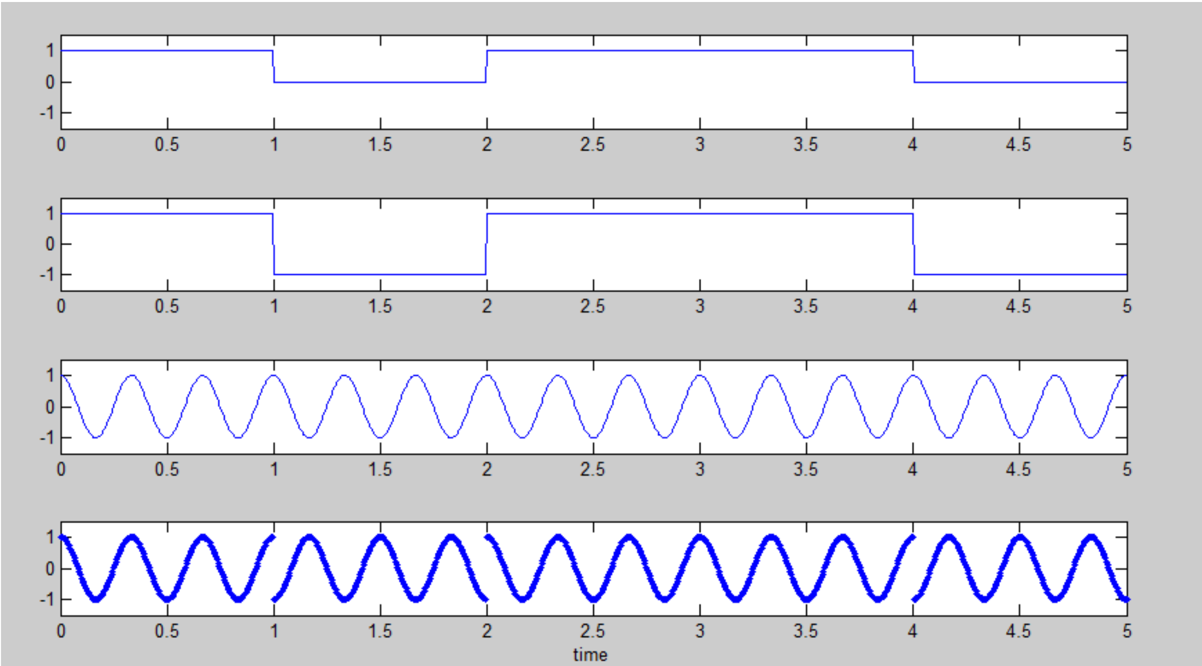

Figure 4.2:*BPSK modulation*

4.2.a Inference

Here a phase shift occurs in the carrier wave form whenever there is a transition between 1 and -1 levels of the bit stream

4.3 Energy Detection Technique

Let r(t) is the received signal which we have to pass from energy detector. The procedure of the Energy Detector is as follows.

Step 1- First estimate Power Spectral Density (PSD) by using periodogram function in MATLAB.

P_{xx} = Periodogram(r)

Step 2- The power spectral density (PSD) is intended for continuous spectra. The integral of the PSD over a given frequency band computes the average power in the signal over that frequency band.

Hpsd = Dspdata.psd (P_{xx})

Step 3- Now one frequency component takes almost 20 points in MATLAB. So for each frequency there points are summed and get the result.

Step 4- On experimental basis when results at low and high SNR are compared then threshold λ is set to be 5000.

Step 5- Finally the output of the integrator, Y is compared with a threshold value λ to decide whether primary user is present or not.

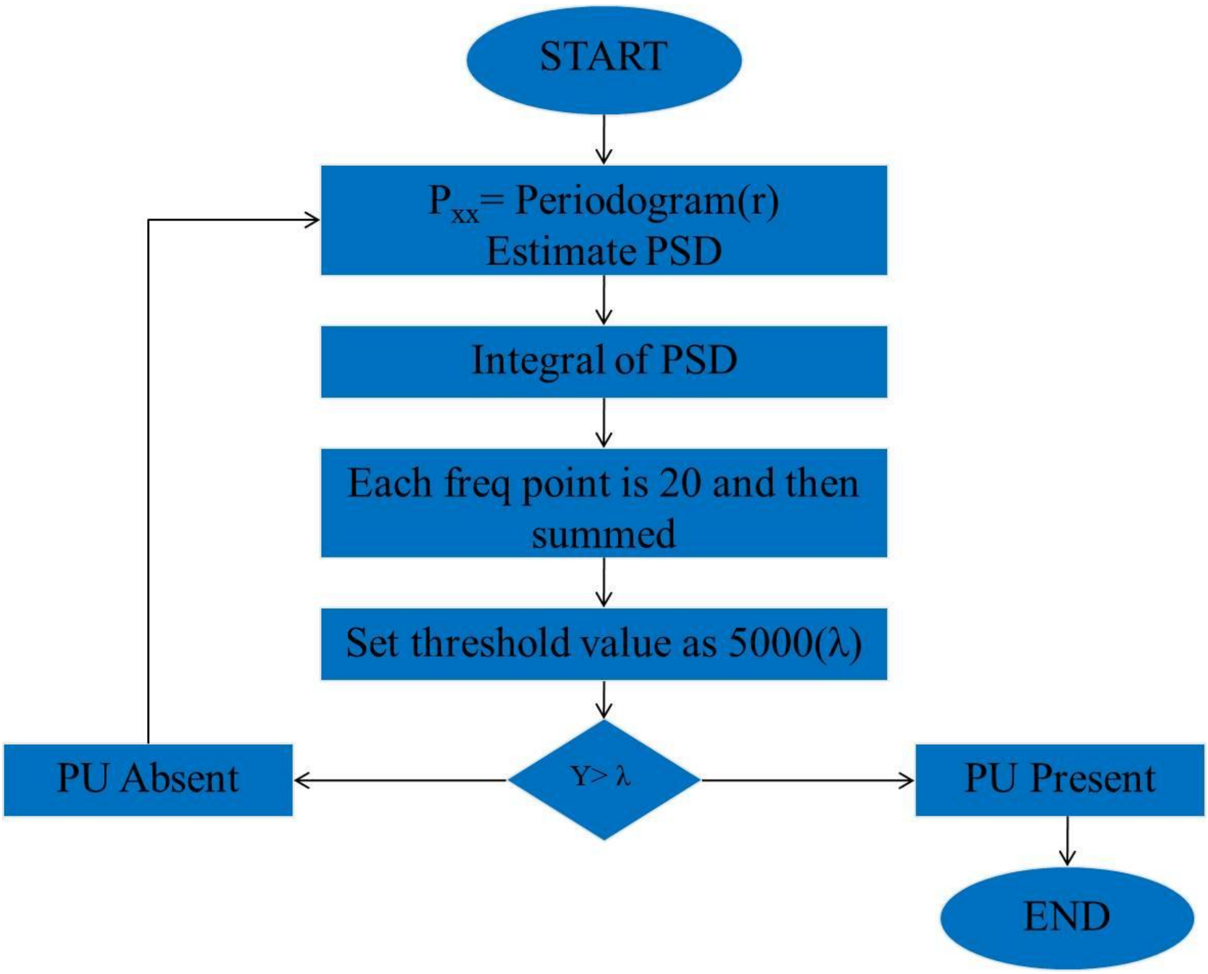

Figure 4.3: *Flow diagram of Energy Detection Spectrum Sensing*

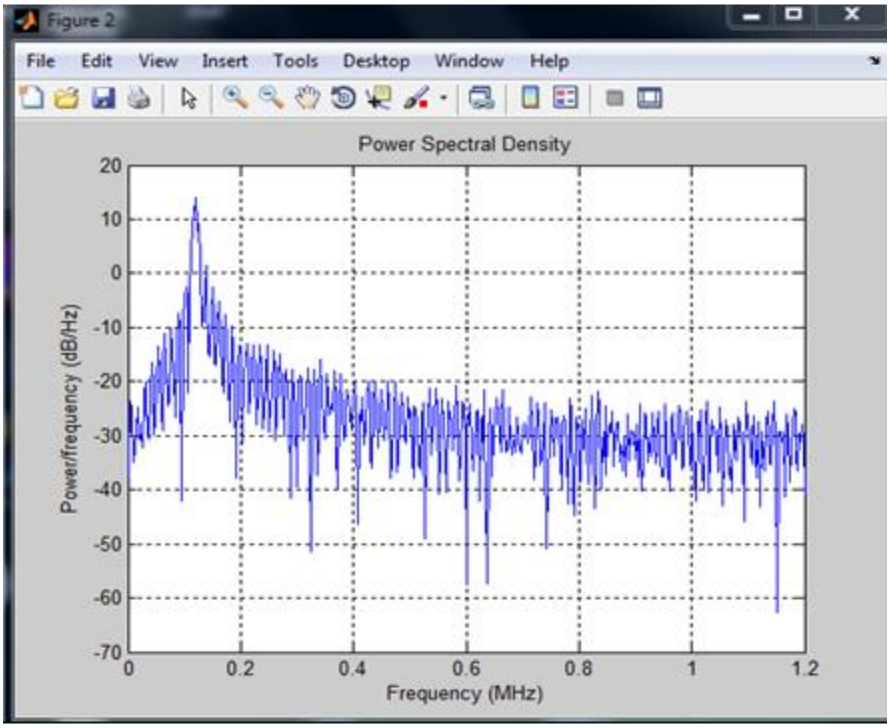

Figure 4.4: *PSD of Primary User using ED*

4.3.a <u>Inference</u>

The primary user is present at around 0.16 MHz which is indicated by the spike. This is obtained from the periodogram function based logic used in Energy Detection method. Each spectral point along the frequency range was given a value of 20 points and by summing using an integrator if the summed value exceeded a threshold set as 5000 (λ) then primary user is taken to be present in that frequency range.

4.4 Matched Filter Detection Technique

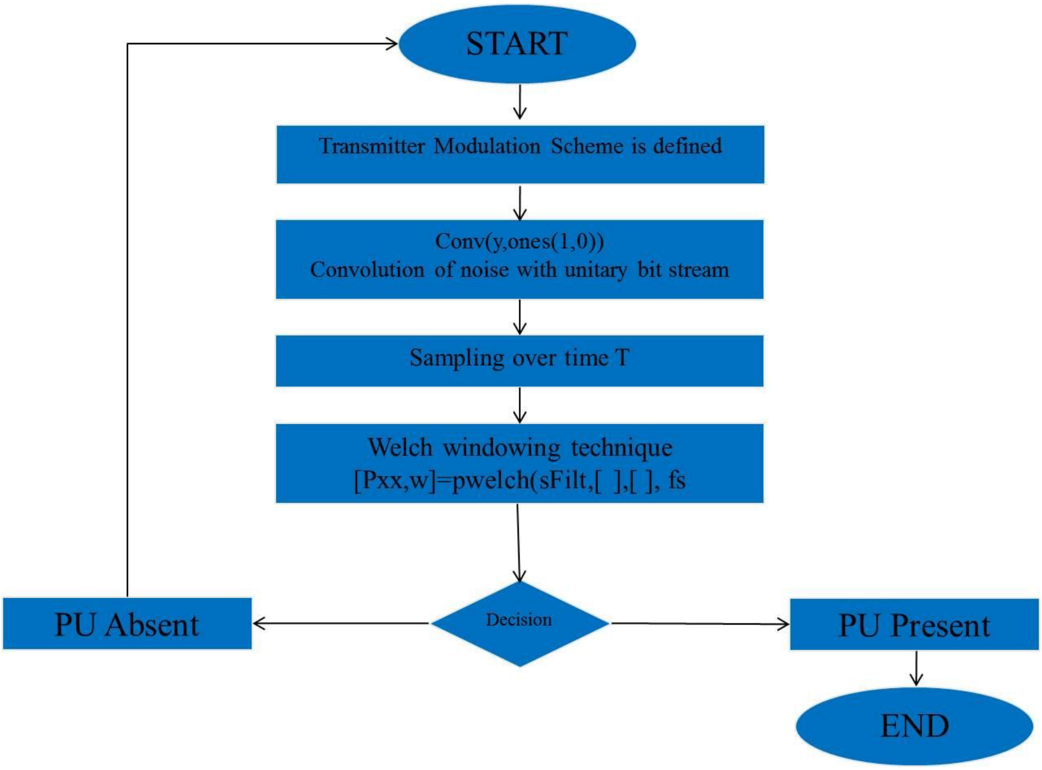

Figure 4.5: *Flow diagram of Matched Filter Spectrum Sensing*

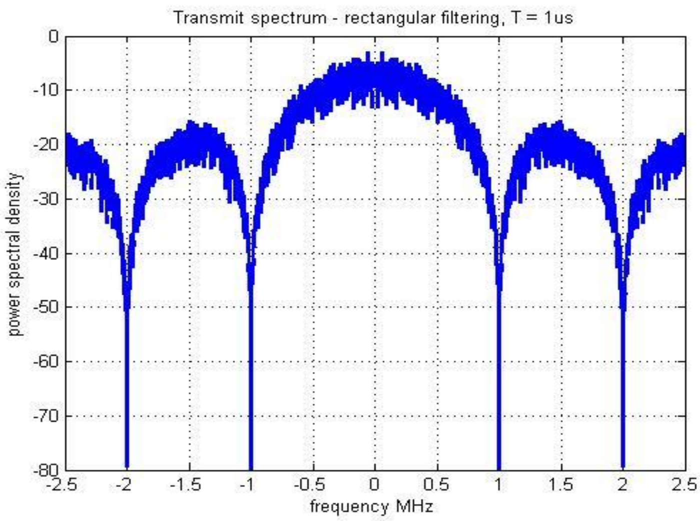

Figure 4.6: *CFD of primary user at -30dB SNR*

4.4.a Inference

Probability of missed detection from region -1 to 1 deviation of the suspected primary user frequency point is low.

4.5 Cyclostationary Feature Detection Technique

4.5.a Algorithm for CFD

Step 1 - The Fourier of the received signal was taken using the FFT function in MATLAB.

R=fft(r)

Step 2-The filtered received signal is multiplied with exp T1 and T2

Step 3 - Correlate XT with R; XY=xcorr(XT,R);

Average over time T; pt= fft(XY).*conj(fft(XY))

T1 and T2 were correlated to obtain XY and Y2 was generated Y2 by taking average.

Step 4 - Results at low and high SNR were compared and threshold value was set.

Step 5 -The output of the feature extractor was compared to threshold value to detect the presence or absence of the primary user.

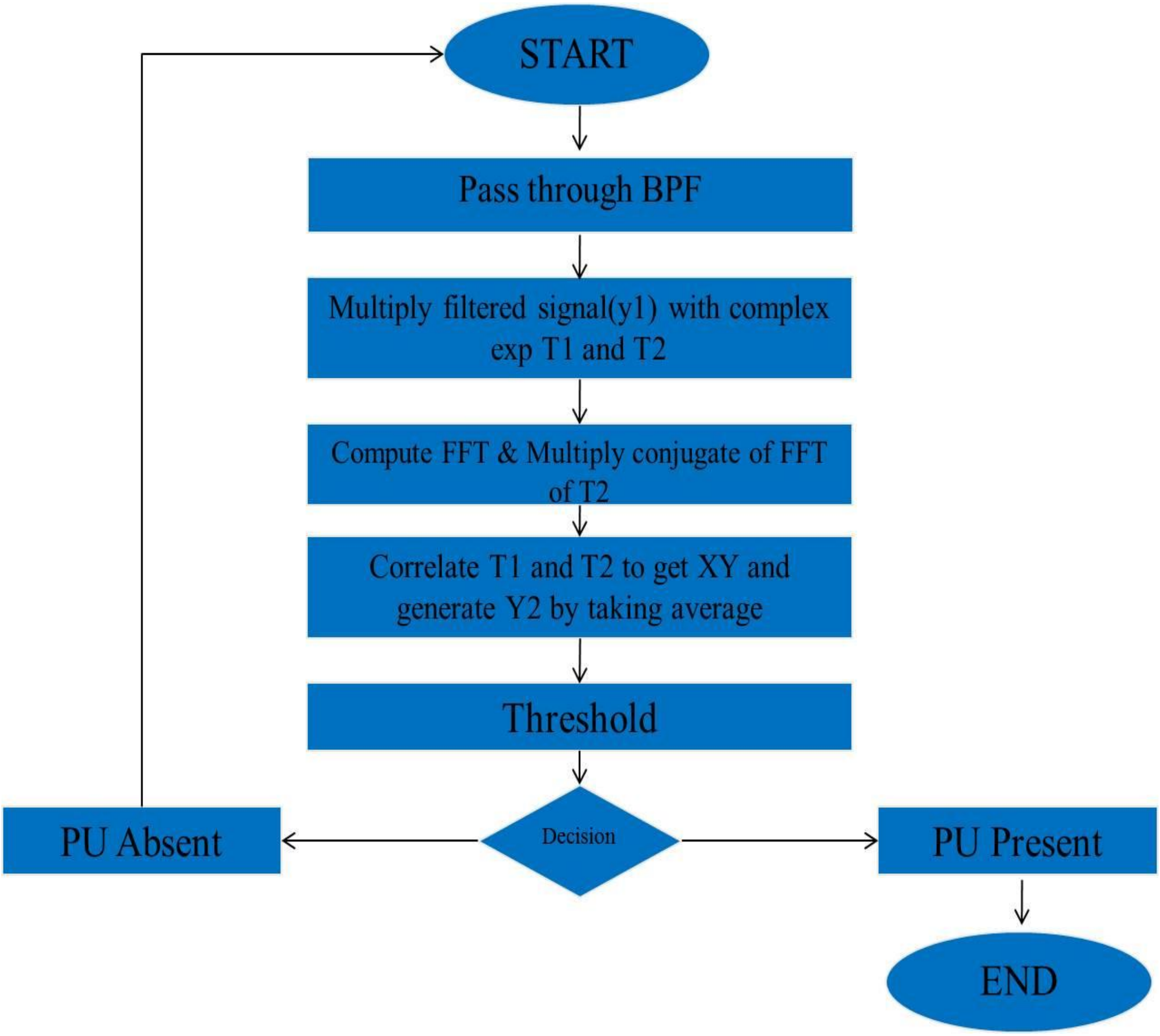

Figure 4.7: *Flow diagram of Cyclostationary Feature Detection Spectrum Sensing*

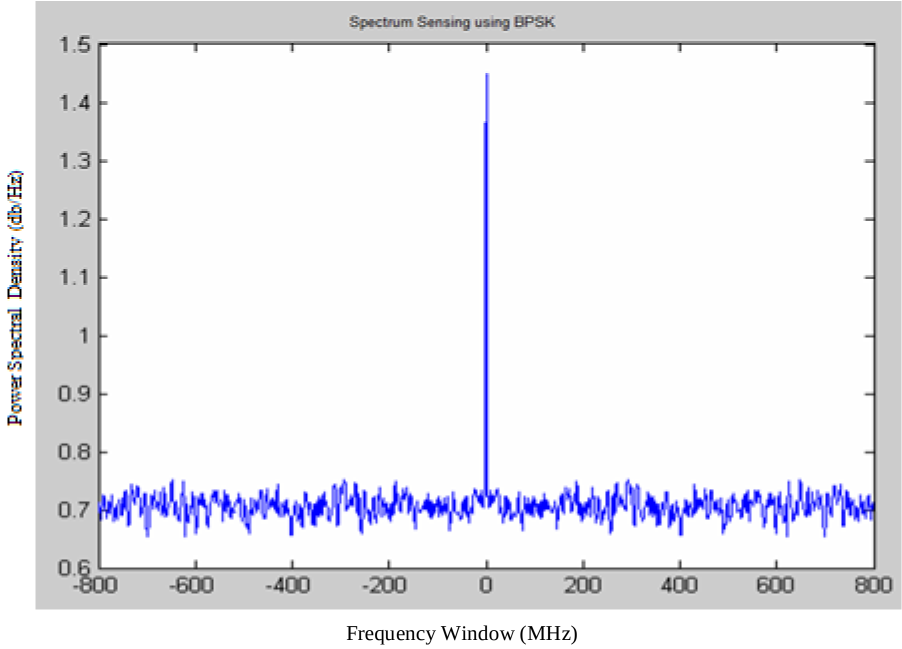

Figure 4.8(a): *CFD of primary user at -30dB SNR*

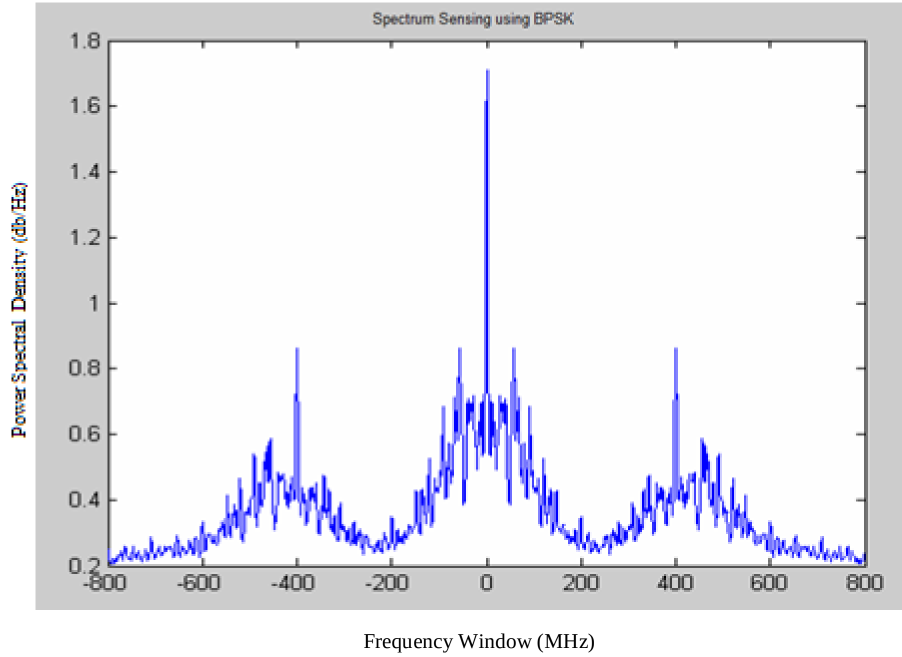

Figure 4.8(b): *CFD of primary user at 30db SNR*

4.5.b <u>Inference</u>

In Fig. 4.8(a), the output of the CFD when primary user is at 300 MHz is shown. There are no subsidiary peaks, so the peak value can be easily compared to threshold and decision can be made. In Fig. 4.8(b), when the transmitted signal used as BPSK modulated and the carrier frequency is 300 MHz and CFD is applied, we get a single peak and two subsidiary peaks showing primary user is using BPSK modulation

Conclusions

Chapter 5

5.1 Probability of Primary Detection

On an experimental basis the probability of primary user detection for the three techniques is plotted as a function of SNR. For energy detection and matched filter detection a much higher SNR is required to obtain a performance comparable to CFD. As per the plot the CFD performs well and attains 100% accuracy for primary user detection at -8 dB.

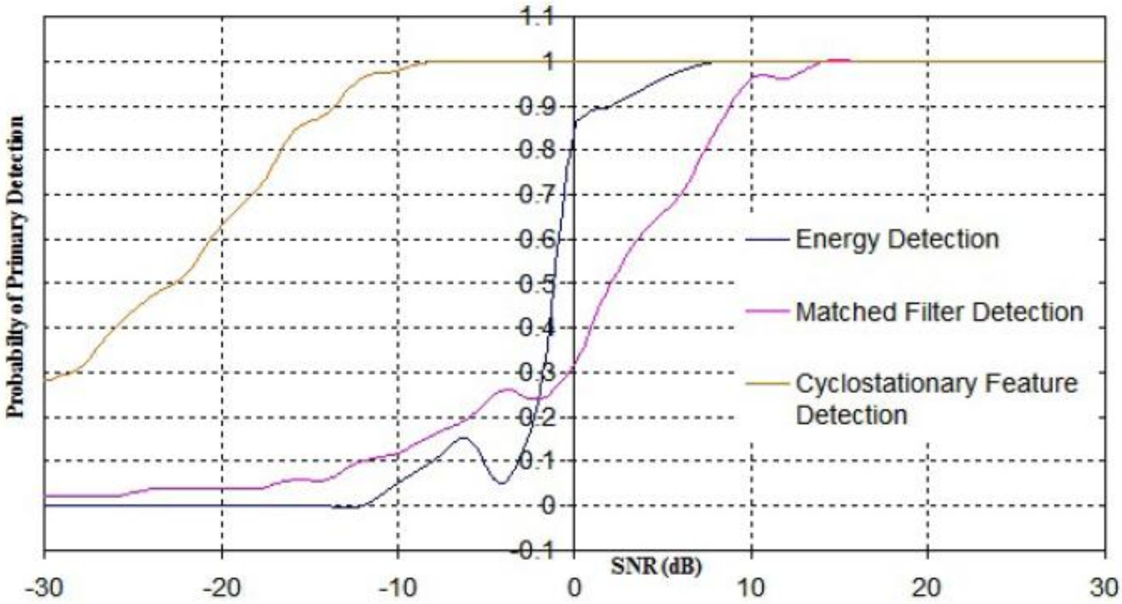

Figure 5.1: *Probability of Primary Detection vs. SNR plot*

5.2 Probability of False Detection

It is observed that the probability of false detection of Cyclostationary Feature Detection is much smaller compared to the other two techniques. At low SNR we have higher probability of false detection because energy detection cannot isolate between signal and noise. The plot indicates that there no likelihood of false detection for the CFD technique. Using this technique either the primary user is present or absent. The question of a pseudo presence doesn't arise.

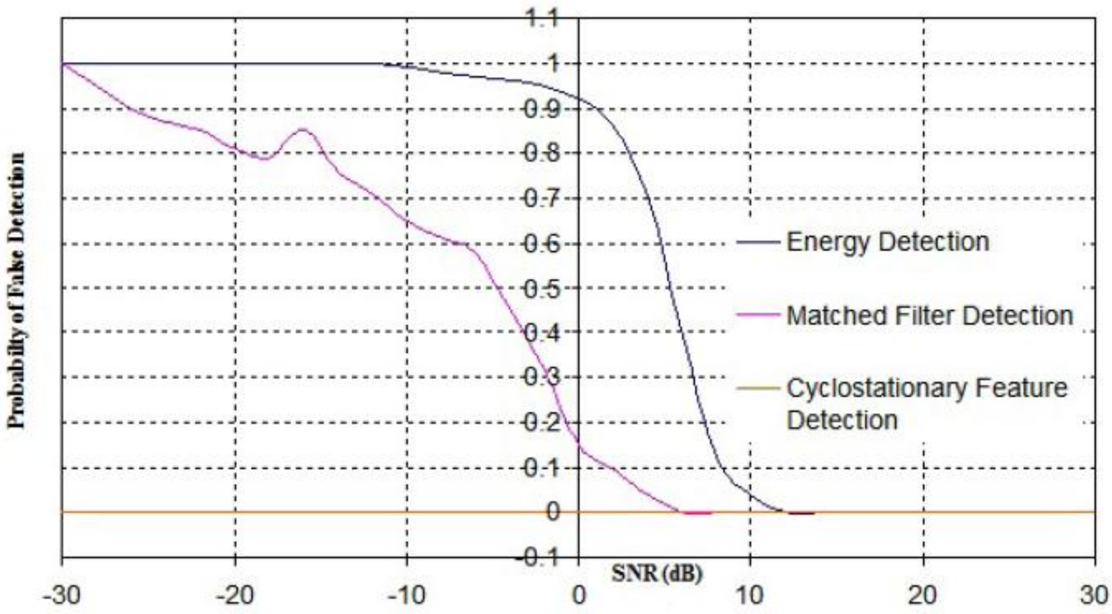

Figure 5.2: *Probability of False Detection vs. SNR plot*

5.3 <u>Comparative Analysis of the Three Methods</u>

Type	Energy Detection	Matched Filter	CFD
Sensing Time	More	Less	Most
Simple To Implement	Yes	No	No
Performance under Noise	Poor	Bad	Good
Prior Knowledge	No	Yes	No

Table 4

5.4 Conclusions

With the advent of modern day technology, the demand of radio spectrum has increased drastically in the past few years. Licensed bands such as TV bands are used inefficiently; improvement in the existing spectrum allocation policy is a dire necessity. Dynamic spectrum access is a means of respite to resolve the spectrum shortage by permitting unlicensed users to dynamically avail spectrum holes across the licensed spectrum in a non-interfering manner.

This work was aimed towards the detection and classification of primary user's waveform in cognitive radio networks. The major requirement of a spectrum sensing system is its real time processing and decision making. Its implementation can be done on FPGA kit or DSP processor.

The transmitter detection techniques are compared on the basis of three measures: Sensing Time, Detection Sensitivity and ease of execution. By comparing these techniques it is concluded that Cyclostationary Feature Detection gives superlative results but takes long computational time compared to other techniques. So by using the results of different techniques simultaneously, better results can be obtained. In this thesis main issues associated with spectrum sensing techniques have been highlighted. The techniques aid the functionality of a Femtocell in the sense that the secondary user avails access rights to a Cognitive Femtocell Network.

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