VLSI Implementation of Energy Detection Algorithm for WLAN and WiMAX Applications

A THESIS SUBMITTED IN PARTIAL FULFILMENT
OF THE REQUIRMENTS FOR THE DEGREE OF

MASTER OF TECHNOLOGY
in
Electronics and Communication Engineering
VLSI and Embedded System Design
by

JHARANA DALAI
Roll No: 211EC2076

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA, ODISHA
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Under the guidance of
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2013

Dedicated to My Loving parents

and my brothers

NATIONAL INSTITUTE OF TECHNOLOGY
Dept. of Electronics and Communication Engineering
Rourkela-769008, Odisha, India

CERTIFICATE

This is to certify that the work entitled in this thesis, “VLSI Implementation of Energy Detection Algorithm for WLAN and WiMAX applications**”** submitted by JHARANA DALAI in partial fulfilment of the requirements for the award of Master of Technology Degree in **Electronics & Communication Engineering** with specialization in **VLSI and Embedded System Design** during 2011-2013 at the National Institute of Technology, Rourkela. This is an authentic work carried out by her under my supervision and guidance. To the best of my knowledge, neither this thesis nor any part of it has been submitted for any degree or diploma elsewhere.

Place: Rourkela
Date:

Prof. Sarat Kumar Patra
(Supervisor)

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Declaration

I certify that

a) The work contained in the thesis is original and has been done by myself under the supervision of my supervisor.

b) The work has not been submitted to any other Institute for any degree or diploma.

c) I have followed the guidelines provided by the Institute in writing the thesis.

d) Whenever I have used materials (data, theoretical analysis, and text) from other sources, I have given due credit to them by citing them in the text of the thesis and giving their details in the references.

Jharana Dalai

29 May 2013

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Lastly, I would like to thank my parents and well-wishers and expressing utmost gratitude before the God Almighty.

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ABSTRACT

The electromagnetic spectrum is a natural resource. The current spectrum licensing scheme is unable to accommodate rapidly growing demand in wireless communication due the static spectrum allocation policies. This allocation leads to increase in spectrum scarcity problem. Cognitive radio (CR) technology is an advanced wireless radio design which aims to increase spectrum utilization by identifying unused and under-utilized spectrum in dynamically changing environments. Spectrum sensing is a one of the key method of cognitive radio which detects the presence of primary user in licensed frequency band using dynamic spectrum allocation policies to utilize unused spectrum.

Energy detection is a simple spectrum sensing technique, which does not require prior information of signal which is present in the frequency band. But in low signal to noise ratio (SNR) conditions, its performance is weak, which can be improved by signal processing algorithm. As energy detection is simple and easily implemented in hardware, so it is preferred in emerging standard like IEEE 802.22, Wireless Region Area Network (WRAN), IEEE 802.11a, Wireless Local Area Network (WLAN) and 802.16, World Wide Interoperability Microwave Access (WiMAX).

In this thesis energy detection technique is applied for WLAN and WiMAX under BPSK modulation method and Monte-Carlo simulations are performed to test the performance of received signals in WLAN and WiMAX. Following to this work VLSI implementation of spectrum sensing using energy detection have been implemented for pseudo random sequence generated signal and BPSK modulates signal. OFDM is used as modulation standard and it is implemented in VLSI for WLAN and WiMAX.

List of Figures

List of Tables

List of Abbreviation

AWGN	:	Additive White Gaussian Noise
BPSK	:	Binary Phase Shift Keying
CR	:	Cognitive Radio
DAB	:	Digital Audio Broadcast
DFT	:	Discrete Fourier Transform
DSP	:	Digital Signal Processing
DVB	:	Digital Video Broadcasting
FCC	:	Federal Communication Commission
FPGA	:	Field Programmable Gate Array
OFDM	:	Orthogonal Frequency Division Multiplexing
PDA	:	Personal Digital Assistants
RF	:	Radio Frequency
RKRL	:	Radio Knowledge Representation Language
ROC	:	Receiver Operating Characteristics
SDR	:	Software Defined Radio
SNR	:	Signal to Noise Ratio
TRAI	:	Telecom Regulation Authority of India
UHF	:	Ultra High Frequency
WLAN	:	Wireless Local Area Network
WIMAX	:	World Wide Interoperability Microwave Access
WRAN	:	Wireless Regional Area Network

Contents

Chapter 1

Introduction

1.1 Introduction to Cognitive radio

Wireless communication usage is increasing day by day due to rapid increasing of communication devices. Due to limited spectrum allocation policy, scarcity of spectral resources is increasing while most of the allocated spectrum is underutilized. Most of the useful spectrum is allocated to licensed users (e.g. mobile carriers, TV broadcasting companies) that do not utilizes allocation spectrum band in all the geographical locations all the time. The licensed users are those users who paid licensing fee to the government agencies like Telecom Regulatory Authority of India (TRAI) and Federal Communications Commission (FCC) in the United States. If this unused spectrum is opened for unlicensed user (e.g. private users, short range networks) then it becomes promising solution to spectrum scarcity problem. Some of the examples are Wi-Fi and Bluetooth operating in unlicensed bands. These two standards share some part of undesirable spectrum with many other technologies [1, 2].

Cognitive radio (CR) has become a promising technology that enables a radio device to monitor, sense, detect electromagnetic radio environment and intelligently adapt its communications channel access in which it exists. CR devices monitor a radio spectrum and modify their operational parameters such as frequency, different modulation schemes, and transmitting power, in order utilize available natural resources. A CR can increase spectrum efficiency leading to higher bandwidth and reduce the burdens of centralized spectrum management by a particular spectrum distribution authority.

The cognitive radio is an emerging technology in wireless communication. It is still too early to tell what a cognitive radio seems to be for different wireless applications due to complexity in implementation of cognitive radio in practical.

1.2 Motivation and Objective

CR is an advanced technique which reduces the problem of spectrum scarcity in electromagnetic spectrum. Spectrum sensing is one of the method which checks the emptiness of primary user allocated to particular frequency spectrum. There are several methods for spectrum sensing for non-cooperative and cooperative CR users. Some of the techniques for spectrum sensing for non-cooperative CR users are energy detection, matched filter, cyclostationary feature detection. Matched filter and cyclostationary methods are complex techniques compared to energy detection technique. The energy detection technique dose not requires any information about signal structure present in the licensing band to detect the occupancy of user in that band. Energy detection works in high signal-to-ratio values compared to other methods.

The main aim of this work is to explain different types of spectrum sensing methods, problem related to spectrum sensing methods. We discussed energy detection spectrum sensing algorithm and studied performance of energy detection for BPSK signal and in wireless technologies like WLAN and WIMAX [3, 4]. The hardware implementation for energy detection using VHDL also explained which is applicable for real time applications.

1.3 Thesis layout

The thesis is organized in five chapters. The current chapter discusses introduction to this thesis in detail. The motivation and objective behind choosing this work are framed out and it ends with its layout.

Chapter 2- Introduction to Cognitive Radio

The history of cognitive radio, CR definition according to different organization, types of CR, classification of CR and its application, advantage, disadvantages are discussed in this chapter.

Chapter 3- Spectrum Sensing

This chapter deals with Spectrum sensing classification. The performance studies using energy detection technique for single carrier and multicarrier applications are discussed in this chapter. The simulation results for BPSK, WLAN and WIMAX through AWGN and Rayleigh channel are discussed.

Chapter 4 – Hardware Implementation for Energy Detection Technique

The purpose of this chapter is to provide architecture for energy detection which is implemented in hardware platform. The architecture is implemented using VHDL coding where input is taken as either random binary sequence or BPSK modulated signal.

Chapter 5- Conclusion and future work

This chapter discussed summary of work and scope for future work. Some limitations to this thesis also are listed out and finally provide a concluding remark to this work

Chapter 2

Introduction to Cognitive Radio

2.1 History of Cognitive Radio

The cognitive radio is an emerging technology in wireless communication. It is still too early to tell what a cognitive radio seems to be for different wireless applications due to complexity in implementation of cognitive radio in practical. Therefore, the following history shows the generics of cognitive radio technology [1, 2, 5] .

- In 1998**:** The concept of cognitive radio was first proposed by Joseph Mitola III in a seminar at KTH (the Royal Institute of Technology in Stockholm).
- In 1999: A comprehensive description of the term cognitive radio was first discussed in a paper written by J. Mitola III and Gerald Q. Maguire.
- In 2000: J. Mitola III wrote his PhD dissertation on cognitive radio as a natural extension of the SDR concept. Mitola described the term cognitive radio 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 provides resources to radio and wireless services.
- In 2002, the FCC published a report which was aimed at the changes in technology and the profound impact that those changes would have on spectrum policy.
- The National Science Foundation (NSF) of United State starts research in the field of spectrum measurements and dynamic spectrum access in 2003.
- The FCC of United States issues a Notice of Proposed Rulemaking on Facilitating Opportunities for Flexible, Efficient, and Reliable Spectrum by employing Cognitive Radio Technologies in 2004.
- DARPA XG and NSF of United States projects are done projects a series of spectrum occupancy measurements. These projects have less than 10 per cent occupancy in time and in space less than 3 GHz, in 2005.
- In 2005, IEEE lunched project of 1900 series standard for next generation and spectrum management.
- In 2006, FCC of United States establishes Rule and Order on to use CR devices in unused portions of the TV Whitespaces by secondary basic in 2006.
- FCC United States initiates testing of prototype TV Whitespace devices in 2007.
- An Ofcom Consultation United Kingdom creates new opportunities for CR to use interleaved spectrum without causing interference in 2007.

- DARPA XG of United States demonstrates spectrum in opportunistic manner in 2008.
- FCC United States released final rule to use licensed user white space by unlicensed user in 2010.
- The IEEE published 802.22 WRAN (Wireless Regional Area Network) as official standard for CR in 2011.

2.2 Cognitive Radio Definitions

CR is an emerging radio technology. The concept and definitions of cognitive radio are given by many peoples. Some of these definitions are as:

Encyclopedia of Computer science [2]**:** It has three points to define cognition

1. Mental states and processes intervene between input stimuli and output responses.
2. The mental states and processes are described by algorithms
3. The mental states and processes lend themselves to scientific investigations.

Mitola [2, 6] **:** The CR definition is given by Mitola as **"**Wireless personal digital assistants and the related networks that are sufficiently computationally intelligent about radio resources, and related computer-to-computer communications, to detect user needs as a function of use context and to provide radio resources and wireless services most appropriate to those needs". The term "cognitive radio" is coined in 1999.The definition of cognitive radio as "A radio employs model to achieve a specified level of competence in radio-related domains."

IEEE 1900.1: IEEE standard definition for CR as

(a) A wireless radio in which communication systems are aware of their environment and internal state and can make decisions about their radio operating behaviour based on that information and predefined objectives*;*

(b) Cognitive radio [as defined in item a] that uses software-defined radio, adaptive radio, and other technologies to adjust automatically its behaviour or operations to achieve desired objectives.

Haykin [2] **:** In the recent cited paper of Haykin CR definition is given **"**Cognitive radio is an intelligent wireless communication system that is aware of its environment (i.e., outside world), and uses the methodology of understanding by building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier frequency, and modulation strategy) in the real time with two primary objectives in mind:

1. Highly reliable communication whenever and wherever needed
2. Efficient utilization of the radio spectrum".

IEEE USA: IEEE USA defines CR as: "A radio frequency transmitter/receiver that is designed to intelligently detect whether a particular segment of the radio spectrum is currently in use, and to jump into (and out of, as necessary) the temporarily-unused spectrum with high mobility and without interfering with the transmissions of other authorized users."

2.3 Cognitive radio Cycle

2.3.1 Rising cognitive radio cycle

Cognitive radios (CR), first proposed by Mitola have been chosen as an enabling platform in realizing such dynamic spectrum sharing due to their built-in cognition capabilities. A cognitive radio system is a 'smart' network that can observe the environment, learn from it, and adjust to changing environment conditions. The SAN (software-adaptable network) is analogous to the software-defined radio (SDR) which is the physical control of the system that provides the action space for the cognitive process. According to SAN cognitive radio is designed using OODA (Observe-Orient-Decide-Act) loop. The OODA loop is first used for military officers, later on it was adopted for general decision making process. The loop consists of four main components with other two components:

1. Observe: This process senses the network environment and creates an internal model of it. Information can be observed through sensor in SAN or extracted from previous decisions taken from sensed results. Possible information which are directly observed include the presence of spectrum signal from primary and secondary users, received signal-to-interference and noise ratio(SINR), packet delays, selection of node parameters(location, channel selection ,transmission power.
2. Orient: In this process priority are set according to observed information. The cognitive radio elements must interface to sources of networks for effectiveness of cognitive radio to orient it. This step provides guidelines to different cognitive radio elements that how to behave in the network.
3. Plan: This schedule are planed according to the systems constraints. This step planned the procedure through which cognitive radio elements work. This process is not good choice.

4. Decide: The cognitive process has observed the network environment and is oriented to the end-to-end objectives, it must make a decision. The decision making is a two-step process
   (i) A centralized decision-making unit that gathers network state data and distributes state information to the nodes of the network, or
   (ii) A distributed process across the network nodes, with each node making decisions under some degree of autonomy.
5. Act: Finally an appropriate action is taken during the act step in which message is send, reconfigure the system and then modify power level.
6. Learn: learning abilities enable communication equipment to evaluate the quality of their past actions. The decision making engine learns from its past successes and failures to tune its parameters and its decision rules to its specific environment.

One of the CR cycle is shown in Figure 2-1 [6].

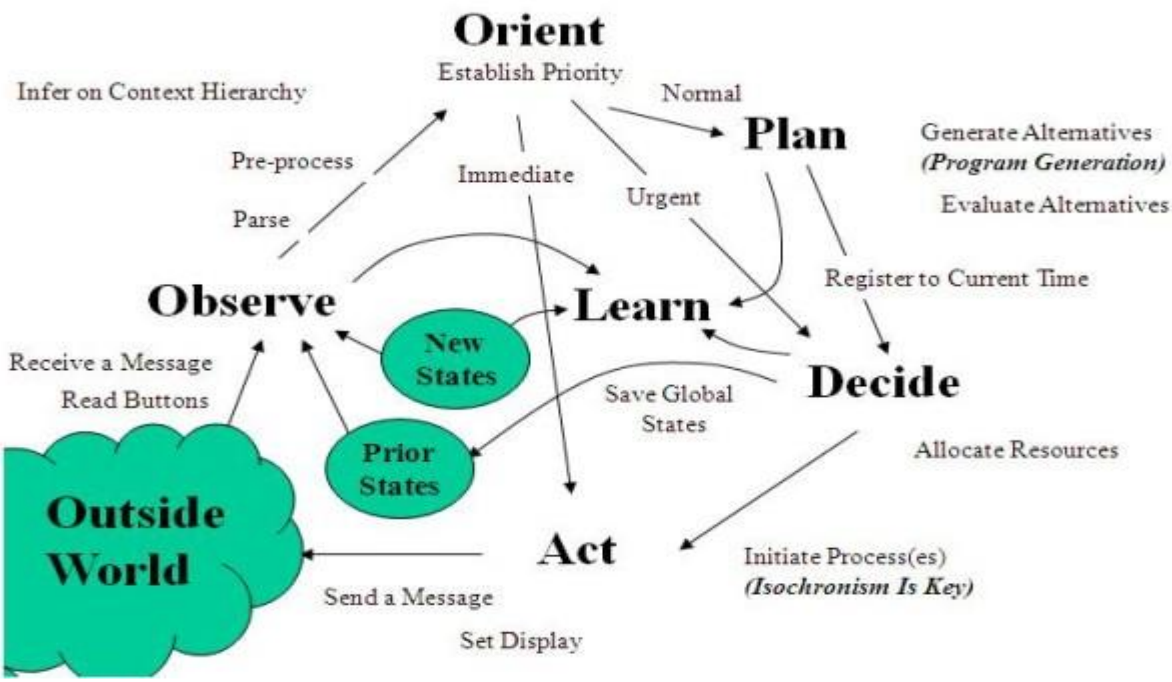

Figure 2-1 Cognitive radio cycle

2.4 Application, advantages and disadvantages of CR

2.4.1 Application:

- Improving reliability in wireless communication system
- Less expensive radio

- Advanced network topologies
- Enhancing SDR techniques
- Automatic radio resources management

2.4.2 Advantages

- Mitigate and solving spectrum access issues
- Spectrum utilization improves
- Improves wireless network performance through increased user throughput and system reliability
- More adaptability and less co-ordination

2.4.3 Disadvantages

- Software reliability
- Loss of control
- Regulatory concerns
- Fear of undesirable adaptations
- Significant research is to be done to commercially use cognitive radio.

Chapter 3

Spectrum Sensing Using Energy Detection Technique

3.1 Introduction

Cognitive radio is a novel approach to utilization of unused natural resources. CR improves spectrum efficiency by allowing secondary user to use free unutilized spectrum of primary user for temporary period. CR is an intelligent radio technology which changes its transmitter and reception parameters according to changes parameters like time, frequency, modulation types, transmission power etc. according to radio environment. A CR is a radio technology which is used to detect whether a particular band of frequency is presently in use and to jump to unutilized band without interfering with the other authorized users. In CR terminology, primary users are those users who have licensed agreement with the Government agencies. And secondary users are those user who have not licensed agreement with government agencies but they try to detect free spectrum by licensed user and if spectrum is unused then they can be utilized that spectrum for that period without interfering with the primary user. Once primary user switches to licensed spectrum then secondary user have to vacant that spectrum to avoid interference Primary user have higher priority with legacy rules whereas secondary users have less priority with these rules.

3.2 Spectrum Sensing from the Cognitive Radio Network Perspective

Signal detection is considered while spectrum sensing for cognitive radio. Spectrum sensing in cognitive radio perspective have some problems due to spectrum policies. There are some policies which have to follow by the CR users to operate in the licensed network. Some of these restrictions are provided below [5]:

3.2.1 No Prior Knowledge on the Signal Structure

There are portions of the spectrum where multiple technologies (using different protocols) share the spectrum. Cognitive radios networks must be able to deal with the existing multiple technologies, as well as new those technologies which are going to be appear in wireless network in future. These networks should be able to work properly in the medium irrespective of the technologies in use. Cognitive user must able to use spectrum without prior information about the signal structure.

3.2.2 Sensing Time

The work of CR user is to detect the presence of primary user if that band is unused then that is used by secondary user. The secondary users must be designed to free the spectrum as soon as it senses that a primary user appear in the legacy network. These secondary networks sense available spectrum as fast as possible, in the minimum possible number of received sample without interfering with the primary users. Cooperative spectrum sensing technique decreases the sensing time for the same level of accuracy.

3.2.3 Fading Channels

Spectrum sensing is particularly sensitive to fading environments. Spectrum-sensing devices must be able to detect in heavily faded channels. Several works have focused on sensing for the fading environment in the noncooperative environment, but it is cooperative sensing performs in a better way in fading channels.

3.3 Cognitive radio functional blocks

CR can be explained in different ways. They are includes four main functional blocks shown in Figure 3-1 [7, 8]:

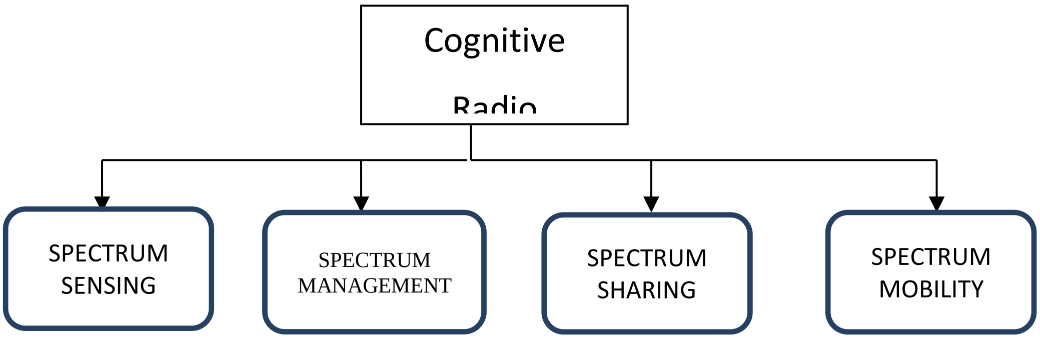

Figure 3-1CR Functional Blocks

Spectrum sensing: aims to determine which spectrum are available and to detect the presence of the licensed users (also known as a primary user) when a user operates in a licensed band. CR continuously monitors the radio spectrum and detect unallocated band which further used by secondary user.

Spectrum management: is to predict how long the spectrum holes are likely to remain available for use to the unlicensed users (also called cognitive radio users or secondary users). To get best available band to unlicensed user, CR checks data rate, modes of transmission before use any free band by primary user.

Spectrum sharing: is to distribute the spectrum holes fairly among the secondary users, bearing in mind usage costs. CR provides different scheduling algorithms among unlicensed user for spectrum hole distribution.

Spectrum mobility: is to maintain seamless communication requirements during the transition to better spectrum utilization. If any spectrum is used by unlicensed user and then

CR user finds primary user then that frequency band is handed over to licensed user to avoid interference.

3.4 Spectrum Sensing

The cognitive radio network analyzes all degree of freedom (time, frequency and space to predict spectrum usage. There are several techniques available for spectrum sensing. Spectrum sensing is a method which determines whether a given frequency band is being used.

3.4.1 Problem Formulation

Spectrum sensing is a signal detection method for identifying the presence of a signal in a noisy environment. Signal detection can be reduced and given by the hypothesis test in (3.1) [5].

$$\boldsymbol{y(k)} = \begin{cases} \boldsymbol{n(k)} & \boldsymbol{H0} \\ \boldsymbol{s(k) + n(k)} & \boldsymbol{H1} \end{cases} \quad (3.1)$$

Where *y(k)* is the sample to be analysed at each instant k

n(k) is the noise (not necessarily white Gaussian noise) of variance $\sigma 2$

s(k) is the signal present in the network which is to be detected

H0 and H1 are the noise-only and signal-plus-noise hypotheses, respectively.

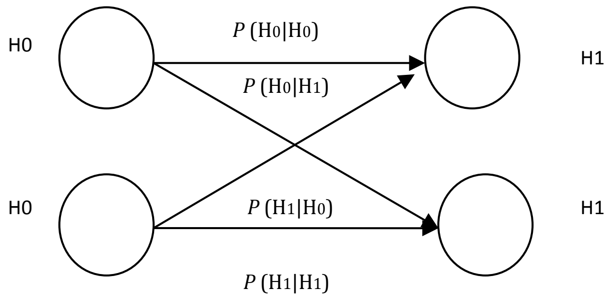

Figure 3-2 Problem formulation using Hypothesis

We can define four possible cases for the detected signal as shown in Figure 3-2

1. (H0|H0): it indicates H0 when H0 is true

2. (H1|H1): It indicates H1 when H1 is true

3. (H0|H1): It indicates H0 when H1 is true

4. (H1|H0): it indicates H1 when H0 is true

Case 1 is for noise which is not detected. Case 2 is known as a correct detection, whereas cases 3 and 4 are known as a missed detection and a false alarm, respectively. Missed detections are the biggest issue for spectrum sensing, as it means possibly interfering with the primary system. Nevertheless, it is desirable to keep the false alarm rate as low as possible for spectrum sensing, so that the system can exploit all possible transmission opportunities.

The spectrum sensor select hypothesis H1, it shows presence of primary user and if select hypothesis H0 otherwise. Unfortunately, spectrum sensing algorithms may fall into mistakes in practice, which can be classified into miss detections and false alarms. Miss detection occurs when a primary signal is present in the sensed band and the spectrum sensing algorithm selects hypothesis H0.Ihis results harmful interference to primary users in CR network. On the other hand, a false alarm occurs when the sensed spectrum band is free and the spectrum sensing algorithm selects hypothesis H1. The false alarm results in missed transmission of signal and therefore in a lower spectrum utilization. A detection occur when a primary signal is present in the frequency band and it spectrum sensing algorithm select hypothesis H1 which results correct detection of signal. Based on these definitions the performance of any spectrum sensing algorithm can be summarized by means of two probabilities: the probability of miss detection $P_{md} = P\ (H0/H1)$, probability of detection $P_d = P\ (H1/H1) = 1-Pmd$.

The performance of the spectrum-sensing technique is usually determined by the probability of false alarm $P_{fa} = P\ (H1|H0)$, because this is the most influential metric. The performance is evaluated by receiver operation characteristic (ROC) curves, which plotted between the probability of detection $P_d = P\ (H1|H1)$ and the probability of false alarm P_{fa}.

H0 andH1 are represented to differentiate signal from noise is required. The noise characteristics are very important for the spectrum-sensing procedure. Most works on spectrum sensing consider noise to be additive white Gaussian noise (AWGN), because many independent sources of noise are added (central limit theory).

Poor Performance is poor for all of the techniques available because of negatively affected by channels are presented in (3.2) as

$$y(k) = \begin{cases} n(k) & H0 \\ h(k)s(k) + n(k) & H1 \end{cases} \quad (3.2)$$

Where gain for fading channel at each instant is *h(k).*

A key problem in cognitive radio is that the secondary users need to detect the presence of primary users in a licensed spectrum and quit the frequency band as quickly as possible if the corresponding primary radio emerges in order to avoid interference to primary users. The technique is called spectrum sensing, which is a fundamental problem in cognitive radio.

3.4.2 Spectrum sensing classification

Spectrum sensing techniques can be classified into three categories: transmitter detection, cooperative detection and interference based detection. These techniques are subdivided into different categories which are presented in Figure 3-3.

3.4.2.1 Noncooperative Sensing Techniques

There are situations in which only one sensing terminal is available or in which no cooperation is allowed due to the lack of communication between sensing terminals. So it is known as noncooperative sensing.

There are several classical techniques for this purpose, including energy detector (ED) [9] matched filter (MF) [8], and cyclostationary feature detection (CFD) [10, 11].

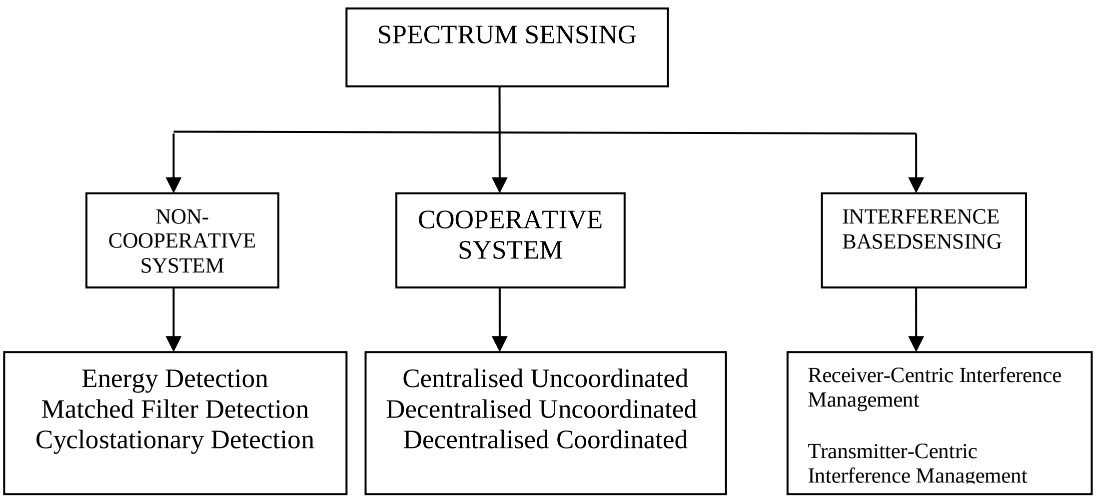

Figure 3-3 Classification of Spectrum sensing Technique

3.4.2.1.1 Energy Detection

It is a no cooperative detection technique .It simple detection technique because it does not require prior information about structure of signal. Energy detection detects the spectrum by measuring the energy of the received signal in a certain frequency band, also called radiometry. It is the most common detection method for spectrum sensing in cognitive radio networks.

ED is a simple detection technique. The ED is said to be a blind signal detector because it ignores the structure of the signal. ED is based on the principle that, at the reception, the energy of the signal to be detected is calculated. It estimates the presence of a signal by comparing the energy received with a known threshold λ derived from the statistics of the noise.

The Figure 3-4 shows the general block diagram of energy detection for anolog input signal [9].

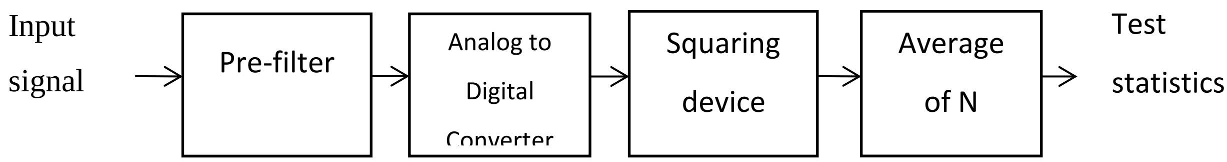

Figure 3-4 Block Diagram of Energy Detector

Let *y(k)* be a samples of received signal *k* =1, 2, . . . ,*N* at the signal detector. Then, the decision statistics can be stated as

$$\boldsymbol{E}(\boldsymbol{K}) = \begin{cases} \boldsymbol{H0}, \ \boldsymbol{if} \quad \boldsymbol{E} < \boldsymbol{\lambda} \\ \boldsymbol{H1}, \ \boldsymbol{if} \ \boldsymbol{E} \geq \boldsymbol{\lambda} \end{cases} \tag{3.3}$$

Where $E = E[| y(k) |2]$ is the estimated energy of the received signal

λ is chosen to be the noise variance σ2 [12]

In practical, one does not dispose of the actual received energy power *E*. The ED technique approximationÊ , where

$$\hat{E} = \frac{\boldsymbol{1}}{\boldsymbol{N}} \sum_{\boldsymbol{1}}^{\boldsymbol{N}} |\boldsymbol{Y}(\boldsymbol{k})|^{\boldsymbol{2}} \tag{3.4}$$

As the number of samples *N* becomes large, by the law of the large numbers, Ê converges to *E*. Nevertheless, in spite of its simplicity, the ED is not a perfect solution. The approximation of signal energy *E* gets better as *N* increases. Thus, the performance of the ED is directly linked to the number of samples.

a) **Advantages**: Implementation simplicity and computational complexities low: an energy detector can be implemented similar to a spectrum analyser by averaging frequency bins of a FFT. Since it is easy to implement, the recent work on detection of the primary user has generally adopted the energy detector. In addition, energy detection is the optimum detection if the primary user signal is not known.

b) **Disadvantages**: The performance of the energy detector is highly susceptible to noise level uncertainty. The noise uncertainty causes problems especially in the case of a simple energy detector because it is difficult to set the threshold properly without the knowledge of the accurate noise level. Secondly, an energy detector can't differentiate between modulated signals, noise, and interference. The performance of an energy detector in shadowing and fading environments degrades clearly. Moreover, it is hard to select the right threshold for energy detection.

Energy Detector in AWGN Channels:

This case has been studied in the work of Urkowitz in 1967 [13]. It is known that the energy detection is the optimal signal detector in AWGN considering no prior information on the signal structure. The performance of ED can be understand by two probabilities: the probability of detection P_d = Prob{ $\hat{E} > \lambda$ |H1} and false alarm P_{fa} = Prob{ $\hat{E} > \lambda$ |H0} behave with the measured received signal energy.

Zero mean Gaussian noise is used to model the AWGN noise signal. The primary signal energy varies with respect to the noise. In the ED method, test statistics E follows a noncentral chi-square distribution with variance σ^2=1 and central chi-square distribution with 2N degree of freedom.

$$\mathbf{E} \sim \begin{cases} \boldsymbol{X^2_{2TW}} & , \boldsymbol{H_0} \\ \boldsymbol{X^2_{2TW}(2\varepsilon)} & , \boldsymbol{H_1} \end{cases} \tag{3.5}$$

Where ε is signal to noise ratio. σ_x^2 is the signal variance and σ_n^2 is the noise variance

The performance of ED method is measured by analysing ROC in term of probability of detection (P_d) vs. probability of false alarm($P_{fa)}$ for given threshold and probability of detection vs. SNR for given probability of false alarm. The signal is detected when the primary user is present and false alarm is occurring when the user is absent. The probability of detection and probability of false alarm are evaluated by:

$$\boldsymbol{P_d = Pr(E > |H1) = Q_m(\sqrt{2\varepsilon}, \sqrt{\lambda})} \tag{3.6}$$

$$P_{fa} = Pr(E > H0) = \frac{\Gamma(TW,\frac{\lambda}{2})}{\Gamma(TW)} \tag{3.7}$$

Energy Detector in Fading Channels

The performance of the ED in fading channels studied in 2002, Kostylev. The analytical expressions for the ED over the Rayleigh fading channel is derived by Kostyley., the problem was revisited by Digham et al. in 20003, who provided an alternative analytical method for Rayleigh,Rice and Nakagami fading channels. In this chapter, however, we discussed only the Rayleigh channel which performs for ED technique.

Kostylev characterized the statistics of the energy of the signal for both the H0 and H1 cases, assuming *h(k)* is for Rayleigh distributed as:

$$\hat{\text{E}} = \begin{cases} X^2_{2(TW+1)} & , H_0 \\ e_{2(1+\varepsilon^2)} + X^2_{2TW}(\lambda) & , H_1 \end{cases} \tag{3.8}$$

Where $e_{2(1+\varepsilon^2)}$ is the exponential distribution with parameter $\alpha = 2(\varepsilon^2 + 1)$ with Probability density function$(x, \alpha) = \alpha e^{-\alpha x}$, where ε is the SNR.

It is clear that, under the hypothesis H0, the statistics are the same as for the AWGN channel case, so the probability of false alarm is the same as in (3.7).

$$P_{fa} = Pr(E > H0) = \frac{\Gamma(TW,\frac{\lambda}{2})}{\Gamma(TW)} \tag{3.9}$$

The probability of detection for H1 given by [22]

$$\text{P}_d = e^{\frac{\hat{\varepsilon}}{2}} \sum_{m=0}^{TW-2} \frac{1}{m!} \left(\frac{\hat{\varepsilon}}{2}\right) + \left(\frac{1+\varepsilon}{\varepsilon}\right)^{TW-1} \left[e^{\frac{\hat{\varepsilon}}{2(1+\varepsilon)}} - e^{\frac{\hat{\varepsilon}}{2}} \sum_{m=0}^{TW-2} \frac{1}{m!} \frac{\varepsilon\, \hat{\varepsilon}}{2(1+\varepsilon)}\right] \tag{3.10}$$

3.4.2.1.2 Matched filter Detection

The best sensing technique in AWGN environment without ant prior information about the signal is ED technique. If we considered the signal structure, then we can get best performance by using matched filter method.

Matched filter is a linear filter which used to maximize signal to noise ratio in presence of additive noise. It provides coherent detection. A coherent detector uses the knowledge of the phase of the carrier wave to demodulate the signal.

Figure 3-5 shows the block diagram for primary user detection using matched filter in which a signal received from primary user is passed through channel. The channel output is applied to matched filter. Matched filter correlates the original signal with time shifted version of signal and compare between final outputs of matched filter and matched filtered signal predetermined threshold which determine the presence of primary user.

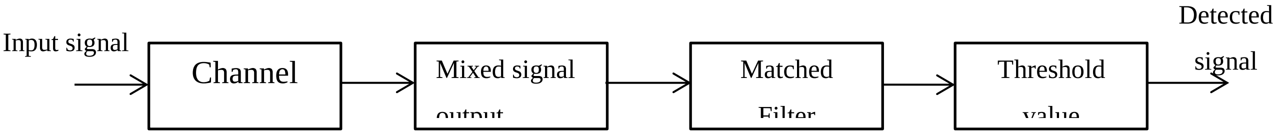

Figure 3-5 Block Diagram of Matched-filter Detection

In wireless communication technologies transmission of pilot carrier is necessary for channel estimation. Secondary systems can exploit pilot signals to detect the presence of transmissions of primary systems in their vicinity. MF detection achieves optimal signal detection if pilot signal is known. It maximizes, the SNR. The threshold value for MF is not like threshold value taken in ED. In ED threshold value is depend on noise variance. MF is performs well in low SNR condition, since MF maximizes power.

Advantages:

1. It requires short time to achieve a particular probability of false alarm.

2. The required number of samples grows as O (1/SNR) for a target probability of false alarm at low SNR.

3. Matched-filtering requires cognitive radio to demodulate received signal. Hence it requires information about primary signal’s features like operating frequency, modulation type and order, bandwidth and frame format.

Disadvantages:

1. Complexity of sensing device due to requirement of receiving unit for all types of signal.

2. Various algorithms are used to detect primary user. Hence it gives rise to more power consumption.

3. Pilot carrier transmission is required for channel estimation. But CR might not recognize which network is in operation in that radio environment in that time. So CR sensor is unable to know which to which pilot sequence it is looking for. So if it detects incorrect pilot then it detects as that spectrum band is free which treated as false detection.

4. MF requires pilot in every medium for signal transmission. But pilot carriers are transmitted in downlink direction and in uplink direction pilot carriers are uncovered.

5. MF is coherent reception method. But in practical to get coherent reception is very difficult.

3.4.2.1.3 Cyclostationary Feature Detection

MF detection performances better in low SNR condition. But MF requires prior information about signal structure for licensed user detection. If knowledge about the signal structure is not good then MF dose not perform well. So with limited information about signal structure primary user detection can be possible by using cyclostationary feature detection.

To detect primary user in spectrum band, it requires periodicity of received signal. The periodicity are generally relies on sinusoidal carriers, pulse trains, spreading codes, pilot sequences, cyclic prefixes and other repetitive carriers. These periodicity characteristics signals are having spectral correlation and periodic statistics properties. But these properties are not found in noise signal. Since noise is a random signal. Cyclostationary feature detection performs better in low SNR condition than ED method because it is robust to noise. But it requires prior knowledge about signal and it able to differentiate primary user signal with CR transmission signal.

CR detects random signals having stochastic noise. The periodic statistics features are extracted using spectral correlation. Figure 3-6 represents block diagram of cyclostationary

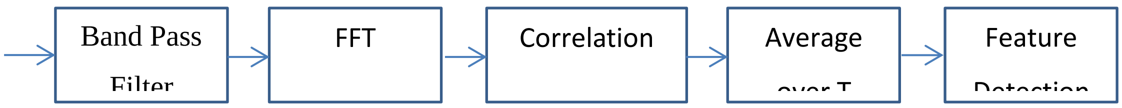

Figure 3-6 Block diagram of Cyclostationary Feature Detection

Feature detection. Spectral correlation function is two dimensional function whose cyclic frequency α and it represents power spectral density when α=0.

Thus the cyclostationaty signal detection technique is a good detection technique because it performs well with less information about signal structure.

Advantages:

1. Accuracy of cyclostationary is more than ED and MF.
2. It provider better performance than Ed method.

Disadvantages:

1. It is a complex technique.
2. It requires larger computational time.

3.4.2.2 Cooperative Sensing Techniques

Noncooperative based sensing method performs well for AWGN channels. But these techniques do not provide satisfactory results for fading channels due to hidden node problems. So cooperative technique provides improvement result upon noncoperative based techniques. Various topologies are provided which explain this technique is in Figure 3-7 [7, 8]. The topologies are:

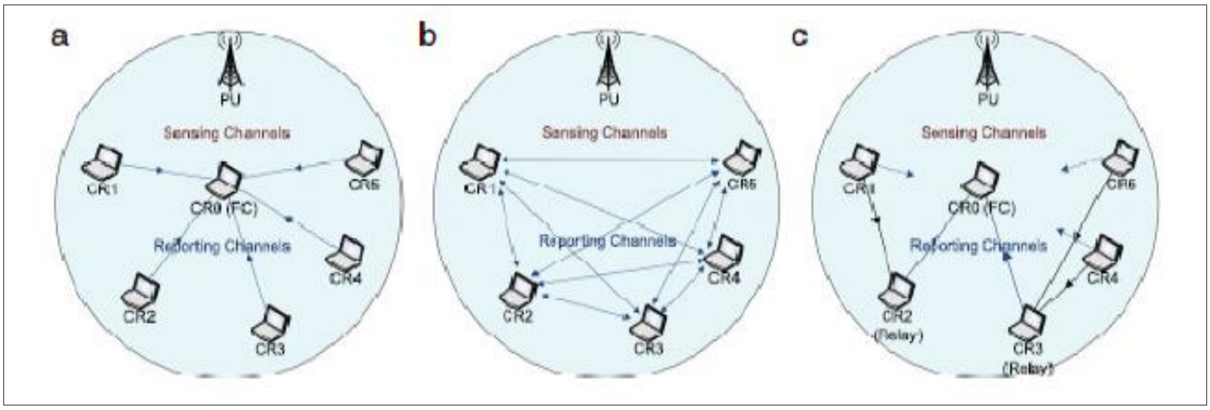

Figure 3-7 Cooperative sensing techniques: - 1. Centralised Coordinated, 2. Decentralised Coordinated and 3. Decentralised Uncoordinated

1. **Centralised Coordinated Topology**: Any CR users (secondary user) in a wireless network detect presence of primary user and it informs this information to centralised control CR. The centralised CR then circulate this message to all other CR users the network.
2. **Decentralised Coordinated Topology**: In this network CR does not play as centralised controller. The CR user gathers information and provides this information to other CR users. In this topology all CR user play same role no controller used. This technique uses different algorithms to convey information to other CR users.
3. **Decentralised Uncoordinated Topology**: CR user does not require any cooperation with other CR users. It has independently detected presence of primary user and leaves the spectrum if primary user present.

Cooperative sensing method is better in conditions like multipath fading, shadowing effect, low power requirement and high sensitivity cases. But it must be periodically senses the network for better performances.

3.4.2.3 Interference Based Sensing

CR networks will have some set of policies which followed by some by regulatory agencies. FCC and TRAI are regulatory bodies for radio which determine the spectrum usage and its policies. The idea behind these policies is central in which primary systems that have the right to the spectrum and secondary systems that are allowed to use the spectrum so long as they do not disturb the communications of the primary systems. So the main idea behind this policy is that secondary user should not interference primary user in any case and follows the legacy rule for white space utilization. The problem is one of interference management. This problem has two different points of view: receiver centric or transmitter centric.

3.4.2.4 Receiver-Centric Interference Management

This approach determines the restriction on the power of the transmitters around it which has interference limitation at the receiver. This interference called the interference temperature. It is chosen to be the worst case that can be accepted without disturbing the receiver operation beyond its operating point. This approach requires information of the interference limits of all receivers in a primary system. It includes individual locations, fading, modulations, coding schemes, and services.

3.4.2.5 Transmitter-Centric Interference Management

In the transmitter-centric approach, the focus is shifted to the source of interference. The transmitter does not know the interference temperature, but by means of sensing, it tries to detect free bandwidth. The sensing procedure allows the transmitter to classify the channel status to decide whether it can transmit and with how much power. In practice, the transmitter does not know the location of the receivers or their channel conditions; it is not able to know how much interference these receivers can tolerate. Thus, spectrum sensing solves the problem for worst-case scenario, assuming strong interference channels, so that the secondary system transmits only when it senses an empty medium.

3.5 Energy Detection for Single-carrier Modulation and Multicarrier Modulation

3.5.1 Energy Detection for Single carrier Modulation

Single-carrier modulation techniques use only one signal is transmitted at all times. But, in the multi-carrier modulation techniques, several signals are transmitted simultaneously. In general single-carrier modulation techniques modify only one of parameters like amplitude, frequency and phase of the sinusoidal signal and according to the binary information to be transmitted. These techniques are known as amplitude shift keying (ASK) for amplitude modification, frequency shift keying (FSK) for frequency modification and phase shift keying (PSK) for phase modification of sine wave respectively. For digital signals, the information is collections of bits called symbols that are modulated onto the carrier. The basic time unit is a symbol, which is composed of a segment of the sinusoidal waveform. There is different combination of symbol formation. If there are only two possible different symbols in a digital modulation, then it is called a binary modulation is a modulation technique.

3.5.1.1 Binary Phase Shift Keying

It is a simplest form of phase shift keying. It is a type of modulation using 2 distinct phases to signal which are separated by 180 degree and so it is termed as 2-psk. The constellation points positioned at any point either in the real axis or in the imaginary axis in the figure but separated by 180.The example of constellation diagram for BPSK where points are positioned in real axis, at 0 degree and 180 degree. 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. BPSK is only able to modulate at 1 bit/symbol and so it is unsuitable for high data-rate applications.

3.5.1.2 Simulation Result for Binary Phase Shift Keying

Result for BPSK using AWGN channel

With the binary hypothesis simulation was made. Input is taken as random bit sequences and the received signal at receiver is original signal with passes through AWGN [14].

The performance of signal can be studied by using ROC curve. The Roc curve is plotted between probability of detection (p_d) and signal-to -noise ratio (SNR) in Figure 3-8. The detection performance can be performed finding the probability of detection by varying SNR from -25 dB to 10 dB using Monte Carlo simulation. The graph is plotted for SNR values on X-axis and probability of detection on Y-axis. Here we have taken different values of probability of false alarm i.e., 0.1, 0.05 and .01 and number of samples N. It is observed that performance is better at higher SNR values for a particular probability of false alarm with higher number of samples. And at high value of probability of false alarm signal detects faster compare to lower value of probability of false alarm for same number of samples.

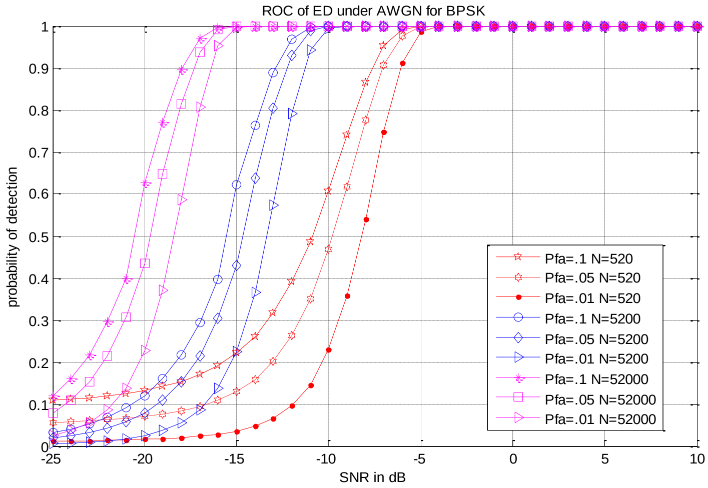

Figure 3-8 ROC for BPSK, P_{fa}=0.1, P_{fa}=0.01, P_{fa}=0.5

Again ROC curve is plotted between probability of false alarm on X-axis and probability of detection on Y-axis as shown in Figure 3-9. Here we have varied probability of false alarm from 0 to 1 with different number of samples and different SNR values. It is observed that detection performance increases with higher value of SNR with a fixed value of N.

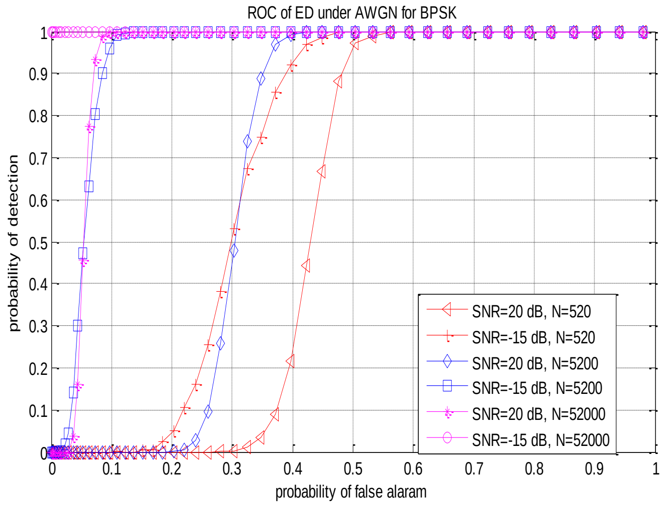

Figure 3-9 ROC for BPSK at different SNR

3.5.2 Energy Detection for Multicarrier Modulation

The success of 4G wireless system will depends on the choice of technology, concepts spectrum allocation method, utilization of spectrum and innovation in architecture. Therefore, advanced technologies and high performance physical layers are required to provide high speed data rate with flexible bandwidth allocation. The past several decades an increasing number of data communication systems have started employing another form of transmission framework based on sending parallel streams of information in the frequency domain on different centre frequencies. Employed in a wide range of applications, including digital subscriber line (DSL) modems, IEEE 802.11a wireless local area networks (WLANs), digital audio broadcasting (DAB), and digital video broadcasting (DVB), IEEE 802.16 (WIMAX), multicarrier modulation has exhibited its potential to transmit large amounts of data across a channel while possessing reasonable error robustness [15].

Signals to be transmitted in any medium usually suffer from fading effects such as flat fading and frequency fading. Researchers proposed many solutions to these fading problems. Wireless medium signals are generally suffers due to frequency selective fading. Single-carrier systems, uses complex equalization schemes to combat frequency-selective fading. The ideal equalizer has a frequency response that is the exact inverse of that of the channel which requires infinite number of equalizer taps. When a deep fade occur, it results in failure of communication link in single-carrier systems.

Multicarrier modulation is proposed to combat frequency-selective fading channels. In this system, system is divided into number of sub-channels which use carriers that fall within faded frequency band. Corrupted sub-channels can be recovered easily using different encoding schemes in multicarrier systems.

The primary advantage of multicarrier modulation is its subcarrier operating parameters on an individual or block-by-block basis. This additional flexibility over high data rate single-carrier transmission techniques makes it an excellent candidate for dynamic spectrum access .Another advantage of multi-carrier transmission is its robustness in frequency selective fading channels is the reduced signal processing complexity by equalization in the frequency domain.

History

The multi-carrier transmission has become more interesting technique for its high data rates for broadband applications. OFDM is a multicarrier transmission which is FDM (e.g. frequency division multiplexing) started in 1950s, which has high spectral and low cost implementation of FDM became possible in the 1970s and 1980s with advances in Digital Fourier Transform (DFT). OFDM is modern wireless communication network started in 1990: A few historical aspects relater to OFDM are given below [16]:

1958: Kinplex, a military multicarrier high-frequency communication system.

1960: Chang published for multi-channel transmission on the synthesis of band-limited signals in mid of 1960s.

1966: R.W.chang at Bell labs describes the concept of using parallel data transmission and FDM.

1970: First patent issued on OFDM [b1]

1971: Weinstein and Ebert presented the Fourier transform for baseband processing.

1881: Hirosaki proposed DFT implementation of FDM.

1990: The breakthrough for OFDM came out which was modulation chosen for ADSL in USA.

1995: ETSI DAB standard first comes out based on OFDM wireless standard for digital audio broadcasting.

1997: DVB-Terrestrial digital video broadcasting standard.

1999: IEEE 802.11a standard for wireless LAN

2004: IEEE 802.16a/d standard for fixed broadband wireless MAN.

2005: OFDM-based mobile cellular networks being developed under 802.16e and IEEE 802.20.

Orthogonal Frequency Division Multiplexing (OFDM):

OFDM is a form of multi carrier modulation that transmits broadband data over parallel narrowband streams. A communication system with multi-carrier modulation transmits N_c complex-valued source symbols S_k, k=0.1…N_c-1, in parallel on to N_c sub-carriers. The source symbols are complex symbols which are transmitted over OFDM modulation. The OFDM signal can be represented by [17]

$$\boldsymbol{x(t) = \sum_{0}^{N_c-1} s_k\ e^{j2\Pi f_k t} = \sum_{0}^{N_c-1} s_k\ \phi_k(t) \qquad where\ o < t < T_s} \tag{3.11}$$

where $f_k=f_0+K\Delta f$ *and*

$$\boldsymbol{\phi_k(t) = \begin{cases} e^{j2\Pi f_k t} & if\ \ 0<t<T_s \\ 0 & otherwise \end{cases}} \tag{3.12}$$

T_s *and* Δf are called the symbol duration and sub channel spacing respectively. The OFDM signal can be demodulated at receiver by using orthogonally condition. The orthogonality condition states as (the symbol duration must be long enough signal) $T_s\ \Delta f=1$.

The orthogonality condition states as:

$$\frac{1}{T_s}\int_0^{T_s} \phi_k(t)\phi_l^*(t)$$

$$= \frac{1}{T_s}\int_0^{T_s} e^{2\pi(f_k-f_l)t}\ dt$$

$$= \frac{1}{T_s}\int_0^{T_s} e^{2\pi(k-l)\Delta f t}\ dt$$

$$= \boldsymbol{\delta[k-l]} \qquad (3.13)$$

Where $\delta[k-l]$ is known as delta function and its definition is given as

$$\delta[n] = \begin{cases} 1, & if\ n = 0 \\ 0 & otherwise \end{cases}$$

(3.11) shows that $\{\phi_k(t)_{k=0}^{N_c-1}$ is set of orthogonal functions.

The OFDM signal can be demodulated using orthogonal property expressed by

$$\frac{1}{T_s}\int_0^{T_s} x(t)e^{j2\Pi f_k t}\ dt$$

$$= \frac{1}{T_s}\int_0^{T_s}(\sum_{l=0}^{N_c-1} s_l\phi_l\,(t))\ \phi_k^*\,(t)dt$$

$$= \sum_{l=0}^{N-1} s_l\ \delta[l-k]$$

$$= S_k \qquad (3.14)$$

FFT Implementation

This section describes the relation between OFDM signal and discrete Fourier transform (DFT).This DFT can be implemented by low complexity fast Fourier transform (FFT).

From (3.12), an OFDM signal can be expressed as:

$$x(t) = \sum_{0}^{N_c-1} s_k\ e^{j2\Pi f_k t}$$

The sampling interval of x(t) is $f_s = \frac{T_s}{N_c}$,then

$$\boldsymbol{s_n = S(n\Delta_s) = \sum_{k=0}^{N_c-1} e^{j2\pi f_k \frac{nT_s}{N_c}}} \qquad (3.15)$$

Taking $f_0 = 0$ *and* $fkTs = k$, equation () becomes

$$\boldsymbol{s_k = \sum_{k=0}^{N_c-1} s_k e^{j2\pi kn} = \mathrm{IDFT}\{s_k\}} \qquad (3.16)$$

where IDFT denotes Inverse discrete Fourier Transform. Therefore, the OFDM transmitter can be implemented using IDFT and receiver can be implemented using DFT.

Instead of DFT and IDFT we can use FFT and IFFT respectively. FFT algorithm provides efficient algorithm to implement DFT and IDFT. Number of complex multiplication reduces from N^2 to $\boldsymbol{\frac{N}{2}\log_2 N}$ for an N-point DFT or IDFT. The FFT algorithm provides OFDM implementation is less complex than DFT algorithm OFDM implementation.

Cyclic Prefix, Power Spectrum and Efficiency

A cyclic prefix is used to deal with multipath delays in OFDM system. There are three different ways to represent cyclic prefix shown in Figure 3-10(a). Let us consider length of cyclic prefix which is inserted between OFDM sub-channel blocks is T_g. The OFDM signal x (t) can be extended to $\hat{x}(t)$ shown in Figure 3-10 (b).

$$\hat{x}(t) = \begin{cases} x(t), & if\ 0 < t < T_s \\ x(t - T_s) & if\ T_s < t \leq T_s + T_g \end{cases} \tag{3.17}$$

Now the duration of OFDM symbol extended from T_s to T_s+T_g. The cyclic prefix extension for OFDM signal is shown in Figure 3-10(b). The other types of cyclic extension are shown in Figure 3-10 (c) and Figure 3-10 (d).

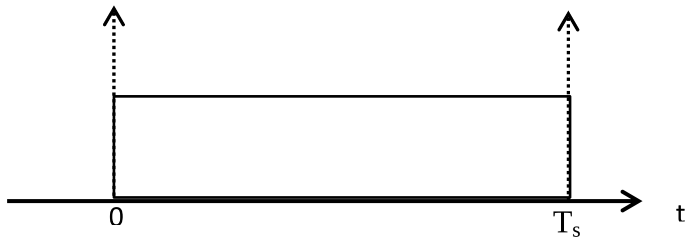

Figure (a) OFDM Signal

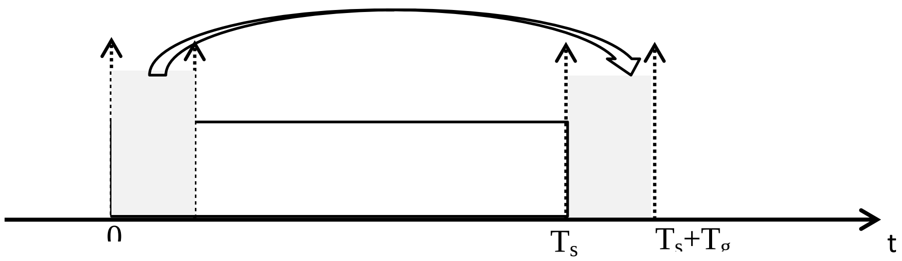

Figure (b) OFDM Signal with cyclic prefix

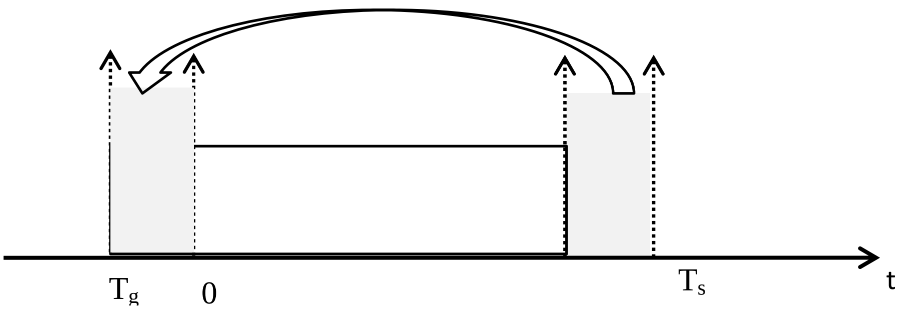

Figure (c) OFDM Signal with cyclic prefix

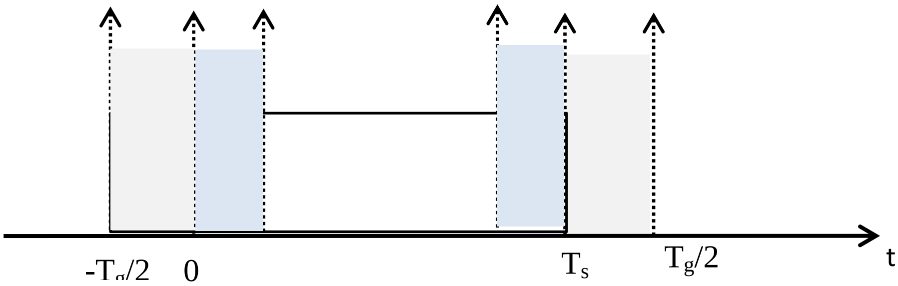

Figure (d) OFDM Signal with cyclic prefix

Figure 3-10 OFDM signal with different cyclic extension.

X(t) expressed in (3.11) is a summation of truncated complex exponential functions with different frequencies. The power density spectrum of x(t) is a function of $|\frac{\sin f}{f}|^2$ as Figure 3-11.

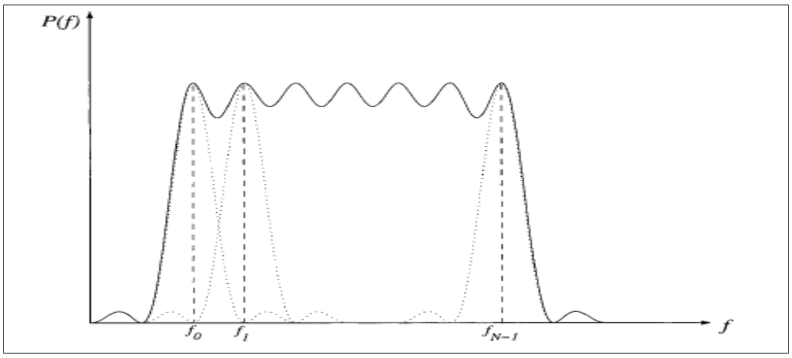

Figure 3-11 Power Spectrum of OFDM signal

The OFDM signal consists of N_c sub channels. Therefore bandwidth of OFDM signal is given about $(\mathrm{Nc}+1)\Delta f$ .The rate of transmission of each sub-channel is $\frac{1}{T}$ symbols/sec and total transmission rate of OFDM signal is $\frac{N_c}{T}$ symbol/sec. Hence, bandwidth efficiency of OFDM signal is

$$\Gamma = \frac{\frac{N_C}{T}}{(N+1)\Delta f}$$

$$= \frac{\frac{N}{T_S(N_C+1)}}{(N_C+1)\Delta f}$$

$$= \frac{1}{1+\frac{1}{N_c}} \quad \frac{1}{1+\frac{T_g}{T_s}} \tag{3.18}$$

It is in symbols/sec. In real time scenario of OFDM system N_c is much larger than 1 and cyclic prefix much smaller than OFDM symbol duration.

OFDM realization

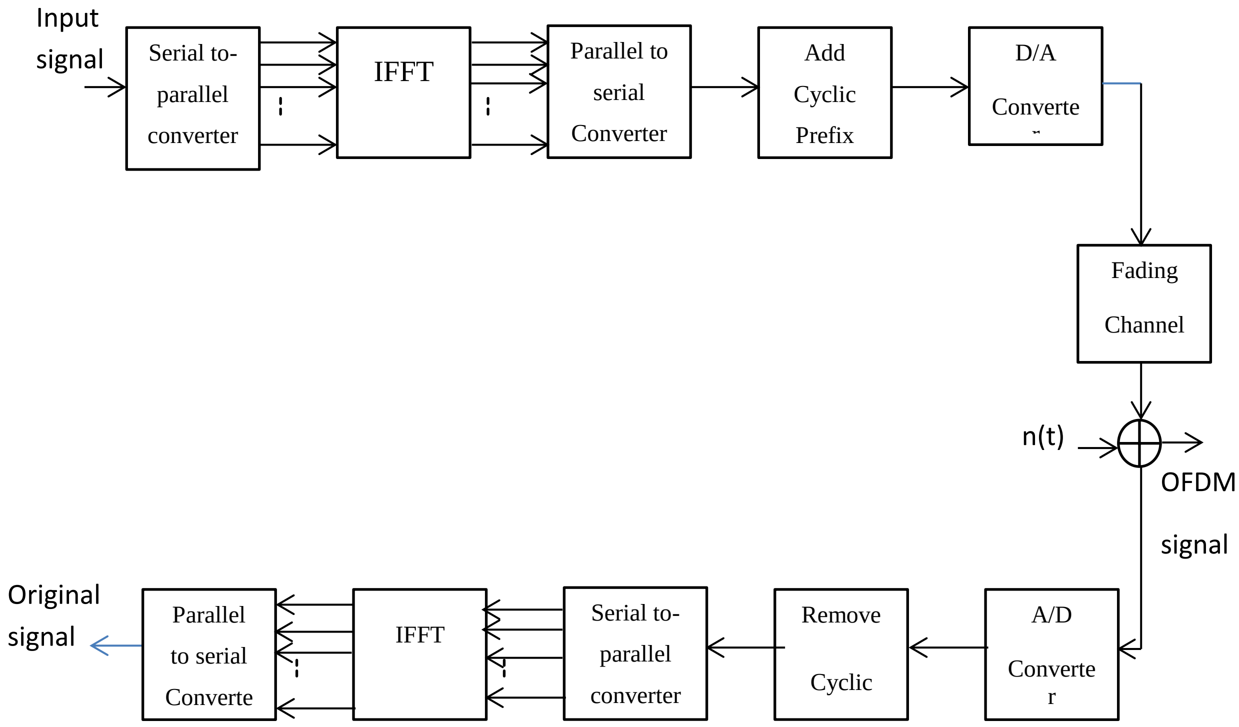

Figure 3-12 Block Diagram of OFDM transceiver

OFDM is a multicarrier communication technique where signal is transmitted using large number of subcarriers orthogonal to each other. OFDM divides the total bandwidth into a number of smaller bandwidths by spreading the transmitted signal over a number of subcarriers. First, at transmitter a sequence of bits carries information is passed through signal mapper to form information-bearing symbol. In OFDM transmitter the information in the form of symbols is passed through serial to parallel converter onto K subcarriers. These parallel bits of data are mapped to the subcarriers using an Inverse Fast Fourier Transform (IFFT) block, where the subcarriers are orthogonal to each other. The OFDM symbols are then appended with a cyclic prefix of L points to nullify the effect of inter-carrier interference and are passed through a parallel to serial converter. The resulting samples are in the form of OFDM symbol transmitted through transmitter.

Figure 3-12 shows Block Diagram of OFDM transceiver. The transmitter output signal transmitted through wireless medium suffers from AWGN and different multipath fading by pass through different channel. The reverse operation is occurring on receiver side using an FFT. Cyclic prefix is removed to form N_c points which passed through serial to parallel converter .The output of serial-to-parallel converter fed to FFT and output of FFT processed through parallel-to-serial converter. Different decoding schemes and different algorithms are used to recover information bits [16, 18].

A block of data consists of information bits that can be represented as the OFDM symbol S_n, n=0, 1… N_c-1 is represented in vector form

$$\boldsymbol{s} = [\boldsymbol{s_0}, \boldsymbol{s_1}, \dots, \boldsymbol{s_{(N_c-1)}}]^{\boldsymbol{T}} \tag{3.19}$$

The IFFT operator is applied to *s* which converts frequency domain signal into time domain signal [16] and the corresponding time domain signal is given by

$$\boldsymbol{x(n)} = [\boldsymbol{x_0(n)}, \boldsymbol{x_1(n)}, \boldsymbol{x_2(n)}, \dots, \boldsymbol{x_{(N_c-1)}(n)}]^{\boldsymbol{T}} \tag{3.20}$$

Where, N_c is the block length of IFFT.

The output of the IFFT block is an OFDM symbol. Acyclic prefix is inserted before the OFDM symbol. N_{cp} numbers of cyclic prefix bits are added and the transmitted signal becomes:

$$[\mathbf{x_{-Ncp}}\boldsymbol{(n)}, \dots, \boldsymbol{x_{-2}(n)}, \boldsymbol{x_{-1}(n)}, \dots, \boldsymbol{x_0(n)}, \boldsymbol{x_1(n)}, \dots, \boldsymbol{x_{(N_c-1)}(n)}] \tag{3.21}$$

Where the extra cyclic block is represented as

$$\boldsymbol{xcp(n)} = [\boldsymbol{x_{-Ncp}(n)}, \dots, \boldsymbol{x_{-2}(n)}, \boldsymbol{x_{-1}(n)}] \tag{3.22}$$

The OFDM signal is transmitted through the fading channels.

The $N_c X N_c$ matrix for channel is

$$H = \begin{bmatrix} H_0 & 0 & 0 \\ 0 & H_1 & 0 \\ 0 & 0 & H_{N_c-1} \end{bmatrix}$$

And AWGN signal can be represented in form of matrix as:

$$n = [N_0, N_1, \dots, N_{N_c-1}]^T$$

At the receiver side original symbol is received after Inverse process of OFDM. The received symbol is represented as

$$r = Hs + n$$

which is in matrix form as $\quad r = [R_0, R_1, \dots, R_{N_c-1}]^T$

Advantages:

1. High spectral efficient due to use of OFDM subcarriers and allowing overlap among subcarriers spectrums.
2. OFDM is more resistant to frequency-selective fading than single carrier systems by dividing spectrum into number of sub-channel spectrums.
   It reduces ICI (Inter-carrier-Interference) and ISI (Inter-symbol-Interference) by adding cyclic prefixes.
3. Symbol lost due to Frequency-selective fading can be reduced using some adequate coding technique and interleaving.
4. Channel equalizer is simpler than single-carrier modulation which uses adaptive equalizer.
5. It is less sensitive to timing offset because of cyclic prefix.
6. Implementation is simple by using FFT and IFFT algorithm.

Disadvantages:

1. It is more susceptive to frequency offset. It is because of tightly spaced subcarriers, FFT and modulation schemes used.
2. The OFDM signal has noise like amplitude in a dynamic range. So it requires high-peak-to-average power ratio in A/Ds and D/As and in linear power amplifier.
3. More susceptive to Doppler spread than single-carrier modulation.
4. Synchronization of frequency and time is required.
5. The performance of transmitter and receiver is imperfect due to phase noise.

Applications:

There are lot of applications which use OFDM technology over the last few years. Some of the application areas are as below:

There are many standard for wireless communication. Some of the standards are

WiMAX (IEEE 802.16), WiFi (IEEE 802.11), LTE (3GPP release 8), DAVB

Proprietary solutions as: Flash OFDM (Flarion)

Wired broadband access: xDSL

Data transmission through power line: (PLC = Power Line Communications)

Wireless Technologies:

Wireless technologies can be classified in different ways depending on their range. Wireless technology is designed in such a sense which serves for a specific usage segment. The requirements for using these segments based on a variety parameters like Bandwidth needs, distance and Power. There are many wireless technologies like Wireless Wide Area Network (WWAN), Wireless Personal Area Network (WPAN), Wireless Local Area Network (WLAN), worldwide interoperability for microwave access (WIMAX***).*** In this thesis only two technologies WLAN and WiMAX are explained.

3.5.2.1 Wireless Local Area Network (WLAN):

WLAN is one of the popular wireless technologies. It is alternative to cable LAN. It provides user to move from one place to another without thinking about wires. It has grown in popularity along with the rise of laptop, computers and low cost netbooks. WLAN meant for short range applications and deliver faster speeds compare WIMAX**.** WLAN provide high speed since its hardware is not meant to transmit or receive signals from far away.

Wireless LAN technology is standardized within the IEEE 802.11 working Group. The IEEE standard for wireless LAN provide flexibility and mobility .This technology has improved access to fixed LAN and higher performance in ad hoc networks. The IEEE 802.11 working Group had different standards. The 802.11a and 802.11g are two standards which utilize OFDM modulation technology. The 802.11a standard has higher bandwidth compare to 802.11g and 802.11b (Wi-Fi).The 802.11a has bandwidth 5GHz (54 Mbps) while 802.11b (Wi-Fi) has bandwidth 2.4 GHz (11Mbps) with 802.11g standard.

IEEE 802.11a:

This standard operates in 5GHz with rates up to 54 Mbps. It uses OFDM technique with 52 sub-carriers. The most popular advantage of this technology is less interference to other network. The application areas are limited to homes and office buildings. The Wireless LAN has the following features:

1. It has less interference to noise.

2. It is easily dealt with hidden node problems.

3. It has provision for time bound services.

4. It requires overlapping of multiple networks.

The 802.11a/g working Group utilizes OFDM modulation technology to provide data rates from 6 to 54Mbps. The parameters of wireless LAN on OFDM is summarized in Table 3-1.

Table 3-1 Parameters for IEEE 802.11 a/g standard

Data rate	6,9,12,18,24,36,48,54 Mbps
Modulation	BPSK,QPSK,16-QAM,64-QAM
Coding rate	1/2,2/3,3/4
Number of sub-carriers	52
Number of pilots	4
OFDM symbol duration	4us
Guard interval	8us
Useful Symbol time	40us
Bandwidth	5GHz

The major limitation of wireless LAN includes less area of coverage with high carrier frequency. It is less secure than 802.11e standard and it cannot penetrate as far as 802.11b standard. The application include transmission of audio, mobile access, video, audio and video conferencing etc.

3.5.2.2 Worldwide interoperability for microwave access (WIMAX)

It is not very popular technology which gaining attention due to its services in industries. WIMAX provides services in between high speed low range WLAN and low speed low range 3G and 2G technologies. The speed that can be achieved with WIMAX is not constant through it is depend on the distance between base station and subscriber. It provides better bandwidth distribution compare to WLAN.

IEEE 802.16:

WIMAX is standardized within the IEEE 802.16 working Group. It is a wireless service designed to cover wide geographical areas with a large number of user at low cost. IEEE 802.16 support point-to-multipoint architecture in the 10-66 GHz range with data rates upto 120Mbps. WIMAX provides portable high-speed packet services. It has the following features:

1. It provides uses OFDM and OFDMA modulation technique.

2. It provides full mobility of data and transmission of data at higher speed.

3. It has variable channel configuration for multiuser diversity.

4. It utilizes multiple-input multiple-output (MIMO) communication.

Table 3-2 Parameters for IEEE 802.16 standard

Parameter	Fixed	Mobile			
Data rate	70 Mbps	70 Mbps			
Modulation	BPSK, QPSK, 16-QAM, 64-QAM				
Coding rate	1/32,1/16,1/8,1/4				
Number of sub-carriers	256	128	512	1024	2048
Number of pilots	8	12	60	120	240
OFDM symbol duration	72us	102.9us			
Guard interval(1/8)	8us	11.4us			
Useful Symbol time	64us	91.4 us			
Bandwidth	3.5 GHz	5GHz			

The application areas of 802.16 include mesh networks, broad band mobile network and wireless DSL to residential. WIMAX allows DSL operates to extend service rapidly and effectively into areas of poor wire quality and lower population density. WiMAX uses OFDM and OFDMA modulation technique. The WIMAX has two categories: Fixed WIMAX and Mobile WIMAX. The WIMAX parameters utilizing OFDM technique is presented in Table 3-2.

3.6 Simulation Results

In this chapter we described WLAN and WIMAX standard in IEEE working Group and its usage in different application areas. The performances are evaluated from simulation results done for WLAN and WIMAX.

3.6.1 Simulation Results for WLAN for AWGN:

In this section the performance of WLAN is studied by using ROC plots. The detection performance can be performed by finding the probability of detection varying SNR from -25 dB to 10 dB using Monte Carlo simulation for AWGN noise taking SNR values on X-axis and probability of detection on Y-axis shown in the Figure 3-13. Here we have taken different values of probability of false alarm i.e., 0.1, 0.05 and .01 and different number of sample points i.e. 520, 5200, 52000.The simulation result shows performance is better at higher SNR values for a particular probability of false alarm and if we consider only number of samples then also detection is faster at higher number of sample value.

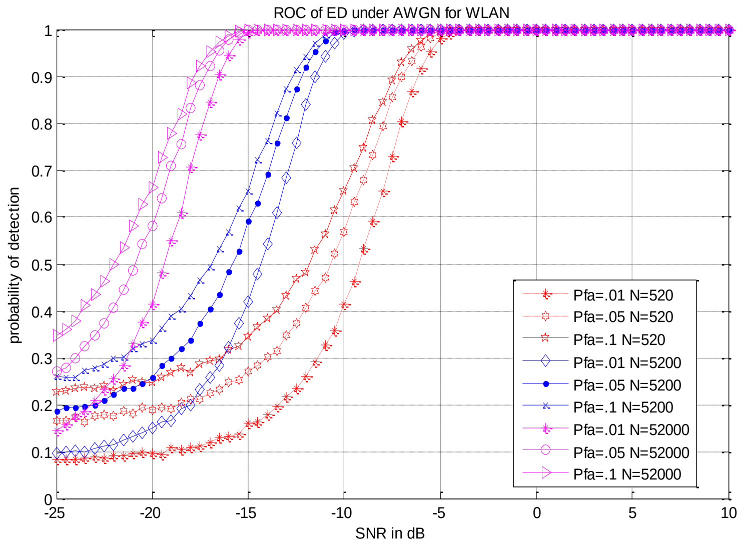

Figure 3-13 ROC for WLAN P_{fa}=0.1, P_{fa}=0.01, P_{fa}=0.5

Figure 3-14 shows the plot between probability of detection and probability of false alarm for WLAN with AWGN. This result indicates at higher value of SNR, detection is faster than lower SNR values and performance is better for more number of samples than less number of sample points.

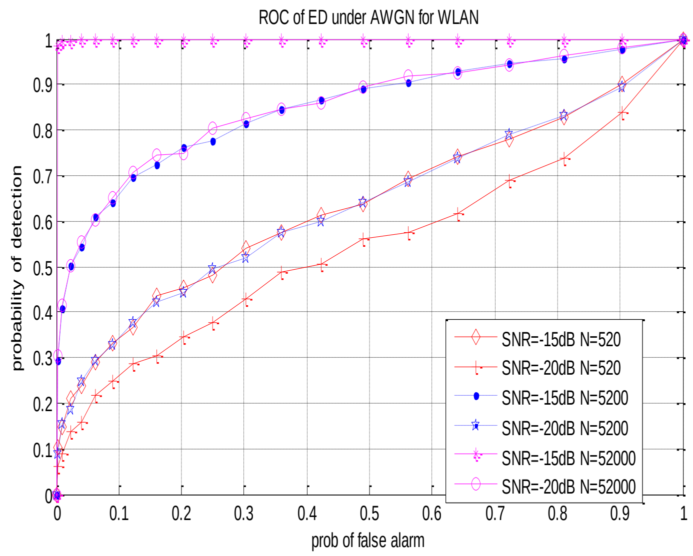

Figure 3-14 ROC for WLAN at different SNR

3.6.2 Simulation Results for WLAN for Rayleigh:

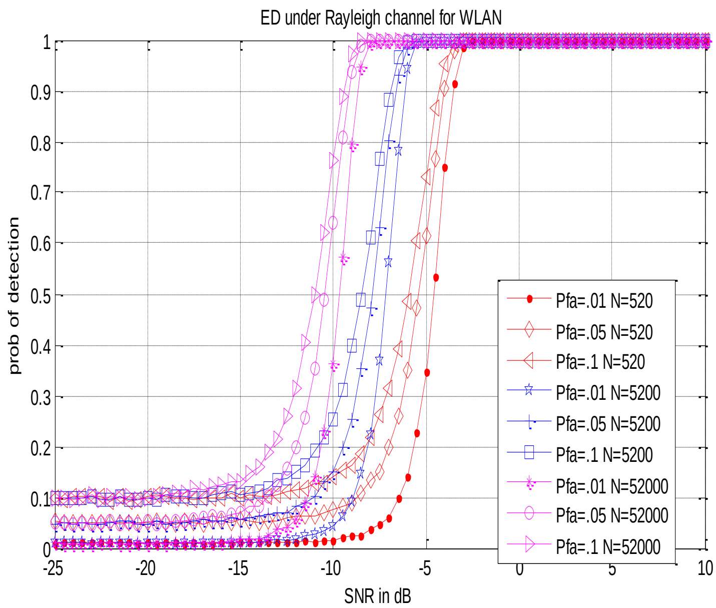

Figure 3-15 ROC for WLAN P_{fa}=0.1, P_{fa}=0.01, P_{fa}=0.5

The Monte-Carlo simulation is performed for WiMAX for Rayleigh channel. The Rayleigh channel has more noise effect compare to AWGN channel. Figure 3-15 indicate ROC curve for WLAN with Rayleigh channel which shows detection is higher with increase the value of probability of false alarm and if the number of sample points are more.

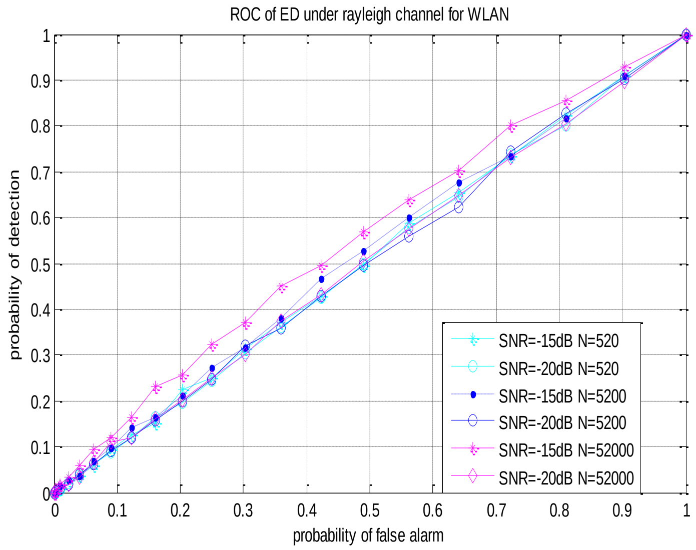

Figure 3-16 ROC for WLAN at different SNR

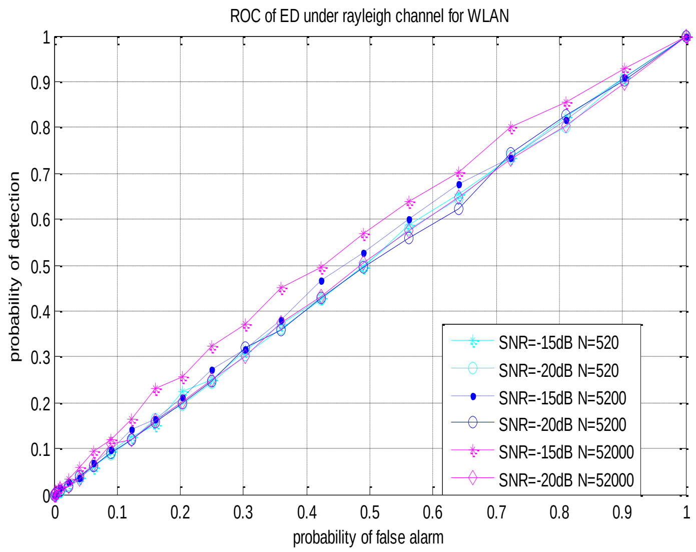

Figure 3-16 shows ROC for WLAN at different values of SNR at different number of sample values. The ROC shows for different SNR values, probability of detection is different and detection quality is good at higher value of SNR. From number of samples it shows that detection is good at high value of SNR and high value of number of samples.

3.6.3 Simulation Results for WiMAX for AWGN:

The performance of WIMAX is evaluated using parameter given in Table 3.2. The detection of primary user is low at low value if SNR and it better at high value of SNR. The performance is studied taking probability of detection in y-axis and SNR in x-axis in Figure 3-17. The simulation is performed for different probability of detection values i.e. 0.1.0.05

and 0.01 and for number of samples i.e. 2560, 25600, 256000. The performance is good for high value of SNR compare low SNR values at a particular value of probability of false alarm and it also shows good result for more number of samples.

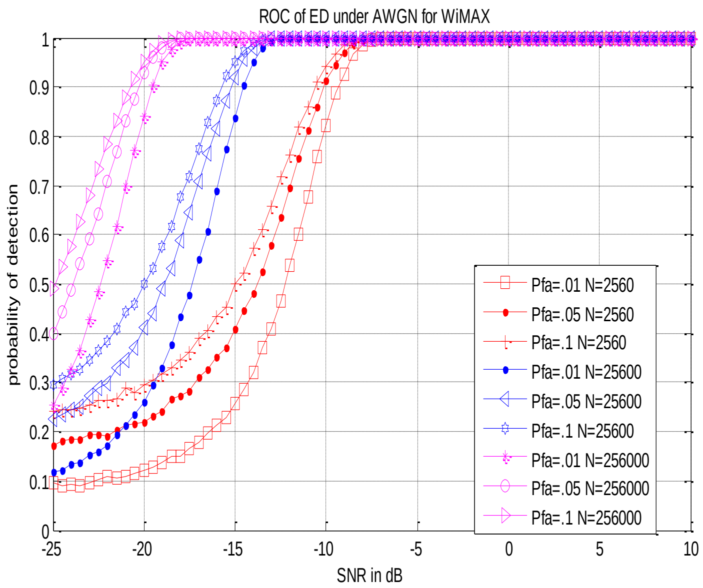

Figure 3-17 ROC for WIMAX P_{fa}=0.1, P_{fa}=0.01, P_{fa}=0.5

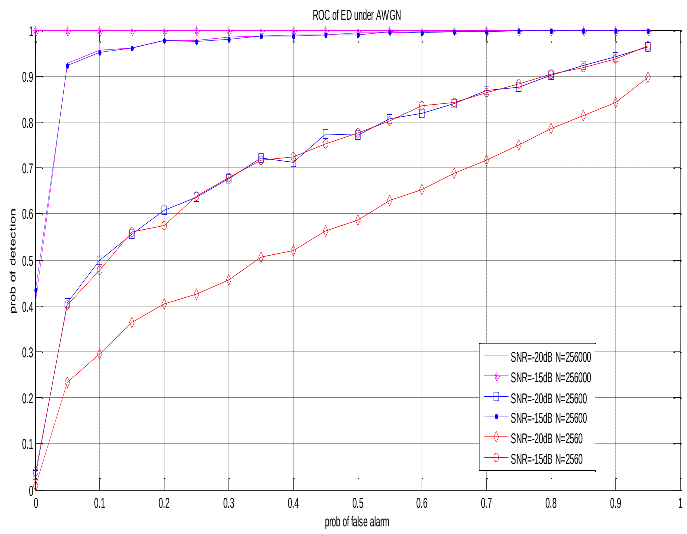

Figure 3-18 ROC for WIMAX at different SNR

Figure 3-18 is the ROC for different SNR values. From ROC probability of detection are different for different value of SNR and different for number of samples. The detection quality is good at higher value of SNR and also it better for more number of samples.

3.6.4 Simulation Results for WiMAX for Rayleigh:

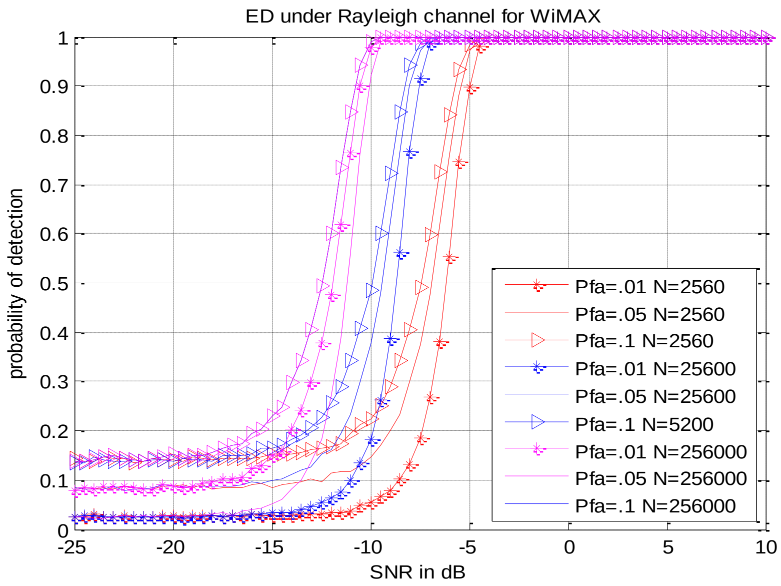

Figure 3-19 ROC for WIMAX P_{fa}=0.1, P_{fa}=0.01, P_{fa}=0.5

This section discusses the performance of WIMAX at rayleigh fading channel. The performance is degraded for fading channel. The signal performance is passed through fading channel and it degraded than AWGN channel. The Monte-Carlo simulation for WIMAX with rayleigh channel is performed at different values of probability of false alarm for different number of samples in Figure 3-19. The performance is good at higher value of SNR and higher number of samples.

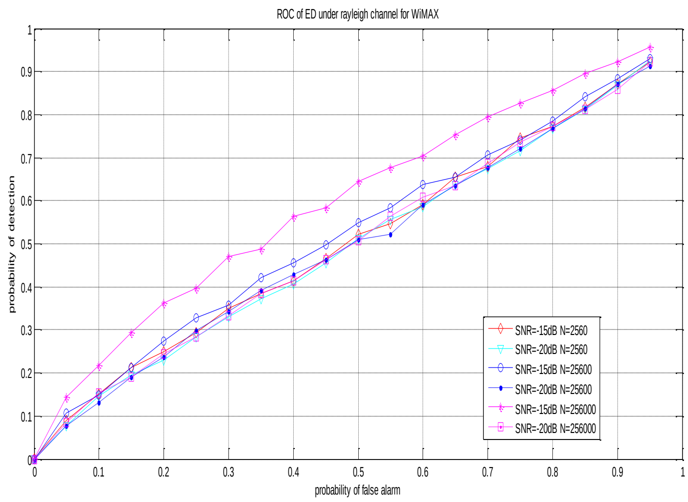

Figure 3-20 ROC for WIMAX at different SNR

The performance is studied for WiMAX at Rayleigh fading channel in Figure 3-20. The ROC is plotted by taking probability of false alarm in x-axis and probability of detection in y-axis. The Rayleigh channel has bad performance compare to AWGN channel due to signal degradation in this channel. The WIMAX performs well for high value of SNR and for more number of samples.

Chapter 4

VLSI Implementation of Energy Detector Technique

4.1 Introduction

The previous chapters are discussed CR, spectrum sensing and one of the techniques of spectrum sensing i.e. Energy Detection to detect presence of primary user in frequency spectrum. The chapter 3 provides the idea about detection of licensed user in single-carrier modulation (BPSK modulation) and multi-carrier modulation (WLAN and WiMAX) wireless technology. This chapter discusses hardware implementation of Energy Detector module using FPGA. This chapter designed Energy detector module for random generated signal and single-carrier modulated (BPSK) signal.

4.2 Architecture of Energy Detection Technique:

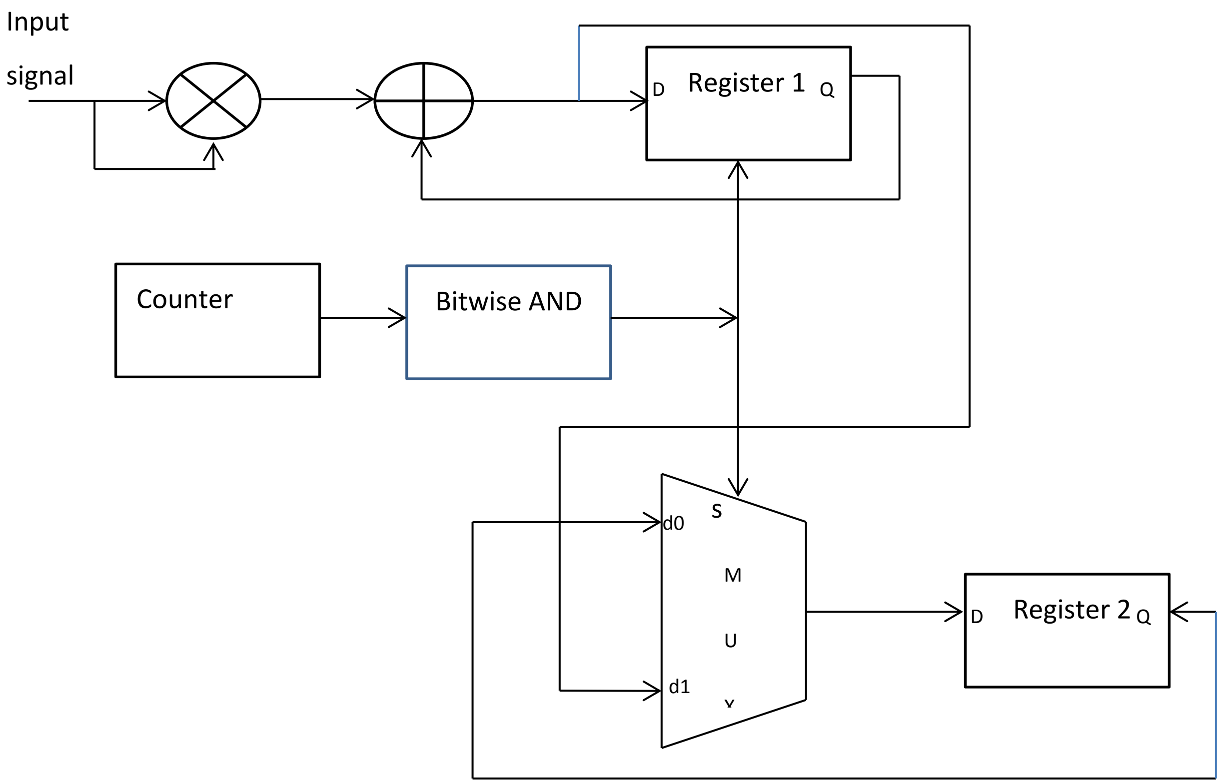

Figure 4-1 Architecture of Energy Detector

Architecture is proposed for ED technique in Figure 4-1. This ED model consists of multiplier, adder circuit, register, counter and multiplexer. The ED model is tested by providing different types of signal to input of ED [19].

The inputs samples are passed through the multiplier in order to get the square of the samples. The resulted squared samples are added and accumulated using an adder–register arrangement, as shown in Figure 4-1. Here different number of samples is taken to get detected energy value However, the value N can be chosen to be higher for better accuracy. The counters count from 0 to total number of samples continuously. For Example if total numbers of samples are taken 16 then, then counter counts and When 16 samples are reached, the content of the counter becomes 15; then, the output of bitwise AND becomes “1,” and Register1 is cleared or reset. The select Signal for multiplexer Mux now becomes “1,” and the energy value for 16 samples is fed to Register2, which forms the output. During the course of counting from 0 to 15, i.e., during the accumulation of 16 samples, the output of bitwise AND gate is “0;” hence, the Mux will select the output of Register2 itself, and hence, the output remains constant. As a result of this, irrespective of the time of duration of the input signal, the energy for 16 samples will be obtained at the output; hence, the proposed energy detector can be used for real time applications.

Initially pseudo–random code is used as input signal. The pseudo random generation block diagram is given in Figure 4-2.

Pseudo Random Generator

The sequence generated by PRSG. It is a shift register whose input is taken as random value. The only single bit is function of XOR logic. Here first input bit provided by taking linear XOR function of first and last bit. The other bits are depended on previous bit. The operation is deterministic to generate random bits. The sequence of bits are produced by shift registers and its current state completely determined by its previous state. The register has finite number of states and random sequence is repeated after some cycles. The PRSG can be well explained in Figure 4-2. It produces a sequence of bits which is random and generates a long cycle sequence. [20]

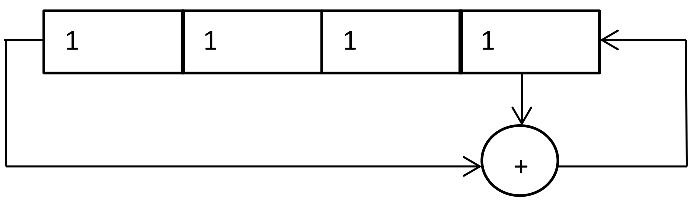

Figure 4-2 XOR operation of Pseudo Random Sequence Generator

Analysis of Pseudo-Random–Sequence-Generator

An n bit Pseudo-Random–Sequence-Generator consists of an n-bit length shift register with feedback to its input. The feedback is formed by using XORing the outputs of selected stages of shift register and then inputting this to least significant bit (0 stages). In this paper first and last bit inputs are EXORed and then it applied to output of least significant bit. The next bit outputs are depending on previous bit. Each stage has common clock. An n bit Pseudo-Random–Sequence-Generator block diagram is shown in Figure 4-3.

PRSG will produce a random sequence of length 2^n -1stages (where n is number of stages). So for 4-bit PRSG total number of stages is 8. The sequences are repeated as long as clock is clocked. Example of 4-bit PRSG generated sequence is given in Table 4-1. In this PRSG initial input is taken as FH (in binary “1111” or hexadecimal F). The output of XOR will be 0(XOR of two input 1 (1 XOR 1) =0) and clock is triggered to all stages. So XOR output is loaded to first stage.

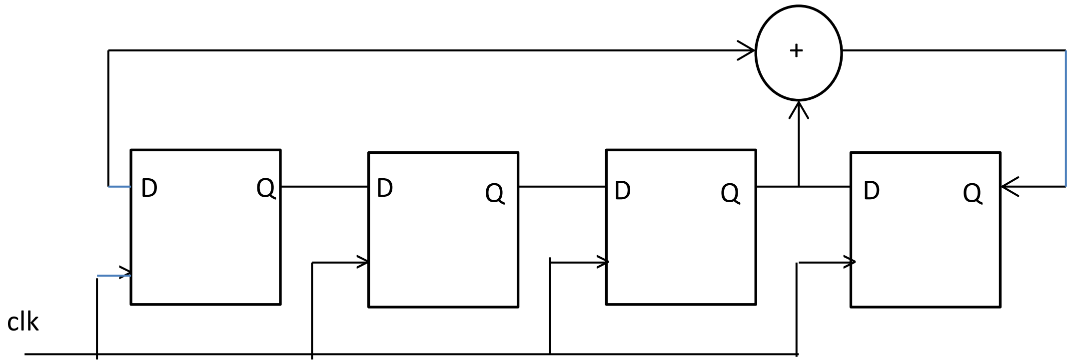

Figure 4-3 A 4-bit Pseudo Random Sequence Generator

The one stage does not pass through PRSG generator is 00H. If the feedback contains 00H then the value to the feedback is 0(0 XOR0= 0) and all stages the output of PRSG is 0. It will never leave 00H stage. It is important since in FPGA platforms, the internal d-type flip-flops clear to 0 on power-up or when the global reset net is activated. This problem can be avoided by using XNOR feedback instead of the XOR feedback (since 0 XNOR 0 = 1). This problem can be avoided in Some FPGAs (e.g. Xilinx) by allowing the individual flip-flops to be either set or reset on power-up or initialisation and providing a non-zero initial value.

Table 4-1 A 4-bit PRSG

PRSG Stages				HEX value(3:0)
3	2	1	0	
1	1	1	1	F
1	1	1	0	E
1	1	0	1	D
1	0	1	0	A
0	1	0	1	5
1	0	1	1	B
0	1	1	0	6
1	1	0	0	C
1	0	0	1	9
0	0	1	0	2
0	1	0	0	4
1	0	0	0	8
0	0	0	1	1
0	0	1	1	3
0	1	1	1	7

4.3 VHDL implementation of BPSK for Energy Detection

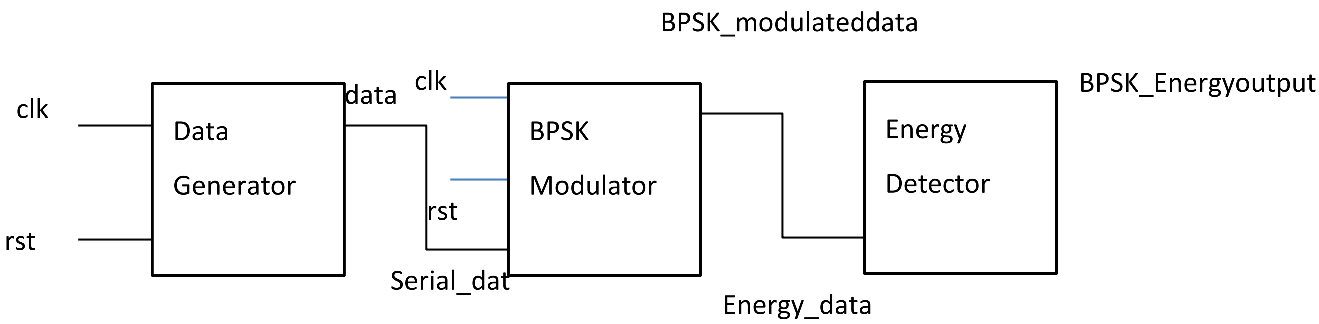

Figure 4-4 Block Diagram of BPSK Modulator with Energy Detector Module.

In this chapter we are described designed of BPSK modulator and energy detected value from this BPSK modulator. The BPSK modulator is constituted by a random generated pseudo sequence and BPSK modulator itself. The BPSK modulator block diagram shown in Figure 4-4.The pseudo random data generator has two inputs (clk and rst) and one output(serial_data), BPSK modulator has three inputs (clk,reset,data), one output(BPSK_modulateddata) and energy detector has 3 inputs (clk, rst ,Energy_data)and has one output(BPSK_Energyoutput).

Data Generation Using Pseudo Random Sequence Generator

The random sequence generator has generated by using Pseudo-random-Sequence-Generator (PRSG). The PRSG is constituted from four registers and total number of sequence generated is=2^4-1. The detail about random sequence generator is explained in previous chapters. The generator of random sequence is little bit different than the previous sections. In this part random sequence is generated by XORing output of LSB and output of MSB. The block diagram is shown in Figure 4-5

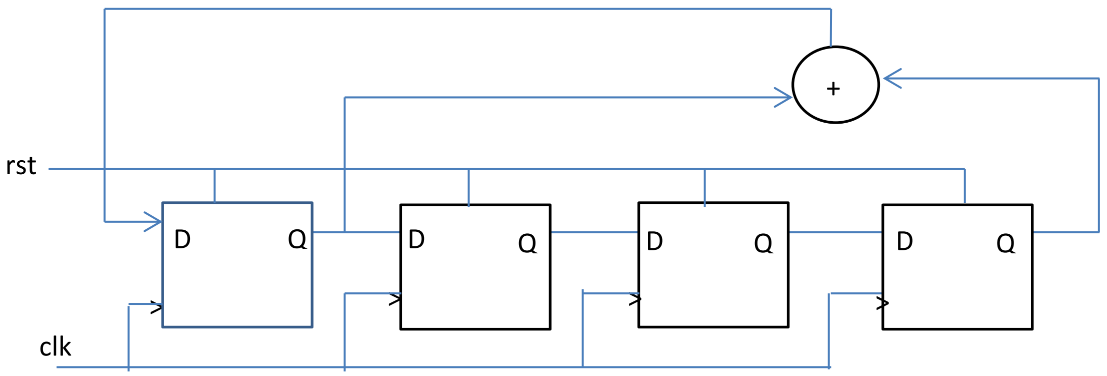

Figure 4-5 Block Diagram for Pseudo-random data generator for BPSK Modulator

The PRSG responds to positive edge triggered of clock signal and negative edge triggered reset signal which forces the register to logic 1 level. The rising edge of clock makes the data of DFF transferred to its output Q.

BPSK Modulator:

In this BPSK Modulator, the on-board clock frequency is 50 MHz. Therefore the modulator clock which controls the sine wave table has to oscillate at a frequency 32 times slower than that of the basis on-board clock. The data generated and provided to sine wave for modulation must be maintained unalterable during at least a complete cycle of the sine wave. It is constituted by M samples; hence the data clock has to oscillate at frequency M times slower than that of the table addressing generated for sine wave. BPSK modulator is designed using this clock frequency.

A package constant is defined which is used during the design of BPSK modulator. In this package constant N is the length of data generator and constant M for the position s of a table which contain the values of sine waves. The number of bits of each word of table is (nbits) and number of bits used as decimals is ndec. All these bits are required to define a constant which used for modulation process of BPSK.

A table is required to generate samples for sine wave. Thus, we created a package, where all the necessary functions are provided to define sine wave samples. The package name is "realbit". It has two functions "trun" to generate samples of sine wave. The function "trun" is converted a real number to a binary number of nbits bits by two's complement method (signed bit). Finally, we have defined a function called sin_table, which contains the sample values of the sine wave in an array of integers in M consecutive positions.

The generated clock signal (clk) is the on-board 50 MHz clock oscillator. A sine_table that contains the samples of the sine wave are stored in an array of integers of M length. Given that the samples are sequentially positioned in the table, at positive edge of clock signal a new sample will be taken from the table along the time. Hence, after M jumps, the representation of the sine wave will be completed.

We have created the value from table in the form that if the data digit supplied by the data generator (serial_data) is "0" or this same value but negated if the data digit is "1". This is generation of process of a BPSK modulation. After that, BPSK modulated data passed through Energy Detector Module and Energy output is found out.

4.4 VHDL implementation of OFDM for Energy Detection

The OFDM modulation is a multicarrier modulation. The single carrier modulation using VHDL is designed in previous section. The basic blocks to design OFDM is signal mapper to implement BPSK modulator, serial to parallel converter, IFFT block, parallel to serial converter and then energy detector. This chapter frame out the entire module to implement OFDM [21].

4.4.1 Serial to parallel converter (SIPO):

In SIPO data are entered serially and comes out parallel manner. The operation is performed by shifting data from left to right hand direction one bit at each clock transition signal. The data entered to the shift register serially one after another from left hand side and after four clock transition the 4 bit register has four bit parallel output. The data are comes out in single clock signal. This register has four serial input and four parallel output. The circuit diagram of Serial to parallel converter circuit is shown in Figure 4-6.

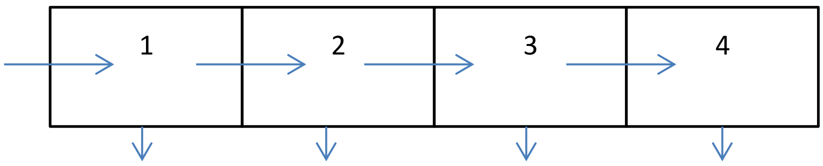

Figure 4-6 Block diagram of Serial to parallel converter

4.4.2 Parallel to serial converter (PISO)

In PISO data entered parallel manner but comes our serially one after another. The register has parallel input and these parallel input data loaded into the register by activating load signal. The data come out serially with the application of the clock transition. Thus 4-data is completely shifter after 4-clock transitions.

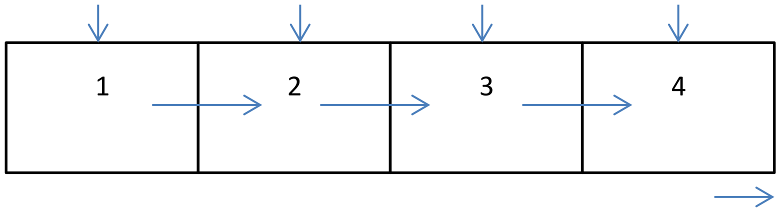

Figure 4-7 Block diagram of Parallel to serial converter

4.4.3 Inverse Fast Fourier Transform (IFFT)

The IFFT is required to do the signal to orthogonal. The IFFT with butterfly diagram is in principle parallel, which make is suitable for FPGA implementation. The principle structure is based on butterfly diagram. The 4-point algorithm is implemented using radix-4 butterfly diagram. Radix-2 butterfly is represented in Figure 4-8 which is used to implement radix-4 butterfly structure.

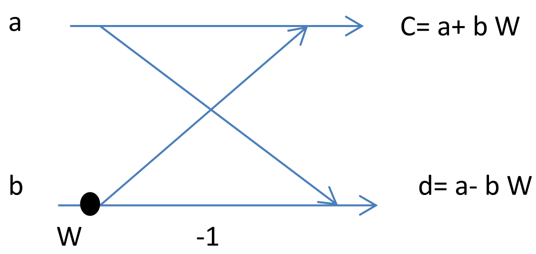

Figure 4-8 Radix-2 butterfly diagram

There are two inputs a and b and two outputs c and d. The twiddle factor is W. The outputs are given as:

C=a + b W   and d=a - b W

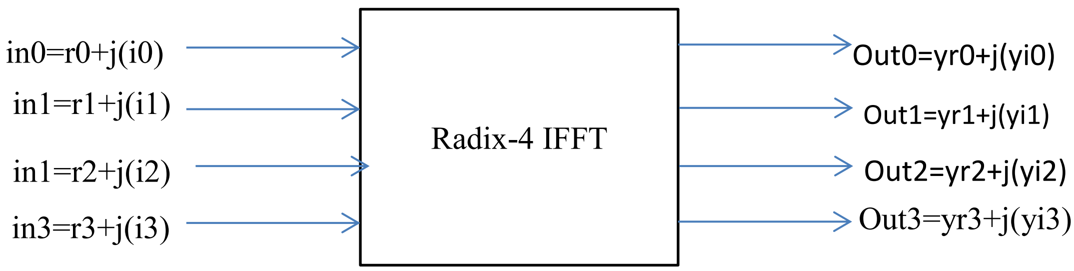

Figure 4-9 Block diagram of radix-4 IFFT

This 2-point butterfly unit is used to implement 4-point IFFT. Here 4-point radix-4 butterfly is generated to get the IFFT of different samples. . A single input is divided into two parts-real and imaginary part and generated output is also consists of two parts real and imaginary part. Total four inputs are taken and total outputs are generated to implement radix-4 IFFT. The inputs are in0, in1, in2, in3 and outputs are out0, out1, out2 and out3. The generated outputs for given inputs are shown below

yr0=(r0 + r1 + r2 + r3)   yi0=(i0 + i1 + i2 + i3)

yr1=(r0 - i1 - r2 + i3)   yi1=(i0 + r1 -i2 - r3)

yr2=(r0 - r1 + r2 - r3)   yi2=(i0 - i1 + i2 - i3)

yr3=(r0 + i1 - r2 - i3)   yi3=(i0 - r1 - i2 + r3)

4.5 Results and Discussion

4.5.1 Simulation Result for Pseudo Random Sequence Generator

The behaviour of the PRSG is checked by using ISE Simulator. We use Xilinx 13.3 to write VHDL code for detected energy value for PRSG. The input to PRSG is clk, rst and output is energy output.

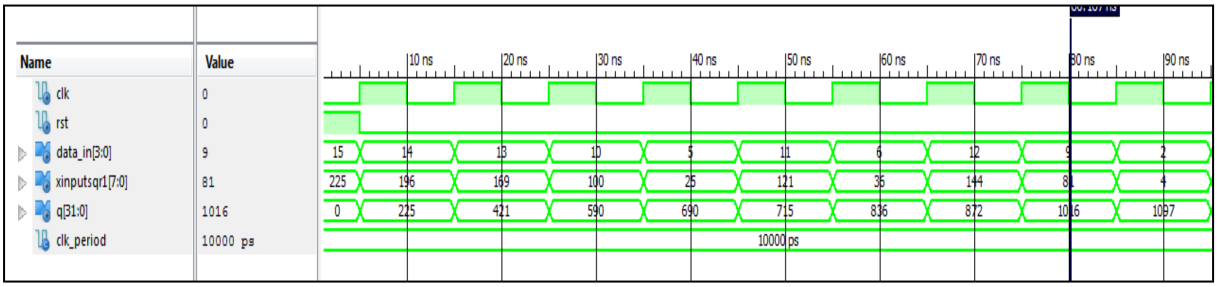

Figure 4-10 Generated Binary Sequence for PRSG

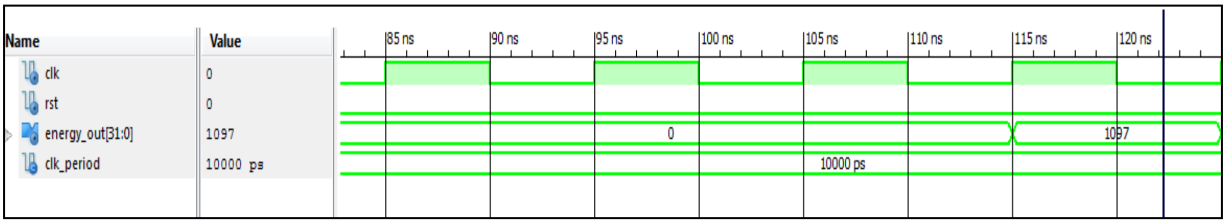

Figure 4-11 Detected Energy value for N=8

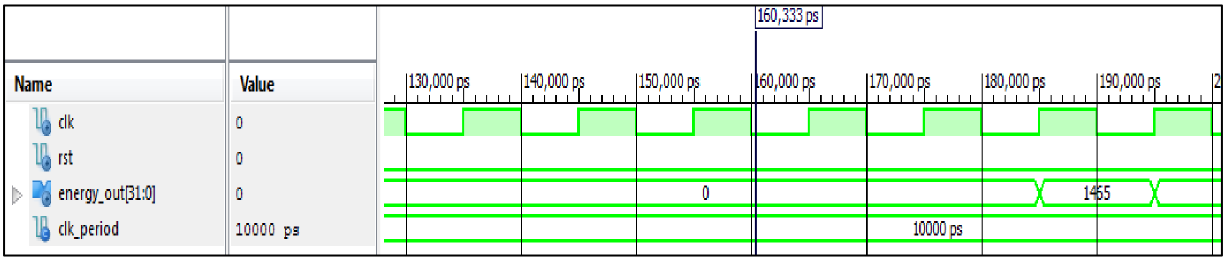

Figure 4-12 Detected Energy value for N=16

In this work all the inputs are taken inform of digital and outputs are also taken as digital. The PRSG is used to generate random 4 bit binary sequence. Figure 4-10 shows that binary sequence is generated for positive edged triggered clk when reset is not set. The detected energy value is found using energy detector architecture, where input sequence is generated from PRSG. Figure 4-11, Figure 4-12 shows detected energy value for number of samples N=8 and N=16 respectively. Figure 4-13 Shows RTL and Table 4-2 presents total device utilization for PRSG.

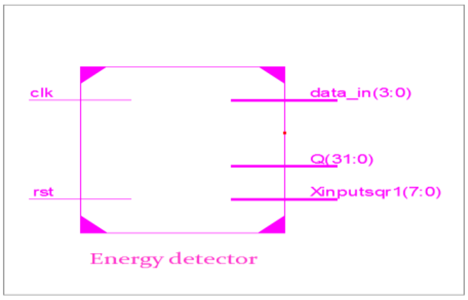

Figure 4-13 RTL for Pseudo Random Sequence Generator

Table 4-2 Design summary for PRSG

Device Utilization Summary (estimated values)			%
Logic Utilization	**Used**	**Available**	**Utilization**
Number of bonded IOBs	32	66	48%
Number of GCLKs	1	24	4%

Design Statistics for PRSG

Cell usage	Gate count
IOS	38
BELS	2
GND	1
LUTS	1
Flip flops/Latches	4
FDP	4
Clock buffers	1
BUFGP	1
IO Buffers	37
IBUF	1
OBUF	36

Speed: 449.438MHz

Total power: 0.034W.

4.5.2 Simulation Result for Binary Phase Shift Keying

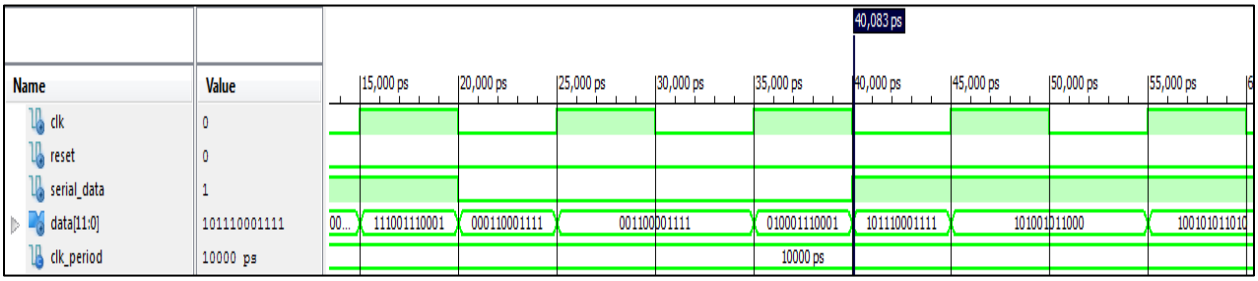

Figure 4-14 Binary output for BPSK

A random binary data is fed to BPSK modulator. The BPSK modulated data with length 12 is generated at output. The generated binary sequence is shown in Figure 4-14.

Simulation Result for detected energy value for Binary Phase Shift Keying

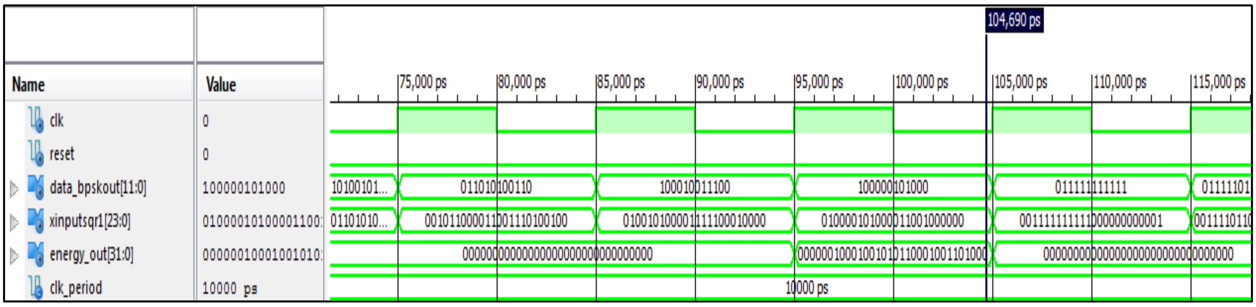

Figure 4-15 Detected energy value for BPSK N=8

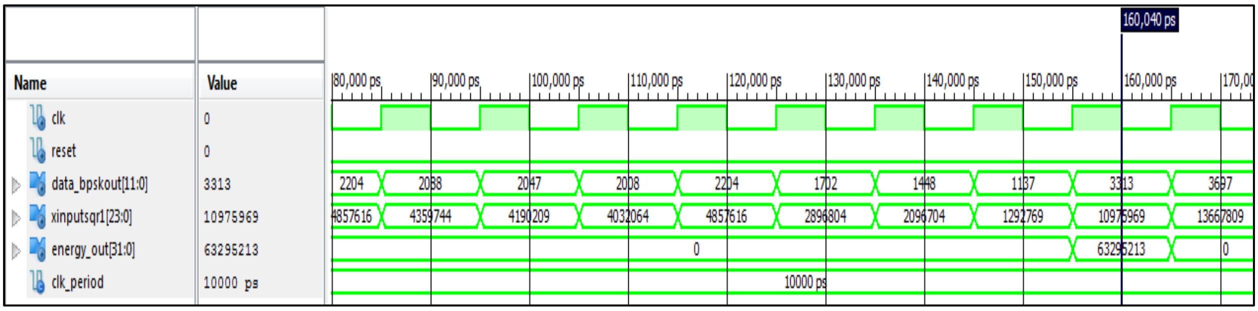

Figure 4-16 Detected energy value for BPSK N=16

The PRSG provides random binary sequence. This binary sequence is fed to BPSK modulator. The modulated output from BPSK modulator is having length 12 in bit. Figure 4-15 and Figure 4-16 shown the BPSK modulated data output ,its squared value for each samples and total detected energy value for N=8 and N=16 respectively. Figure 4-17 Shows RTL of BPSK and Table 4-3 presents design summary of BPSK modulator.

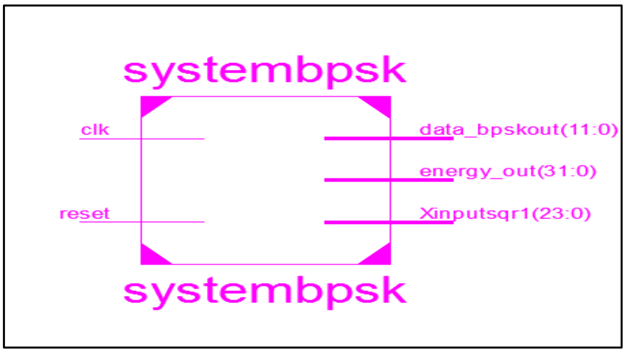

Figure 4-17 RTL for BPSK modulator

Table 4-3 Design summary for BPSK modulator

Device Utilization Summary (estimated values)			%
Logic Utilization	**Used**	**Available**	**Utilization**
Number of Slices	29	960	3%
Number of Slice Flip Flops	7	1920	0%
Number of 4 input LUTs	54	1920	2%
Number of bonded IOBs	17	66	25%
Number of GCLKs	1	24	4%

Design Statistics for BPSK modulator

cell	Gate count
IOS	18
BELS	91
GND	1
INV	10
LUT2	1
LUT2_L	1
LUT3	14
MUXCY	11
MUXF5	12
VCC	1
XORCY	12
Flipflops/latches	7
FDP	7
Clock Buffers	1
BUFG1	1
IO Buffers	17
IBUF	3
OBUF	14

Speed: 302.057MHz

Power: 0.034 W

4.5.3 Simulation result for different blocks of OFDM

The OFDM consists of different blocks. These blocks are SIPO, PISO, and IFFT blocks. Figure 4-18 gives information that parallel output generated with positive clock and negative reset signal for serial input data. Figure 4-19 represents serial data output generated with positive clock and negative reset signal for parallel input data. The load and shift are act as control signal. When load is 1, all the parallel data are loaded and when load is 0, data are comes out serially.

Simulation result for SIPO

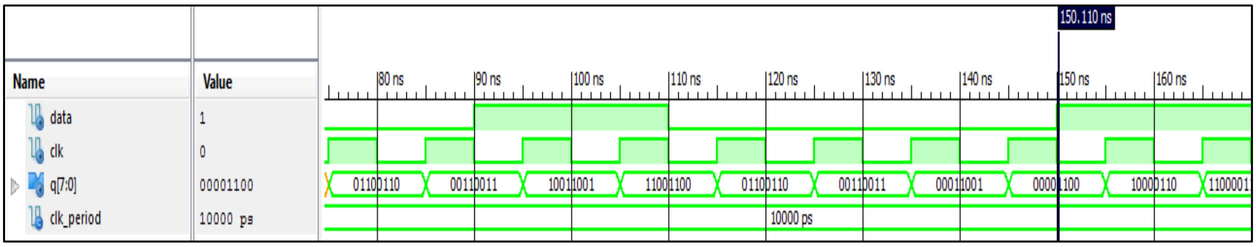

Figure 4-18 Simulation result for Serial in parallel out shift register

Simulation result for PISO

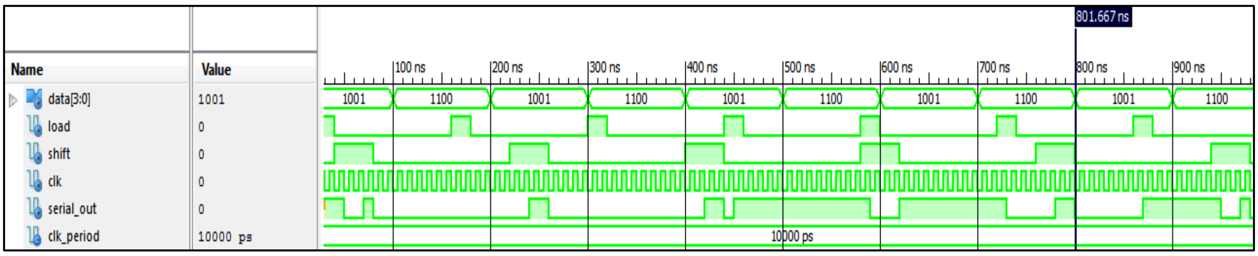

Figure 4-19 Simulation result for parallel in serial out shift register

Simulation result for IFFT

In this section radix-4 is realized. OFDM requires IFFT for orthogonality. A single input is divided into two parts- real and imaginary part and generated output is also consists of two parts real and imaginary part. Total four inputs are taken and total outputs are generated to implement radix-4 IFFT shown in

Figure 4-20 Figure 4-21 Shows RTL of BPSK and Figure 4-21 RTL for radix IFFT and Table 4-4 presents design summary of BPSK modulator.

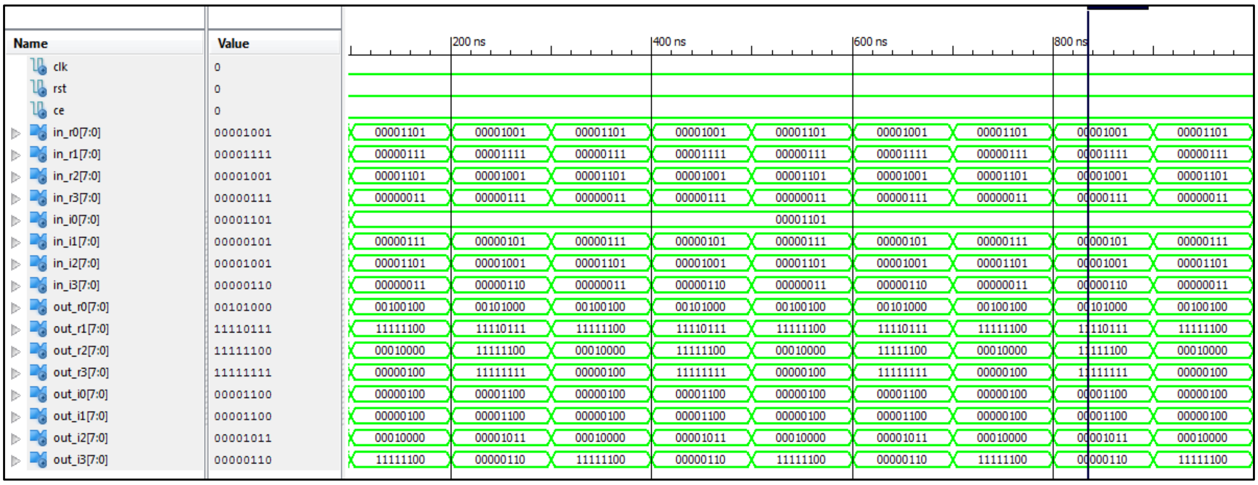

Figure 4-20 Simulation result for radix-4 IFFT

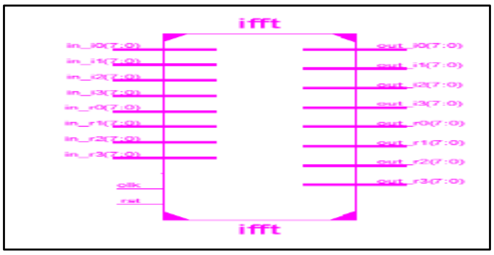

Figure 4-21 RTL for radix-4 IFFT

Table 4-4 Design summary for IFFT

Device Utilization Summary (estimated values)			%
Logic Utilization	**Used**	**Available**	**Utilization**
Number of Slices	4	960	0%
Number of Slice Flip Flops	8	1920	0%
Number of 4 input LUTs	8	1920	0%
Number of bonded IOBs	11	66	16%
Number of GCLK	1	24	4%

Design Statistics for 4 point radix-4 IFFT

cell	Gate count
IOS	11
BELS	8
LUT2	1
LUT3	7
FD	8
Flip flops/latches	8
Clock Buffers	1
IO Buffers	10
BUFGP	1
IBUF	9
0BUF	1

Speed- 485.909MHz

Power: 0.034W

Simulation result for IFFT for N=8

In this section radix-4 is realized. The radix-4 algorithm is used to found out IFFT of N =8 number of samples. Finally IFFT of eight samples are taken at output side and energy value is detected. Total eight inputs are taken and total eight outputs are generated using radix-4 IFFT shown in Figure 4-22. Figure 4-23 Shows RTL of BPSK and Table 4-5 presents design summary of BPSK modulator.

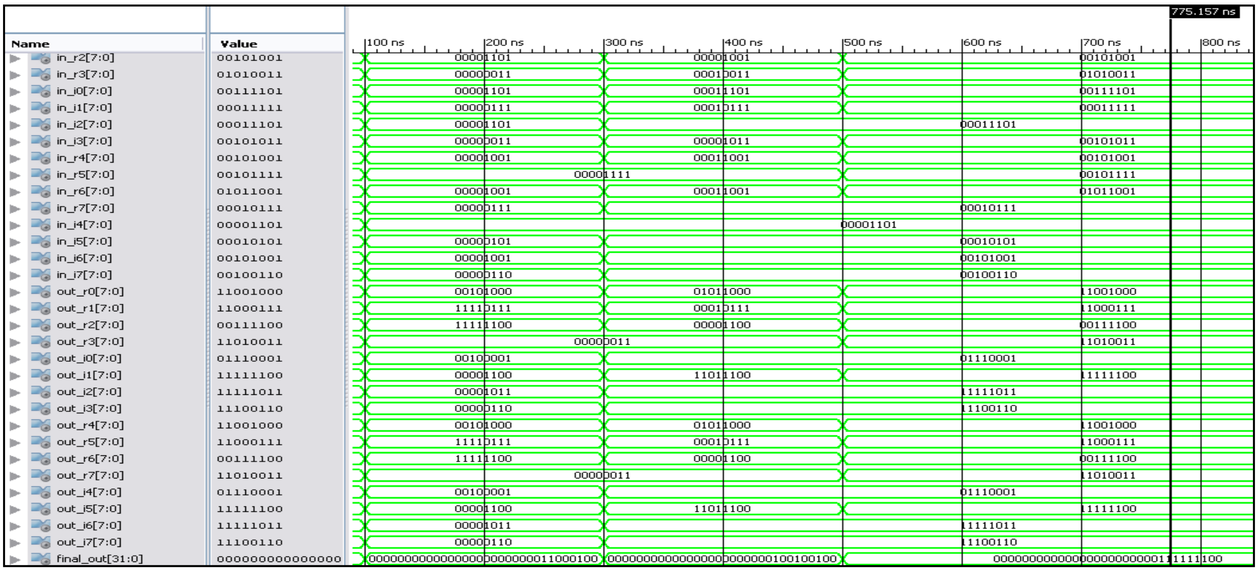

Figure 4-22 Simulation result for radix-4 IFFT

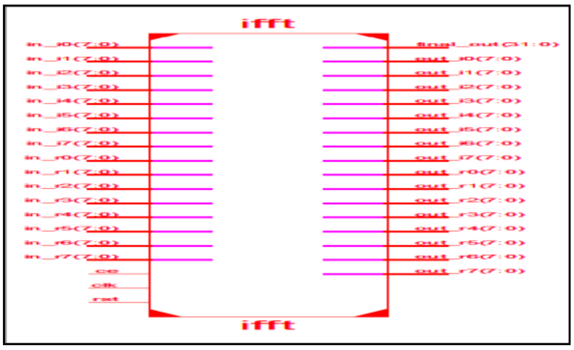

Figure 4-23 RTL for radix-4 IFFT

Table 4-5 Design summary for radix-4 IFFT for N=8

Device Utilization Summary (estimated values)			%
Logic Utilization	Used	Available	Utilization
Number of Slice LUTs	395	28800	1%
Number of bonded IOBs	272	480	56%

Design statistics for radix-4 IFFT for N=8

Cell	Gate
IOs	291
LUT2	387
LUT3	4
LUT6	4
MUXCY	334
VCC	1
XORCY	392
IO Buffers	272
IBUF	112
BEL	183
OBUF	160
GND	1

4.6 Hardware implementation of Energy detection for PRSG

The energy detector module is implemented using PRSG with Xilinx 10.1. The generated output is binary sequence .This energy detection for PRSG is dumped in Sparten-3E. The resultant energy detected signal is viewed through chipscope pro shown in Figure 4-24. The result shows energy detected Figure 4-24 value for many samples.

The behaviour of the PRSG is checked by using ISE Simulator. We use Xilinx 13.3 to write VHDL code for detected energy value for PRSG. The input to PRSG is clk, rst and output is energy detected values.

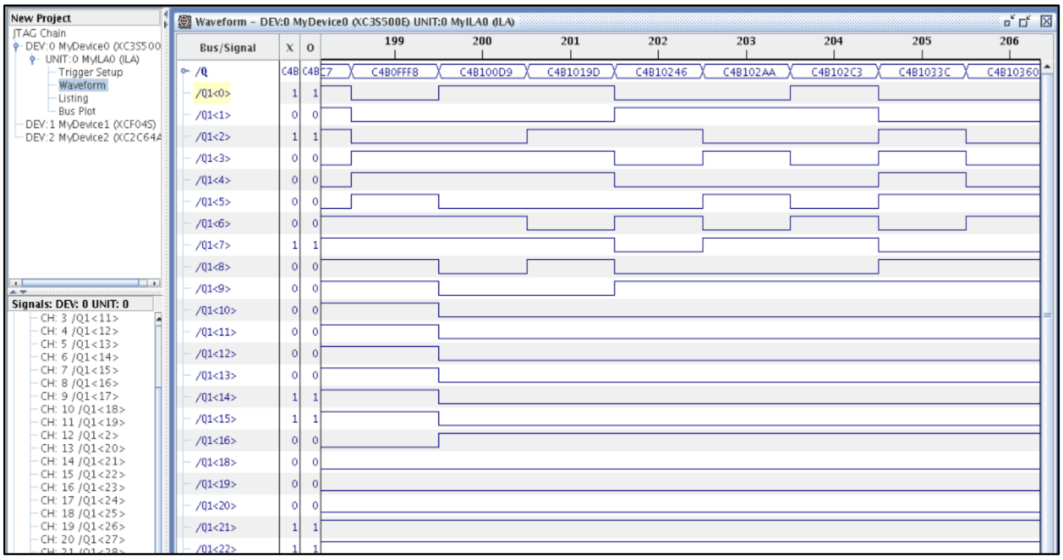

Figure 4-24 Result from chipscope for PRSG

Chapter 5

Conclusion and future work

5.1 Conclusion

5.1.1 Introduction

This thesis provides some idea about cognitive radio technology, its different classifications and different spectrum sensing techniques. The work of this thesis contributes toward energy detection technique in different wireless communication areas and finally energy detection technique implemented using VHDL code.

5.1.2 Contribution

The performances of spectrum sensing using energy detection technique are studied for single-carrier modulation and multicarrier modulation. The single carrier modulation and multicarrier modulation technique performances are verified using Monte-Carlo simulation. The performance analysis can be done by plotting ROC cure between probabilities of false alarm vs. probabilities of detection and signal to noise ration vs. probability of detection. This thesis presents performance of single carrier modulation for BPSK and multicarrier modulation for OFDM. In this thesis OFDM modulation is figured out in the field of WLAN and WiMAX standards. WLAN uses IEEE 802.11a standard and WiMAX uses IEEE 802.16 standard. The works are figured out using parameters based on IEEE standards for WLAN and WiMAX. The BPSK modulation and OFDM modulation performances are studied.

The VHDL implementation of energy detector module is provided in this thesis. The performance is figured out for energy detector module using input as pseudorandom sequence generation for different number of samples. The Energy detection is carried out for BPSK for different number of samples. The energy detector for OFDM is studied only for 8-point IFFT.

5.1.3 Limitation

All the works in this thesis are based on MATLAB and VHDL simulation. The simulation results are taken for different number of samples to study energy detection performances. The Monte-Carlo simulation done only for WLAN and WiMAX using OFDM. In this work simulation works are taken for digital input signal and output are also taken out inform of digital. In this thesis IFFT is implemented using radix-4 algorithm. The higher sample IFFT implementations are required to transmit higher samples of data in VHDL. This implementation can be done through floating point IFFT implementation using VHDL.

5.1.4 Future Work

This thesis work is for one year Master degree course. The energy detection for OFDM in WLAN and WiMAX will be carried out in VHDL and it will be implemented in hardware using FPGA. The energy detection for cooperative methods and its hardware implementation will be carried out in future.

Publication

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