UHF COMMUNICATION LINK FOR MIMO SDR

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ABSTRACT

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Aim of this project is to develop a UHF communication link for MIMO SDR, which can transmit real time video, audio and data from one node to another node through USRPs and RF front ends.. The purpose of the project was to make a prototype which could use modern techniques to efficiently enhance the communication quality and data rate. A system has been developed that is capable to communicate at higher data rates and with very less interference. MIMO system helps in achieving the target of higher data rate. 2x2 MIMO (Multiple Input Multiple Output) systems used in the test bed doubles data rate of information transfer as compare to conventional SISO (Single Input Single Output) systems. The requirement of efficient communication using bandwidth efficiently has increased. This need is fulfilled using OFDM (Orthogonal Frequency Division Multiplexing) as a modulation scheme. It incorporates FFT block which divides the whole available spectrum into sub-carriers. Cognitive technique is used for spectrum sensing. It allows users to find holes in the spectrum, and also detects that the spectrum is currently in use or free. This technique also allows user to use spectrum efficiently where the free bandwidth is utilized instead of being wasted. ZF VBLAST Detection is used for better detection of signals as compared to ZF detector. This communication model includes the use of MIMO-OFDM which is the basic need of a 4G technology. This prototype, radio link, can enhance the communication efficiency. The purpose of this test bed is to achieve those targets and take the communications carried out in military and civil industries to another level.

DECLARATION

No portion of the work presented in this dissertation has been submitted in support of another award or qualification either at this institution or elsewhere.

DEDICATION

All work and efforts are dedicated to our beloved parents and to our teachers who have been a constant source of encouragement for us throughout the project. May Allah bless them with prosperous and happy lives and always provide us their loving and thorough guidance.

ACKNOWLEDGEMENTS

All praises to the Almighty Allah, who enlightened us with the requisite knowledge to accomplish the project goals that were set for this project prior to the start of the project, and on a broader level in the completion of our degree.

We would also like to thank all the people who helped us to accomplish the goals of our project. We would like to thank our project supervisor Col. (R) Raja Iqbal for his constant guidance, support and help to us whenever we needed it. We would also like to thank our external supervisor Lt. Col. Dr. Adnan Ahmed Khan for his help and ideas in our project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure No. **Page No.**

CHAPTER 1

PROJECT INTRODUCTION

1.1. Introduction

Nowadays, there is fast growth of the modern digital communication. The (terrestrial, satellite and mobile) communications industries face this problem for providing those technologies that are capable to support a multiplicity of services from the digital voice communication system having bit rate of a few kbps to the complex wireless multimedia systems in which bit rate up to 100 Mbps can be achieved. Many modern systems have been developed and MIMO coupled with OFDM has gained much attention for being a better technique among the modern systems that are currently available.

1.2. Overview

This chapter gives the basic introduction to the project. This section includes the statement of problem and the solution devised by this project, the end goal and academic objectives. This chapter also gives the information (that is, equipments, knowledge required and softwares) required to complete the project and how this thesis is organized chapter-wise.

1.3. Statement of Problem and Solution

In wireless communication such as radio, there is usually distortion of signals (voice) at reception. This is fading which increases as the distance between the receiver and transmitter increases. The bandwidth used in everyday communication is not being efficiently used which requires a major attention for the telecom engineers to take these two factors (data rates and bandwidth efficiency) into account. The SISO system allowed data rates to be normal and does not allow correction for the fading of signals. MIMO, on the other hand, solves the problem of multipath fading, disallowing the signals to distort to great extent. The data rates are increased and on the whole the communication becomes better than the SISO system. Multiple Input Multiple Output - MIMO uses the physical presence of several transmitting and receiving antennas to achieve higher data rates and reliability by fighting off fading and multipath interference effects. Nowadays, every user is assigned a particular frequency. Each allocated frequency is an expensive commodity and with the rapid population growth and need for frequency, assigning every user a separate frequency can be a problem. Orthogonal Frequency Division Multiplexing - OFDM is a technique whereby single frequency is divided into subcarriers and the symbols are modulated with these subcarriers which are closely and orthogonally spaced. Using this technique the problems of Inter Symbol Interference (ISI) and less bandwidth efficiency are reduced.

1.4. Application / End Goal Objectives

The aim of the project is to develop a 2x2 MIMO-OFDM (Orthogonal Frequency Division Multiplexing) UHF SDR. Cognitive technique, for spectrum sensing, will be used. This system works on UHF frequency (around 2.4 GHz). Performance of the system will be compared with a SISO system and practically will be shown that 2x2 MIMO has double the data rate than that of SISO and less bandwidth is used using OFDM. Also, basics of Cognitive technique (spectrum sensing) shall be shown.

To Develop a 2x2 MIMO SDR for UHF and incorporate OFDM as modulation and BPSK as mapping scheme. This project will have significant applications in both military and commercial sectors.

1.5. Academic Objectives

To put the skills learnt in Digital Signal Processing, programming languages and hardware equipments in to practical implementation. Also to know how real world communication is done and how it is affected by different factors and learns how to minimize the effect of those factors which degrade the quality of communication. This project will help to learn how to design a complete end to end wireless communication system.

1.6. Project Design, Development, Testing and Analysis Plan

This section depicts the main features required to complete the project. These main features include methodology, the software and operating systems used. The project is focused at compiling a comparative analysis of wireless communication protocols. Wireless SISO and 2x2 MIMO links will be simulated in MATLAB/C/Python. Algorithms simulating these environments will be used and the output results such as BER and throughput will be used to quantify the performance of different wireless systems.

1.7. GNU Radio

Various open ended operating systems have provided the provision for developers to write blocks for specialized purposes. Ubuntu is one such Linux based open ended operating system in which a block for communications has been developed named GNU RADIO. The block has been written in Python which is a widely acclaimed programming language. Simulation of implemented systems can be done using sub-blocks from GNU. These have the advantage of being specially developed for communications. Required fields can be appended with existing blocks using Python.

1.8. MATLAB/C

The simulation can also be carried out in a MATLAB environment which has an unparallel library of mathematical and communication functions. Microsoft Windows and Linux (UBUNTU) are used, Windows is used for MATLAB simulation and UBUNTU is used for development of GNU radio platform. MATLAB, GNURADIO, Python and Microsoft Visual C++ are also used.

1.9. Requirements

To complete the project programming skills (C++, Python), Knowledge about GNU radio and USRP, OPENCV Linux (Ubuntu) and Knowledge about modulation schemes must be known. Details of the equipment required to develop the system including MIMO-OFDM and cognitive energy detection spectrum sensing are given in table 1-1.

***Table 1-1*: Equipments Required**

Sr. no.	Equipment	Quantity
1.	USRP1	3
2.	Daughter cards (RFX-2400)	5
3.	General purpose computers	3
4.	Antennas (VERT2450)	5

1.10. Organization of the Report

There are a total of four chapters in this report. The first chapter includes the basic information regarding the project. This chapter also includes basic need of this project (solution to communication problems). Basic requirements to complete the project are also included in this project.

The second chapter shows the design and procedure carried out in the project. Firstly, this chapter shows the diagrams of the transmitting side, receiving side and the cognitive concept. In the second part, basic techniques (MIMO, OFDM, VBLAST Detection and Cognitive) are described and the way these techniques are implemented on USRP and computers.

The third chapter highlights the results that were given after performing different tasks that were aimed at the start in this project. First it will be shown what results were produced on MATLAB and then using GNU Radio, Python and USRP, it will show how practical transmission takes place and to find the effects of implementing those techniques over a real channel (air interface).

The fourth chapter tells about the summary, future work and conclusions. The summary highlights those points, briefly, which involve different techniques used in the project and their usages. This chapter also involves the future work that can be done on the project to make it simpler and better. The conclusions draw the attention towards those aspects that are learnt and confirmed during the project.

1.11. Summary of this Chapter

This chapter is an introduction chapter. In this Chapter introduction of wireless communication and demand of increased data rates has been discussed. Overview of project is provided in this chapter. Problems faced due to the lowered data rates are discussed and then their solution is provided by proposing 2x2 MIMO systems. The main features to complete the project are discussed and information of hardware used in the project has been provided.

CHAPTER 2

DESIGN AND PROCEDURES

2.1. Introduction

This chapter explains the block diagram of the project. Explanation of different techniques through the signal passes from transmission to reception is discussed in detail. Implementation of techniques used in the project is discussed in detail. Cognitive transmission is discussed in detail. This chapter covers all the details of transmission and reception of the signal.

2.2. Design

This section includes the block diagrams of the transmitting and receiving sides of the project. Parallel Cognitive technique is also described diagrammatically to illustrate the use of energy detection cycle. Figure 1 show different block used in the transmitter side. It shows the processes though a signal passes before transmission over air interface.

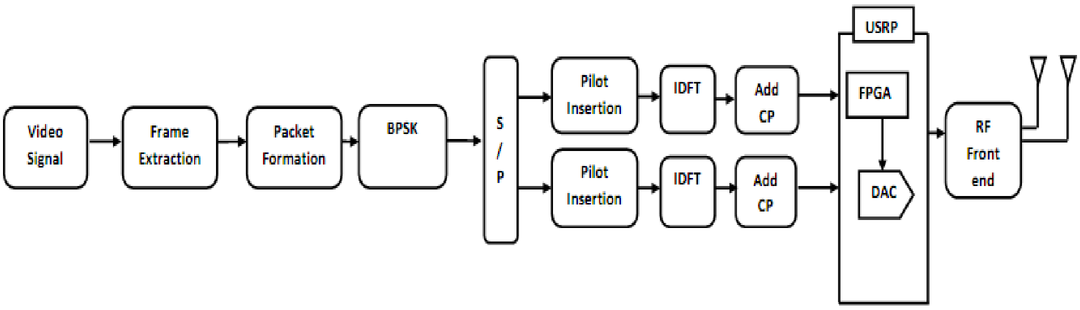

Figure 1: **Transmitting Side**

Figure 2 shows the receiver side of the system. Reverse processes are carried out at the transmitter side from that of the transmitter side to demodulate, detect and correctly receive the signal. Video is recovered at the receiver side that consists of individual frames played back to back on a specific rate. The frame per second rate is same at the transmitter and receiver side.

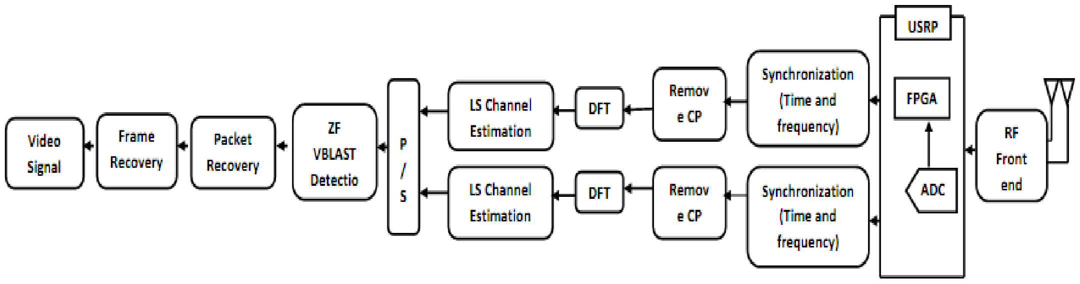

Figure 2: **Receiving Side**

Figure 3 shows the detection and transmission cycle for the cognitive radio system. Detection and transmission is performed after one another. During the transmission cycle the detector discards all the samples it receives and during the detection cycle the transmitter stops its transmission and waits for the result of energy detector. The whole process is repeated after specific interval of time.

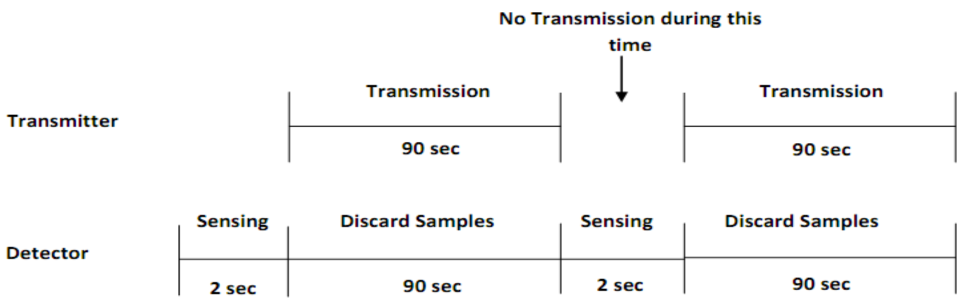

Figure 3: **Cognitive Detection and Transmission**

2.3. Procedure

The main goal of this project is to achieve real-time video transmission over wireless system employing MIMO transmission which enables high data rate. The basic idea is that the input video sequence is divided into frames. Each frame is then converted to bit stream. The resulting bit stream is processed to be transmitted over the MIMO link. Then practical MIMO platform is set for the real-time transmission analysis of the video. It will focus on developing algorithms for synchronization and channel estimation of the MIMO system. USRPs will be used as front ends and thus are needed to complete this platform. Next objective is to implement OFDM technique. Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier transmission technique, which divides the available spectrum into many carriers, each one being modulated by a low rate data stream.Cognitive radios can handle unanticipated channels and events as well. Cognitive radios intelligently optimize their own performance in response to user requests. Cognitive radio transmits on a piece of spectrum found not utilized by the primary user. VBLAST technique will be applied for detection. Using ZF VBLAST Detection, the computational and implementation complexities are removed as one can see from the ZF equation for removing the channel affect

$$\hat{a} = (H^{*}H)^{-1}Hx = H^{+}x \quad (1)$$

The ZF receiver converts the joint decoding problem into M single stream decoding problems thereby significantly reducing receiver complexity.A well thought model of the hardware implementation is based on the USRP boards with protocol development in C/Python in GNU radio. The project once completed would provide students and faculty for further research and development in MIMO OFDM and Cognitive Networks.

2.4. MIMO

Now days the transmission of data is required to be carry out at higher rates to support different applications of 3G and 4G. Not only mobile communication but satellite communication and micro-wave line of sight (LOS) communication also requires higher data rates to compete with the latest technologies. Besides other methods to improve the efficiency of wireless communication systems like modulation types, error correction etc the multiple antenna system (Multiple Input, Multiple Output – MIMO) have gained a lot interest. The coming part explains the MIMO technique, it`s working and the implementation in different radio communication systems.

2.4.1. Introduction to MIMO

It is obvious that the main goals in developing next generations of wireless communication systems are increasing the link throughput (i.e., bit rate) and the network capacity. Since radio propagation conditions appear to limit the realm of wireless and mobile communication systems to the range around 1 GHz to 6 GHz, the available frequency spectrum is limited. So to fulfil the above goals, future systems should be characterized by improved spectral efficiency. The use of multiple transmit and receive antennas can improve the performance of wireless communication systems significantly by providing higher data rates and higher spectral efficiency [1].

2.4.2. Conventional Radio System (SISO)

All traditional techniques of transmission use single input antenna and single output antenna for wireless communication. This is called Single Input, Single Output (SISO). Figure 2.4.1 shows a conventional SISO system.

***Figure 2.4-1*: Single Input Single Output (SISO) System**

The data rates are lowered as compared to a MIMO system. This is an ordinary system through which daily life communication takes place.

2.4.3. Multiple Antenna Systems

In Multiple Input Multiple Output systems, generally there are m input and n output antennas (Figure 2.4-2). Every receiving antenna receives not only direct component but also in-directs component through the same transmission channel. A time-independent, narrowband channel is assumed. The direct connection from antenna 1 to 1 is specified with h_{11}, etc., while the indirect connection from antenna 1 to 2 is identified as cross component h_{21}, etc. From this is obtained transmission matrix H with the dimensions n x m.

$$H=\begin{bmatrix} h11 & h12 & h.. & h1m \\ h21 & h22 & h.. & h2m \\ h.. & h.. & h.. & h.m \\ hn1 & hn2 & hn. & hnm \end{bmatrix} \quad (2)$$

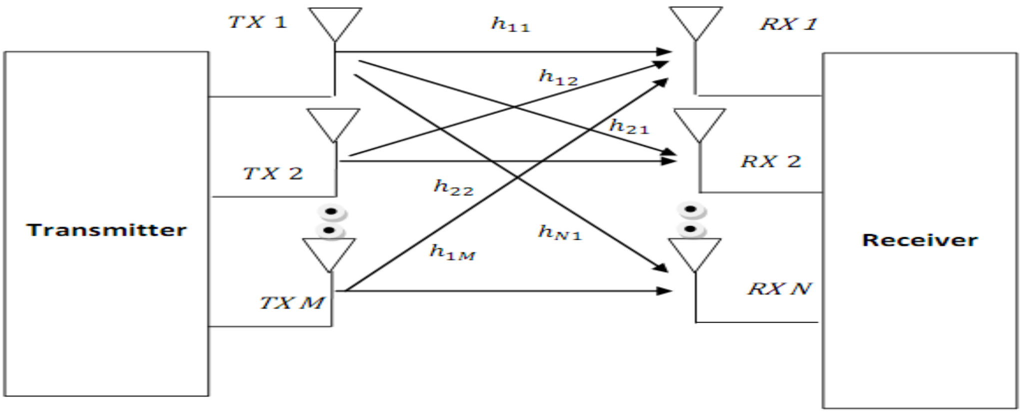

***Figure 2.4-2*: MIMO System**

2.4.4. 2x2 MIMO

Figure 2.4-3 shows a 2x2 MIMO system in which there are two transmitting and two receiving antennas. During the transmission both transmitting antennas send their respective data to both of the receiving antennas hence forming four channels, two direct channels identified as h_{11} and h_{22}, and indirect channels are identified as h_{12} and h_{21}.

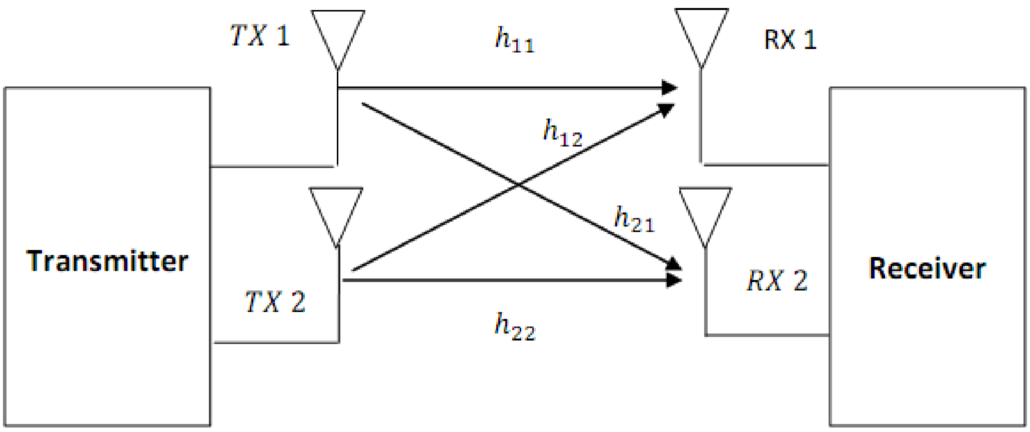

***Figure 2.4-3*: 2x2 MIMO System**

Comparing this system with a Single Input Single Output (SISO) system, it can be proven that the data rate increases two times theoretically and 1.8 to 1.9 times practically in a 2x2 MIMO system.

2.4.5. Target Applications

Benefits of MIMO technology can be observed in various fields, among them one particular section is wireless local area networks (WLANs). Now a day's present standards of WLAN i.e. IEEE 802.11a as well as IEEE 802.11g are both based on OFDM. To achieve higher data rates these standards can be based on Multiple Input Multiple Output. These combinations will provide higher data rates with increased spectral efficiency and help in fighting against frequency selective fading and interference due to narrowband OFDM. One of the benefits of wireless local area network is that it is generally used in indoor places. An advantage of wireless LAN systems is that they are mainly deployed in indoor environments. In these indoor places multipath scattering is an essential feature. This provision allows MIMO capacity to be large.

2.4.6. Advantages of MIMO

The technique MIMO has a lot of advantages in the communication world. It is employed in next generation communication systems. Research work done in this area proves the advantage of using MIMO over conventional SISO communication systems. That is one reason because of which MIMO is preferred in modern systems. Few of the advantages are discussed in the upcoming section.

2.4.6.1. MIMO Systems are More Resistive to Fading

The advantages of a MIMO-based WLAN are increased range, throughput and robustness of the data link. MIMO systems are more resistive to fading which results in better Quality of Service. Few other benefits are that it enhances the coverage, capacity, bit rate, and bandwidth efficiency and uses less power.

2.4.6.2. Increases Throughput

The basic benefit of MIMO is that it enhances the data rate even under bad environmental conditions and noises due to other signals. The sole purpose of andy communication link is to provide high speed data transmission with les BER at greater remoteness. For so many decades, engineers have been thinking that the channel capacity boundaries were defined (theoretically) by Shannon's theorem

$$\text{Capacity} = BW * log_2(1 + SNR) \tag{3}$$

Equation (3) shows, if the SNR is enhanced the channel capacity and hence channel throughput increases. It can also be comprehended from (1) that increasing the bandwidth, higher channel capacity can be achieved. But there is a disadvantage as well that is by enhancing the bandwidth and the signal rate the signal becomes vulnerable to any type of fade (multipath). The communication link data rate increases using multiple antennas at transmitting and receiving sides simultaneously. Such a system provides high data rates with less usage of power and hence less is the required sensitivity of receiver.

2.4.6.3. Spectral Efficiency

In channels with very wide bandwidths, the problem of multi-path scattering is addressed and solved by using carriers that overlap each others. Due to this overlapping technique two major advantages are achieved. First of all it reduces the required bandwidth and then the decreased rate of symbols results into minimizing the effect of multipath fading and their products. In Multiple Input Multiple Output technique, the multipath effect is used because MIMO requires more than one signal paths.

In MIMO communications, by using more than one transmitting and receiving antennas the information about channel is gathered. So by the use of this technique , both the direct and cross channels are utilized and hence the data rate of MIMO systems is theoretically doubled as compared to the SISO systems. In other words the same data rate is achieved in less bandwidth by using MIMO technique hence it is a spectrum efficient technique

2.4.7. Implementing 2x2 MIMO on USRP

Implementation on USRP was done to develop the SDR platform to test various algorithms and techniques used in modern systems. It involves testing and performance analysis of the system on GNU radio which is a software package for rapid development and testing of SDR platform. Various steps of implantation are discussed in the upcoming section.

2.4.7.1. OpenCV

Handling of this video data and frames is not directly supported in python. So another tool was required for this purpose. OpenCV is a special library which is written in different programming languages.. Primarily developed for the purpose of image processing, the library was utilized to advantage in this very project. The main issue was how to integrate python with C++ as it is the language of OpenCV. A wrapper which integrates the modules of OpenCV with those of python is SWIG or Simplified Wrapper Interface Generator can generate the interface between C++ and Python programming languages.. In addition to that, to make the OpenCV modules fully functional in python the GNU radio package named python-OpenCV was installed, available on the PPA Launchpad standard repository.

2.4.7.2. Reason for Choosing OPENCV

Importing video in the GNU radio python was a difficult task as python itself did not provide with the option to do it straight away. OPENCV is written in optimized C and can take advantage of multi-core processors [2]. Initially the G-streamer built in player was used to manipulate with the video data but that turned out to be too complex. Figure 2.4-4 shows components of OPENCV.

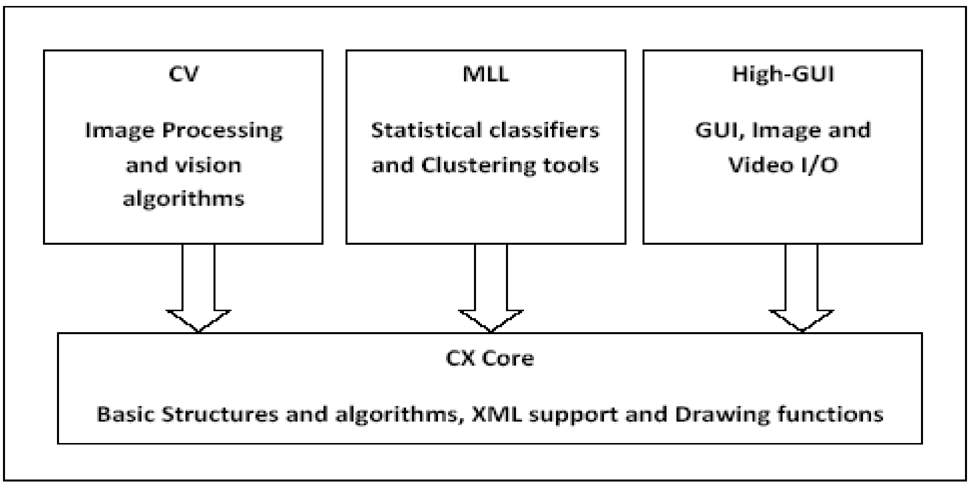

***Figure 2.4-4*: OpenCV Structure and Contents**

OPENCV proved to be the perfect tool to import video in GNU radio python. OPENCV was designed for computational efficiency. The video is divided into frames. The frames are divided into bits. Bits are converted to OFDM symbols and are transmitted using two 2.4 GHz daughter cards, as it is 2x2 MIMO. The symbols with the strongest SNR are detected (coming from the same antenna). Symbols are demodulated to get the vectors of bits. Channel is estimated and is used for VBLAST Detection. Two columns of the channel matrix are formed and then the received vector having the noise portion is generated as well. The vectors are ordered first and then moved to the VBLAST phase and go through the VBLAST Detection.

2.5. OFDM (Orthogonal Frequency Division Multiplexing)

World is moving from Analog Communication to Digital Communication. Use of Digital communication has been increasing so rapidly from last few years, due to its rapid growth need of high data rate is also increasing. Mobile communication industry has to provide many different services to users for this Mobile Telecom industry need very high speed for transmission in order to meet the demands of users. There are different data rate requirements for different services. Wireless multimedia requires data rate nearly 100 Mbps as compared to the voice transmission that requires data rate of few kbps. Many techniques of Multiplexing have been proposed and implemented. OFDM is one of them, and it is gaining more importance nowadays.

2.5.1. Introduction to OFDM

OFDM provides the way to avoid inter symbol interference (ISI) and inter channel interference (ICI). In multi channel transmission environment OFDM helps to combat against crosstalk between adjacent channels. As multiple input multiple output (MIMO) system is used, it will be preferred to use OFDM scheme as a modulation scheme. MIMO-OFDM systems are now being used for 4G applications. 4G is an uprising technology that can be achieved by

2.5.2. Principle of OFDM

Orthogonal frequency division multiplexing (OFDM) works on multi channel transmission systems in which the whole spectrum is divided into different sub channels. These channels are orthogonally separated from each other. Data is divided into small data streams and modulated with these sub channels. Frequency division multiple access (FDMA) divides users on the basis of frequency. Each users is assigned different channel or frequency. OFDM works on the same principle. Major difference between these two techniques is that OFDM uses the spectrum very efficiently by closely spacing the channels. Channels are orthogonal that's why channels would be closely spaced and ISI and ICI can be avoided.

2.5.3. Orthogonality

Orthogonality is defined for both real and complex valued functions. The functions $\varphi_m(t)$ and $\varphi_n(t)$are said to be orthogonal with respect to each other over the interval a < t < b if they satisfy the condition:

$$\int_a^b \varphi_m(t)\varphi^*{}_n(t)dt = 0 \quad where\ n \neq m \tag{4}$$

OFDM divides the whole spectrum into many narrowband channels each having its own sub-carrier [3]. The number of sub-carriers into which the whole spectrum can be divided depends upon the N-point IFFT. These sub-carriers are orthogonal to each other. Each sub-carrier has an integer number of cycles over a symbol period. Thus the spectrum of each sub-carrier has a null at the centre frequency of the other sub-carriers in the whole system. Figure 2.5-1 illustrates the orthogonality of sub carriers.

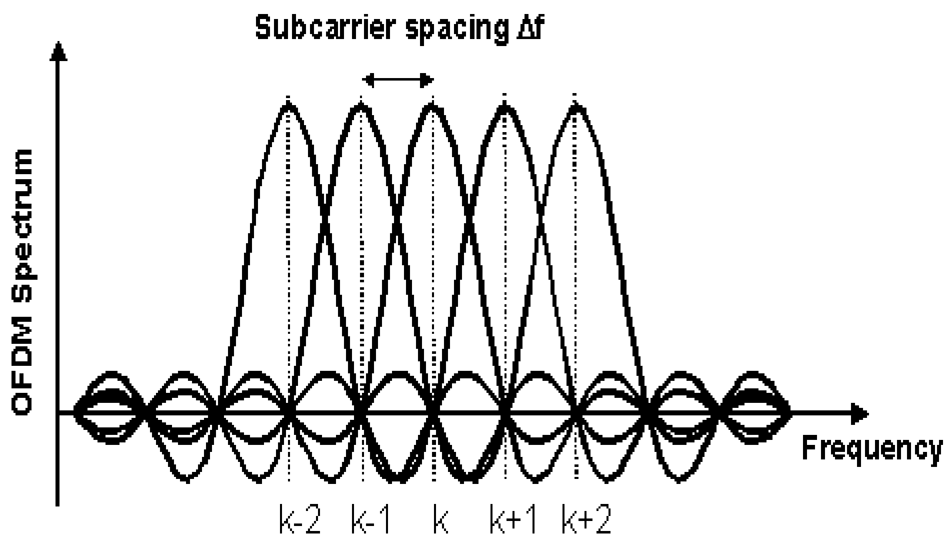

***Figure 2.5-1*: Orthogonality of sub-carriers**

By using this spacing technique the sub-carriers will not interfere and they will be very close to each other. When such technique is used there will be no need for the user to be multiplexed in time, and there will be no overhead associated while switching between users. The problem of overhead carrier spacing in FDMA is over come by this method.

2.5.4. OFDM Carriers

Orthogonal Frequency Division Multiplexing is a type of Multi Carrier Modulation. The waveforms in time domain are chosen in such a manner that orthogonality is maintained even when the sub carriers overlap. This statement depicts that when the carriers are closely spaced each carrier has a maximum value respectively when all the remaining carriers are at zero.

2.5.5. Advantages of OFDM

OFDM has several advantages compared to other type of modulation technique implemented in wireless communication systems. OFDM is also used as a preferred modulation scheme in fourth generation communication systems. Below are some of the advantages that describe the uniqueness of OFDM compared to other modulation techniques.

2.5.5.1. Bandwidth Efficiency

Bandwidth efficiency is the most important aspect of high speed communication systems. When wireless communication includes sharing of range of carrier frequencies which are already crowded, the bandwidth efficiency becomes more important. In orthogonal frequency division multiplexing (OFDM) the base-band message signal is sub-divided into large number of parallel data streams.

These streams are then assigned a low frequency carrier called sub-carriers. These resulting sub-carriers are placed in a manner that they are orthogonal to one another so that at the receiver their separation is carried out without any interference from the neighboring carriers [3]. So the channel spacing in case of OFDM is much smaller which makes it spectral efficient as compared to the other old multiple access technique, so by using OFDM technique, the required bandwidth can be effectively reduced and hence increasing the efficiency.

2.5.5.2. OFDM overcomes the effect of ISI

Inter symbol interference (ISI), limits the data rate and hence slow down the transmission speed. As the information transmission speed is increased in a wireless communication system, the transmission time for each bit becomes less. As the delay time due to multi path almost remains constant, the inter symbol interference becomes a limitation for sending high data rate in wireless communication. This problem is removed in OFDM transmission systems by simultaneously sending number of low-speed transmissions. Figure 2.5-2 shows the effect of OFDM on duration of symbol.

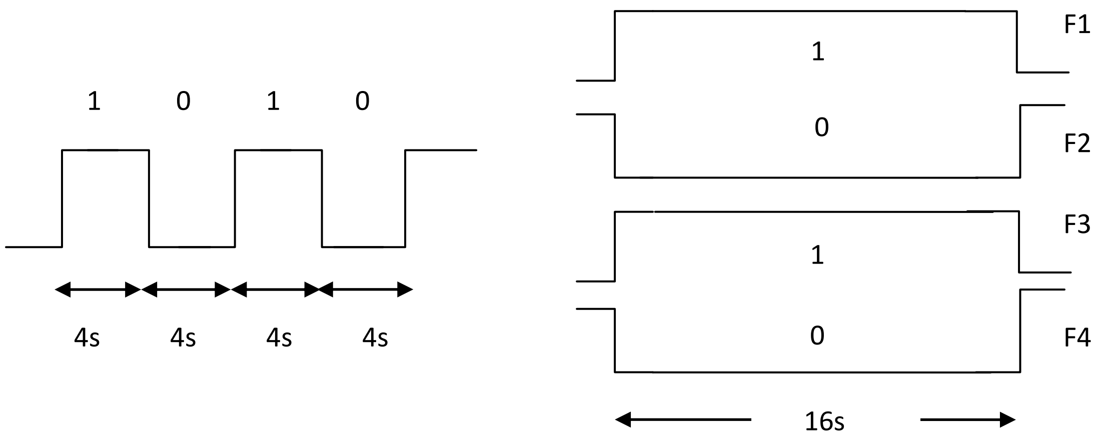

Figure 2.5-2: **Two Ways to Transmit the Same Four Pieces of Binary Data**

Suppose this data transmission is done in four seconds. Then each symbol of the data in left picture has duration of four second. When this data is transmitted by OFDM, the four symbols would be simultaneously sent. In this scenario, each symbol of data has occupied 16-second duration. As the duration of symbol has increased so the ISI will be reduced.

2.5.5.3. OFDM Fights Frequency Selective Fading and Burst Error

In OFDM, the frequency selective fade is spread over number of symbols. Due to this, the burst errors are randomized which were caused by high fading or disturbances due to neighboring signals, hence besides complete distortion of few or many neighboring symbols, many symbols become degraded on a small scale. It will allow the renewal of maximum symbols without even using corrections codes such as FEC. Due to this division of the complete bandwidth of channel into large number of small frequency parts, each sub-band will be facing the same frequency response

2.5.6. Implementing MIMO-OFDM on USRP

A video is taken as input from the OPENCV software inside the Python code. The video is divided into frames. The frames are divided into bits. Bits are converted to OFDM symbols and are transmitted using two 2.4 GHz daughter cards, as it is 2x2

MIMO. Omni directional antennas are used in the transmission of the signal from the transmitter side to the receiver side.

2.5.6.1. Generation of OFDM Symbol

For the implementation of OFDM in wireless communication, first of all the digital message signal is modulated and then carrier is divided into closely spaced orthogonal sub-carriers. For mapping of symbols, any of the modulation scheme can be implemented such as Binary Phase Shift Keying (BPSK), Quadrature Phae Shift Keying (QPSK) or QAM. Digital signal processing is applied for this purpose. Phase shift keying is a digital modulation scheme that conveys the data by changing, or modulating, the phase of a carrier signal. BPSK as a modulation scheme is used. In BPSK, each data symbol is represented by one bit. Figure 2.5-3 represents 8 symbols (01011101) in time domain and the modulation scheme being used is BPSK. When it`s spectrum is observed in the frequency domain, it shows that the phase shift in carrier expanded the bandwidth occupied by the BPSK signal such that it became a Sinc function. 0 and 1 are assigned different frequencies. Zeros of the sinc frequency occurs at the interval of symbol frequency.

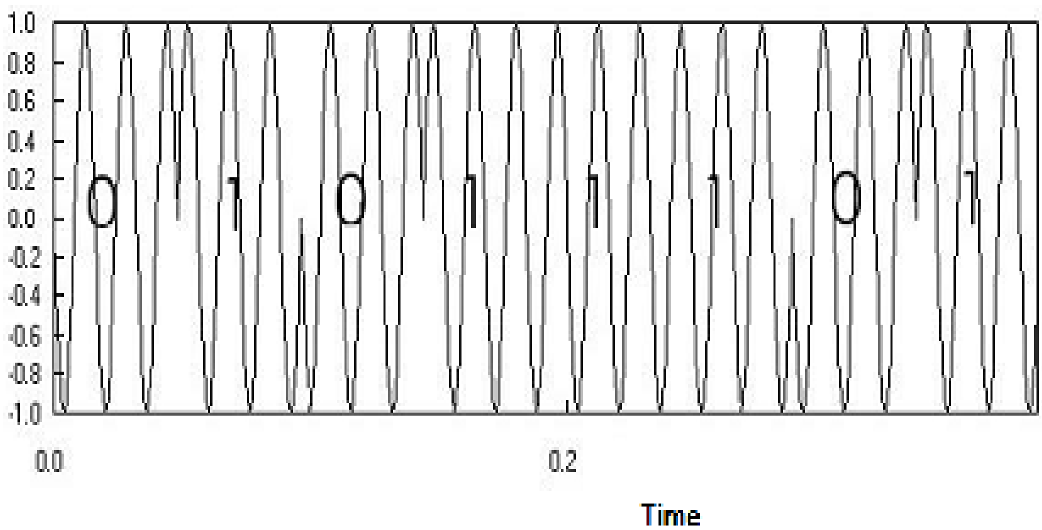

***Figure 2.5-3*: Binary Phase-Shift Key (BPSK) representation of "01011101"**

The Figure 2.4-5 shows that after the BPSK modulation as mapping scheme there certain known preambles (pilot symbols) that are inserted into the start of every of every OFDM symbol. These symbols are used for channel estimation (Fig. 2.4-5). For the conversion of sub-carriers to number of orthogonal signals, at first the information assembled in frames of an optimum size for FFT or IFFT. Fast Fourier Transform (FFT) should be according to length of 2N (here N represents integer). Then N-point Inverse Fast Fourier Transform (IFFT) is performed and the output of transmitter will be a data stream. So when signals of IFFT output are sent in a sequence, each of the N channel bits will appear at a particular different sub-carrier frequency. In IFFT, the space between the sub-carriers is chosen such that at the frequency where the receiving signal is evaluated, all other nearby signals will be zero. To achieve this exact orthogonality, the transmitter and the receiver must be synchronized perfectly. Figure 2.5-4 shows implementation of OFDM on USRP.

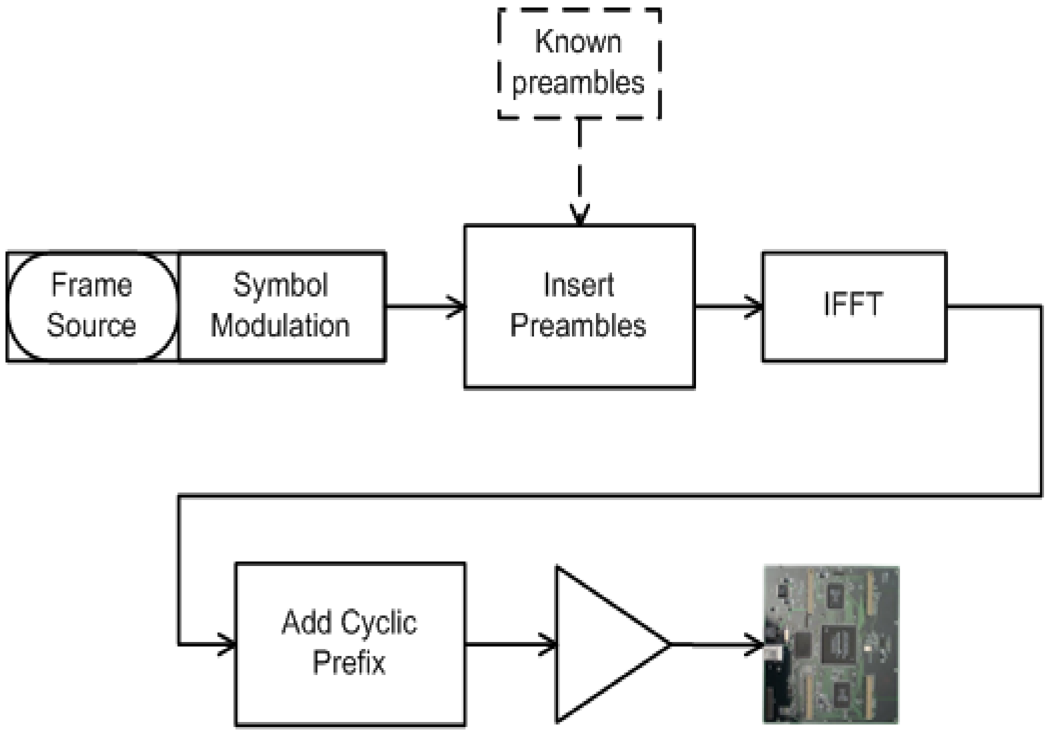

***Figure 2.5-4*: OFDM Implemented on USRP**

2.5.6.2. Guard Period

The most prominent feature in OFDM scheme is that it is robust against multi-path delay. If the sub-carriers of signals are to retain their orthogonality during the transmission then guard periods are inserted. These guard periods gives time for the multi-path signals from earlier symbol to dispel completely before the data from the present symbol is received.

In OFDM commonly used guard period is a cyclic prefix. Cyclic prefix is added at front of every symbol of OFDM. The replica of last part of OFDM symbol is used as cyclic prefix, and it is of almost equal or a little greater in length than maximum delay spread of channel. Although the bandwidth efficiency is compromised by inserting cyclic prefix, it is the best compromise between system`s performance and it`s efficiency in presence of ISI. Figure 2.5-3 shows how cyclic prefix is added to the original symbol.

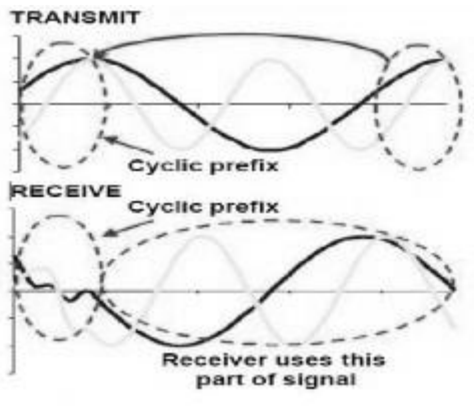

***Figure 2.5-5*: Implementation of Cyclic Prefix**

The symbols with the strongest SNR are detected (coming from the same antenna). OFDM symbols are demodulated (Inverse OFDM) to get the vectors of bits. To get the best results in OFDM transmission, two types of synchronization is needed. Time synchronization and the frequency synchronization are performed. For this purpose, some already known pilot symbols are inserted in OFDM symbol or by appending some tracking algorithms which are based on fine frequency synchronization at the cyclic prefix. This is illustrated in Figure 2.5-6.

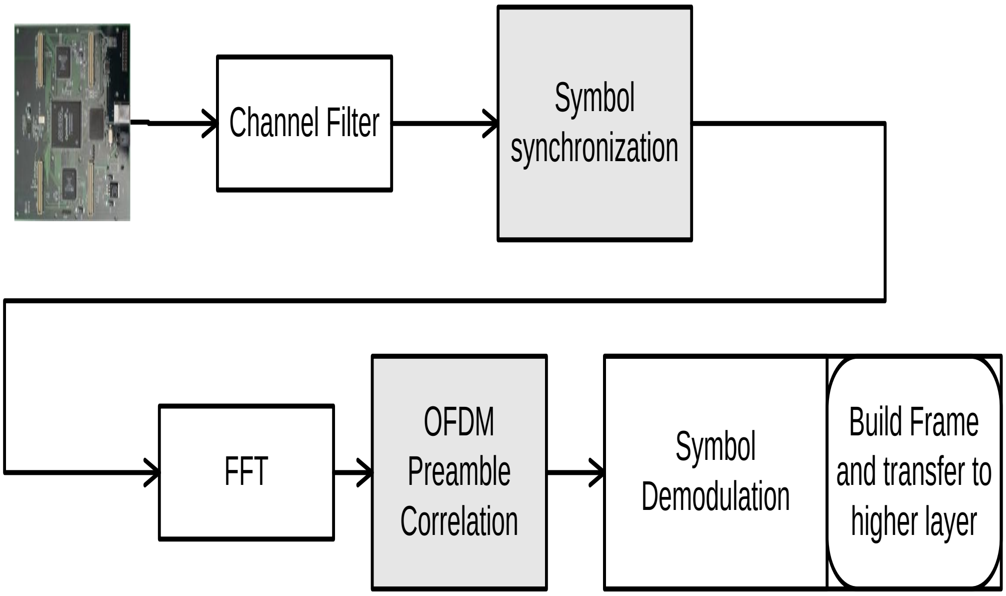

***Figure 2.5-6*: Inverse OFDM implemented on USRP**

By the preamble Correlation an estimate of the channel is obtained and channel matrix will be formed. After that FFT and demodulation takes place.

2.5.6.3. Channel Estimation - Least Squares (LS)

The Least Squares Error (LSE) estimation method can be used to estimate the matrix H by minimizing the squared error between estimation and detection In matrix form, it can be written as

$$y = X\,h \tag{5}$$

So the error 'e' can be defined as

$$e = y'' - y \tag{6}$$

Where y" is the expected output.

The squared error (S) can be defined as

$$S = | e |^2 \tag{7}$$

$$S = (y"- y)^2 \tag{8}$$

$$S = (y"- y)*(y"- y)^t \tag{9}$$

Where the super-script ‘t‘ stands for complex transpose of a matrix.

$$S = (y"- Xh)*(y"- Xh)^t \tag{10}$$

This equation can be minimized by taking its derivative with respect to ‘h‘and equating it to zero. The final equation is:

$$h" = (X^t \text{ X })^{-1} X^y y \tag{11}$$

Which can be written as,

$$h_{LS} = X^{-1} y \tag{12}$$

This equation can be implemented on SISO as well as MIMO systems.

2.5.6.4. Synchronization

Synchronization is implemented using the method mention in the paper “Robust Frequency and Timing Synchronization for OFDM” by Timothy M. Schmidl and Donald C. Cox. Training symbols are inserted in the transmitted frames. They are already known at the receiver side. Based on those training symbols synchronization is performed at the receiver side .Synchronization is done both in time and frequency domain. Both are discussed briefly in the following section

2.5.6.4.1. Estimation of Symbol Timing

In symbol timing recovery search for identical training symbols is carried out that remain the same after passing through the channel. There will be only phase shift between the two symbols. PN (Pseudonoise) sequence is transmitted on even frequencies and zeros are transmitted on odd frequencies for the first training symbol.

The second training symbol contains a PN sequence on the odd frequencies to measure these sub channels, and another PN sequence on the even frequencies to help determine frequency offset. The Table 2.4-1 shows the use of training symbols

Table 2.4-1: Illustrating the use of PN sequences for Training symbols

Illustrating the use of PN sequences for Training symbols			
Freq number k	c_{1_k}	c_{2_k}	$v_k = \sqrt{2}\frac{c_{2_k}}{c_{1_k}}$
-4	7+7j	5-5j	-j
-3	0	-5-5j	
-2	-7+7j	-5-5j	J
-1	0	-5+5j	

In the training symbol the first part is same as the second part , but there will be a phase shift between the two parts. If the conjugate of a sample from the first half is multiplied by the corresponding sample from the second half (T/2 seconds later), the effect of the channel should cancel, and the result will have a phase of approximately $\emptyset = \pi T \Delta f$. At the start of the frame, the products of each of these pairs of samples will have approximately the same phase, so the magnitude of the sum will be a large value. Let there be complex samples in one-half of the first training symbol (excluding the cyclic prefix), and let the sum of the pairs of products be

$$P(d) = \sum_{m=0}^{L-1} r_{d+m}{}^{*}\, r_{d+m+L} \tag{13}$$

Note that d is a time index corresponding to the first sample in a window of 2L samples. This window slides along in time as the receiver searches for the first training symbol. The received energy for the second half-symbol is defined by

$$R(d) = \sum_{m=0}^{L-1} \|r_{d+m+L}\|^2 \tag{14}$$

Output of P(d) in the frame lies between the two peaks

2.5.6.4.2. Estimation of Carrier Frequency Offset

The main difference between the two halves of the first training symbol will be a phase difference of

$$\emptyset = \pi T \Delta f \tag{15}$$

which can be estimated by

$$\hat{\emptyset} = angle(P(d)) \tag{16}$$

Close to best timing point. If $|\hat{\emptyset}|$ can be assured to remain less than π, then estimate of frequency offset is

$$\widehat{\Delta f} = \frac{\hat{\emptyset}}{\pi T} \tag{17}$$

The even PN frequencies on the second training symbol would not be needed. Other than that, the actual frequency offset would become

$$\frac{\emptyset}{\pi T} + \frac{2z}{T} \tag{18}$$

Where z is an integer. By partially correcting the frequency offset, adjacent carrier interference (ACI) can be avoided, and then the remaining offset of 2z/T can be found. After the two training symbols are frequency corrected by $\hat{\emptyset}/\pi T$ (by multiplying the samples by$e^{-j2T\hat{\emptyset}/T}$), let their FFT's be x_{1_k} and x_{2_k} , and let the differentially-modulated PN sequence on the even frequencies of the second training symbol be v_k (as illustrated in Table 2). The PN sequence will appear at the output except it will be shifted by positions because of the uncompensated frequency shift of

$2z/T$. There would still be a phase shift between x_{1_k} and x_{2_k} of $2\pi(T + T_g)2z/T$. Since at this point the integer z is unknown, this additional phase shift is unknown.

However, since the phase shift is the same for each pair of frequencies. Let be the set of indices for the even frequency components,

$$X = \{-W, -W + 2, \dots \dots - 4, -2, 2, 4, \dots .. W, W + 2\} \quad (19)$$

The number of even positions shifted can be calculated by finding $\hat{g}$ to maximize

$$B(g) = \frac{\left|\sum_{k \epsilon X} x_{1,k+2g}{}^{*} v_k{}^{*} x_{2,k+2g}\right|^2}{2\left(\sum_{k \epsilon X} \left|x_{2,k}\right|^2\right)^2} \quad (20)$$

with integer g spanning the range of possible frequency offsets and W being the number of even frequencies with the PN sequence. Then the frequency offset estimate would be

$$\widehat{\Delta f} = \frac{\widehat{\emptyset}}{\pi T} + \frac{2\hat{g}}{T} \quad (21)$$

Channel is estimated and is used for VBLAST Detection. Two columns of the channel matrix are generated and the received vector having the noise portion is produced as well. The vectors are ordered first and then moved to the VBLAST phase and go through the VBLAST Detection. Video is reconstructed after frame recovery and combination.

2.6. VBLAST Detection

Lately, theoretical evaluations have shown that the wireless communication multipath channel can have huge capacities only if the multipath scattering is richly provided and is properly used by using appropriate architecture. A simplified version of

BLAST known as vertical BLAST or VBLAST, which has been implemented in real-time in the laboratory, is described.

2.6.1. Introduction to VBLAST

Foschini proposed the diagonally-layered space-time architecture [4], diagonal BLAST (Bell Laboratories Layered Space Time) or DBLAST, is a way of approach. DBLAST uses multiple antennas at both transmitter side and receiver side and diagonally layered coded structure. In this structure the blocks of codes are scattered in diagonals in space-time. Within the Rayleigh`s scattering environment this diagonal structure gives data rates (theoretically) that grow linearly with the increase in number of antennas (if number of transmitters and receiver is same), and with these rates extending to 90% of Shannon`s capacity. But, the diagonal procedure comes across some implementation problems which makes it inappropriate for initial implementation. A simplified version of BLAST known as vertical BLAST or VBLAST, which has been implemented in real-time in the laboratory, is described. Spectral efficiencies of 20 - 40 bps/Hz at an average SNRs ranging from 24 to 34 dB has been demonstrated in the laboratory using a prototype [5].

2.6.2. System Overview

A high-level block diagram of a BLAST system is shown in the figure 2.6-1. A single data stream is distributed into M sub streams, and each sub stream is then transformed into symbols and given to its respective transmitter. All transmitters operate co-channel at symbol rate 1/T sym/sec, with synchronized symbol timing. Each transmitter is itself an ordinary QAM transmitter. The transmitters comprise, in effect, a vector-valued transmitter, where elements of each transmitted M-vector are symbols drawn from a QAM constellation. Assuming that the same constellation is used for each sub-stream, and that transmissions are organized into bursts of some symbols. The power radiated by each transmitter is proportional to 1/M so that the total launched power is constant and independent of M. Figure 2.6.1 shows a general setup for implementation of VBLAST algorithm on MIMO systems.

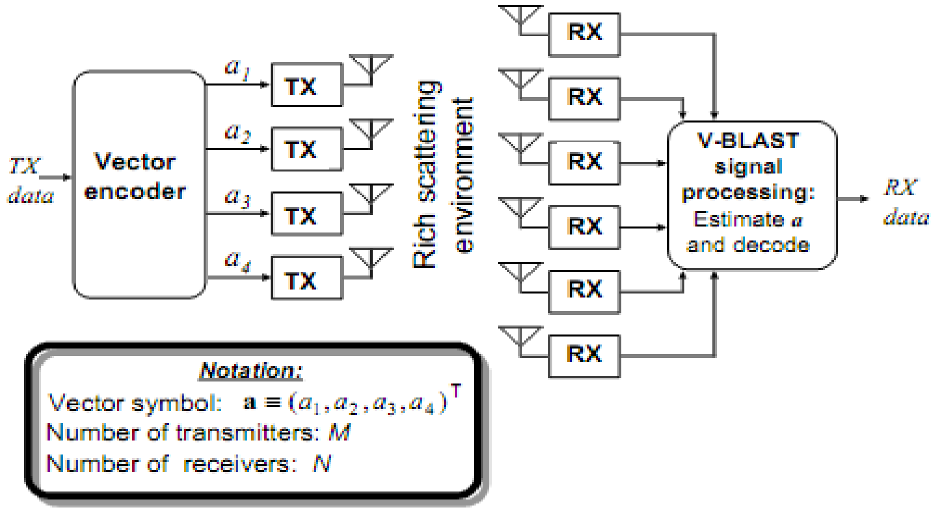

***Figure 2.6-1*: VBLAST: A high level system diagram**

All receivers are, individually, QAM receivers. These receivers also operate co-channel, each receiving the signals radiated from each M transmit antennas. For simplicity in the process, flat fading is assumed, and the matrix channel is depicted as H^{NxM}, where h_{ij} is the (complex) transfer function from transmitter j to receiver I, and M less or equal to N.

The main difference between DBLAST and VBLAST lies in the vector encoding process. In DBLAST, redundancy is introduced between the sub streams through the use of specialized inter-sub stream block coding. Code blocks of DBLAST are organized along diagonals in space-time. It is this coding that leads to DBLAST's higher spectral efficiencies for a given number of transmitters and receivers. In

VBLAST, however, the vector encoding process is simply a de multiplex operation followed by bit-to-symbol mapping of each sub stream. No inter-sub stream coding, or coding of any kind, is required; however conventional coding of the individual sub streams may certainly be applied.

Although VBLAST, is essentially a single-user system which uses multiple transmitters, one can naturally ask in what ways the BLAST approach differs from simply using traditional multiple access techniques in a single-user fashion, i.e. by driving all the transmitters from a single user's data which has been split into sub streams. Some of these differences are worth pointing out: First, unlike code division or other spread-spectrum multiple access techniques, the total channel bandwidth utilized in a BLAST system is only a small fraction in excess of the symbol rate, i.e. similar to the excess bandwidth required by a conventional QAM system. Second, unlike FDMA, each transmitted signal occupies the entire system bandwidth. Finally, unlike TDMA, the entire system bandwidth is used simultaneously by all of the transmitters all of the time.

Taken together, these differences together are precisely what give BLAST the potential to realize higher spectral efficiencies than the multiple-access techniques. In fact, an essential feature of BLAST is that no explicit orthogonalization of the transmitted signals is imposed by the transmit structure at all. Instead, the propagation environment itself, which is assumed to exhibit significant multipath, is exploited to achieve the signal de correlation necessary to separate the co-channel signals. V-BLAST utilizes a combination of old and new detection techniques to separate the signals in an efficient manner, permitting operation at significant fractions of the Shannon capacity and achieving large spectral efficiencies in the process.

2.6.3. V-BLAST Algorithm

Now the process of detection for one transmitted vector symbol will be explained in discrete time given the conditions of synchronous-symbol sampling of receiver and timing is ideal. Let a = $(a_1, a_2, \ldots, a_M)^T$ is the vector of transmit symbols, so accordingly the received N-vector will be:

$$r_1 = Ha_1 + v \tag{22}$$

Here ν represents the noise vector and components taken from the wide-sense stationary processes with the variance σ^2. Desired signals are the sub-streams while the remainders are called Interferers. By weighting the signals in linear fashion, the process of nulling is accomplished to assure and fulfill some performance-related requirements, for example minimum mean square error (MMSE) or zero forcing (ZF). Zero-forcing nulling can be done by carefully picking weight vectors w_i when i = 1, 2, . . ., M, so that

$$w_i{}^T(H)_j = \delta_{ij} \tag{23}$$

Here $(H)_j$ represents j-th column of H, and δ represents Kronecker delta. So the statistic of decision for the i-th sub stream is

$$y_i = w_i{}^T r_1 \tag{24}$$

For performing detection, two things have to be done i.e. symbol cancellation and nulling in linear fashion. Using symbol cancellation, interference from already-detected components are subtracted out from the received signal vector, resulting in a modified received vector in which, effectively, fewer interferers are present. This is somewhat analogous to decision feedback equalization. When symbol cancellation is used, the order in which the components of a are detected becomes important to the overall performance of the system. First general detection procedure with respect to an arbitrary ordering is discussed. Let the ordered set

$$S = \{k_1, k_2, \dots \dots \dots \dots k_M\} \tag{25}$$

be a permutation of the integers 1, 2, . . . , M specifying the order in which components of the transmitted symbol vector a are extracted. The detection process proceeds generally as follows:

Step 1:

Using nulling vector w_{k1}, form decision statistic y_{k1}

$$y_{k_1} = {w_{k_i}}^T r_1 \tag{26}$$

Step 2:

Slice y_{k_1} to obtain $\hat{a}_{k_1}$

$$\hat{a}_{k_1} = Q(y_{k_1}) \tag{27}$$

Where Q(.) denotes the quantization (slicing) operation.

Step 3:

Assuming that $\hat{a}_{k1} = a_{k1}$, cancel a_{k1} from the received vector r_1, resulting in modified received vector r_2:

$$r_2 = r_1 - \hat{a}_{k_1}(H)_{k_1} \tag{28}$$

Where $(H)_{k1}$ denotes the k_1-th column of H. Steps 1 - 3 are then performed for components $k_2, \dots, k_M$ by operating in turn on the progression of modified received vectors $r_2, r_3, \dots, r_M$. [5]

The full ZF V-BLAST detection algorithm can now be described compactly as a recursive procedure, including determination of the optimal ordering of the signal antennas receiving the signals. Figure 2.6.2 shows steps involved in VBLAST detection.

$$\boldsymbol{Initialization}$$

$$i \longleftarrow 1$$

$$G_1 = H^+$$

$$k_1 = arg_j min\left\|(G_1)_j\right\|^2$$

$$\boldsymbol{Recursion}$$

$$w_{k_i} = (G_i)_{k_i}$$

$$y_{k_i} = w_{k_i}{}^T r_i$$

$$\hat{a}_{k_i} = Q(y_{k_i})$$

$$r_{i+1} = r_i - \hat{a}_{k_i}(H)_{k_i}$$

$$G_{i+1} = H_{\overline{k_i}}{}^+$$

$$k_{i+1} = argmin\left\|(G_{i+1})_j\right\|^2$$

$$i \longleftarrow i + 1$$

***Figure 2.6-2*: Algorithm of ZF VBLAST Detection**

This algorithm was implemented on MATLAB and then on Python to get the results. The results of ZF and ZF VBLAST were plotted and compared. Performance of ZF-VBLAST is better as compared to ZF detection.

2.6.4. MIMO-OFDM ZF VBLAST on USRP

ZF VBLAST Detection is implemented using the same algorithm's concept as described previously in the section 2.5.3.. A video is taken as input from the OPENCV software inside the Python code. The video is divided into frames. The frames are divided into bits. Bits are converted to OFDM symbols and are transmitted using two 2.4 GHz daughter cards as it is 2x2 MIMO. The symbols with the strongest SNR are detected (coming from the same antenna). Symbols are demodulated (inverse OFDM) to get the vectors of bits. Channel is estimated and is used for VBLAST Detection.

Two columns of the channel matrix are generated and the received vector having the noise portion is produced as well. The vectors are ordered first and then moved to the VBLAST phase. Following procedure takes place within the VBLAST department: First the weight symbols are found through Kronecker's Delta and decision vectors is produced from it. Slicing (Quantization) takes place of the decision vectors. The sliced vector is multiplied by k-th columns of the channel matrix and subtracted from the received vector to get the desired vector. Figure 2.6.3 shows the concept that how multiple channels are formed between transmitter and receiver side.

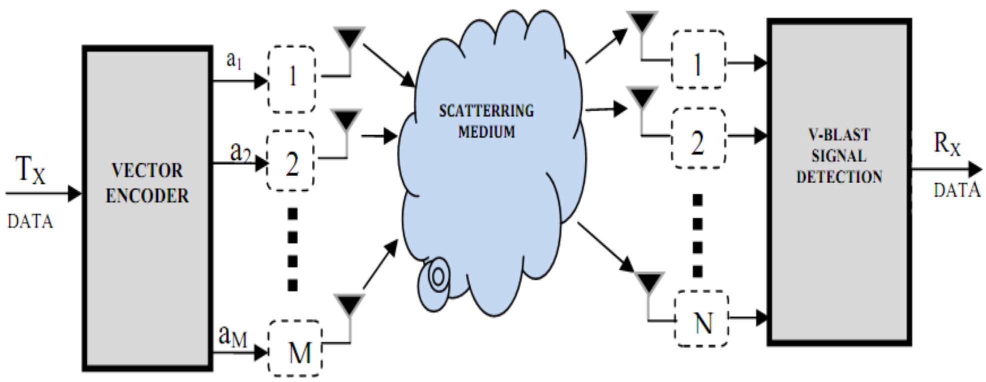

***Figure 2.6-3*: VBLAST Detection diagram**

2.6.5. Advantages of ZF VBLAST Detection

Every technique used in the system has its practical advantages over conventional techniques used for performing similar task. ZF algorithm gives an initial guess to the VBLAST algorithm which then performs cancellation of interference and signal detection. ZF-VBLAST detection has many advantages few of which are discussed in the upcoming section.

2.6.5.1. Complexities are Removed

Using ZF VBLAST Detection, the computational and implementation complexities are removed as one can see from the ZF equation for removing the channel affect

$$\hat{a} = (H * H)^{-1} H x = H^{+} x \quad (29)$$

The ZF receiver converts the joint decoding problem into M single stream decoding problems thereby significantly reducing receiver complexity.

2.6.5.2. Removes Noise and Channel's Effect

ZF VBLAST involves cancellation process which is equivalent to equalization. Hence the interferers (noise and channel) are removed and the remaining signals are detected in the absence of those signals whose cause more interference to the signals. It used the channels efficiently. Ordering is performed in which the signals are detected. The use of this algorithm maximizes the use of available channel capacity.

2.7. Cognitive Technique

Cognition is an upcoming technology and is now being experimented all over the world. This technique has not yet been applied in the world's communication but is going to be a part of telecommunication soon. In this technique a user buys a frequency from frequency allocation board and that particular frequency band is allotted for that user. This user is termed as the primary or licensed user. Another user who does not buy any frequency band and try to use the frequency band of other user completely or partially termed as secondary or unlicensed user.

In this technique the secondary user uses the frequency of the primary user in an intelligent way ensuring there is no interruption between the users' transmissions. This process involves measuring the Receiver Operating Characteristics (ROC) of the detector experimentally. There are free channels allocated to the cognitive transmitter to jump to just in case a primary user is detected. The cognitive transmitter must sense the spectrum regularly and jump to a new channel as soon as the primary user is detected. The cognitive receiver must make sure that it changes the band as the cognitive transmitter changes its band in order for continuous reception of packets. The receiver must constantly resynchronize itself with the cognitive transmitter.

2.7.1. Introduction to Cognitive Technique

Every user is assigned a particular bandwidth when he buys it from the frequency allocation board. But nowadays the spectrums are being used in irregular intervals, almost 15% to 85% according to the FCC [6]. The remaining frequency is rarely used and hence the cognitive approach takes place. The unlicensed user uses the frequency band of the licensed user only if the licensed user is not using that band. The unlicensed user must cause as little interference as possible and the cognitive receiver must remain synchronized to the cognitive transmitter constantly as the latter changes the channel. So to approach the process that takes place using cognitive technique. It was defined as a technique in which spectrum sensing takes place in order to fine "holes" in the spectrum so that it can be used and the band is not wasted. Cognitive is a "smart" radio technique now being worked on in the world.

2.7.2. Motivation for Cognitive Radio

The Figure 2.7-1 shows the under utilization of the available RF spectrum

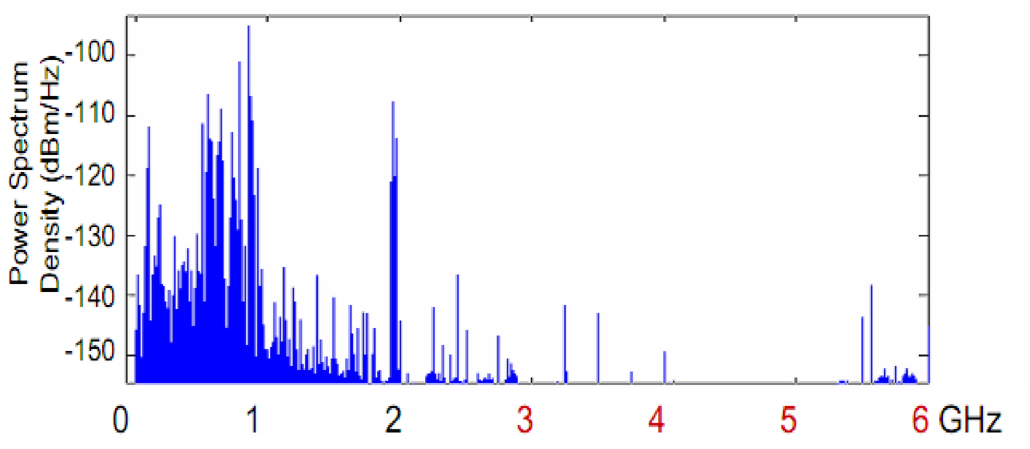

***Figure 2.7-1*: Motivation of Cognitive Radio**

Now the graph in Figure 2.6-1 is analyzed. A band of 6 GHz is allocated to a user. Out of this 6 GHz he utilizes 2 GHz to 3 GHz of frequency, rest is not being used. Table 2.6-1 shows the values of graph in figure 2.6-1 [7].

***Table 2.6-1*: Analysis of band for Cognition**

Freq (GHz)	0-1	1-2	2-3	3-4	4-5	5-6
Utilization (%)	54.4	35.1	7.6	0.25	0.128	4.6

Now it can be seen from the table and also from the diagram that the allocated spectrum is hardly used above 2 GHz frequency band. Above 2 GHz the frequency can be considered as a hole. The secondary user would find this hole and would start transmitting over this band.

2.7.3. Cognitive Radio Cycle

The cognitive radio cycle is shown in the figure 2.7-2:

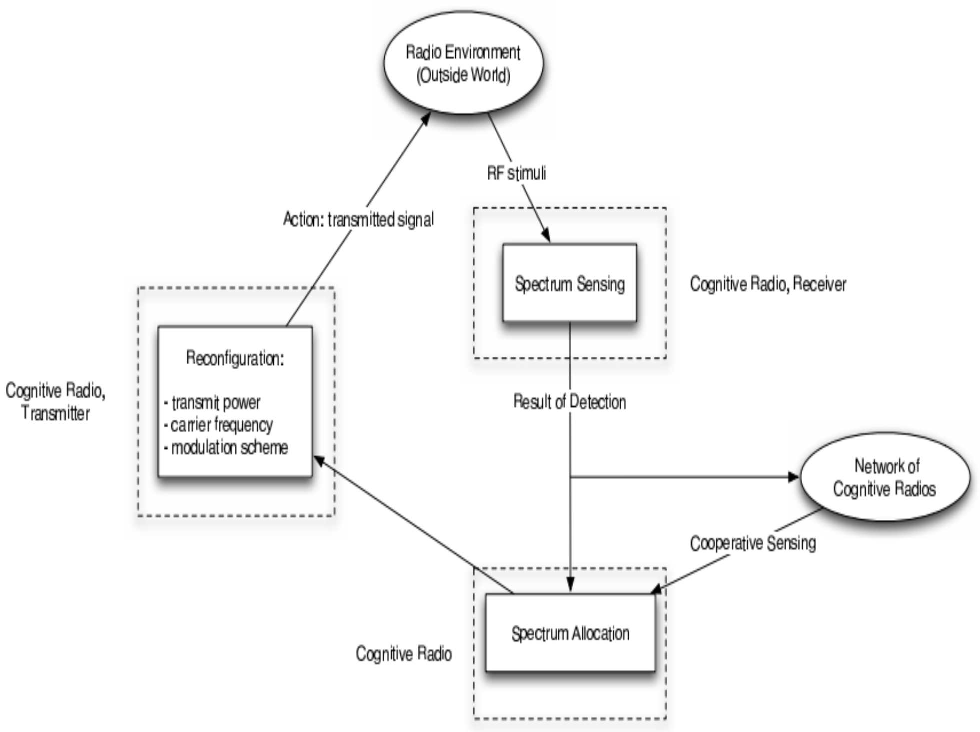

***Figure 2.7-2*: Cognitive Radio Cycle**

Cognitive technique has four basic steps to complete its cycle [6]. Spectrum Sensing, Spectrum Allocation, Reconfiguration and then Transmission. The first step in the cycle involves spectrum sensing. As its name suggests, spectrum sensing is a process in which it is detected whether the primary user is present on the band or not, that is, whether the primary user is transmitting over his band or not. After the spectrum sensing, the results are shared with a cluster of cognitive radios connected together. The cooperative sensing tells the cognitive radios about the holes in the spectrum and also tells which band to use. The cooperative sensing helps detecting the primary users that are far away from the cognitive receivers and hence tells the cognitive receivers to lock onto a certain band in the absence and presence of the primary user. The second step involves the spectrum allocation. In this step a band is allocated to the secondary user. That band is allocated which is free of the primary user. In case, where there is more than one secondary user, the band is shared among them.

The third step involves reconfiguration of the cognitive transmitter. This process involves changing in various mechanisms such as change in the carrier frequency, transmission power and modulation scheme. The fourth and the last step involve the transmission over that band which was found free and is ready to use now. Figure 2.7-3 shows the flow diagram for power detection decision making process.

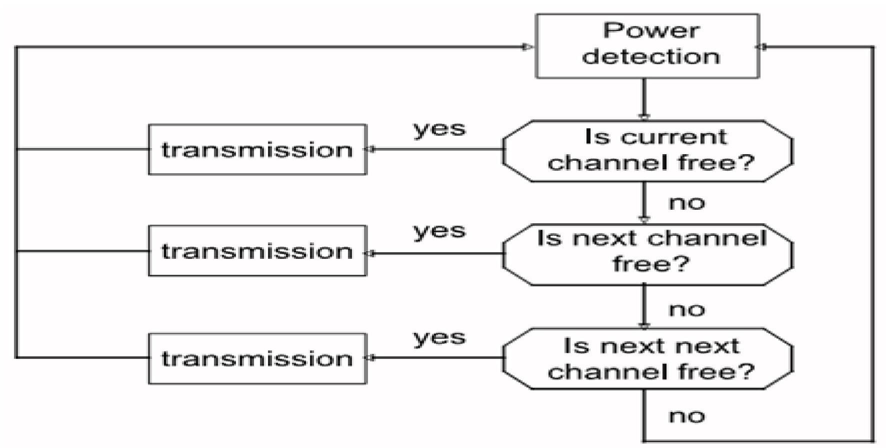

***Figure 2.7-3*: Flow Chart for the Cognitive Transmitter**

Energy is detected on the spectrum (to find the primary user) is done using one of the two transmitting antennas used for MIMO Transmission. After that the channel switching takes place.

2.7.4. Advantages of Cognitive Technique

Cognitive technique has many advantages because of its finding of empty frequencies in bands and transmission on channels which has holes. This technique has many advantages few of them are discussed. It utilizes the bandwidth smartly and also allows the unlicensed users to use the licensed user's bandwidth by causing little or no interference to the licensed user

2.7.4.1. Causes Jamming

Cognitive radio is an intelligent technique to utilize the bandwidth to the fullest if there are holes present. It must not interfere with the primary user in any case. However, if an enemy is trying to send information against us that can be jammed by using cognitive technique that the secondary user starts transmitting over his complete bandwidth interfering with his transmission at all times.

2.7.4.2. Utilizes Holes in the Spectrum

As already discussed the cognitive transmitter makes sure that the holes in the band are readily used if the primary user is not using those bands. Those parts of spectrum are used that are not in use currently. Then the cognitive radio shifts its transmission frequency to that frequency band which is currently not utilized by any primary user. So it smartly use the available spectrum band

2.7.4.3. Does not let the Primary User know about its presence

Cognitive transmitter does not let the primary user know about the usage of licensed user's own bandwidth. It is a smart radio considering all the factors regarding interference. Minimum setup time is required for the cognitive user, so that there is no interference to the licensed user or primary user. Usually the time for detection of the primary user is 2 seconds

2.7.4.4. All of the benefits of software defined radio

Cognitive is smart radio technique. Every command is gone through software. If it needs to be a changed then only amendments in the software are required. Cognitive technique is usually implemented on software defined radio which enhances the efficiency of the system even more. Reconfiguration of the system is easy and it can be done within a short duration of time.

2.7.5. Cognitive Radio Implementation on USRP

A cognitive transmitter first scans the spectrum and then jumps onto other channels depending upon the presence or absence of the primary user. After selecting a channel, the cognitive transmitter locks onto that band.

Figure 2.7-4 reflects the work being done through the USRP for cognition. You can see here that when detection takes place there is no transmission that is, the transmission stops and only spectrum sensing takes place. After the detection phase the results are taken into account and the cognitive transmitter starts transmitting on the new channel.

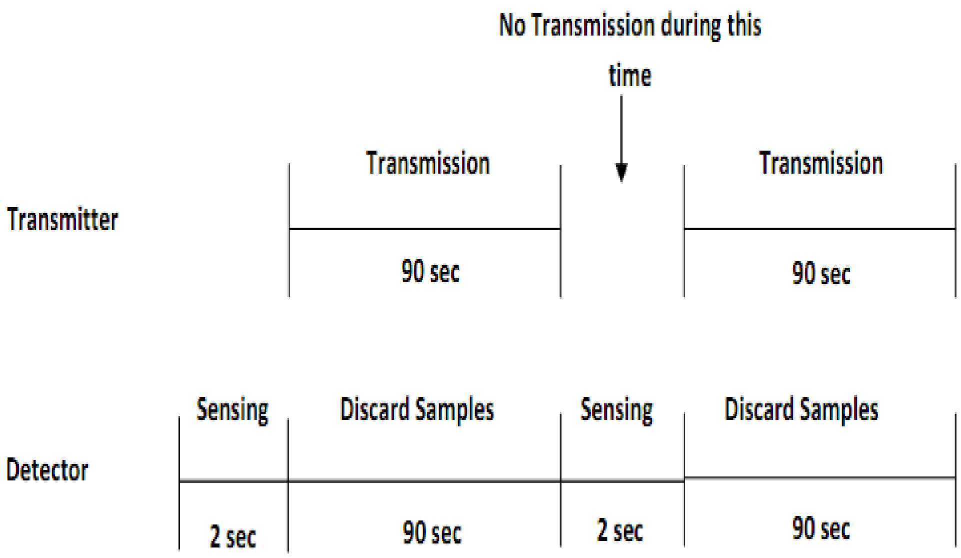

***Figure 2.7-4*: Parallel Detection and Transmission**

A video is taken as input from the OPENCV software inside the Python code. The video is divided into frames. The frames are divided into bits. Bits are converted to OFDM symbols and are transmitted using two 2.4 GHz daughter cards, as it is 2x2 MIMO. The symbols with the strongest SNR are detected (coming from the same antenna). Symbols are demodulated (inverse OFDM) to get the vectors of bits. Channel is estimated and is used for VBLAST Detection. Two columns of the channel matrix are obtained and the received vector having the noise portion is formed as well. The vectors are ordered first and then moved to the VBLAST phase and go through the VBLAST Detection.

After the VBLAST Detection the process starts again. If there is a primary user and he starts transmitting on his desired frequency, the cognitive transmitter changes its frequency and the receiver synchronizes itself with the secondary user. Figure 2.7-5(a) shows the result of energy detector when scanning takes place and all channels are open.

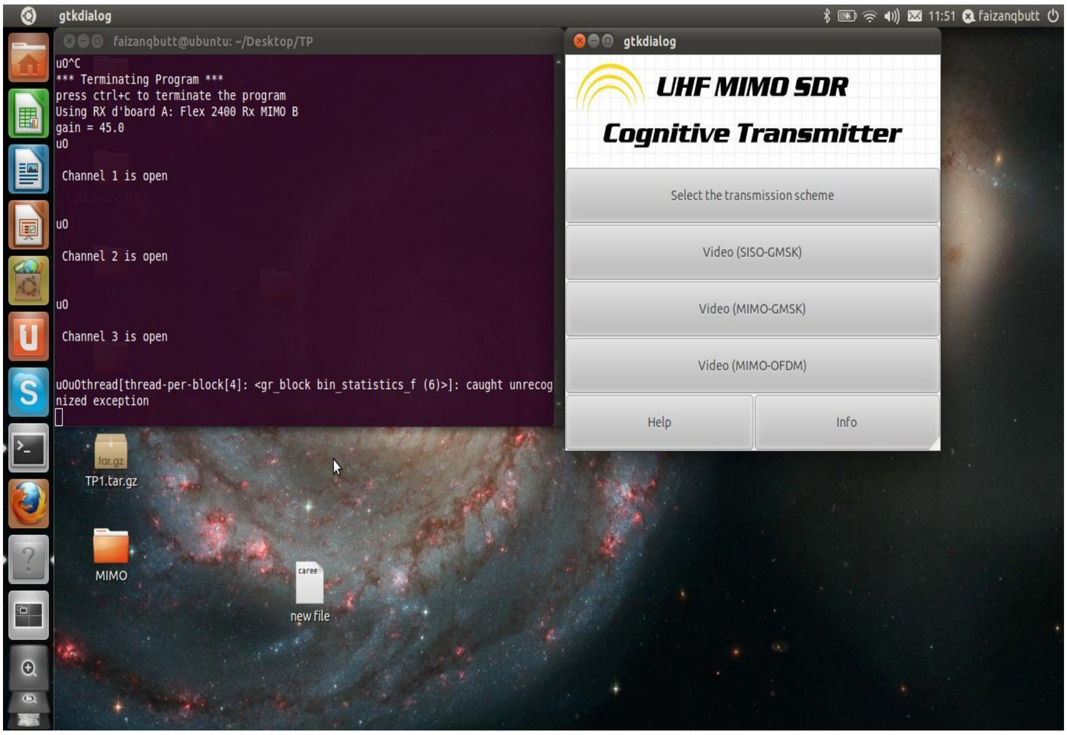

***Figure 2.7-5(a)*: Status of Channels**

Three channels are chosen having center frequency of 2.399 GHz, 2.4 GHz and 2.401 GHz. The cognitive transmitter starts the transmission first by scanning the channels in order to detect the presence of the primary user. In the picture above, you can see that all the channels are open, that is, there are no transmissions going on over these channels. The cognitive transmitter chooses any one of the channels and starts transmitting over it. The cognitive receiver synchronizes itself with the cognitive transmitter and starts receiving the packets (of video).

Now, there is another scenario in which there is a transmission going on over one of the three channels, that is, there is a primary user using his frequency to transmit. Figure 2.7-5(b) shows the result of energy detector when scanning takes place and channel 1 is closed.

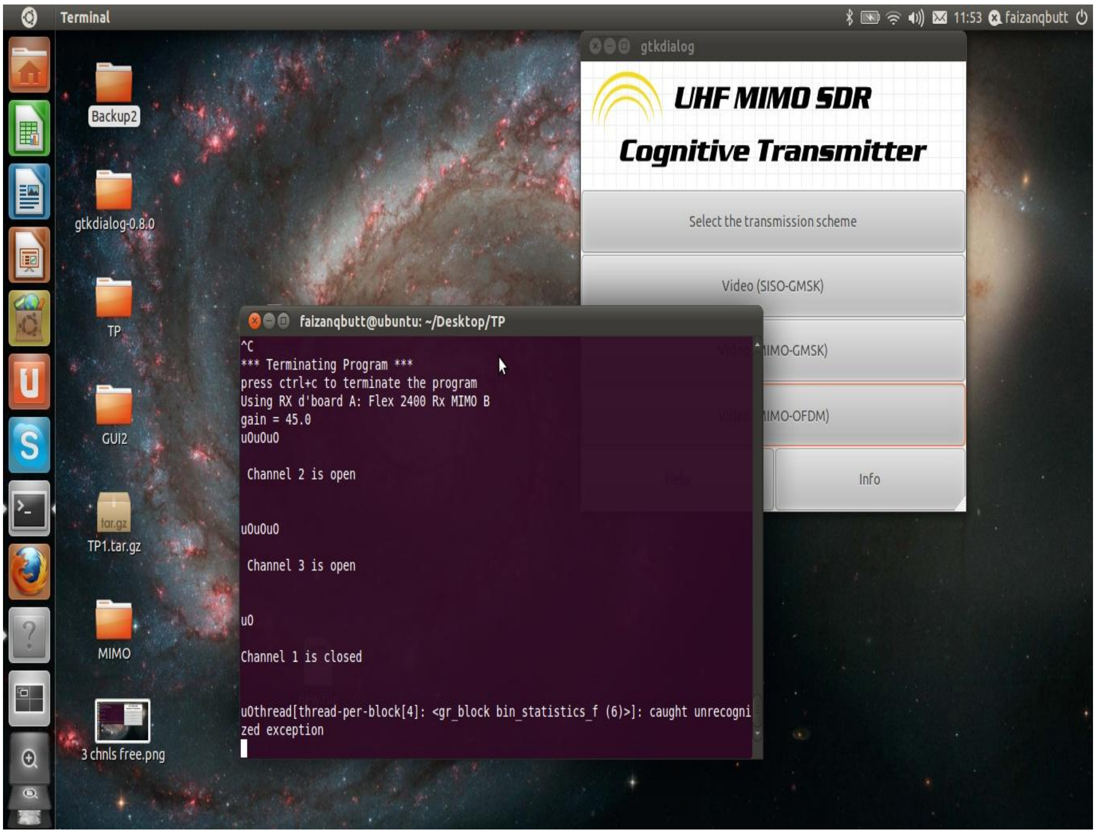

***Figure 2.7-5(b)*: Status of Channels**

Here you can see that when a user starts transmitting over his frequency on channel 1, that is on 2.399 GHz, the cognitive transmitter scans the channels and shows that channel 1 is closed and rest of the channels are open and ready to use. Once the free channels are found the secondary user (cognitive transmitter) just chooses one of the free channels and starts transmitting over it. The cognitive receiver synchronizes itself with the cognitive transmitter and starts receiving the packets.

2.8. Summary Of This Chapter

Chapter 2 explains all the techniques implemented in the project. Project design is discussed in detail and respectively procedure to be followed is explained. Details and advantages of MIMO system, which is the main part of the project, have been discussed. OFDM, V-BLAST and Cognitive techniques and each of their advantages have been explained in detail. After the explanation portion the complete procedure of the implementation of all these techniques on USRP is discussed. All these techniques are combined on one platform and live video is transmitted using all these techniques.

CHAPTER 3

RESULTS AND ANALYSIS

3.1. Introduction

This section shows the results of the implementation of the project on different software. First implantation of MATLAB is discussed. System model for SISO and MIMO are presented and simulated on MATLAB. Then the same system models are implemented on GNU radio platform to analyze the performance. Bandwidth comparison, data rate comparison, and BER comparison are also presented in this section.

3.1.1. Implementation On MATLAB

First the implementation on MATLAB will be discussed and then the corresponding results will be displayed. MATLAB implantation is important in simulating the behavior of cognitive radios and other digital communication systems like MIMO-OFDM. Simulation gives an approximate of how the current system will perform in the real transmission environment.

3.1.1.1. SISO Model

The project was first completed on MATLAB. SISO model was implemented. By changing the EbNo it was checked that whether an image quality changes or not. In the MATLAB code, two antennas were set, one for the transmitter and one for the receiver. OFDM and QPSK were implemented as modulating technique. Spectrum sensing takes place after regular intervals. From here it can be seen that the image quality reduces by reducing the EbNo and the quality gets better as EbNo was increased that is the bit energy as the direct affect on the detection process. Figure

3.1-1 shows the effect of changing the ratio EbNo on the quality of the image that is received on the receiver side.

Figure 3.1-1**: Effect of changing EbNo**

3.1.1.2. MIMO Model

After making the SISO model, MIMO was implemented on MATLAB. See Figure 1 for reference. The same techniques were used (QPSK, OFDM as modulation, Cognitive technique for spectrum sensing and ML for detection). First a GUI on MATLAB was made which is shown in the Figure 3.1-2. This GUI allows any arrangement of 8 bits (0's and 1's) to be taken as input from the user. After processing those 8 bits the user gets the output of figures which will be shown next to the GUI model. Figure 3.1-2 shows different parts of the MATLAB GUI.

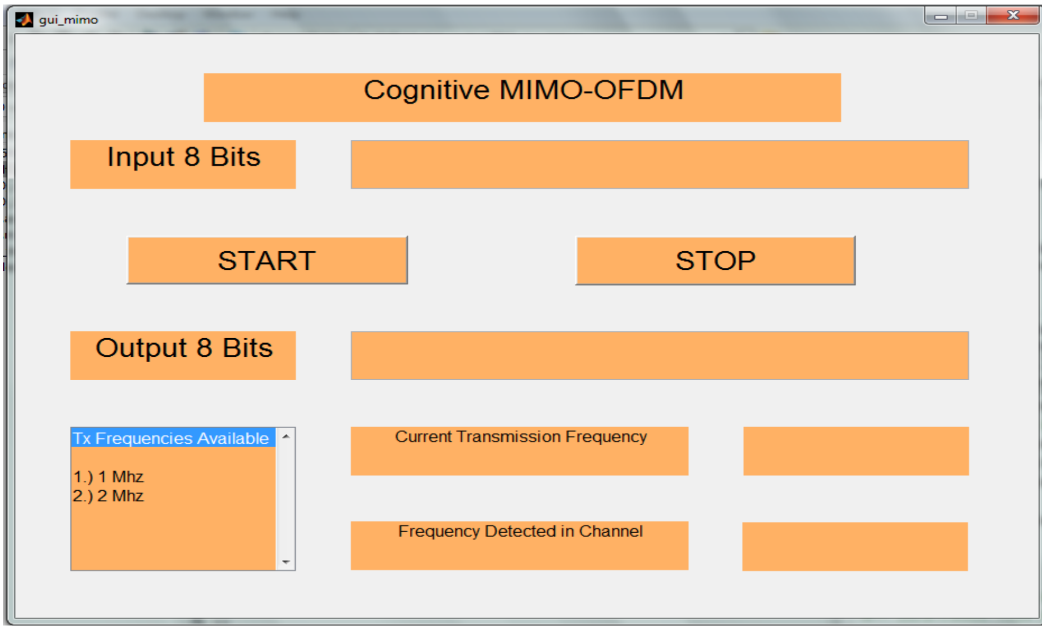

***Figure 3.1-2*: GUI on MATLAB**

The box that shows the current transmission frequency tells the user on which frequency system is operating currently and the frequency detected in channel tells which frequency is not being used. There were two frequencies used during the process – 1 MHz and 2 MHz frequencies. There are three figures shown as the result of the code when the START button is pressed. After the processing the output is shown after the detection. Figure 3.1-3 shows the QPSK and OFDM waveforms transmitted by the transmitter side.

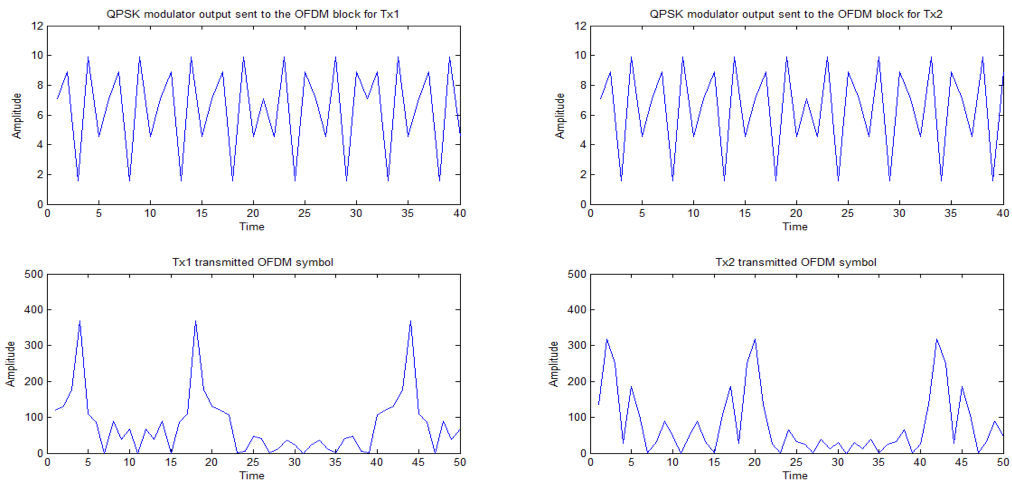

***Figure 3.1-3*: QPSK and OFDM symbols**

Input bits were entered by the user. This graph shows that the QPSK mapping of those input bits for two separate transmitters. Four QPSK modulated bits move to one transmitting channel and the remaining four QPSK modulated bits move to the other transmitting channel. These modulated bits on both channels go through OFDM and become as OFDM symbols shown at the bottom figures of the above snapshot and sent from the two transmitters. As it can be observed that the bits are transmitted as OFDM symbols and not as QPSK modulated waves. These symbols are received at the receiving side. Figure 3.1-4 shows the QPSK and OFDM waveforms received at the receiver side.

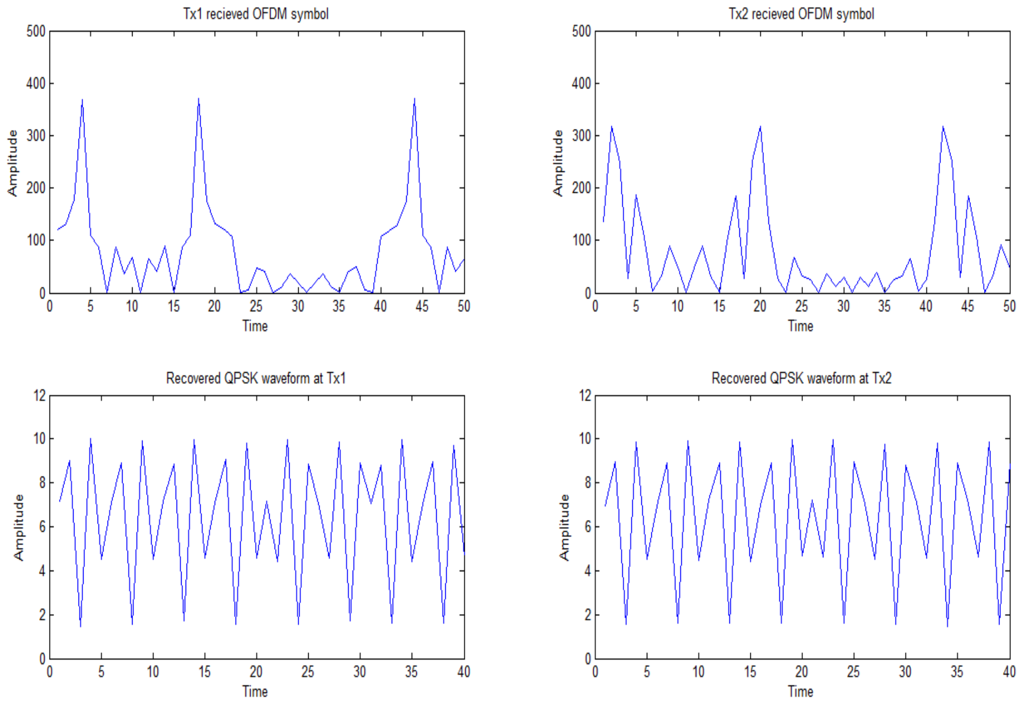

***Figure 3.1-4*: QPSK and OFDM waveforms at the receiving end**

Both channel symbols move to the inverse OFDM phase and the outputs after the inverse process are the QPSK modulated bits on both channels. Each channel having four QPSK modulated bits. Here it can be seen that the QPSK modulated waves are exactly the same as those that were transmitted, the reason is that MATLAB was not implemented on a real channel. It is just a simulation, proving concepts theoretically.

Both four bits streams are joined together and are further sent for ZF detection. After the detection process BER vs. EbNo plot of the transmitted bits was obtained. Figure 3.1-5 shows the input given to the system and the results after complete processing on those bits.

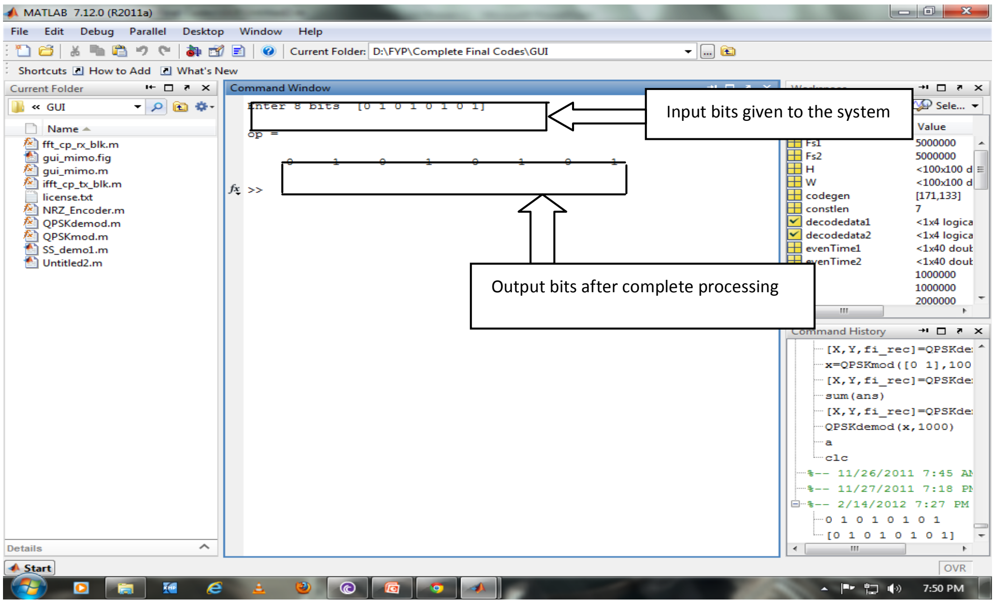

***Figure 3.1-5*: Result after complete processing**

These are the bits that were transmitted and are shown as output. The figure 3.1-6 shows the BER vs EbNo plot for MIMO-OFDM system with ZF detection.

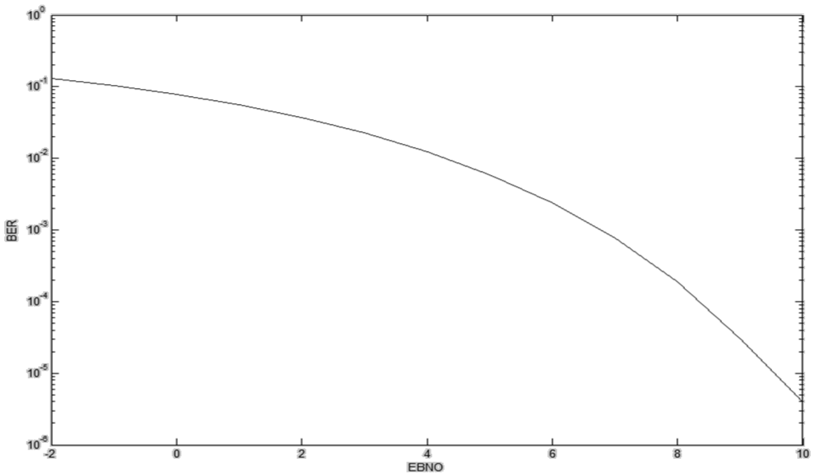

***Figure 3.1-6*: BER vs EbNo for 2x2 MIMO-OFDM with ML detection**

3.1.2. Implementation on GNU RADIO Python

After the MATLAB implementation, the attention was directed towards communication over real channel. In USRP implementation Python was used as the software for interfacing computer with the USRP. First of all a 2x2 MIMO link is established. BPSK mapping scheme and OFDM as modulation techniques were used. ZF VBLAST was used as Detection. Cognitive technique for spectrum sensing was done and video was transmitted over this channel.. The results of each technique will be shown in this section.

3.1.2.1. SISO GMSK Link

First a SISO model was implemented in order to establish a link using GMSK as modulation. See figure 1 for reference. GMSK modulation involves the signal to spread as it is sort of pulse shaping. Signal is transmitted over the air using the USRP front end having one daughter board of 2.4 GHz. The antenna connected on the daughter board sends with a power suitable for reception and detection. When the transmission starts, the terminal shows the frames per second of the video being transmitted. Each frame has 10KB size. Figure 3.1-7 shows the transmission using SISO link and the frames per second for the transmission.

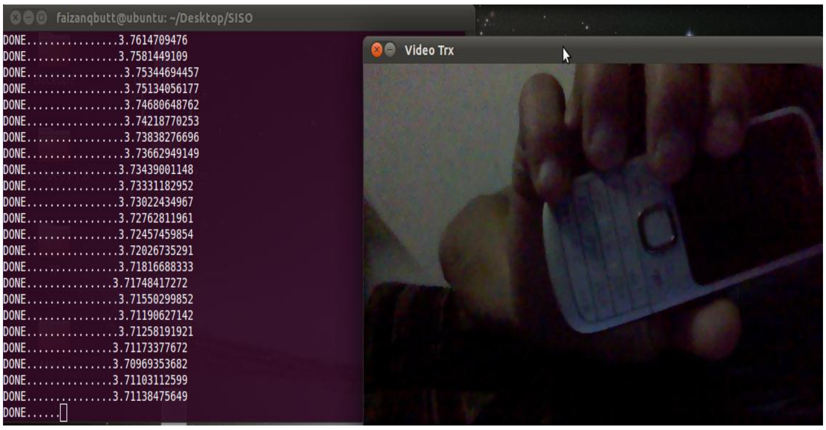

***Figure 3.1-7*: FPS of SISO GMSK link**

Here it can be seen that the video is being transmitted at 3.7 frames per second. 2x2 MIMO's frame rate should theoretically be two times that of the SISO. The reason is that having two transmitter and two receivers the bits are divided and are sent at the same time, that is for example if 8 bits are sent on a SISO link then 16 bits can be sent using 2x2 MIMO link (two links having 8 bits each). Practically the data rate is less than two times. It is an ideal case where there is no loss of packets and no noise. But in a real life link, 2x2 MIMO has 1.8 to 1.9 times the SISO's data rate. Figure 3.1-8 shows the FFT plot of the transmission using this link.

***Figure 3.1-8*: FFT Plot for SISO GMSK link**

3.1.2.2. MIMO GMSK Link

After implementing the SISO GMSK model, MIMO model was implemented. See figure 1 for reference. Here two daughter boards are used, which are 2.4 GHz each, to transmit signals in four channels as described in chapter 2. Signal having the best SNR will be detected and the other received replica is discarded.

Figure 3.1-9 shows the transmission taking place from the system using MIMO link along with the frame per second rate.

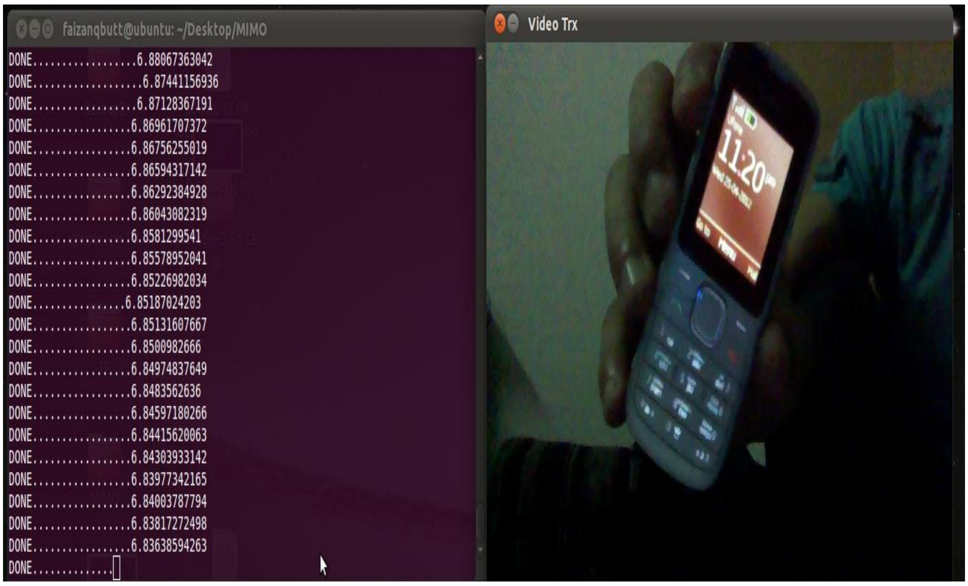

***Figure 3.1-9*: FPS of MIMO GMSK link**

Here it can be seen that the FPS for the 2x2 MIMO system has increased. It is almost 1.83 times more than that of the SISO FPS. Figure 3.1-10 shows the FFT plot for this link.

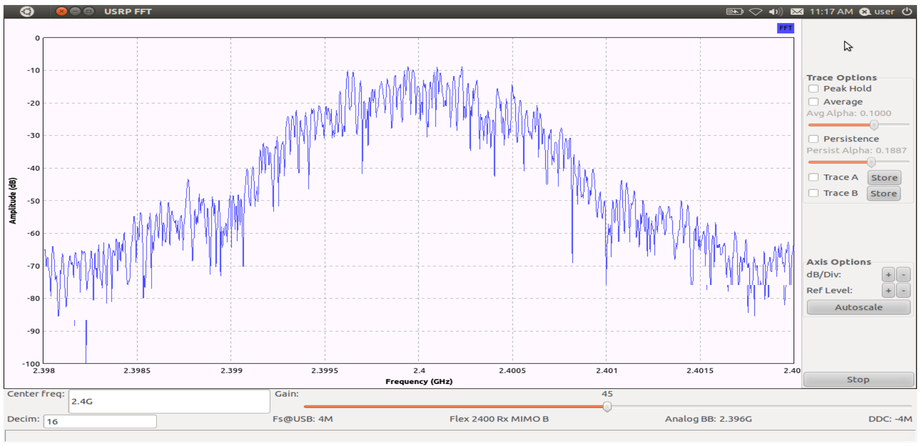

***Figure 3.1-10*: FFT plot MIMO GMSK link**

3.1.2.3. SISO OFDM Link

After making the GMSK links both on SISO and 2x2 MIMO, OFDM part was developed which was the main target, but starting from the SISO link. The results shown were better as compared to the SISO link. It can be seen that the FPS has increased. Figure 3.1-11 shows the transmission using SISO-OFDM link and the frames per second for the transmission.

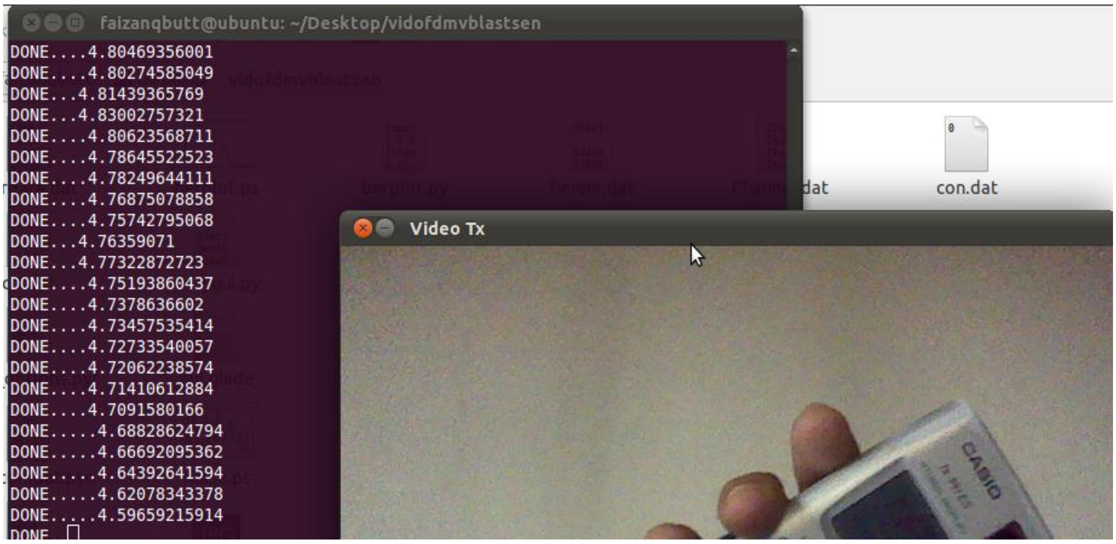

***Figure 3.1-11*: FPS of SISO OFDM link**

FPS has now increased to 4.59. This is a remarkable increase, showing that using OFDM technique you can utilize less bandwidth and hence transmit more as the sub carriers are orthogonally spaced and reduce the ISI. Figure 3.1-12 shows the FFT plot for this link.

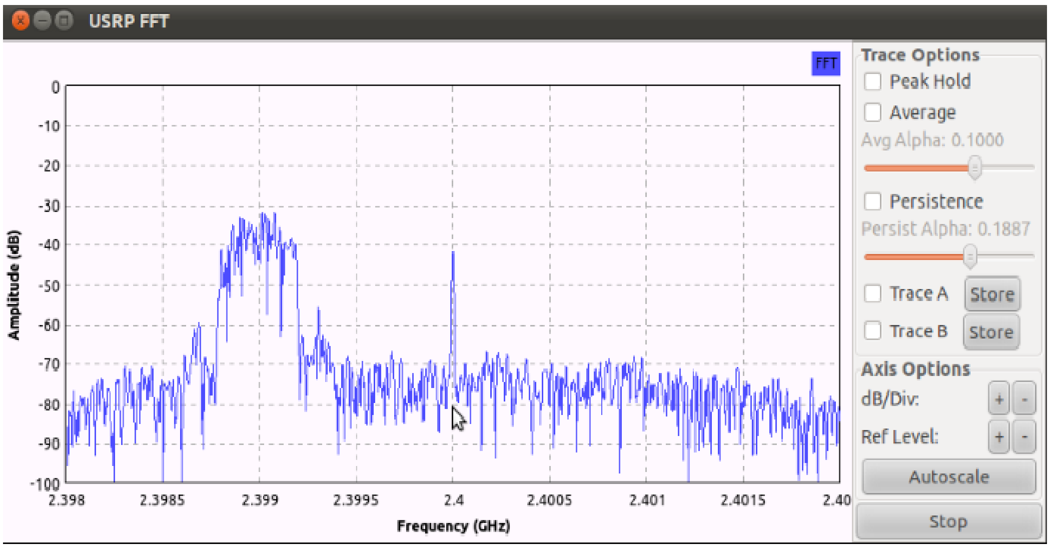

***Figure 3.1-12*: FFT plot for SISO OFDM link**

3.1.2.4. MIMO OFDM Link

The FPS will be increased almost two times than that of SISO OFDM link. The reason is the same as that described in the GMSK case. It can be observed that the transmission rate is now more as compared to SISO link and the bandwidth used is same. Figure 3.1-13 shows the transmission using SISO-OFDM link and the frames per second for the transmission.

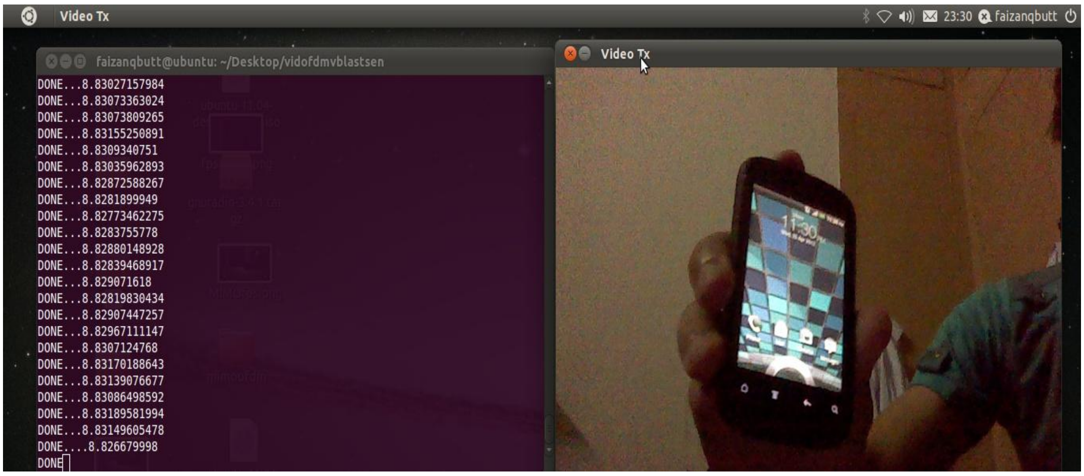

***Figure 3.1-13*: FPS of MIMO OFDM link**

Here you can see that the FPS has also increased more than that of MIMO GMSK and the reason the orthogonality of the carriers that are closely spaced and hence allow more data to go in a little time. This FPS is almost 1.9 times more than that of SISO OFDM link. Figure 3.1-14 shows the FFT plot for this link.

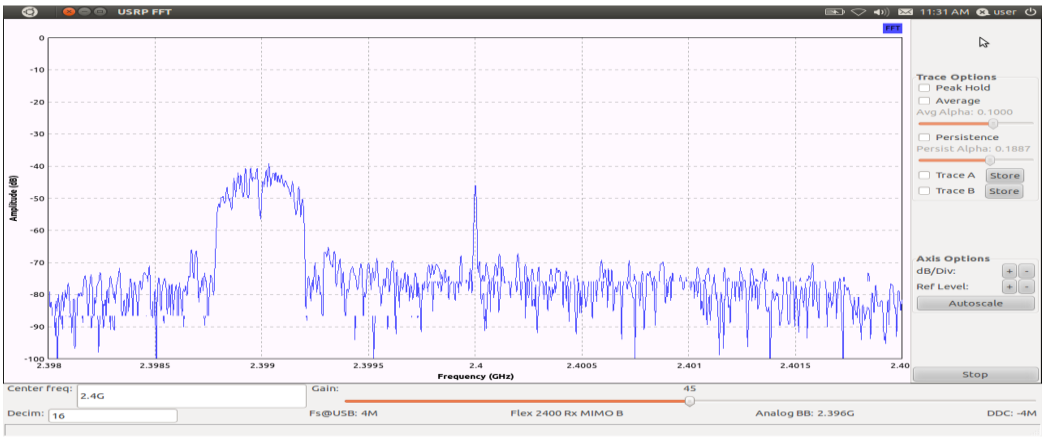

***Figure 3.1-14*: FFT plot for MIMO OFDM link**

3.1.2.5. Cognitive MIMO OFDM Link

When the work regarding MIMO OFDM link was complete, work on cognitive technique was started. Three channels of 2.399 GHz, 2.4 GHz and 2.401 GHz frequencies were used. The cognitive transmitter starts the transmission first by scanning the channels in order to detect the presence of the primary user.

In Figure 3.1-15 it can be seen that all the channels are open, that is, there are no transmissions going on over these channels. The cognitive transmitter chooses any one of the channels and starts transmitting over it. The cognitive receiver synchronizes itself with the cognitive transmitter and starts receiving the packets (of video). Now, there is another scenario in which there is a transmission going on over one of the three channels, that is, there is a primary user using his frequency to transmit. In the next picture, it is shown what is displayed on the terminal when a primary user is detected.

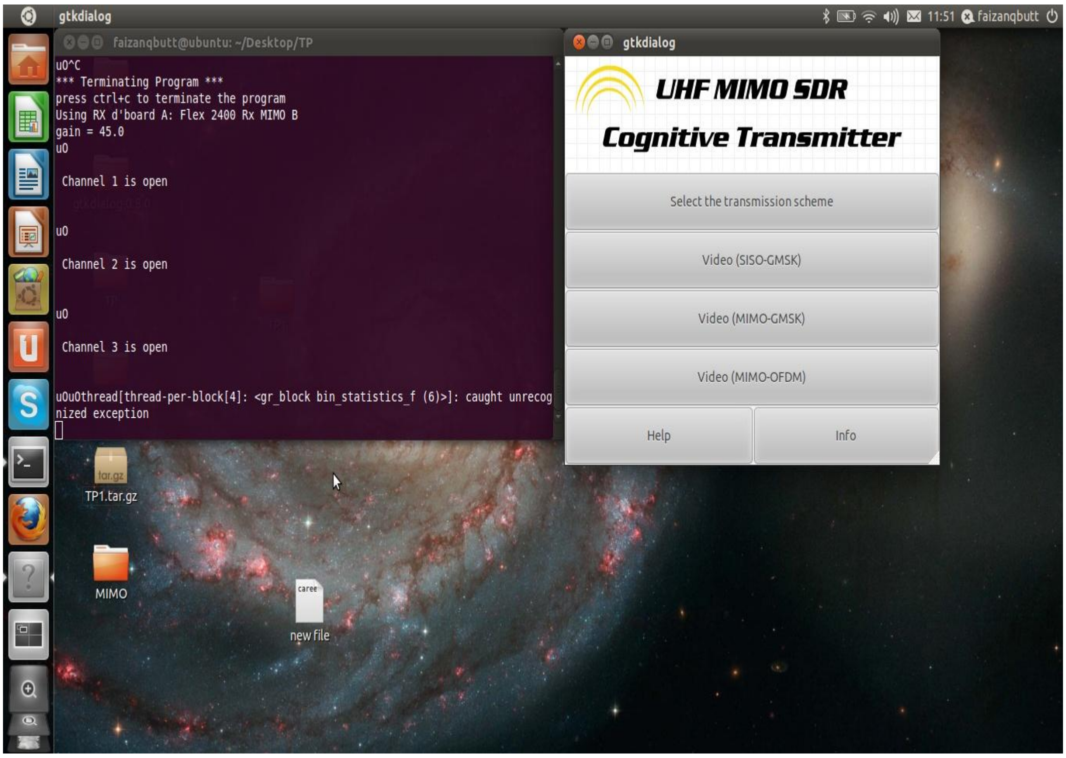

***Figure 3.1-15*: (Cognitive Technique) Three channels are open**

In Figure 3.1-16 it can be seen that when a user starts transmitting over his frequency on channel 1 that is on 2.399 GHz the cognitive transmitter scans the channels and shows that channel 1 is closed and rest of the channels are open and ready to use. Once the free channels are found the secondary user (cognitive transmitter) just chooses one of the free channels and starts transmitting over it. The cognitive receiver synchronizes itself with the cognitive transmitter and starts receiving the packets.

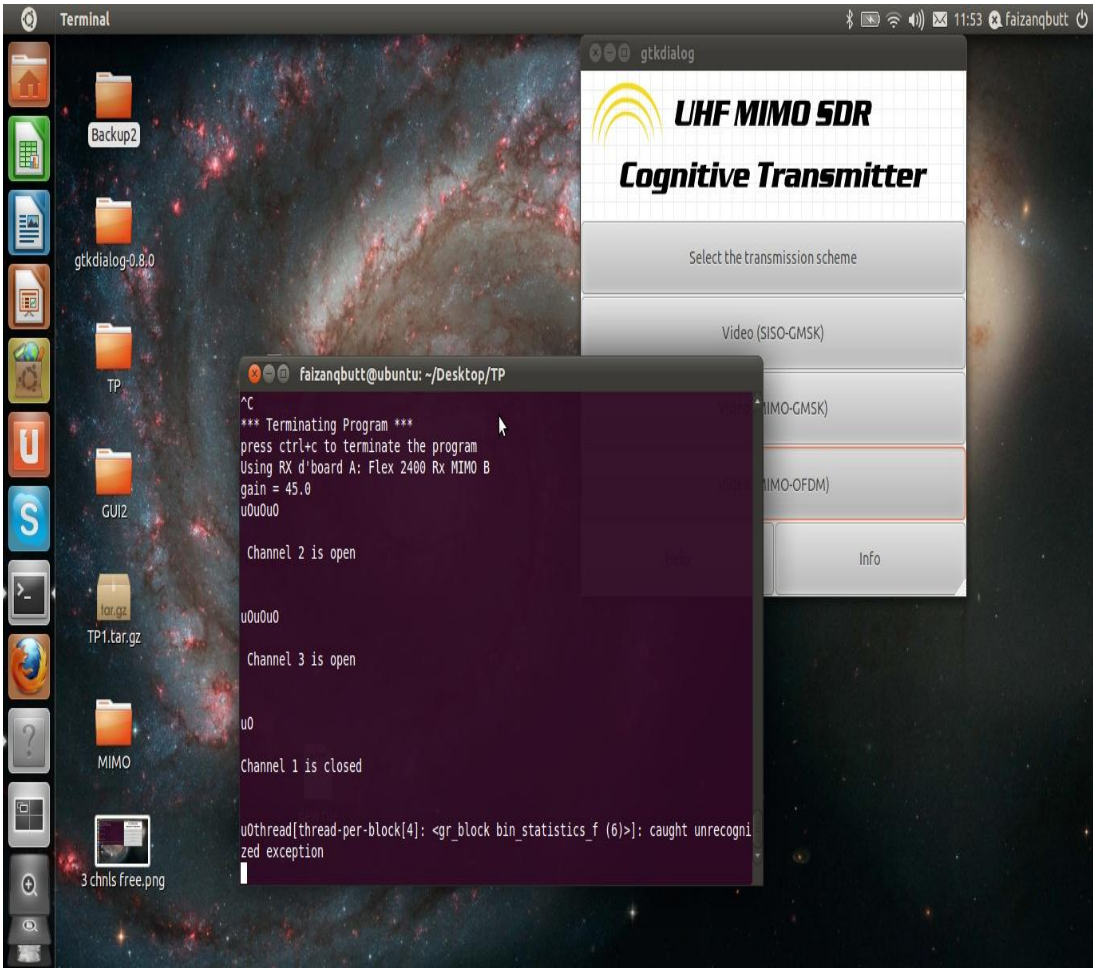

***Figure 3.1-16*: (Cognitive Technique) One channel is closed**

3.1.2.6. ZF VBLAST Detection

ZF VBLAST detection was implemented during the MIMO OFDM implementation. Million bits were transmitted to check the BER. Figure 3.1-17 shows the BER vs SNR performance of the system.

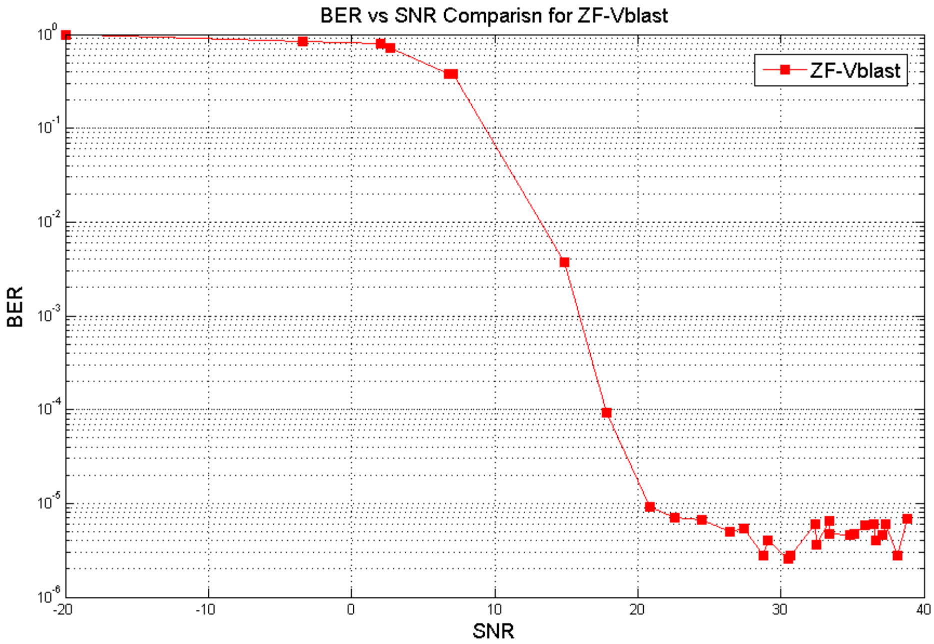

***Figure 3.1-17*: BER vs SNR (ZF-VBLAST Detection)**

This curve is very close to the curve given in the paper "A recursive link adaptation algorithm for MIMO systems" by Srečo Plevel, Tomaž Javornik (Figure 3.1-18(a)).

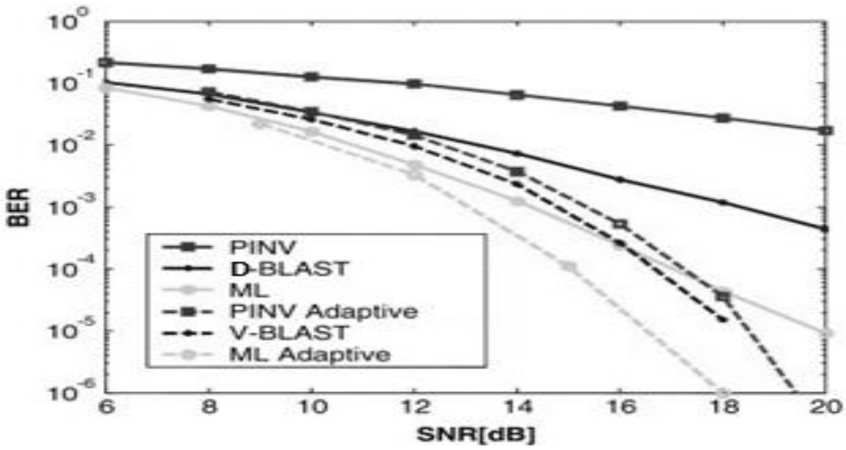

***Figure 3.1-18(a)*: Receiver Operating Characteristic (ROC)**

3.1.2.7. Receiver Operating Characteristics (ROC)

The Receiver Operating Characteristics (ROC) is the major parameter implied while using the cognitive technique. The ROCs shows that condition of the detector in the absence and presence of the primary user. False alarms are those faults in the cognitive transmitter (detector) when, there is no transmission but the cognitive transmitter shows detection or there is transmission going on but the cognitive transmitter does not change the frequency band. Looking at these conditions, a threshold value is set so that the detector detects the transmission efficiently and correctly. Figure 3.1-18(b) shows the receiver operating characteristics for the energy detector.

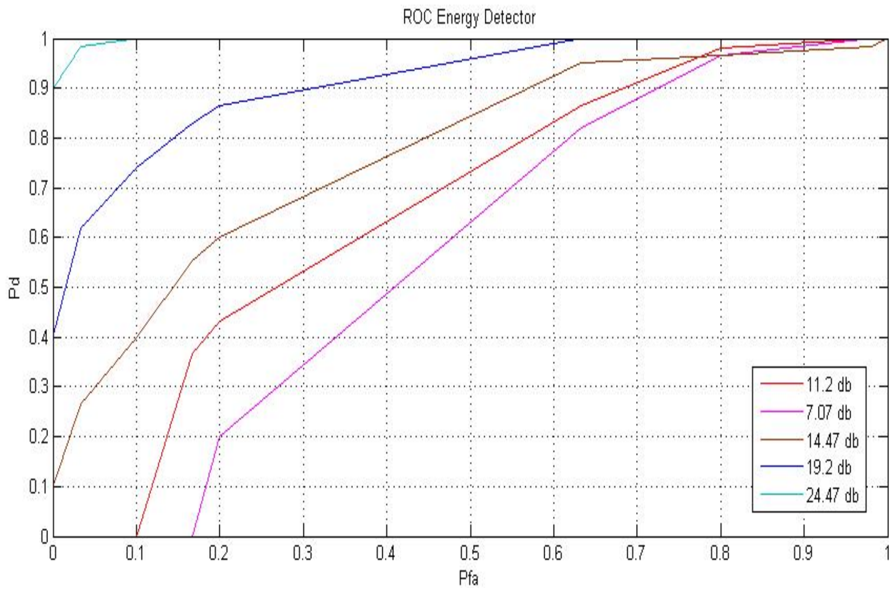

***Figure 3.1-18(b)*: Receiver Operating Characteristic (ROC)**

The graphs show that when the SNR is increased above 24 dB, the cognitive transmitter’s probability of correct detection also increases as well as the probability of false alarms (faulty detections) decreases.

3.2. Analysis

The theoretical phenomenon is usually based on the immense knowledge on the subject and practically they are proved using certain equipments and techniques. Analysis of the test bed developed is carried out on MATLAB and GNU radio platform. Analysis of all the work done was made, practically proving the theoretical observations.

3.2.1. Bandwidth Comparison

Figure 3.2-1 illustrates that by using different techniques, what is the effect on the bandwidth used. It is proved that OFDM uses bandwidth effectively and efficiently. This analysis was made by sending a fixed amount of data rate. Figure 3.2-1 shows the bandwidth used by SISO and MIMO systems.

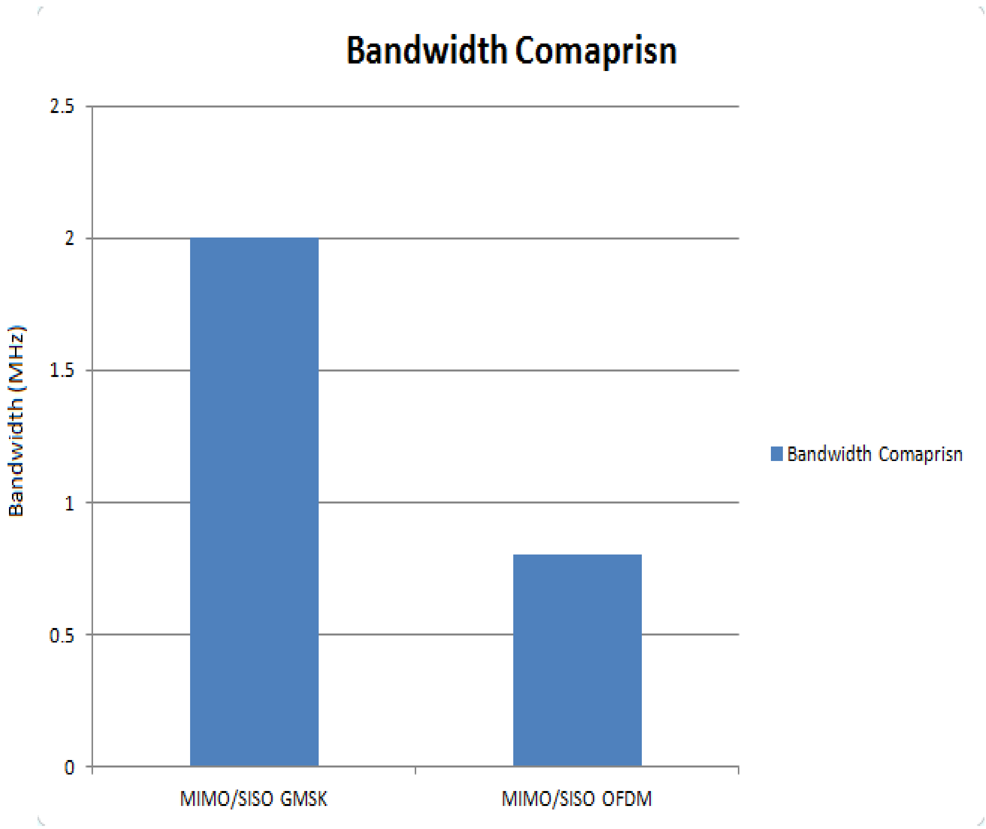

***Figure 3.2-1*: Bandwidth Comparison**

3.2.2. Frames Per Second (FPS) Comparison

The processors are slow for such enhanced computation and processes. The frames per second tend to decrease as the time passes by. This frame per second screenshot was taken at the earlier stages of the project. By the passage of time this FPS has lowered down but the video can yet be seen to prove the concepts. Figure 3.2-2 shows the frames per second comparison for different transmission schemes.

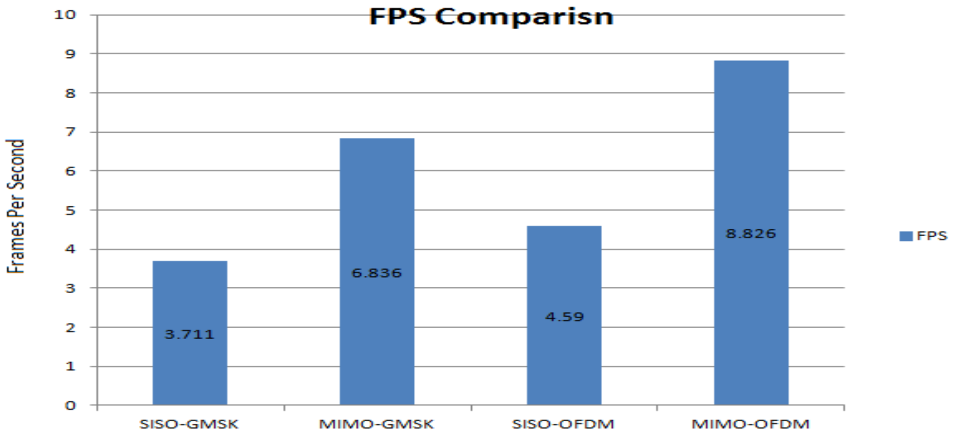

***Figure 3.2-2*: Frames Per Second Comparison using each link**

3.2.3. Data Rate Comparison

By keeping the bandwidth same, the data rates of each link were computed. As each image (frame) had a size of 10 kilo bytes (10 KB), multiplying the frame size by the FPS for each link and by 8 (to convert bytes into bits) bit rate over each link was found. Figure 3.2-3 shows the date rate comparison for different transmission schemes used in the system developed.

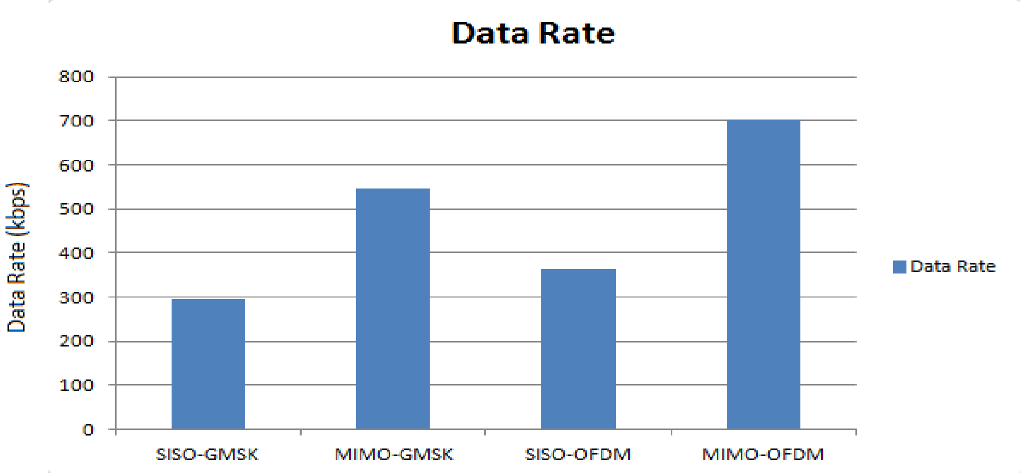

***Figure 3.2-3*: Data Rates of each link**

3.2.4. ZF and ZF VBLAST Comparison

ZF VBLAST detection, theoretically speaking, is a better detection technique than simple ZF. It involves successive cancellation (equalization) in its algorithm which removes the effects of channel and other interferers very efficiently. Million bits were transmitted using both ZF and ZF VBLAST Detections simultaneously and Figure 3.2-4 was obtained. It can be seen that after 25 dB SNR, the BER for ZF is between 10^{-4} and 10^{-5} while that for ZF VBLAST detection it is between 10^{-5} and 10^{-6}. This means using ZF VBLAST detection BER is lowered as compared with ZF Detection. Figure 3.2-4 shows the BER vs SNR curve for ZF-VBLAST detection.

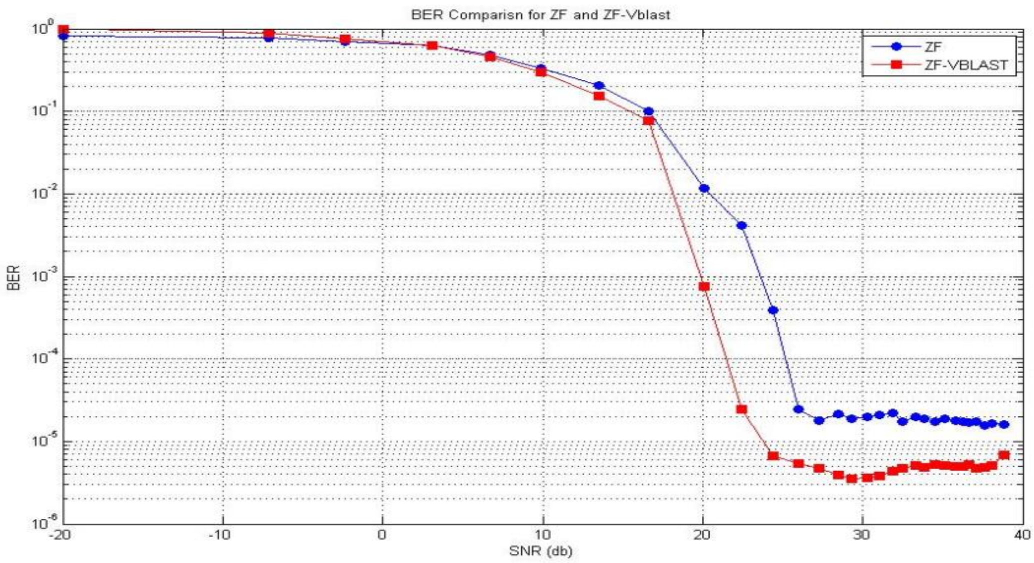

***Figure 3.2-4*: ZF and ZF VBLAST Detection Comparison**

3.3. Summary of this Chapter

In this chapter, results are shown corresponding to all the techniques that were implemented. Firstly, using MATLAB, results of SISO and MIMO models are shown separately. Then results are shown after implementing all the modulation and other techniques on GNU RADIO PYTHON. In the end, Analysis has been done which includes bandwidth, data rate, Frames per second and ZF and ZF V-BLAST detection. Their comparison has been done in order to prove the efficiency of the techniques implemented in the project.

CHAPTER 4

SUMMARY, FUTURE WORK AND CONCLUSION

4.1. Summary

This project was a prototype involving the basics of different upcoming techniques of radio communication. This platform provides a proof of concepts of theory. This project involves the making of a 2x2 MIMO link having two transmit antennas and two receive antennas. The data rate of such a system is increased almost two times than that of a SISO system. MIMO system is also used to remove the multipath fading effects. OFDM (Orthogonal Frequency Division Multiplexing) is used as a modulation technique. MIMO together with OFDM are used in 4G technologies for enhanced data rates as well as ensured bandwidth efficiency. The closely spaced orthogonal sub carriers in this technique allow the bandwidth to be used efficiently and reduce the Inter Symbol Interference (ISI). ZF VBLAST Detection is used. Its algorithm involves successive cancellation process which removes the effects of channel and other interferers.

Cognitive technique is used for spectrum sensing in which the secondary user uses partial or complete frequency band of the primary user. The secondary makes sure that there isn't any sort of interference while carrying out this process. This technique allows the use of bandwidths effectively and reduces its wastage.

4.2. Future Work

The processing speed has become the major problem in this project. Due to the less computational efficiency and more heat the computers suffer from less efficiency as time passes by. The communication can be made better using better processors. The project can be integrated on high speed processing boards as no one can carry laptops for fast communication. The project can be made portable in a user friendly way.Instead of BPSK as mapping scheme, QPSK can be used which sends more bits over the same bandwidth hence increasing the data rate. In this project, QPSK was used but its data rate was so high that the receiving side was not able to reconstruct the image. Using Channel feedback techniques, the channel estimates can be known at transmitter side and thus the knowledge of the channel conditions at the transmitter side is known. The channel with more favorable conditions for transmission can be selected.

4.3. Conclusion

The proposed platform allows a better technique of transmission and reception of data over the link. 2x2 MIMO not only reduces the multipath effects but also increases the data rate. The OFDM modulation with BPSK mapping scheme is a basic step towards better effective transmissions utilizing bandwidth efficiently. Using ZF VBLAST Detection the effect of channel is removed accurately along with other interferers allowing better detection than ZF detection. The cognitive technique implemented, ensures the bandwidth not to be wasted. This technique also disallows interference between the secondary and primary transmissions.

This project is a proof of concepts of different mechanisms when carried out in real time communication. The results from the project highlight that using such or better techniques, communication can be enhanced. Those points are helpful for better transmissions in near future. This prototype, containing the software defined radio involving different techniques, is capable of a good real time terrestrial, mobile and satellite communication which can be made better and better.

4.4. Summary of this Chapter

Chapter 4 highlights the summary of the project. It answers the question of why such techniques have being implemented which results in depicting the advantages of those techniques. What else can be done in the future in order to make the system more efficient performance wise is also discussed. Finally, conclusion is given showing what was learnt in this project and why these techniques must be used to increase the performance of the communication system.

APPENDIX – A

“USRP – UNIVERSAL SOFTWARE RADIO PERIPHERAL”

Universal Software Radio Peripheral (USRP)

The (USRP) is a hardware device that allows the user to create software defined radio using any general purpose computer and a USB 2.0 computer port. Different plug-on daughter boards connected to it allow USRP to operate on different regions in radio frequency bands. Daughter boards operate from DC level (logical zero) to 2.9 GHz. Complete schematics design and diagram of USRP is open source and available to public. A setup of USRP device consists of one main board or mother board and from one to four daughter boards. Figure 4-1 shows typical USRP setup.

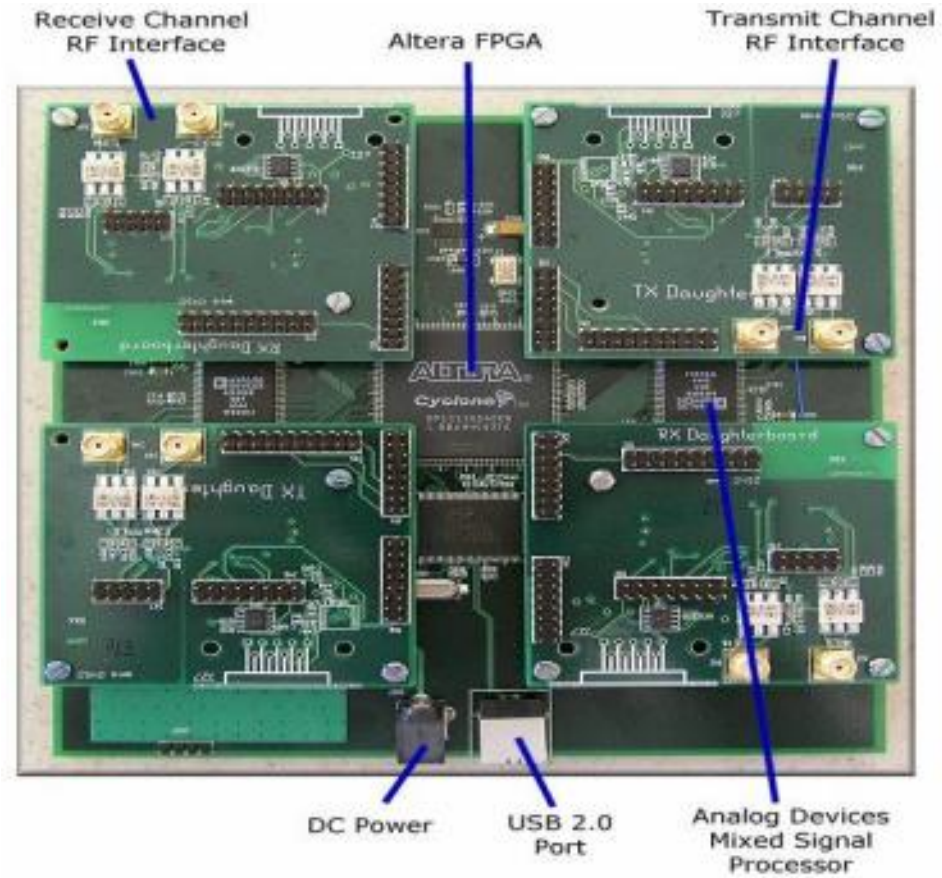

***Figure 4-1*: USRP Board**

USRP device has a main board or mother board having four 12-bit and 64M sample/sec analog to digital converters, four 14-bit, 128M sample/sec digital to analog converters, a FPGA board and also a programmable USB 2.0 port controller.

Each USRP mother board can have up to four daughter boards, two are used for receiving and two are used for transmitting EM waves. RF front end is also implemented on daughter boards. A USRP can transmit and receive at the same time using two antennas in the real time environment. All the sampling block clocks and all local oscillators used are coherent allowing the user to create MIMO (multiple input, multiple output) systems. In USRP, very high sampling rate signal processing is done on the FPGA, where as the lower sampling rate processing functions occurs in general purpose computer. Two digital down converters also known as DDCs mix the signal, filter, and then decimate the incoming signals on the FPGA chip. Two digital up converters also known as DUCs interpolate the baseband signals to the rate 128 MS/s before translating the signal to the output frequency band. DDCs and DUCs with the use of high sampling rates simplify the analog filtering requirements. Daughter boards connected to USRP provide flexibility and also integrated RF front ends. USRP supports two RF full duplex daughter boards.

A/D AND D/A Converters

Four very high speed 12-bit analog to digital converters sample the signal at the rate of 64MS/s. It can digitize a frequency band 32MHz wide. Analog to Digital converters band pass sample the signals of 150MHz bandwidth. Intermediate frequency signal greater than 32MHz can be sampled introducing aliasing. Greater the frequency of sampled signal, then more SNR degrades by the effect of jitter. Recommended upper frequency limit is 100MHz. Full range of Analog to digital converter is 2V peak to peak. Input resistance is 50 ohms matched. Programmable gain amplifier can be used before Analog to Digital converters to amplify incoming signal, and also to utilize full input range of Analog to Digital Converter when the signal is not strong. PGA dynamic range is 20dB. Other sampling rates for the signals can also be used when required. Available sampling rates are always the submultiples of 128 for example 32 etc. In the transmitting path of the signal, there are up to four high speed 14 bit Digital to Analog converters. Digital to Analog clock frequency is set to be 128 MS/s, so by the Nyquist theorem sampling frequency is 64MHz. Staying below the 50MHz bandwidth will make the filtering process easier. Therefore, a useable output frequency range in this case is DC signal to around 50MHz. The Digital to Analog Converter can also supply output voltage of 1V max. PGA that is used after Digital to Analog converter provides 20dB gain to the signal. PGAs that are used on both the RX and the TX paths are fully programmable.

In USRP 4 input and the 4 output channels available make use of real samplings. However, there is more flexibility in the system if a complex or IQ sampling sampler is used. For example, input and the output channels available can be combined to make two complex inputs and also two complex outputs.

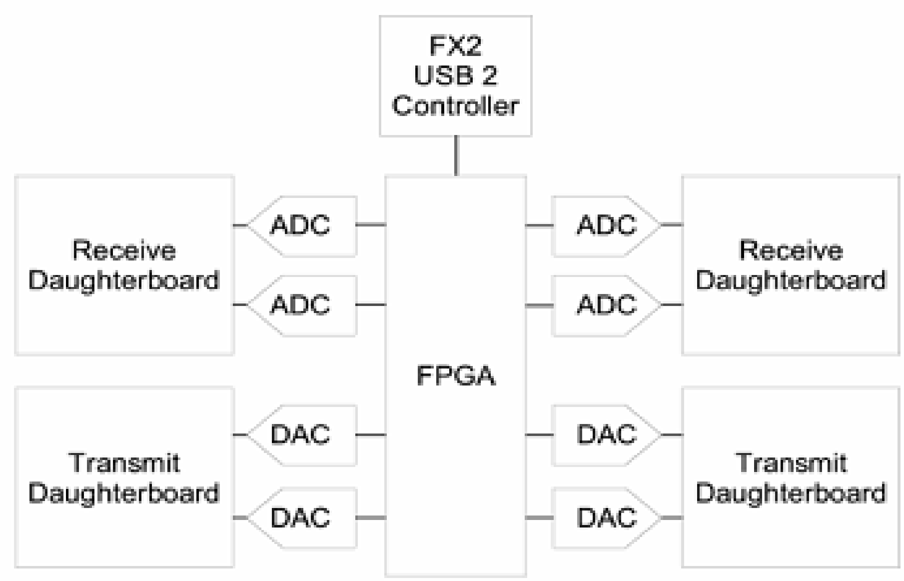

***Figure 4-2*: USRP Block Diagram**

Daughter Boards

Four slots are available on the mother board. They can also be used to plug in two RX daughter boards and the two TX daughter boards. Daughter boards can be used to hold RF receiver interface and also the RF transmitter. There are allocated slots for two TX daughter boards too. Each daughter board's port has the access to two of the available four high speed analog to digital and digital to analog converters. It allows every daughter board that uses the real (not the IQ) sampling to have two independent RF bandwidth sections and also two antennas. If the complex or IQ sampling is used currently then each board can maintain a single RF bandwidth section for the total of two for complete system. There are two SMA Cable connectors on each of the daughter board. Normally those connectors are used for the purpose to connect input or the output signals.

FPGA Features

Understanding the function and operation of the FPGA is the important step for the GNU software users. All analog to digital converters and digital to analog converter are connected at the end to FPGA. FPGA also plays very important role in GNU Radio software system operation. FPGA performs the high bandwidth math operations, and help the users to reduce data rates. FPGA connected to an USB 2.0 port interface chipset known as Cypress FX2. The FPGA internal circuitry and the USB 2.0 Microcontroller port both are programmable over USB 2.0 port bus. Standard FPGA chip configuration also includes DDC that are implemented with the cascaded integrator comb or CIC filters. The CIC filters used are high performance filters that use only adds and the delays. FPGA implements four DDC that allows up to four RX channels. At RX path of the system, there are four analog to digital converters and also four digital down converter. Each of the DDC has at least two inputs that are I and Q. Each of four analog to digital converter can be routed to the I or Q input of any of four digital down converters which also allow the system to have multiple (more than one) channels that can be selected out of the analog to digital sample stream.

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