IMPLEMENTATION OF NARROWBAND AND WIDEBAND WAVEFORM FOR SOFTWARE DEFINED RADIO

By

Sarah ShahidSahibzada

Qurat-ul-Ain

MidhatJavaid

Submitted to the Faculty of Electrical Engineering, Military College of Signals

National University of Sciences and Technology, Rawalpindi in partial fulfillment for

the requirements of a BE in Telecommunication Engineering

JUNE 2012

ABSTRACT

IMPLEMENTATION OF NARROWBAND AND WIDEBAND WAVEFORM FOR SOFTWARE DEFINED RADIO

Software Defined Radio symbolizes a huge shift in the design model for radios. A major portion of the functionality is implemented through programmable signal processing devices, giving the radio the ability to change its operating parameters to accommodate new features and capabilities. SDR provides a framework by which flexible and reconfigurable devices may be developed, making it especially attractive for future multi-mode wireless communication systems.

GNU Radio is a free software package. Using the USRP board in conjunction with a GPP, a RF daughterboard, and the GNU Radio software, we created a software defined radio that can transmit and receive voice and videowirelessly.Python programming language is used to write signal processing graphs which are the functional entities are written in C++ using processor floating point extensions where available.

A Narrowband FM waveform is designed for wireless audio transmission and Wideband OFDM waveform is designed for wireless video transmission between the indigenously designed SDR.

The project is to acquire the existing SDR technology, carry out research to overcome the existing weaknesses, provide a low-cost and ideal and a unique SDR solution for public safety communication, broadband service providers, mobile operators, law enforcing agencies, emergency responders and military.

DEDICATED TO OUR BELOVED FAMILIES

ACKNOWLEDGEMENTS

We would like to take this opportunity to pay our humble gratitude to Almighty Allah(S.W.A.T), the most merciful.

We are extremely thankful to our Project Supervisor Maj Dr. Adnan Rashidiwhosupervised the project in a very encouraging and helpful manner.His keen interest, helpful suggestions, important advice and constant encouragement during the course of the project provided a ray of hope in difficult times. We are really thankful to his valuable contributions in our project work.

We would like to specially thank and express our heartily gratitude to our friends for taking out time and taking interest in our project as well as providing valuable suggestions. We would like to pay all our gratitude to the staff of Research and communication Lab at Military College of Signals for providing us a congenial environment. We are obliged to their support in understanding official procedures. We have found people here very cooperative and fun to work with.

Heartfelt thanks and appreciation must also go to our beloved parents for their financial and moral support throughout the project. We are also grateful to the whole staff of the Department of Electrical Engineering for their support in all forms.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

KEY TO SYMBOLS

RF Radio Frequency

ADC Analog to Digital Converter

DAC Digital to Analog Converter

SDR Software Defined Radio

GPP General Purpose Processor

GNU GNU Not Unix

USRP Universal Software Radio Peripheral

FPGA Field Programmable Gate Array

VHF Very High Frequency

UHF Ultra High Frequency

FM Frequency Modulation

OFDM Orthogonal Frequency Division Multiplexing

QoS Quality Of Service

DSP Digital Signal Processor

SFF Small Form Factor

BSDK Board software development kit

MBDK Model-based development kit

CORBA Common Object Record Broker architecture

SCA Software Communication Architecture

CRC Cyclic redundancy Check

OS operating System

RRS Reconfigurable Radio System

SWIG Simplified Wrapper and Interface Generator

IPC Inter-Process Communication

USB Universal Serial Bus

MIMO Multiple input multiple output

DDC Digital Down Converter

DUC Digital Up Converter

PGA programmable gain amplifier

AD Analog to Digital

DA Digital to Analog

CIC cascaded integrator-comb

COTS commercial-off-the-shelf

MILCOM Military Communications

AES Applications Engineering Service

IDS Integrated Development System

IF Intermediate Frequency

EMIF External Memory Interface

PLB Processor Local Bus

ePMCEnhanced PMC

STRS Space Telecommunication Radio System

NASA National Aeronautics) and Space Administration

JTRS Joint Tactical Radio System

DOD Department of Defense

DAQ digital acquisition

CF Core framework

IDL interface definition language

OSSIE Open Source SCA implementation: Embedded

CD Compact Dick

AM Amplitude Modulation

FM Frequency Modulation

PM Phase Modulation

ASK Amplitude Shift Key

PSK Phase Shift Key

FSK Frequency Shift Key

DSSS Direct sequence spread spectrum

BPSK Binary Phase shift Key

ISI Inter symbol interference

CP Cyclic prefix

SNR Signal to noise Ratio

Chapter: 1

INTRODUCTION

1-1 Problem statement

Wireless communication is progressing at a rapid pace as new standards and protocols surface every day. Rapid adoption of the wire line-base Internet has led to demand for wireless Internet connectivity but with added capabilities, such as integrated services that offer seamless global coverage and user-controlled QoS. The challenge in creating sophisticated wireless Internet connectivity is compounded by the desire for future-proof radios, which keep radio hardware and software from becoming obsolete as new standards, techniques, and technology become available.[1]Two separate features are a must to be supported by radios for the notion of integrated flawlessworldwide coverage: first, all geographic regions having global roaming or seamless coverage; second, interfacing with different systems and standards to provide seamless services at a fixed location. Further, the rate of technology evolution is accelerating, and predicting technological change and its consequences to business and industry is especially troublesome. As a result, to keep their systems up to date, wireless systems manufacturers and service providers must respond to changes as they occur by upgrading equipments to incorporate the latest technological evolution or to debug as they are discovered. In recent years many manufacturers have experienced the embarrassment of releasing hundreds of thousands of defective phones that had to be recalled and discarded. Since redesigning frequently is expensive, does not happen immediately andisinconvenient for end users as well as the industry, interest is increasing in future-proof radios.

1-2 Background

The on handmachinery for voice, video, and data use different packet structures, data types, and signal processing techniques. Incorporated services can be acquired from solo devices proficient in providing multiple services or having a radio that can communicate with devices providing corresponding services. The physical location of the user might dictate the supporting technologies andnetworks that the radio has to use. To successfully communicate with different systems using different air-interfaces, the radio has to communicate and de-code the signals of devices. In addition, to administer changes in networking protocols, services, and environments, devices supporting reconfigurable hardware also need to flawlessly support numerousprotocols.

1-3 Solution

The term software defined radio was coined by Joe Mitola in 1991 to refer to the class of reprogrammable or reconfigurable radios. In other words, the same piece of hardware can perform different functions at different times. The SDR Forum defines the ultimate software radio (USR) as a radio that accepts fully programmable traffic and control information and supports a broad range of frequencies, air-interfaces, and applications software[1]. The user can switch from one air-interface format to another in milliseconds, use the Global Positioning System (GPS) for location, store money using smartcard technology, or watch a local broadcast station or receive a satellite transmission.

The exact definition of a software defined radio is controversial, and no consensus exists about the level of reconfigurability needed to qualify a radio as anSDR. A radio that includes a microprocessor or digital signal processor does not necessarily qualify as anSDR. However, a radio that defines in software its modulation, error correction, and encryption processes, exhibits some control over the RF hardware, and can be reprogrammed is clearly an SDR. A good working definition of SDR is a radio that is substantially defined in software and whose physical layer behavior can be significantly altered through changes to its software. The degree of reconfigurability is largely determined by a complex interaction between a number of common issues in radio design, including systems engineering, antenna form factors, RE electronics, baseband processing, speed and reconfigurability of the hardware, and also power supply management.

The functionality of conventional radio architectures is usually determined primarily by hardware with minimal configurability through software. The hardware consists of the amplifiers, filters, mixers (probably several stages), and oscillators. The software is confined to controlling the interface with the network, stripping the headers and error correction codes from the data packets, and determining where the data packets need to be routed based on the header information. Because the hardware dominates the design, upgrading a conventional radio design essentially means completely abandoning the old design and starting over again. In upgrading a SDR design, the vast majority of the new content is software and the rest is improvements in hardware component design. In short, SDRs represent a paradigm shift from fixed, hardware-intensive radios to multi-band, multimode, software-intensive radios.

In summary, five factors are expected to push wider acceptance of software radio.

1. Multi-functionality—Countless range of services are supported by a Software Defined Radio System.
2. Global Mobility—the need for transparency, i.e., the ability of radios to operate with some, preferably all, of these standards in different geo-graphical regions of the world has fostered the growth of the SDR concept.
3. Compactness and Power efficiency— SDRs are compact and have power efficient designs.
4. Ease to manufacture—It s design requires less parts and thus less time to manufacture as the signal is digitized early at the receiver.
5. Ease to upgrade—the bendystructuraldesignpermitsdevelopment and additional functionalities with no expense of altering the hardware and in less time.

1-4 Objectives

Our research was concentrated on the development of a standalone SDR which can handle voice and video transmission and reception, wirelessly. The project has the following objectives:

i. Carrying out research on the existing software defined radio technology.
ii. Designing and development a standalone SDR platform.
iii. Study digital signal processing techniques and existing SDR frameworks.
iv. Designing and development narrowband and wideband networking waveform for implementation on the SDR platform.
v. Porting of waveforms developed on the indigenous platform to provide a complete audio and video SDR communication system.

1-5 Applications

Software defined radio is an up-and-comingtool for meeting the flexibility requirements of future wireless communication devices. The project will provide an ideal and unique SDR solution for

i. **<u>Military.</u>**Military Applications was the main center of Software Defined Radio research group in the initial years.To allow Military Services to operate with each other flawlessly through wireless video, voice and data communication the JTRS (Joint Tactical Radio Systems) is used. It allow communication through all ranks of authority withstraight contact to near real-time information from in the air and combat zone sensors. [2]

Figure 1-1 Joint Tactical Radio System in Military

JTRS is imagined to work less like a usual radio and more like a computer. It can be upgraded and changed to work with different communication systems without the usual change or redesigning of hardware but opposite to that only software additions have to be done.Thus it is less costly and less time taking process. A number of separate radios can be swapped by a single JTRS radio with severalwaveformspermitting easy maintenance. As everything is in software in JTRS the additional advantage is that is has a longer lifetime due to minimum wear and tear of the hardware during operations.The above two features can proposelikely long-term cost savings to all organizations in military.

ii. **Public Safety Communication.**The Public Safety domain has never been the principal center of SDR industrial dealers. SDR growths were first and foremost based on inside research and expansion activities of terrain mobile radio dealers.Though, over the past few yearsmore than a fewincidents have proven that the public safety community requires the use surfacing SDR and cognitive radio technology to deal withdangerous public safety communications issues. Public safety communicationsrequireinteroperability between different systemswhich has always been difficult to achieve. There have been numerous situations where the operators were unable to communicate due to incompatible radios in state of emergency or natural disaster.[3]

Figure 1-2 Natural disaster

Many sources have complained about the difficulty of applying interoperability in public safety communication systems. A lot of efforts have been made to deploy shared systems, shared channels and gateways but still manytroublesexistdue to which at an incident users may havemismatched radios. The most favorable interoperability answerto this problem would be a something that has the ability to configure itself andmeet up the necessities and the abilitieswanted by public safety responders.

iii. **Cognitive Radio.**The interoperability of SDR itself is a strong reason for pursuing its research and application in public domain but there are many other reasons to drive the development of SDR for Public Domain. SDR is measuredas a technology that will permit the cognitive radio accomplishment. Cognitive Radio is a radio that interacts with the environment in which it operates and changes its parametersand capabilities accordingly. To apply more vigorous, flexible, and dependable public safety systemstheCognitive Radio can be used. It can implement vibrant spectrum reuse, cancellation of interference and other facilities. [4]

iv. **Other applications.**The SDR will be a solution for broadband service providers, mobile operators, law enforcing agencies and emergency responders.

1-6 Methodology

Software Defined Radio changed the world of radio communication devices by separating them into a platform and a waveform. In this nomenclature the platform is defined as the non functional unit of the radio communication, meaning the hardware on the one side but also the underlying firmware, operating system and Application Programming Interfaces (APIs). These platforms are typically architected for flexibility by using a mixture of GPP, DSP and FPGA processing elements to support a family of radio waveforms implemented as heterogeneous multiprocessor software applications. The waveform describes the functional units and configures the platform in a manner to fulfill the underlying radio communication standard. By definition a waveform is a set of transformations applied to information that is transmitted over the air and the corresponding set of transformations to convert received signal back to the information contents.The project focuses both on the platform and the waveform.

Through study of different SDR platforms is the basis of the research. The project includes the selection of a low cost, low power, efficient, high speed, easily available and easily configurable SDR platform and measures to make it a standalone device. In the project to design and develop waveformsSDR Framework is selected to be ported on the SDR platform. The parameters for the waveforms are decided keeping in mind the hardware and waveforms coded.

Chapter:2

SOFTWARE DEFINED RADIOS

2-1 SDR Platforms

Several commercial SDR development platforms are available for SDR waveform/API development. Small Form Factor Development Platform by Lyrtech[5], Universal Software Radio Peripheral Platform by Ettus[6] and SDR-4001 by Flexcom[7] are the mostly in use SDR development platform.

2-1-1 Lyrtech Small Form Factor SDR Development Platform

The SFF SDR development platform is conceived and designed to be used in the development of applications in the field of software-defined radio for military, public safety and commercial applications [5]. The platform is composed of three boards:

i. Digital Processing Module

ii. Data Conversion Module

iii. RF Module

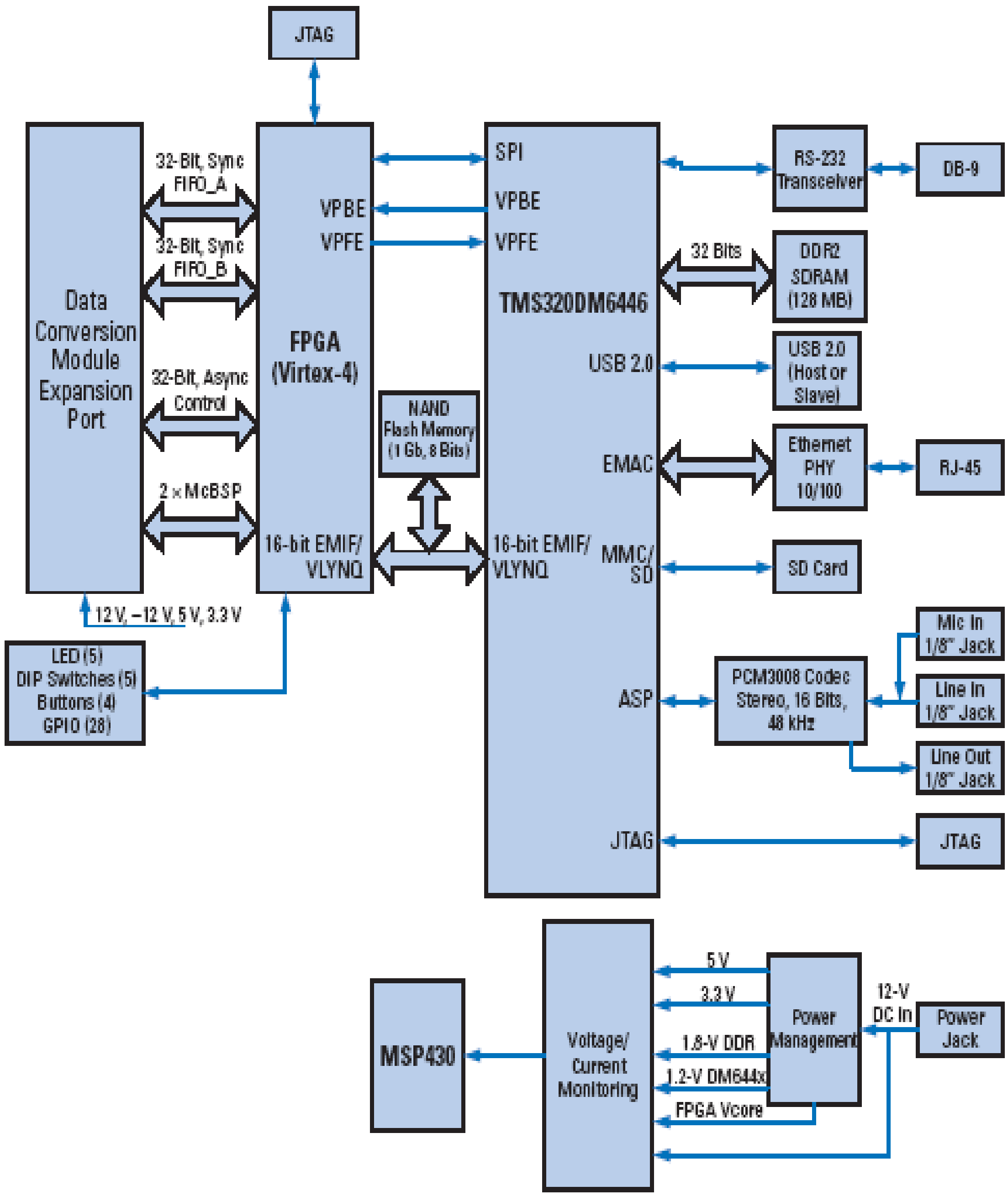


Figure 2-1a Digital Processing Module

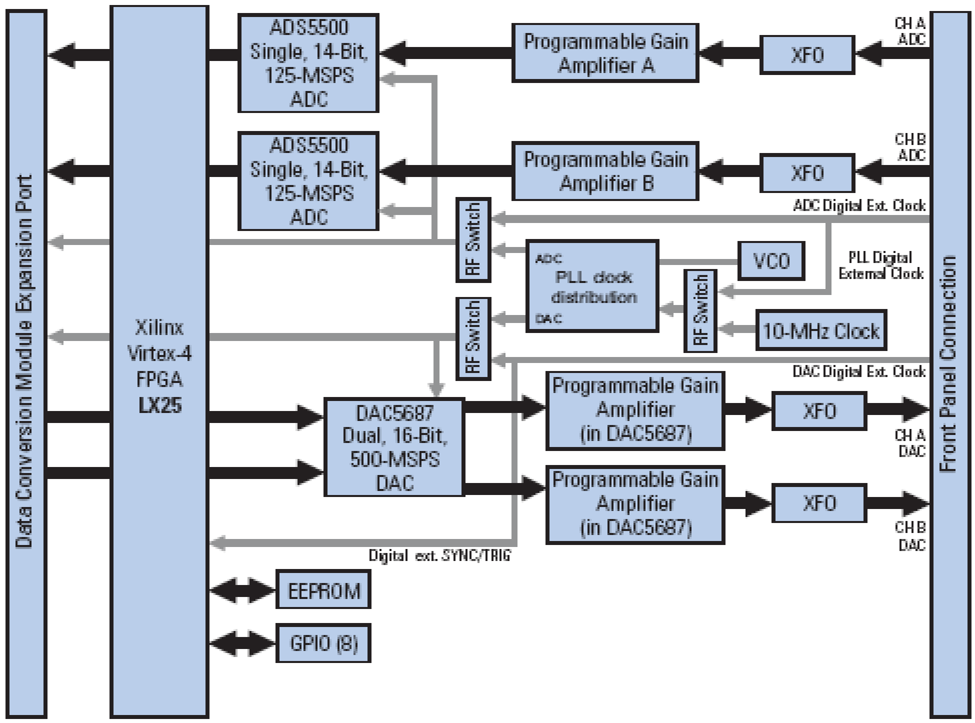


Figure 2-2 Data Conversion Module

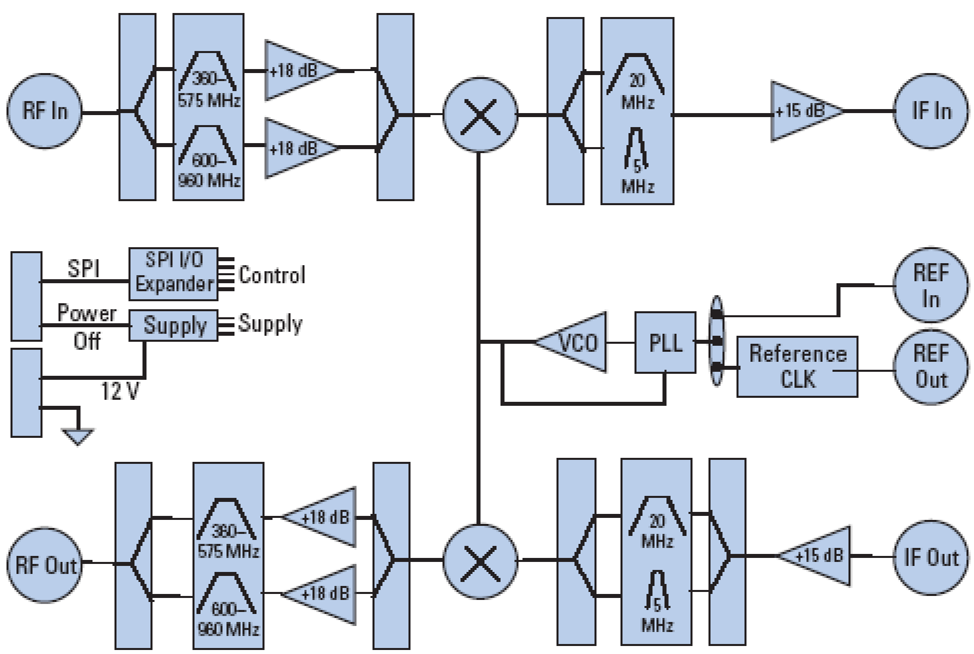


Figure 2-3 an RF Module

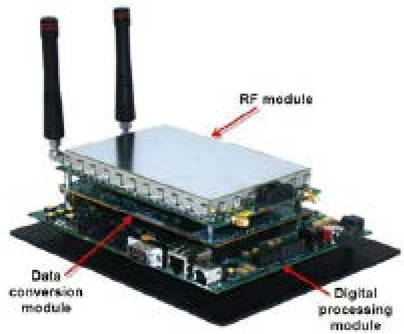


Figure 2-4Lyrtech SFF SDR Platform

The SFF SDR development platform comes with two board software development tools

- Board software development kit :giving users an understanding of all the platform's major interfaces such as the VPSS, audio codec, data conversion module, or RF module. This helps the user to start coding in C, C++, or assembly language code for the DSP and GPP, or HDL code for the FPGA.
- Model-based development kit:allows users to develop applications for the platform with Simulink within MATLAB.

By targeting the DSP and FPGA with MBDK tools, users can arrange and confirm algorithms on the hardware more rapidly. The crucial full-signal chain for multiprotocol SDR is provided by SFF SDRs which are a hybrid of software and hardware. This is uncommon in other commercially available SDR developments platforms. SFF SDRs do not maintain a single, fixed architecture but instead divides it into separate modules of baseband, IF, and RF. This aids the user to broaden their capabilities and optimize costs and power consumption. The architecture of the platform is Common Object Record Broker Architecture enabled and capable to develop Software Communication

Architecture compliant waveforms with the SCARI core SDR framework from CRC and Lyrtech tunable low band RF module.

2-1-2 Universal Software Radio Peripheral Platform

The Universal Software Radio Peripheral hardware platform is designed by Ettusetal.Tobe fully functional USRP requires a host PC or a GPP along with GNU Radio.To implement a software radio, signal processing blocks are offered by GNU Radiowhichis a zero-cost, open-source software development toolkit. [10] A layer-wisepicture of the USRP hardware with the GNU Radio is shown in Figure 2-5.

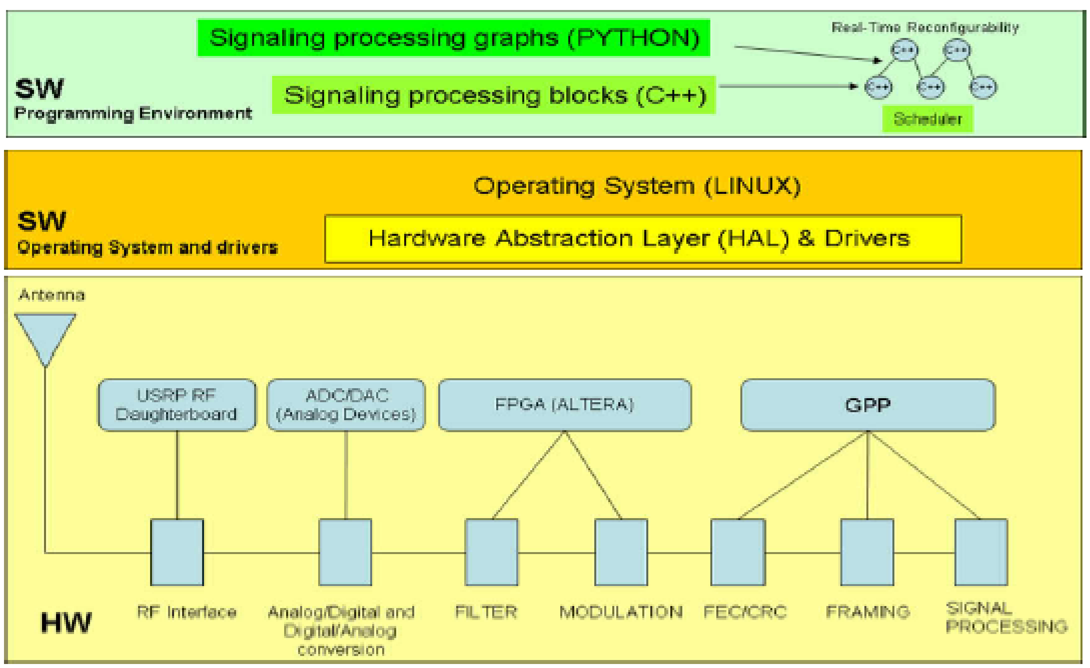


Figure 2-5GNU Radio and USRP Architecture

The programming environment is a combination of signal-processing graph and signal processing blocks making a runtime system. The signal-processing graph uses an interpreted, interactive, object-oriented, extensible programming language Python, describing data flowin the RRS. The C++ is for realizing the functional bodies which are the signal processing blocks .Every block have specific input ports and specific output ports in which the signal processing blocks operate instreams.To wrap the two languages that is Python with C++ the SWIG is used [11]

GNU Radio offersanenormous library which is still growing. This library has entity signal processing routines at the same timewhole signal processing chunks.According to the input output rate of the chunks the real time offers a dynamic buffer allotment and development. The runtime reconfigurability is managed by the buffer developer which also supports signal graph modifications. The combination with the Linux operating system is supplied by the environment which provides support for the services of the operating system for example standard communication between processesor Linux pipeline. The USRP drivers are maintained by the Hardware Abstraction Layer and it manages the Hardware.

The USRP is a cheap, uncomplicated and flexible peripheral, which serves the purpose of transmission and reception separately and simultaneously. A 6VDC of power supply with 3A current is necessary to power it. It is connected to a host PC or general purpose processor through a USB 2.0 interface. A throughput of 32Mbps is the maximum for a USRP.

2-1-2-1 Supported Operating Systems

- Linux
- Mac OS X
- Windows XP, Windows 2000

- FreeBSD, NetBSD

2-1-2-2 USRP Features

USRP includes the following features.

i. Four 64 MS/s 12-bit analog to digital Converters and four 128 MS/s 14-bit digital to analog Converters
ii. Four digital downconverters with programmable decimation rates and two digital upcconverters with programmable interpolation rates
iii. High-speed USB 2.0 interface (480 Mb/s) and capable of processing signals up to 16 MHz wide
iv. One Altera Cyclone EP1C12 FPGA
v. Works with multiple daughterboards
vi. Secondary digital and analog Input and outputholds up complex radio controls such as received signal strength indication and automatic gain control
vii. MIMO system.

The analog to digital conversion and the digital to analog conversion along with the interpolation and decimation of the sample rate is carried out by the mother board.on the other hand the daughterboardsholdpermanent RF front ends. The arrangement of the USRP this way allows great level of flexibility as any daughter board can be linked to the motherboard depending on the radio frequency spectrum necessary and the type of communication. [11]

Independently USRP cannot be an SDR, its digital signal processing takes place on a separate device to which it is connected through aUSB.This setup of the USRP linked through a USB to another device is shown in Figure 2-6. The host device can be any device having at least oneUSB 2.0 connection, and should include components like General Purpose Processors, Digital Signal Processors, Field Programmable Gate Arrays, Application Specific Integrated Circuits, etc. But the host device is usually a personal computer with a General Purpose Processor.

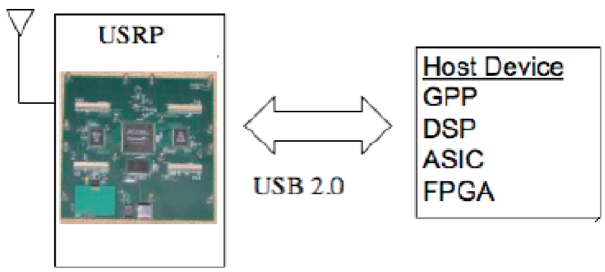


Figure 2-6USRP and a Host Device

The USRP has a complete open source design.USRP's design is completely open to the public (including the FPGA source code). A typical setup of the USRP board consisting of one mother board and up to four daughter boards is shown in Figure2-6.

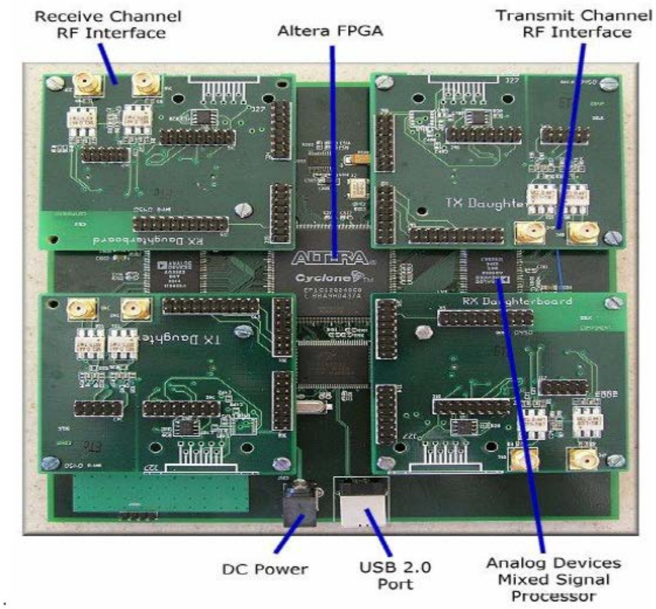


Figure 2-7USRP Motherboard and Four Daughter Boards

2-1-2-3 Motherboard

The USRP contains many different components, but the central hardware piece is the motherboard, containing upto

- four 12-bit, 64M sample/sec ADCs,
- four 14-bit, 128M sample/sec DACs,
- Two digital up converters
- Four digital down converters
- a million gate,
- Field Programmable Gate Array
- a programmable USB 2.0 controller.

Figure shows a block diagram of the current architecture of the USRP motherboard.

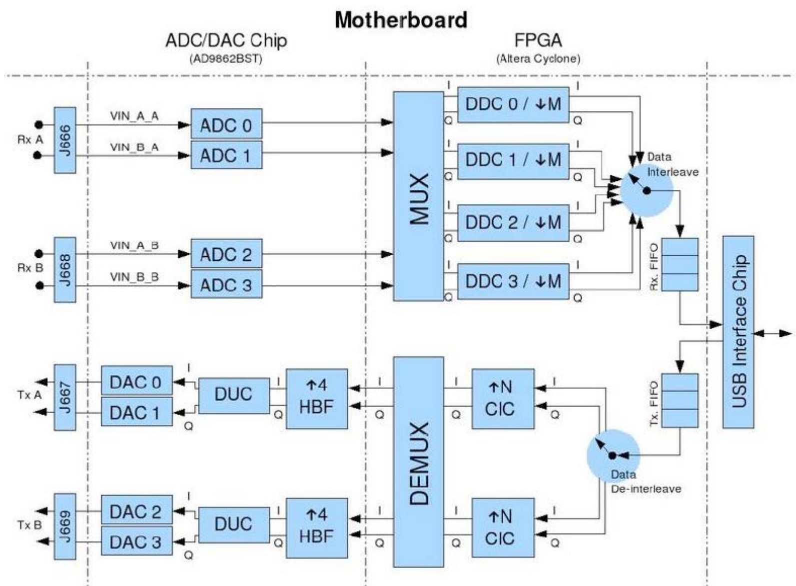


Figure 2-8USRP Motherboard Block Diagram

Each USRP motherboard can handle up to four daughter boards. Generally out of these two daughter boards are used for transmission and the other two for reception. These daughter boards are where the flexible, fully integrated RF front-ends are implemented. The motherboard accommodates for a large bandwidth (limited by the bandwidth of the A/D converters) to support many different modular RF front-ends. A USRP can act as a transceiver in real time by using two antennas simultaneously. The MIMO system is created in USRP by the coherent sampling clocks and at the same time the consistent local oscillators. [12]

2-1-2-4 Analog to Digital and Digital to Analog Converters

The 4 high-speed 12-bit AD converters as shown in Figure

- has a sampling rate of 64MSps
- works on a digitalized 32MHz band

- maximum of 150MHz of bandpass-sampling of signalsisachievable
- introduce aliasing in intermediate frequency higher than 32MHz
- has full range of $2V_{p-p}$
- has input of40mW or 16dBm which is50ohms
- has recommended upper limit of 100MHz
- has a PGA before it with range up to 20dB

At the transmitting path there are fast 14 bit digital to analog converters. The digital to analog converters

- has 128 M samples per seconds as the frequency of its clock
- has 64MHzis the frequency for Nyquist criteria
- has output frequency range is DC to about 50MHz
- can supply an output of 1V peak to a 50 ohm differential load, or 10mW (10dBm)
- PGA used after the DAC, providing up to 20dB gain.

The PGAs on both RX and TX paths are programmable.

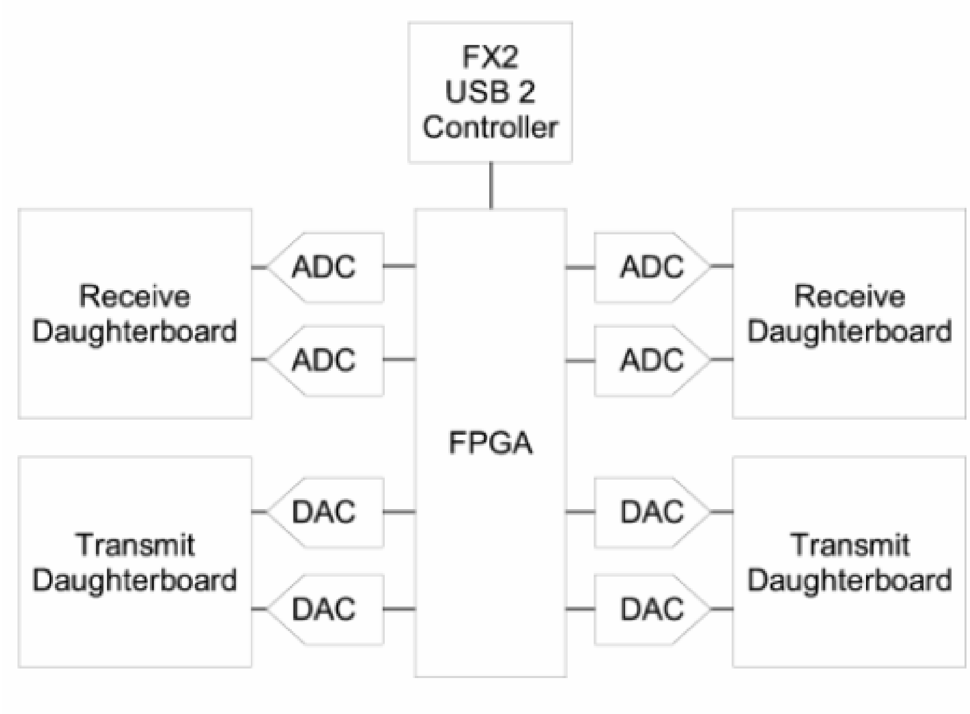


Figure 2-9USRP Block Diagram

2-1-2-5 Daughter Boards

The motherboard has four slots to fix a maximum of two receive daughter cards and two transmit daughter cards. The holes where the receive daughter cards are connected aremarkedasRXA and RXB, and those for transmit daughter boards are labeled TXA and TXB. These slots give the daughter board access to two of the four AD/DA converters (DAC outputs for TX, ADC inputs for RX) which in return allows each daughter board to have two RF sections thus two antennas are placed on each. The variety of daughter cards that are accessible are:

i. Basic cards. The signal generator also known as the external turners are connected using 2 Sub Multi Assembly connectors. These do not affect the signal and act as the point of entry or leaving. But it is in the need of a radio frequency front end that is outside.

ii. DBSRX cards. These cards have a 800Mega Hz – 2.4Gega Hz of frequency range and can only be used for reception.

iii. Transceiver cards.There is a wide variety of such cards.

Named as RFX2400, RFX1200,RFX400, RFX1800, RFX900

There frequency ranges are 2.3 to 2.9 GHz,1150 MHz to 1450 MHz, 400 to 500 MHz,1.5 to 2.1 GHz and 800 to 1000MHz respectively.

They are allTransceiver with output power of 20mW and above, 200mW and above, 100mW and above, 100mW and above, and 200mW and above respectively.[12]

2-1-2-6 FPGA Features

The FPGA (Altera Cyclone II), in the USRP performs the entire large sampling rate processing, reducing the data rate to such a level that is small enoughto be conveyed across the interface of the 2.0 USB.TheField Programmable Gate Arrayhas cascaded integrator-comb filters and an amalgamation of the convertors that perform digital down conversion.

At the receiver side there are4 ADCs and 4 DDCs and at the transmit side there are DUCs in the AD9862 CODEC chips not on the FPGA. The FPGA only does interpolation on the transmit path. It is a must that all transmit channels are at same rate and same goes for the receive channels. The MUX determines the connections of ADC to each DDC input.

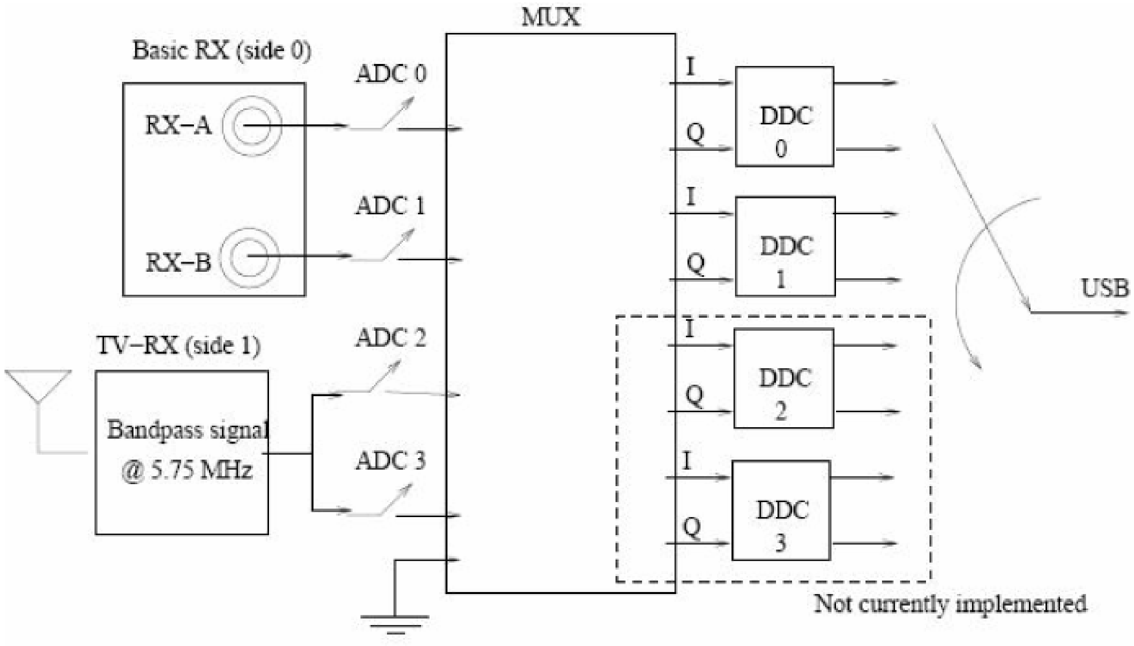


Figure 2-10Showing reception and transmission on USRP with MUX

It is the DDC that converts a signal from IF band to baseband. It also decimates the signal to be transferable over the USB 2.0. Figure 2-11 shows the block diagram of the DDC.

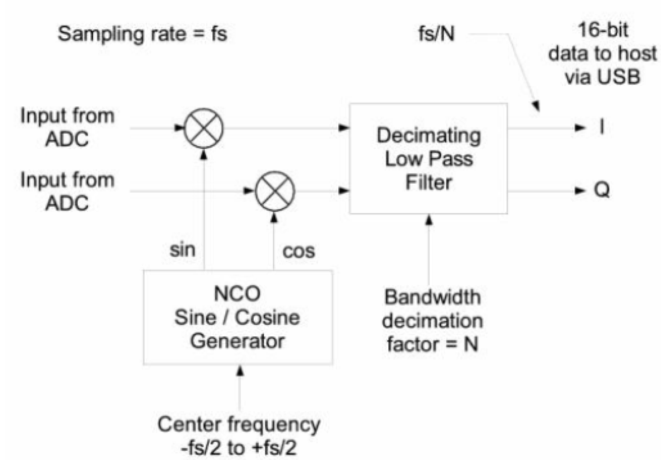


Figure 2-11 DDC Block Diagram

The intermediate frequency signal which is the input signal is multiplied with an exponential constant frequency signal to perform digital down conversion which yields a signal centered at 0 and also complex. The decimation factor of N is then used on the signal.

The down sampler is preceded by theLPF of the system which is the decimator. Stated previously the decimation factor is N thus LPF (decimator) picks a band of [-p/N, p/N] reducing the bandwidth by N. The down-sampler that follows LPF shifts the band to [-p, p]. The maximum throughput of 32MBps can be handled by the USB 2.0 bus. But usually 8 mega complex samples per second pass through the USB bus with 16complex I bits and 16 complex Q bits. Thus according to the Nyquist criteria the bandwidth of the system can be up to 8MHz. The operational bandwidth of the system can be changed by changing the factor N. But N should always be in the range of 1 till 256.

Generally FM operates at 200KHz.If N is set to 250 then 64MHz / 250 = 256kHz will be the rate with which data will flow across the USB bus. This will prevent loss of information.[13]

In the Host PC the processing starts as the signal come into it by the USB. This signal is complex and all these steps are carried out in the reverse at the transmit path.

2-1-3 SDR-4000 Platform

Tactical Military Communications systemsuse the SDR-4000 product family for their wireless radio frequency solutions by using the hardware and software available in the market.The SDR-4000is both compact and can withstand intensive external conditions this is because it is 3U in size and has PCI specifications. At the same time it has a widerange for tolerating temperatures, has conduction cooling and is shock proof with vibration resistance. It makes it ideal for military applications.[7]

ThePRO-4600 SDR and theXMC-3321 are the two major products of SDR-4000 series. As SDR-4000 provides modem solutions these two products provides 2channels/slot wireless modems. To fulfill the needs of military applications these two products have been designed by such methods that allows the platforms to be efficiently resized and its weight reduced. Its cost and maximum power utilization can be altered thanks to its flexible design.

The SDR-4000 product portfolio consists of a series of 3U cPCI-based carriers and XMC modules, software, development systems, Applications Engineering Service, Training and Technical Support Services including:

i. PRO-4600: A 3U cPCI SDR processing engine supporting a Xilinx Virtex-4 User FPGA, TI TMS320C6416T DSP, and Freescale MPC8541E General Purpose Processor integrated through a high-speed communications fabric.
ii. XMC-3321: A dual transceiver XMC module that supports IF-to-digital conversion via two 14-bit A/D converters sampling at up to 105 MSPS and digital-to-IF conversion via two 14-bit D/A converters up to 300 MSPS. The XMC-3321 supports an on-board Xilinx Virtex-4 User FPGA for wideband processing.
iii. SDR-4001 Integrated Development System: An air-cooled system integrating the PRO-4600 and the XMC-3321 in a single chassis. A development PC hosts the quicComm software and all of the tools necessary to quickly commence development on the SDR-4000 platform.

iv. SCA and ORB: For systems requiring Software Communication Architecture compliance, an operational SCA Core SDR Framework and associated toolkit preloaded on the SDR-4000 is available as a product option.

The link layer and the network layer are the two layers of the software defined radio which functions on SDR-4000 Tactical MILCOM modem. It has two cards that are PRO-4600 and XMC-3321 of which one is an SDR processing engine and the other is a dual transceiver XMC module.These two cards have been engineered for Military communication in which they support the development of difficult waveforms. Tactical MILCOM network which require synchronization use waveforms on these platforms, due to its ability to handle data. The block diagram of the two cards and how these interact is shown in Figure 2-12.

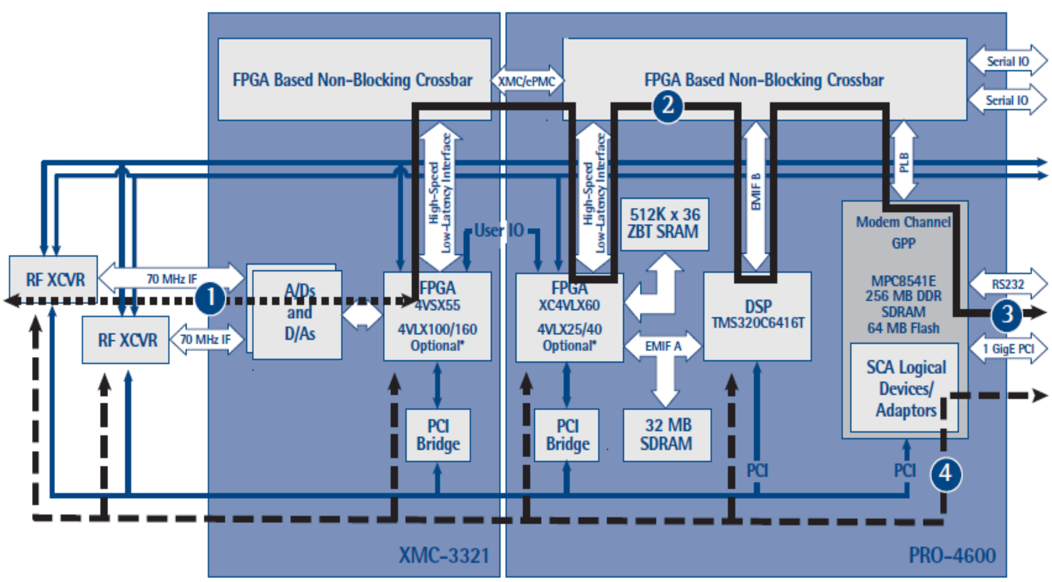


Figure 2-12[14]

2-1-3-1 PRO-4600 Hardware Module

The PRO-4600 is a 3U cPCI heterogeneous processing engine, employing a combination of Xilinx Virtex-4 FPGA, TMS320C6416T DSP and MPC8541E GPP to support the black-side processing requirements of size, weight and power-limited SDR applications. The PRO-4600 is equipped with a single-width XMC site, capable of hosting parallel RapidIO (XMC) modules as well as Spectrum's Enhanced PMCmodules or industry-standard PMC modules. See the PRO-4600 datasheet for further details.

2-1-3-2-XMC-3321 Hardware Module

The XMC-3321 is a dual channel transceiver module optimized to operate with the PRO-4600 for Tactical MILCOM applications or as a "stand-alone" XMC module on other industry standard XMC-compliant cards. The XMC-3321 is also capable of operating on Spectrum's ePMC carrier cards using Spectrum's Solano high-speed communications technology. The XMC-3321 supports industry standard 10.7, 21.4 and 70 MHz IF frequencies through the use of dual 14-bit A/D converters sampling at up to 105 MSPS and dual 14-bit D/A converters sampling at up to 300 MSPS in a single-width XMC form factor. The module also features a single user-programmable Xilinx Virtex-4 FPGA device for wide bandwidth signal processing and filtering in the digital domain.

2-2 SDR Frameworks

SDR Frameworks run on embedded systems to make a complete SDR. In the coming years the requirement of these SDRs will increase in wireless industry. The SDR Frameworks are acting as a catalyst in the development of SDRs. By porting SDR Frameworks on embedded platforms users can check the increased overhead, latency etcof the system which aids in removing their concerns about the system and attracts them. There are various published frameworks for implementing SDR functionality. Examples include Space Telecommunication Radio System of National Aeronautics and Space Administration, GNU RADIO of open source community and Software Communication Architecture developed under Joint Tactical Radio System program of US Department of Defense.

2-2-1 STRS

NASA developed a special STRS, SDR architecture which is suitable for NASA's missions which are subject to the constraints of space environment, like space craft power, mass constraints etc. STRS architecture does two main things, firstly it splits the application waveforms from operating environment and secondly it makes the hardware platform and operating environment two unique entities. As application specific integrated circuits are the base of legacy radios, STRS design anticipates architecture development for each generation of radios. Although due to progress in hardware technology the functionality of radios has shifted and will ultimately shift completely to firmware and software-based processors like field programmable gate arrays, digital signal processors and general purpose processors. STRS

- Defines modular architecture.
- Provides abstraction by identifying interfaces.
- Focuses on component reuse and portability.
- Defines similar waveform as reusable and portable software application that is independent of the operating system, middleware, and hardware.

- Puts strict constrains on required resources e.g. power, mass etc.

2-2-2 GNU Radio

GNU Radio is afree and open source SDR framework or a software toolkit for building software defined radios and is an official GNU project. It is a framework that offers a library of signal processing blocks and a glue to tie them all together for realizing software defined radios with a low-cost external RF hardware. As low cost external RF hardware is used by GNU Radio, real time radio systems are put into operation on it. The RF hardware causes it to be used for wireless communication projects. GNU Radio also supports the development of signal processing algorithms using generated data, which eliminates the need for actual RF hardware. Python programming language is used to write signal processing graphs but the signal processing blocks which are the functional entities are written in C++ using processor floating point extensions where available. GNU Radio allows the user to apply real-time, high-throughput radio systems in simple and quick growth environments. Universal Software Radio Peripheralis also crafted by GNU Radio which is an SDR platform when connected to a GPP processor through a USB. It contains four 64 mega sample-per-second 12 bit analog to digital converters, four 128 MS/s 14 bit digital to analog converters. The USRP is capable of processing signals up to 32 MHz and several transmitter and receiver daughter boards are available which covers various bands between 0 and 5.9 GHz.GNU Software Radio is an open source SDR framework option but it targets primarily to desktop environments.

2-2-3 Software Common Architecture

It is an open architecture framework that tells designers how elements of hardware and software are to operate in harmony within a software defined radio. SCA governs the structure and operation of the U.S. military's Joint Tactical Radio System (JTRS), enabling programmable radios to load waveforms, run applications, and be networked into an integrated system.[9] A Core Framework, providing a standard operating environment, must be implemented on every hardware set. Interoperability among radio sets is enhanced because the same waveform software can be easily ported to all radio sets.The SDRs generated by JTRS are flexible and modular enabling secure wireless communication and networking services for mobile and fixed forces. These SDRs act as nodes of a network. SCA has many features which makes it particularly useful in commercial and military applications as the same time in non-military designs. SCA has been developed to aid in the expansion of software defined radios while encompassing the benefits of present evolution of machinery and minimizing the enlargement and consumption costs. Key goals of SCA are to

- Provide portability of applications software between different SCA implementations.
- Leverage commercial standards to reduce development cost.
- Reduce software development cost by reusing design modules.
- Build on evolving commercial frameworks and architectures.

SCA is not hardware specific. It is only a set of rule providing limitation to the design of the system. SCA defines a software infrastructure for the management, control, and configuration of a software defined radio and doesn't specify any architecture, design or the radio system hardware. Different areas of SCA specifications are defined subsequently.

The SCA software architecture is defined by dividing it into several parts

- Operational environment
- Applications
- General software rules

2-2-3-1 SCA Operating Environment

The application and the hardware platform are separated in the SCA operating environment. OE offersordinarymeans to set up applications on platforms with varying hardware devices and describes interfaces to administer and organize applications and their components. OE specifies rules, constraints, and procedures that must be stick on to in order to design an SCA-compliant SDR. OE comprises of four layers which provides distinct levels of abstraction

- Operating system
- Middleware
- Core framework
- Services

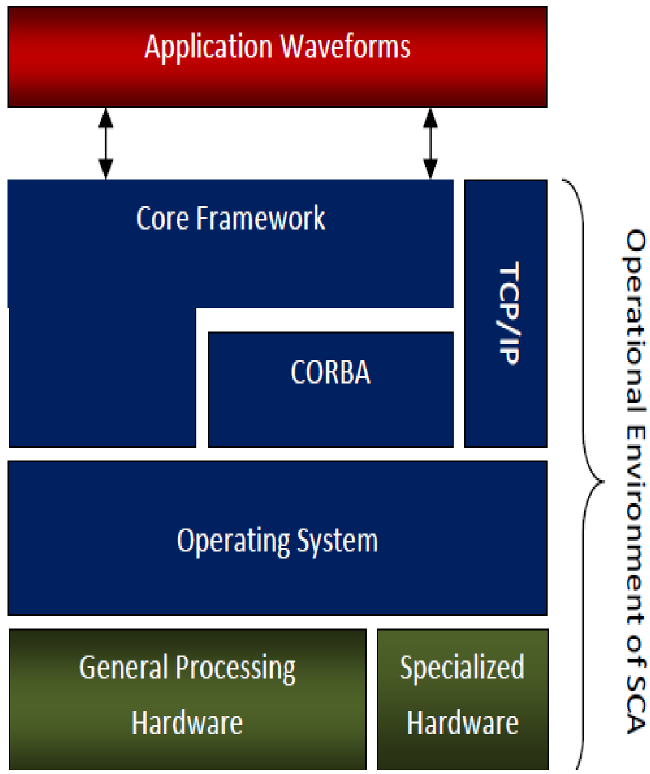


Figure 2-13 SCA Software Architecture

2-2-3-2 Applications

SCA applications (Waveforms) are programs which are developed to perform the functionality of a specific SCA-compliant product and are collection of one or more resources.

2-2-3-3 Software Development Languages

According to SCA specifications software for an SCA-compliant system shall be developed in a standard higher order language and should be independent from platform and environmentdependencies and will be easily portable. There is no need to rewrite legacy software and it shall interface with the Core Framework in accordance with SCA specification.

2-2-4 SCA Compliant SDR Frameworks

Available SCA compliant frameworks include

- *OSSIE* from Wireless @ Virginia Tech group
- *SCARI Open* of Communication Research Center Canada
- *dmTk*from HARRIS Corporation.

SCARI Open is open source and Java base, on the other hand OSSIE developed by *Wireless @ Virginia Tech* group is also open source but C++ based. OSSIE (Open Source SCA Implementation: Embedded) is developed by to facilitate education and research on SDR and wireless communication. OSSIE software includes SDR core framework according to SCA specifications, waveform workshop, tools for rapid development of SDR components and waveforms and library of pre-built components and waveforms. OSSIE project is written in C++ and uses Omni-ORB and Xerces XML parser both of which are open source. First version of OSSIE was Windows based but current versions are focused on the Linux operating system. VMware images are available to use OSSIE on Windows using VMware player. OSSIE includes a set of development and debugging tools which facilitate the rapid prototyping of components and waveforms, this set is called the OSSIE Waveform Workshop. This workshop includes the OSSIE Eclipse Feature which is a tool for component and waveform development. ALF tool is for waveform visualization and debugging environment and Waveform Dashboard tool is for execution and runtime configuration of waveforms.

Chapter: 3

DESIGN AND DEVELOPMENT OF INDEGENIOUS SDR PLATFORM

There are a few options when deciding on a software defined radio. The requirements of this project are: small size, low cost, low power and efficient, high speed, easily available and easily configurable SDR platform that has the ability to create any modulation through code. For this reason a USRP with GPP platform was selected.

3-1 Why USRP?

Using USRP has its own perks. USRP enables the user to design rapidly and make a powerful and flexible software defined radio. As it connects to a large range of daughter boards it provides a wide range of frequencies to work on. The SDR framework running on USRP is GNU radio that is simply required to be downloaded with no license or purchasing as it is open source. To develop an SDR on USRP low budget and minimum effort is required with best outcomes. As a lot of engineers and developers have researched and worked on USRP, leading to many applications on USRP. It can receive and transmit simultaneously thus making a MIMO system in real time. Its design is open source so no license or software needed to be purchased.

Due to its flexible hardware, open source software and all the aid available from the experienced users it is an ideal platform for developing SDR.

Figure 3-1 USRP

Table 3-1 Modulation Type and Price Differences of SDRs[16]

Board	Manufacturer	Modulation Type	Out of the Box demo	Availability	Price
WARP Radio Board	Mango Communications	Programmable	Online labs	available	$6,500
USRP1	Ettus Research	Programmable	Source code provided	available	$700
RadioProcessor board	SpinCore	Programmable	C code demos	available	$6,995
PulseBlasterDDS	SpinCore	Programmable	C code demos	available	$2,495
PMG-M-130 DDS	BASIL Networks	Configurable		Minimum order needed	min $100,000 order

Table 3-2 Frequency and Software Differences of SDRs[16]

Board	Frequency range (MHz)	Software	Notes
WARP Radio Board	2400-2500, 4900-5875	Xilinx ISE, EDK	the radio board and FPGA board are included in the cost
USRP1	depends on daughterboard	GNU Radio	
RadioProcessor board	0-100	SpinAPI Package	A complete communication system on the board, can program modulation in C
PulseBlasterDDS	0.005-100	SpinAPI Package	Just the Tx of the system, still need Rx
PMG-M-130 DDS	0-130	PMG-M-1300 Software	PCI Interface, don't sell one board at a time

Proposed System Design

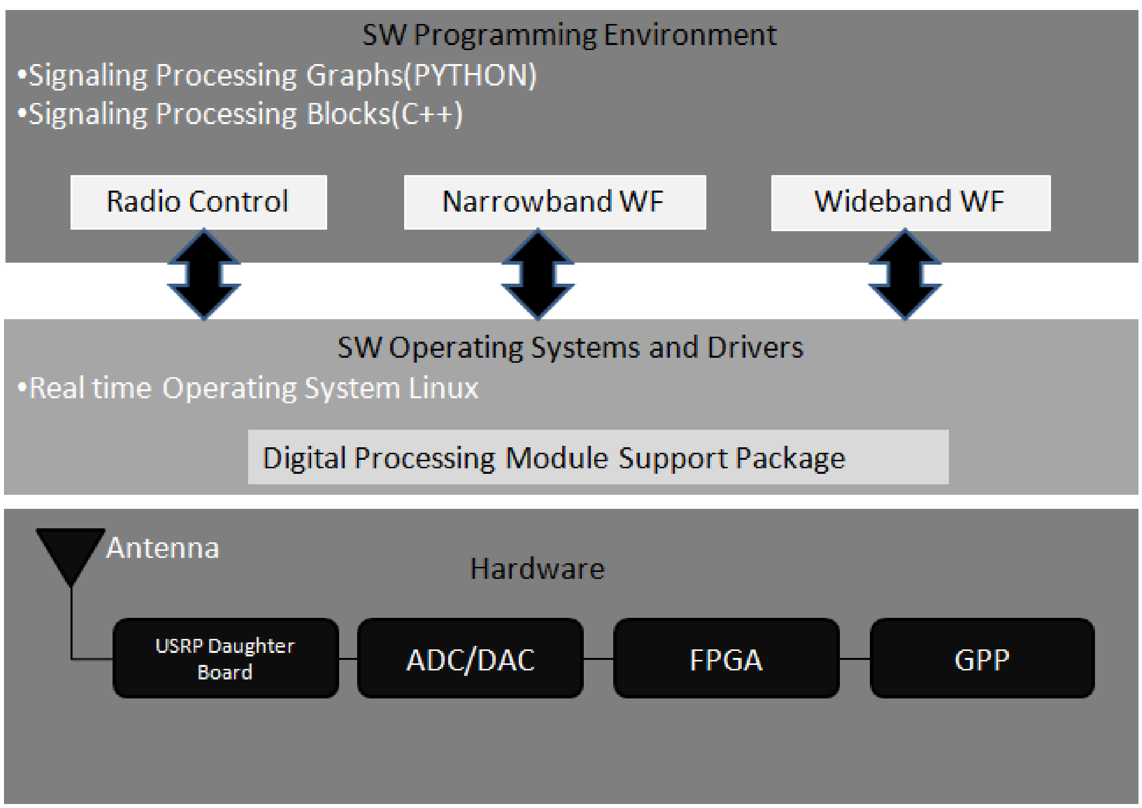


Figure 3-2 Proposed System Diagram of Project

3-2 Software on Hardware

In this project GNU radio is built and installed on Ubuntu Linux to create the upper to layers of the system as shown in the above diagram. Ubuntu 11.10 is installed on the general purpose processor as an operating system. If the GPP is the user PC then the steps followed to install Ubuntu 11.10 can be easily installed from a CD or from an ISO image on the computer. This prepares the system and the drivers for baseband processing in general purpose processor.

After the operating system is ready the SDR framework has to be ported on the operating system. There arefour basic parts of GNU Radio installation:

- Install the pre-requisites
- Get the GNU Radio source code
- Configure, compile and install GNU Radio
- Configure USRP

3-2-1 Installing the pre-requisites:

For assembling different parts of GNU the following packets are needed. These packages can be installed via "synaptic" or using the command lines.

<u>Development Tools</u>

- g++
- git
- make
- autoconf, automake, libtool

- sdcc
- guile
- ccache
- Libraries
- python-dev
- SWIG
- FFTW 3.X
- cppunit
- Boost 1.35
- GSL GNU Scientific Library
- libusb and libusb-dev
- ALSA

<u>GNU Radio Companion</u>

python-numpy, python-cheetah and python-lxml should to be installed for GRC

<u>WX GUI</u>

python-wxgtk2.8 and python-numpy should be installed

<u>QT GUI</u>

PyQT4, PyQwt5 for Qt4, QT-OpenGL,Fontconfig, Xrender and Xinput should be installed

Video-SDL

Simple DirectMedia Layer development libraries (libsdl1.2-dev) should be installed

Polyphase Filter Bank examples

python-scipy, python-matplotlib, and python-tk should be installed

Other useful packages

- doxygen (for creating documentation from source code)
- octave (from "universe")

3-2-2 Install Dependencies:

To install the dependencies the commands given below are to be performed in the command line.

- sudo apt-get -y install libfontconfig1-dev libxrender-devlibpulse-dev \
- swig g++ automakeautoconflibtool python-dev libfftw3-dev \
- libcppunit-devlibboost-all-devlibusb-dev fort77 sdccsdcc-libraries \
- libsdl1.2-dev python-wxgtk2.8 git guile-1.8-dev \
- libqt4-dev python-numpyccache python-opengl libgsl0-dev \
- python-cheetah python-lxmldoxygen qt4-dev-tools \
- libqwt5-qt4-dev libqwtplot3d-qt4-dev pyqt4-dev-tools python-qwt5-qt4

If any other version of Ubuntu is being used the commands on the terminal for installing GNU Radio will be different.

3-2-3 Installing GNU Radio:

The commands for GNU Radio are:

- git clone http://gnuradio.org/git/gnuradio.git

or

- git clone git://gnuradio.org/gnuradio.git

Configure and build GNU Radio:

- cd gnuradio
- mkdir build
- cd build
- cmake ../
- make

For making sure the GNU Radio is installed successfully the following commands shuld be run:

- make test

Then:

- sudo make install

3-2-4 Configuring USRP support:

To configure USRP the following commands are run in the command line.

- sudoaddgroupusrp
- sudousermod -G usrp -a <YOUR_USERNAME>

- echo 'ACTION=="add", BUS=="usb", SYSFS{idVendor}=="fffe", SYSFS{idProduct}=="0002", GROUP:="usrp", MODE:="0660"' >tmpfile

- sudochownroot.roottmpfile
- sudo mv tmpfile /etc/udev/rules.d/10-usrp.rules

The USRP is configured but the new rules need to be loaded for that the following commands are used:

- sudoudevadm control --reload-rules

or

- sudo /etc/init.d/udev stop
- sudo /etc/init.d/udev start

or

- sudokillall -HUP udevd

To check if the installation is complete connect the USRP to the PC and run the following commands:

- ls -lR /dev/bus/usb | grepusrp

If USRP is successfully installed the following should appear in the command line:

- crw-rw---- 1 root usrp 189, 514 Mar 24 09:46 003

Each device file will be listed with group 'usrp' and mode 'crw-rw----'.

At this point it has been examined that the USRP has been successfully installed. The GNU radio works with USRP and this testing of GNU radio with the USRP is done using an example in the GNU radio library. To ensure that the USRP works at the maximum through put the following commands are run to run the example in the library.

- cd gnuradio-examples/python/usrp
- ./usrp_benchmark_usb.py

If the maximum throughput of 32Mbps is achieved then the GNU Radio and USRP are ready to use.[15]

Chapter: 4

DESIGN AND DEVELOPMENT OF SDR WAVEFORM

Waveform is a set of transformations applied to information that is transmitted over the air and the corresponding set of transformations to convert received signal back to the information contents. There are multiple choices when deciding on the type of modulation schemes, type of synchronization methods, channel coding techniques, error correction mechanisms etc to set for a waveform.

4-1 Waveform Families

Narrowband waveform communications are traditionally secure links used by vehicle-mounted, rotor, and fixed systems that operate at VHF where each connected group of users occupies 25KHz of bandwidth. Narrowband waveform communications provides links up to 50 kilometres range due to the favourable propagation physics exhibited by the VHF band [6] and the narrow bandwidth, but with throughputs limited to about 96kbps. Many national radios use a unique proprietary waveform and do not interoperate, especially in secure modes. There is a large installed base of national radios which must be a factor in considering the overall wireless architecture

Wideband waveforms are used by vehicle mounted, fixed, and possibly air systems that operate at UHF, and occupy significantly more than the 25KHz of VHF users. Bandwidth of wideband waveforms is expected to be several MHz, following trends of commercial cellular systems. Wideband waveform links will rarely exceed approximately 5km (depending on power amplifier properties) due to the poorer propagation at the higher frequencies and the wider bandwidth, but will provide several megabits per second throughput. Wideband waveforms provide a tactical internet backbone.

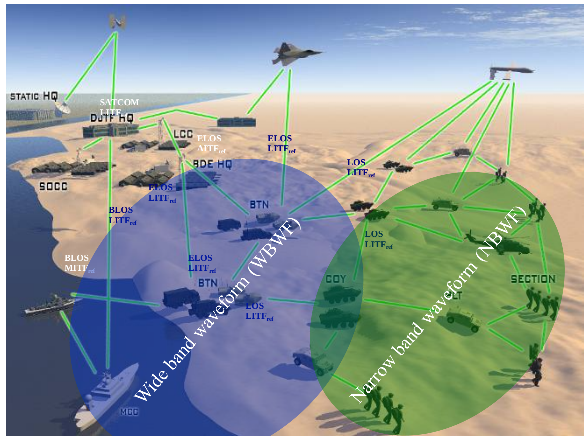


Figure 4-1 Narrowband and Wideband Waveforms

Soldier systems communications are customized wide-bandwidth waveforms implemented on person-mounted radios that connect dismounted soldiers to each other and possibly to the wideband waveform via gateways.

Clearly the narrowband, wideband, and soldier communications systems offer complementary services. The unique features of narrowband communications are inherent long range and coverage provided by the traditional use of the 30MHZ-108MHz VHF band, and the robust communications enabled by the use of FM waveform technologies such as FSK and CPM. This standards activity described herein are specifically for modern narrowband waveforms.[17]

The two types of waveforms which are studied in this project are VHF/UHF Narrowband Waveform and Wideband Waveform and research had been done on these waveforms to implement them.

Analog Narrowband waveforms are

- Amplitude modulation

AM is the most common technique of the electronic communication systems that uses a radio carrier to transmit the user information. In AM change the strength of the signal which the signal transmitted with respect to the user's information signal.Theoverall power of the signal varies with respect to the instantaneous amplitude of the modulating data.[18]

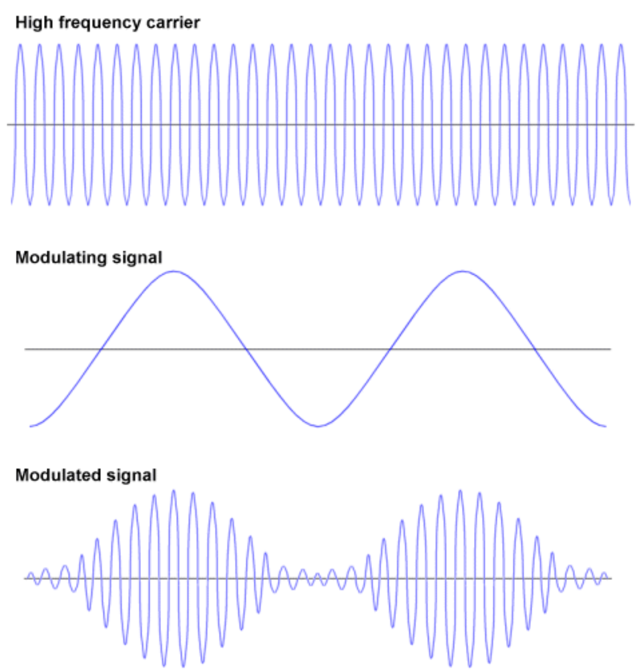


Figure 4-2 Amplitude modulation

In telecommunications, amplitude modulation of a sinusoidal wave is done with an audio signal that is the carrier signal. It is only transmitted once it is modulated. During modulation the audio signal changes/modifies the amplitude of the carrier and also calculates its envelope. AM produces sidebands in frequency domain, these sidebands are actually the sum and differences of the carrier and the modulator frequency. Amplitude modulation resulting in two sidebands and a carrier is called "double-sideband amplitude modulation".

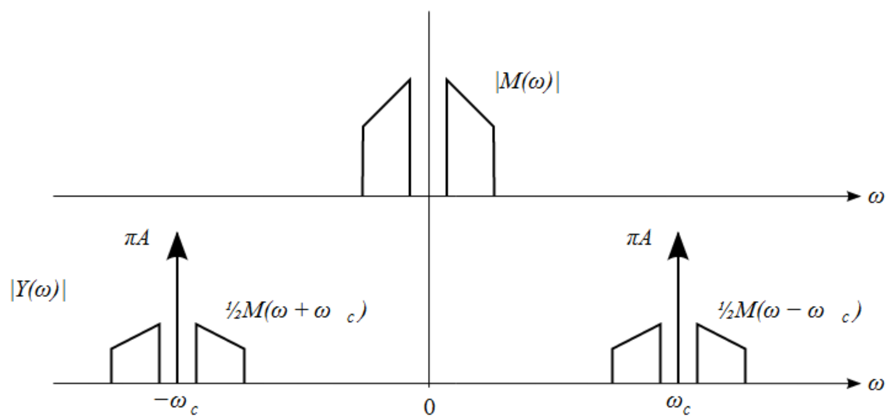


Figure 4-3 Double-sided Amplitude Modulated signals

Carrier is suppressed when further try to increase the efficiency of the transmitter. DSB "double-sideband suppressed-carrier" signalare the outcome of this suppression.This suppressed signal is 3 times more efficient, in term of power, than the simple amplitude modulated signal.But the reduced-carrier signal is produced if suppressed partially.

If furthermake transmitter and receiver more complex better bandwidth improvement can be achieved. In other words do the single-sideband modulation;completely suppress the carrier and a side band to have improved bandwidth.[19]

- Frequency Modulation

Frequency modulation, FM has major applications in telecommunication field. FM broadcasts on the VHF bands still provide exceptionally high quality audio, and FM is also used for a variety of forms of two way radio communications.

In view of its widespread use, frequency modulation, FM, is an important form of modulation among all the present digital transmissions in use.

The most obvious method of applying modulation is to superpose an audio signal on the amplitudesignal. It is also possible to vary the frequency of the signal to give frequency modulation or FM. It can be seen below that the frequency of the signal varies as the voltage of the modulating signal changes.

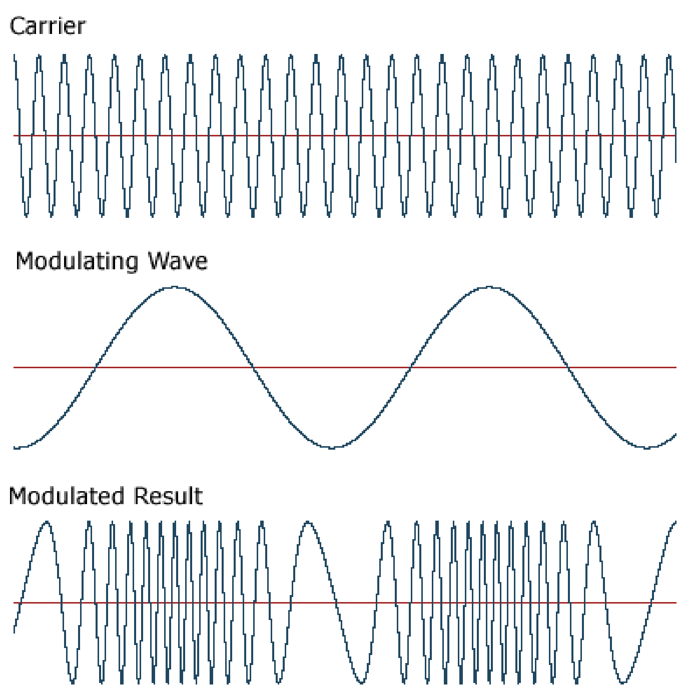


Figure 4-4 Frequency modulation

The amount by which the signal frequency varies is very important. This is known as the deviation and is normally quoted as the number of kiloHertz deviation. As an example the signal may have a deviation of ±3 kHz. In this case the carrier is made to move up and down by 3 kHz.

- Narrowband FM, NBFM, and Wideband FM, WBFM

  The level of deviation is important in many aspects. It obviously is important in finding/calculating the signal's total bandwidth. Telecommunication on the VHF section of the frequency spectrum in the range 88.5 to 108 MHz has deviation equal to±75 kHz. This is called wideband FM (WBFM). They provide high quality signal transmissions. But in doing so it takes greater bandwidth. Usually 200 kHz is allowed for each wideband FM transmission. Intelecommunications less bandwidth is used. Narrowband FM, NBFM uses deviation value equal to±3 kHz or possibly slightly more.

- Improvement in Signal to Noise Ratio

  It has already been mentioned that FM can give a better signal to noise ratio than AM when wide bandwidths are used. The amplitude noise can be removed by limiting the signal to remove it. In fact the greater the deviation the better the noise performance. When comparing an AM signal to an FM one an improvement equal to 3 D2 is obtained where D is the deviation ratio.

- Pre-emphasis and de-emphasis when using frequency modulation

Betterment in S/N (signal to noise ratio) can be achieved if the audio signal is pre-emphasized. To achieve this, the lower level high frequency sounds are amplified to a higher degree compared to the low frequency sounds just before they are transmitted. Once at the receiver the signals are passed through a network with the opposite effect to restore a flat frequency response.

To achieve the pre-emphasis the signal is passed through a capacitor-resistor (CR) network. At frequencies above the cut-off frequency the signal increases in level by 6 dB per octave. Similarly at the receiver the response falls by the same amount.

Both the receiver and transmitter networks must match one another. The break frequency is 3183 Hz. In North Americabroadcasting values of 75µs and break frequency of 2.1 kHz is employed.

Pre-emphasizingof an FM signal is operative because the noise output of FM system is proportionate to frequency. To reduce the level of this effect, the receiver's amplifier must have a response that falls in proportion frequency. To prevent the signal from dropping higher frequencies, the transmitter should increase level of higher frequencies to compensate. It is achieved because level of the high frequency audio is less than those of lower frequency.

- Modulation index Narrowband FM

It is useful to know the modulation index of a frequency modulated signal. The modulation index is corresponding to the ratio of frequency deviation andmodulating frequency. Modulation index varies according to frequency which is modulating transmitted carrier and quantity of deviation. When designing a system we need to know the maximum allowable values. These are given by the deviation ratio. It is found by injecting the maximum values into formula of modulation index.

D = (Max devfreq) / (Max mod freq)

This may also be expressed as:

$$\beta = \Delta\omega \; / \; \omega m$$

In a FM broadcast transmitter the max deviation is 75 kHz. Maximum modulation frequency equals 15 kHz which gives us a deviation ratio of 5.

NBFM is defined as the where the value of B is small enough that the terms in the Bessel expansion, i.e. sidebands are negligible.

$$\beta = \Delta\omega \; / \; \omega m < 0.5$$

Often a figure of < 0.2 may be used.

- BW of a FM signal

An amplitude modulated signal's bandwidth required is twice the highest frequency of modulation. Same goes for a NBFM signal; this is not correct for wideband FM signal. The required bandwidth can be to a great extentbigger, with measurable sidebands spreading out over huge amounts of spectrum. Normally it is necessary to bound the bandwidth of a signal to ensure least amount of excessive interfere with stations any side.

As a frequency modulated signal has sidebands that extend out to infinity, it is normal accepted practice to determine the bandwidth as that which contains approximately 98% of the signal power.

A rule of thumb, often termed Carsons' Rule states that 98% of the signal power is contained within a bandwidth equivalent to the deviation frequency, in addition modulation frequency is doubled, i.e.:

$$\mathbf{BT = 2(\Delta f + fm)}$$

Normally the bandwidth of a wideband FM signal is limited to the Carson's Rule limit - this reduces interference and does not introduce any undue distortion of the signal. So for a VHF FM transmitting station it should be 175 kHz. So we have a total of 200 kHz which is allowed, permitting stations to have a minor guard band, their center frequencies on integral multiples of a 100 kHz.

There are a few interesting points of summary relative to frequency modulation bandwidth:

- The bandwidth of a frequency modulated signal varies with both deviation and modulating frequency.
- Increasing modulating frequency reduces modulation index - it reduces the number of sidebands with significant amplitude and hence the bandwidth.
- Increasing modulating frequency increases the frequency separation between sidebands.

- The frequency modulation bandwidth increases with modulation frequency but it is not directly proportional to it.

  Frequency modulation bandwidth is of importance as it is with any other form of signal. With band occupancy growing, and pressure on spectrum space, it isessential to confirm the bandwidth of a frequency modulated signal comes within the defined allowance. Any undue signal spread outside this is likely to cause interference to other users. [20]

- Phase Modulation

  It is a form ofmodulation that embodiesdata as deviations in the instantaneous phase of the carrier signal.[21]

  Phase Modulation is notgenerally used for radio transmission. The reason is that it tends to necessitatea more complicated receiving hardware. So there can be imprecision issues in defining whether, i.e. the signal has changed phase by +180° or -180°.

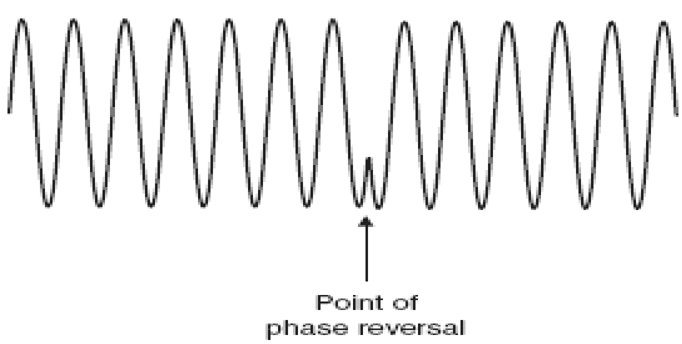


Figure 4-5 Phase Modulation

While Digital Narrowband waveforms include

- Amplitude Shift Key

ASKis another form of modulation that denotes digital information as deviations in the amplitude of a carrier signal.

All digital modulation techniques use a finite number of different signals to denote digital information. ASK uses a fixednumber of amplitudes. Amplitude isallotted a unique arrangement of binary digits. Each amplitude encodes the same number of bits. Every pattern of bits then forms the symbol that is denoted by the certain amplitude. Demodulatordesigned specially for the symbol-set that is in use, governs the amplitude of the received signal and then it maps it back to the symbol it denotes, hence recovering the information. Frequency, phase of the carrier signal are constant.[22]

ASK is linear and hence it is sensitive to atmospheric noise, distortions and propagation conditions on different routes in the PSTN, etc. ASK modulation and demodulation processes are economical. This technique is generally used to transmit digital information via optical fiber. In LED transmitters, 1 is represented asa short pulse of light while the 0 is depicted by the absence of light. Laser transmitters usually have a fixed "bias" current that results in the device emitting a small light level. This small level represents a 0, while a higher-amplitude light signal represents 1.

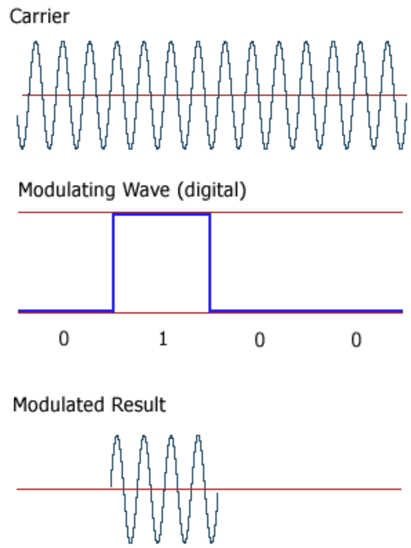


Figure 4-6 Amplitude Phase Shift Key

- Phase Shift Key

Phase-shift keying is a digital modulation scheme that conveys data by changing, or modulating, the phase of a reference signal (the carrier wave).

Any digital modulation scheme uses a finite number of distinct signals to represent digital data. PSK uses a finite number of phases, each assigned a unique pattern of binary digits. Usually, each phase encodes an equal number of bits. Each pattern of bits forms the symbol that is represented by the particular phase. The demodulator, which is designed specifically for the symbol-set used by the modulator, determines the phase of the received signal and maps it back to the symbol it represents, thus recovering the original data. This requires the receiver to be able to compare the phase of the received signal to a reference signal — such a system is termed coherent (and referred to as CPSK).[23]

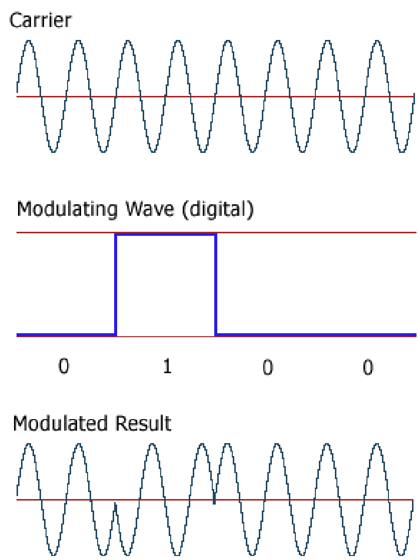


Figure 4-7Phase Shift Key

Alternatively, instead of operating with respect to a constant reference wave, the broadcast can operate with respect to itself. Changes in phase of a single broadcast waveform can be considered the significant items. In this system, the demodulator determines the changes in the phase of the received signal rather than the phase (relative to a reference wave) itself. Since this scheme depends on the difference between successive phases, it is termed differential phase-shift keying. DPSK can be significantly simpler to implement than ordinary PSK since there is no need for the demodulator to have a copy of the reference signal to determine the exact phase of the received signal (it is a non-coherent scheme). In exchange, it produces more erroneous demodulations.

There are two fundamental ways of utilizing the phase of a signal in this way:

- By viewing the phase itself as conveying the information, in which case the demodulator must have a reference signal to compare the received signal's phase against; or

- By viewing the change in the phase as conveying information — differential schemes, some of which do not need a reference carrier (to a certain extent).

A convenient way to represent PSK schemes is on a constellation diagram. This shows the points in the complex plane where, in this context, the real and imaginary axes are termed the in-phase and quadrature axes respectively due to their 90° separation. Such a representation on perpendicular axes lends itself to straightforward implementation. The amplitude of each point along the in-phase axis is used to modulate a cosine (or sine) wave and the amplitude along the quadrature axis to modulate a sine (or cosine) wave.

In PSK, the constellation points chosen are usually positioned with uniform angular spacing around a circle. This gives maximum phase-separation between adjacent points and thus the best immunity to corruption. They are positioned on a circle so that they can all be transmitted with the same energy. In this way, the moduli of the complex numbers they represent will be the same and thus so will the amplitudes needed for the cosine and sine waves. Two common examples are "binary phase-shift keying" which uses two phases, and "quadrature phase-shift keying" which uses four phases, although any number of phases may be used. Since the data to be conveyed are usually binary, the PSK scheme is usually designed with the number of constellation points being a power of 2.

- <u>Frequency Shift Key</u>

  In digital FM, the carrier frequency shifts abruptly, rather than varying continuously. The number of possible carrier frequency states is usually a power of 2. If there are only two possible frequency states, the mode is called frequency-shift keying. In more complex modes, there can be four, eight, or more different frequency states. Each specific carrier frequency represents a specific digital input data state.

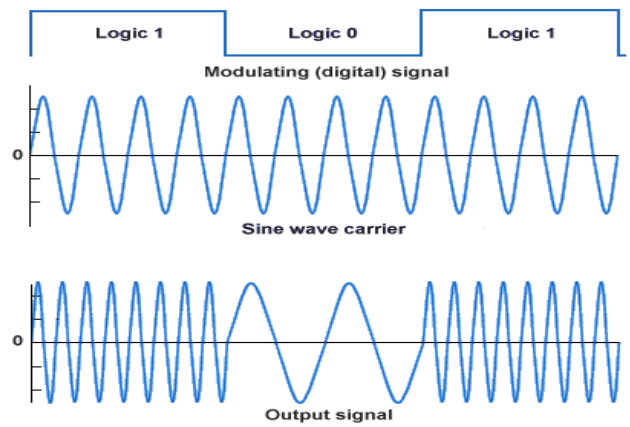


Figure 4-8Binary frequency Shift Key

The wideband waveforms are

- OFDM
    - Multiple subcarriers and orthogonality

    OFDM stands for Orthogonal Frequency Division Multiplexing. As its name reveals, OFDM isa multiplexing method, which means that different data channels share the bandwidth available.In the particular case of OFDM the signal is made of independent channels. Each of them willuse a fraction of the available bandwidth. Each of this independent channel is called subcarrierand transports data that is modulated in the amplitude and phase of the signal. All subcarrierstogether form the OFDM carrier. OFDM is called orthogonal because all subcarriers areorthogonal to each other. This orthogonality can be achieved by multiplexing the subcarriersby Frequency-division multiplexing, which is called multi-carrier transmission or byusingCode Division multiplexing, which is called multi-code transmission.

Therefore it uses the same concept as FDM, which assign different frequencies to different signals.Each sub-carrier will use a range of the frequencies available to transmit data that will travelin the phase of the signal.

The OFDM modulation method relies on the orthogonality between its subcarriers to achieve agood spectral performance. In the case of multi-carrier transmission the chosen frequencies mustbe orthogonal between each other. This means all frequencies must bemultiples of the inverseof the symbol duration. Each of the OFDM subcarriers has a range of frequencies assigned to it, and all of themtogether fill the spectrum used for the OFDM carrier, that is the bandwidth available. Thedata in bits will be split among the subcarriers by using a serial to parallel converter and foreach subcarrier it is independently modulated using, in most cases, a Quadrature amplitude modulation or a Phase-shift keying modulation. Then, the OFDM carrier iscreated with all the modulated subcarriers by using an inverse Fast Fourier Transform module that calculates the time-domain signal with all subcarriers to create a single broad-bandcomplex signal containing all data belonging to all subcarriers: the OFDM carrier signal. Thissignal will be used to modulate an Radio Frequency (RF) carrier.

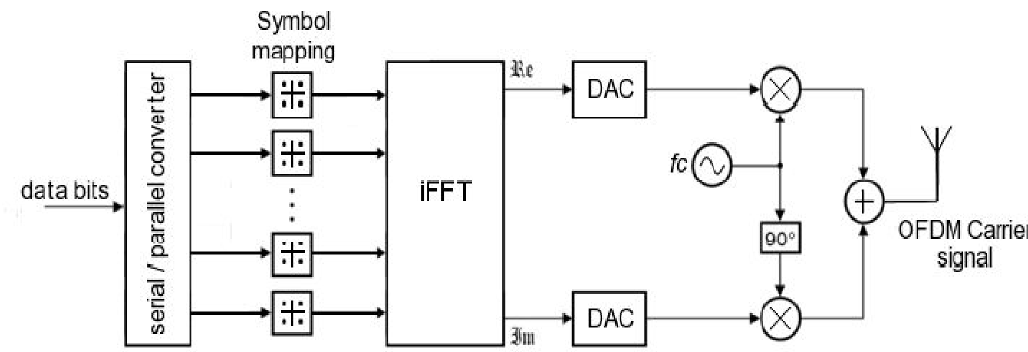


Figure 4-9OFDM modulator module diagram

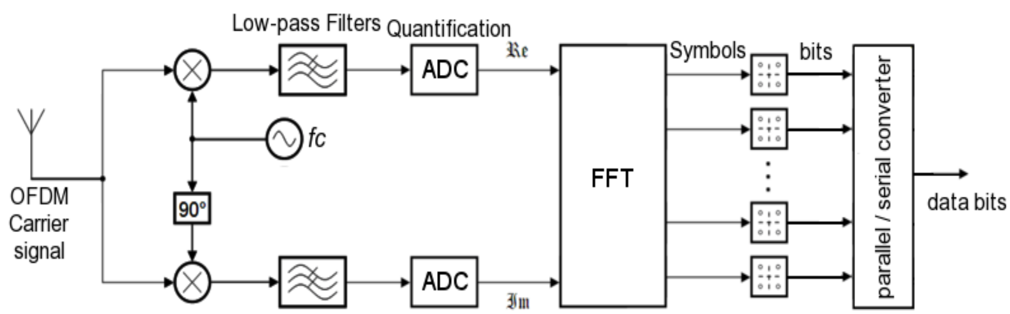


Figure 4-10OFDM demodulator module diagram

The receiver will separate the received signal in its real and imaginary parts, and then they willbe low-pass filtered to eliminate mirrored frequencies of the carrier frequency (2fc). Afterwards,they will be quantified with Analog to Digital Converters and then the frequency-domainsignals will be calculated with a Fast Fourier Transform module. The FFT module willoutput the different streams corresponding to the subcarriers used and the data in each of themwillbe independently demodulated using the appropriate symbol detector that corresponds tothe modulation used to map the bits into symbols in the modulator module.

This functionalityhas not been implemented in the prototype but is proposed as a future development. Obviously,the sender and the receiver must know the modulation used for each subcarrier in order todemodulate its data correctly. Figures show the block diagrams of the OFDMmodulator and demodulator.

- Delay spread and cyclic prefix

In wireless communication systems the received signal will always be received many times due to the multipath propagation. This effect gives as a result in the receiver a number of signals with different amounts of delay respect the first multipath signal that usually corresponds with the line of sight path. The difference of delay between the first of the multipath components and the last one is called *delay spread*. The effect of delay spread is especially present in urban environments, in which the number of multipath components is higher than in rural environments, but

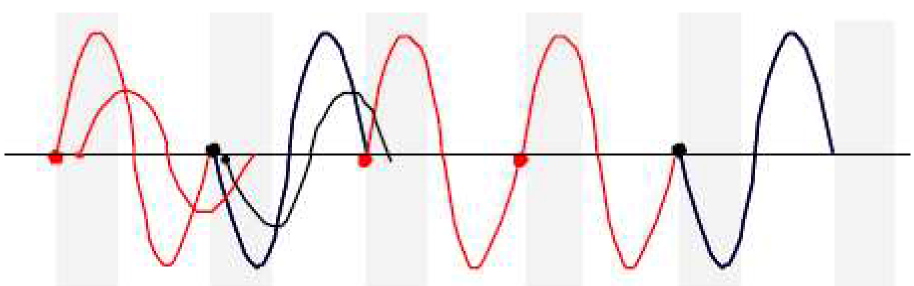


Figure 4-11Signal in the presence of ISI

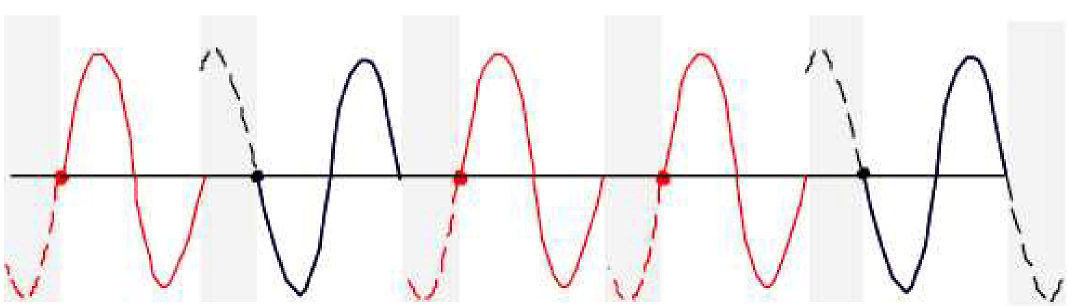


Figure 4-12The effect of adding a cyclic prefix to a signal

also in environments where sender or receiver are moving at high speeds. This scenario could cause the multipath echoes to have important delays in time, as the target might be moving close to some of the multipath components and far from others. The problems that delay spread can cause are basically two. First of all the different echoes that arrive at different times can come with a different phase in respect to the main signal and they can cause some distortion in the main component. The second problem is the effect that the delayed echoes can cause in the next transmitted symbol. This is called inter symbol interference. Figures show the effect that multipath echoes can cause on a transmitted signal. The solution that OFDM proposes to reduce the effect of the multipathpropagation in the form of ISI is the addition of some redundancy in the transmitted signal called cyclic prefix. This redundancy is applied to the signal in the time domain and it is meant to create a kind of guard band at the beginning of each symbol that will protect the transmitted symbol from the echoes that cause ISI. The objective of the cyclic prefix is to provide some guard time between symbols that will be discarded by the receiver and will contain the undesired remains of the echoes of the previous symbol. The best way to provide this guard time is to add to the beginning of the symbol a prefix containing the last bits of the same symbol that is being sent. This method is also good for the sender, because it will also have it easier to generate the signal. We have to keep in mind that the oscillators in the sender behave better with a relatively constant rate of bits to send than constantly switching between sending and not sending data. Figure show how the signal looks like with the inclusion of the cyclic prefix. We see that the effect of the ISI is nullified by the CP.

- Synchronization and channel equalization

  In most wireless systems synchronization plays a very important role in the receiver side. Thereceiver needs to find the beginning of each symbol correctly. In OFDM systems it includesfinding the right time delay, the frequency deviation of each of the different subcarriers andfinally the phase shift of each of the symbols that travel in the subcarriers.All those parametersneed to be found by doing some calculations on the incoming signal.More concretely, onsome redundancy that is added to the data signal in order to find all these parameters.These redundancies are often referred to as pilots or preamble depending on its situation in the wholetransmitted signal.

  Pilots are used in many OFDM communication systems and they are known symbols thatare sent in some of the subcarriers of the ones used in the transmission. The pilot signalswill be known by the receiver, and by looking for them in the received signal all parametersregarding synchronization and equalization will be deduced. The density of pilots in the signalwillbe proportional to the quality of the synchronization process, but it will also be inverselyproportional to the amount of data transmitted. That is the reason why choosing a convenientdensity of pilots is an important part of the design of the application. Obviously, the qualityand variance of the channel will be the key factors that will influence the amount of redundancydedicated to synchronization in the form of pilots.

Similarly to pilots, preamble redundancy also works in multiple frequencies at the same time.In the case of preambles, the synchronization data will occupy the whole time slot of an OFDM symbol. During the time the preamble is being transmitted all subcarriers will contain preamble data. This method has some advantages and also some weaknesses compared to the pilots one. In this case the information provided by the preamble will give more accurate information regarding all subcarriers. For example, we can find out if there is one subcarrier that fails to send any data or that shows a wrong behaviour. On the other hand, when no preamble data is being sent the system will not be calculating any parameters regarding synchronization, so the updating of the channel data is slower than with the pilots.

The usual procedure for finding the frequency shift is by correlating the signal with itself with a certain delay, and the resulting signal will show a peak from which the frequency and time delay will be extracted. Different algorithms will use slightly different systems, but most of them, including the one used in the implementation, use this correlation method. The equalization process is usually a simple combination of an amplitude normalizer and a phase corrector. The amplitude in systems that use PSK as modulation for each subcarrier is as simple as amplifying or attenuating all the symbols to the same amplitude. The procedure for finding the phase shift a bit more complicated but it is also similar in most implementations, with some small differences. What the method will do is calculating the expected phase delay between each of the subcarriers. In the case of the synchronization with preambles, the phase difference between subcarriers is extracted from the known symbols of the preamble, and then applied to all the following symbols until the next preamble comes. In the case of using pilots, the difference in phase will be computed by using interpolation between the pilots, which will estimate the expected phase difference between each of the subcarriers. Then the correction is done by rotating the received symbols according to its phase shift.

- Phase modulation in the subcarriers

  This section explains how exactly the information travels in each of these subcarriers. Each subcarrier is independent from all other subcarriers in terms of how the data of one or another subcarrier is transmitted. Each subcarrier can use a different modulation to transmit the data assigned to it, and the receiver will not depend on any information about the other subcarriers to be able to receive the data belonging to a subcarrier. The sender will be able to modulate the data that goes to one subcarrier with any digital modulation. This decision must be shared by the sender and the receiver, but not by the other subcarriers. As an example, we could use binary phase-shift keying for the transmission of some of the subcarriers and Quadrature Phase-shift keying or QAM for some others, and we would only need to make sure the receiver knows which subcarriers use which modulation. This method helps us optimize each subcarrier by using modulations that fit the subcarrier's SNR. The subcarriers that have better channel conditions could use modulations with more bits per symbol, while subcarriers with lower SNR in the channel could use modulations that are easier to receive, such as BPSK.

- Forward Error Correction

  FEC is one of the most widely used mechanisms to improve the capacity of a channel and thus increase the rate of received data packets in noisy communications, specially in wireless links such as satellite communications. Its basic concept is the addition of redundancy in the transmitted data that will be useful to fix errors produced in the transmission. The correction will not rely on any additional information but the data transmitted itself. This process is known as channel coding.

  There are two different ways to apply channel coding to a stream of data: Block coding and convolutional coding. Block coding takes small chunks of data of a fixed size (usually up to few hundreds of bytes) and apply redundancy that contains information about the whole block of data. Therefore, each block is independent from all other blocks. Convolutional coding operates on serial data. It will take data in continuously and the redundancy will use a number of bits (called constraint length and represented with the letter *L* or *K*) to generate the output bits. Another important value is the code rate, which shows the relationship between input and output bits. All FEC implementations can be characterized by the parameters *n*, *k* and *m*. The following formulae show the relationship between the constraint length or the code rate and these three basic parameters.

n = number of output bits

m = number of input bits

k = number of memory registers

$$L = k(m - 1)$$

$$\text{code rate} = k/n$$

Choosing the value of the parameters chosen for the FEC system we want to implement is a very important task in the design of a communications system. There are several issues that must be taken into account. First of all, the characteristics of the channel that we will work on should be known. Then a set of parameters must be chosen in order to find the best performance. The first trade-off that we will face is the threshold SNR of the channel. FEC implementations usually work well in environments with up to a certain SNR. If the SNR falls lower than that threshold the performance of the FEC algorithm is likely to fall down to a point of not performing well at all, outputting data worse than the received in its input in most cases. The second fact that we need to take into account is that adding more redundancy will increase the amount of data to be sent, and that will affect directly the throughput of the channel.

Finally, bigger values of m also increase the complexity of the decoder exponentially. To give a general idea of this magnitude, most applications use constraint lengths up to a value of 9 bits.

Viterbi decoders are one of the two mechanisms to decode data encoded with convolutional codes. The other mechanism is sequential decoding. The main advantage of Viterbi decoders is that the decoding takes a fixed amount of time to conclude. That helps us estimate the feasibility of its inclusion in our system. It is also well suited for hardware implementations.

Viterbi decoding can work on soft bits and hard bits. The data that it works with can be almost analog and the outputted data will be digital. If we use hard bits as input for the Viterbi decoder there must be a decision block before the decoder that takes analog received data in its input and outputs one of the possible symbols received, which will probably be the one thatis closest to the analog data received. When the Viterbi decoder works with soft bits it willquantify the analog data first and then work with the quantified values directly, which usuallyimproves its performance.

Themain idea of the Viterbi decoding algorithm is to find the stream of data that was sent amongall possible streams sent. This is calculated in a rather simple way thanks to the way the datais encoded by the convolutional code algorithm. Each symbol received at the decoder will befollowed by another symbol with a fixed known probability. This way, if we receive two symbolsthat should not come one after the other we detect a possible error. Each time a new symbolcomes a path is drawn for all the possible sequences of received symbols and its count of possibleerrors. In the end the path that accumulated the least amount of errors is the path chosen.According to the success rate of the received data, the use of FEC algorithms can be seen as anincrease of the channel's SNR. As an example, a convolutional code with rate 1/2 with constraintlength of 7 can be seen as an increase of 5 dB in the channel's SNR. This way of analyzingthebehaviour of the algorithm can be useful for knowing the increase of the performance thatwe achieve by using the FEC. Then we can decide on its need or we can modify some of itsparameters if necessary.

- DSSS

Direct sequence spread spectrum, also known as direct sequence code division multiple access, is one of two approaches to spread spectrum modulation for digital signal transmission over the airwaves. In direct sequence spread spectrum, the stream of information to be transmitted is divided into small pieces, each of which is allocated across to a frequency channel across the spectrum. A data signal at the point of transmission is combined with a higher data-rate bit sequence (also known as a *chipping code*) that divides the data according to a spreading ratio. The redundant chipping code helps the signal resist interference and also enables the original data to be recovered if data bits are damaged during transmission.

Direct sequence contrasts with the other spread spectrum process, known as frequency hopping spread spectrum, or frequency hopping code division multiple access, in which a broad slice of the bandwidth spectrum is divided into many possible broadcast frequencies. In general, frequency-hopping devices use less power and are cheaper, but the performance of DS-CDMA systems is usually better and more reliable.

Spread spectrum first was developed for use by the military because it uses wideband signals that are difficult to detect and that resist attempts at jamming. In recent years, researchers have turned their attention to applying spread spectrum processes for commercial purposes, especially in local area wireless networks.

This project is concentrated on developing two networking waveforms, one for handling audio and other for handling video communication. Narrowband FM is chosen for audio and Wideband OFDM for video communication for SDR implementation.

4-2 Narrowband Waveform

4-2-1 Advantages of frequency modulation

There are many advantages to the use of frequency modulation. These have meant that it has been widely used for many years, and will remain in use for many years.

- Resilient to noise: One of the main advantages of frequency modulation that has been utilized by the broadcasting industry is the reduction in noise. As most noise is amplitude based, this can be removed by running the signal through a limiter so that only frequency variations appear. This is provided that the signal level is sufficiently high to allow the signal to be limited.

- Resilient to signal strength variations: In the same way that amplitude noise can be removed, so too can any signal variations. This means that one of the advantages of frequency modulation is that it does not suffer audio amplitude variations as the signal level varies, and it causes FM to be ideal for use in mobile communications where signal levels constantly change. This is provided that the signal level is sufficiently high to allow the signal to be limited.
- Does not require linear amplifiers in the transmitter: As only frequency changes are required to be carried, any amplifiers in the transmitter do not need to be linear.
- Enables greater efficiency than many other modes: The use of non-linear amplifiers, e.g. class C, etc means that transmitter efficiency levels will be higher - linear amplifiers are inherently inefficient.

4-2-2 Disadvantages of frequency modulation

There are a number of disadvantages to the use of frequency modulation. Some are can be overcome quite easily, but others may mean that another modulation format is more suitable.

- Requires more complicated demodulator: One of the minor disadvantages of frequency modulation is that the demodulator is a little more complicated, and hence slightly more expensive than the very simple diode detectors used for AM. Also requiring a tuned circuit adds cost. However this is only an issue for the very low cost broadcast receiver market.

- Some other modes have higher data spectral efficiency: Some phase modulation and quadrature amplitude modulation formats have a higher spectral efficiency for data transmission that frequency shift keying, a form of frequency modulation. As a result, most data transmission system uses PSK and QAM.
- Sidebands extend to infinity either side: The sidebands for an FM transmission theoretically extend out to infinity. To limit the bandwidth of the transmission, filters are used, and these introduce some distortion of the signal.

There are many advantages to using frequency modulation. FM is still greatly used for a lot of broadcast and radio communications uses. However with more systems using digital formats, phase and quadrature amplitude modulation formats are on the increase. Nevertheless, the advantages of frequency modulation mean that it is an ideal format for many analogue applications.

4-2-3 Parameter of Waveform in Project

Bandwidth 200 KHz

Audio Rate 44.1 KHz

Decimation Factor 250

ADC64 MS/s

DAC 128 MS/s

4-3 Wideband Waveform

4-3-1 Advantages of OFDM

- The orthogonality of the frequencies used reduces greatly the crosstalk interference between sub-carriers and increases the spectrum utilisation.
- It also allows the sender and receiver to be simpler than in the case of FDM. An example of this simplicity is that FDM uses a different filter for each used sub-channel, while OFDM can work with one filter for all subcarriers.
- An OFDM signals offers an advantage in a channel with frequency selective fading response. As we can see, when we lay the OFDM frequency spectrum against frequency selective response of the channel, only two subcarriers are affected, all the others are perfectly ok. Instead of the whole system being knocked out we lose only a small subset of the bits.

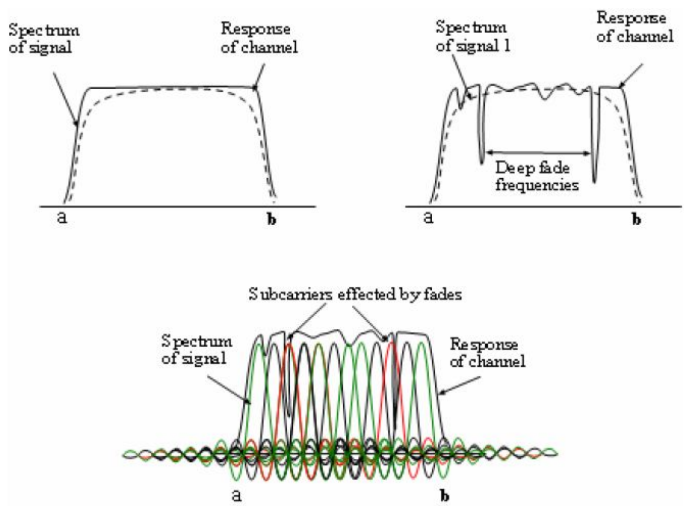


Figure 4-13Channel Response

- The BER of an OFDM system is signals in a fading channel is much better than the performance of FDM/QPSK which is single carrier wideband signals. The underlying BER of the OFDM is exactly the same as the underlying modulation.
- CombatsInter symbol interference with CP

4-3-2 Disadvantages of OFDM

The disadvantage of OFDM is that it requires a good frequency synchronization mechanism, because as the subcarriers are very close to one another small frequency deviationscan cause important inter-carrier interference, i.e. cross-talk between subcarriers. Thesekinds of interferences are mostly caused by Doppler shift due to movement, especially when therearereflex ions caused by multipath.

4-3-3 Parameter of Waveform in Project

Data Rate	1Mbps
Bandwidth	500 KHz
Modulation	BPSK
FFT size	64 point with 52 subcarriers being used
Subcarrier Frequency spacing	4 KHz
Guard Band	12 KHz

4-3-4 TUN/TAP Adapters

TUN/TAP offers packet reception and transmission for user space processes. It can be understood as a modest Point-to-Point or Ethernet device, which, in place of receiving packets from physical media, receives packets from the user space process and in turn in place of sending packets via physical media it writes the packets to the user space process.

To use the driver, a program has to start /dev/net/tun and issue a corresponding ioctl() to record a network device with the kernel. A network device will appear as tunXX or tapXX, depending on the choicesselected. When it closes the filedescriptor, the network device and all parallel routes will vanish. Liable on the nature of the device selected, the userspace program will have to read/write IP packets (with tun) or Ethernet frames (with tap). The one in use is dependant on the flags assigned to the ioctl().

Virtual network device can be regarded as a modest Point-to-Point orEthernet device, which in place of receiving packets from a physical media, receivesthe packets from user space program and instead of sending packets via physicalmedia sends the packets to the user space program. You configured IPX on the tap0 so now whenever the kernel sends an IPX packet to tap0, it is handed over to theapplication (VTun, for example). Thenthe app encrypts then compresses and then sends it to the other side over TCP/UDP. The application on the second side decompresses anddecrypts the data received and writes the packet to the TAP device, where the kernelhandles the packet like it came from real physical device.

The project a "TAP" interface is established in the kernel, it is typically gr0, and transmits and receives Ethernet frames through it this interface.

APPENDIX

USER GUIDE

Objective:

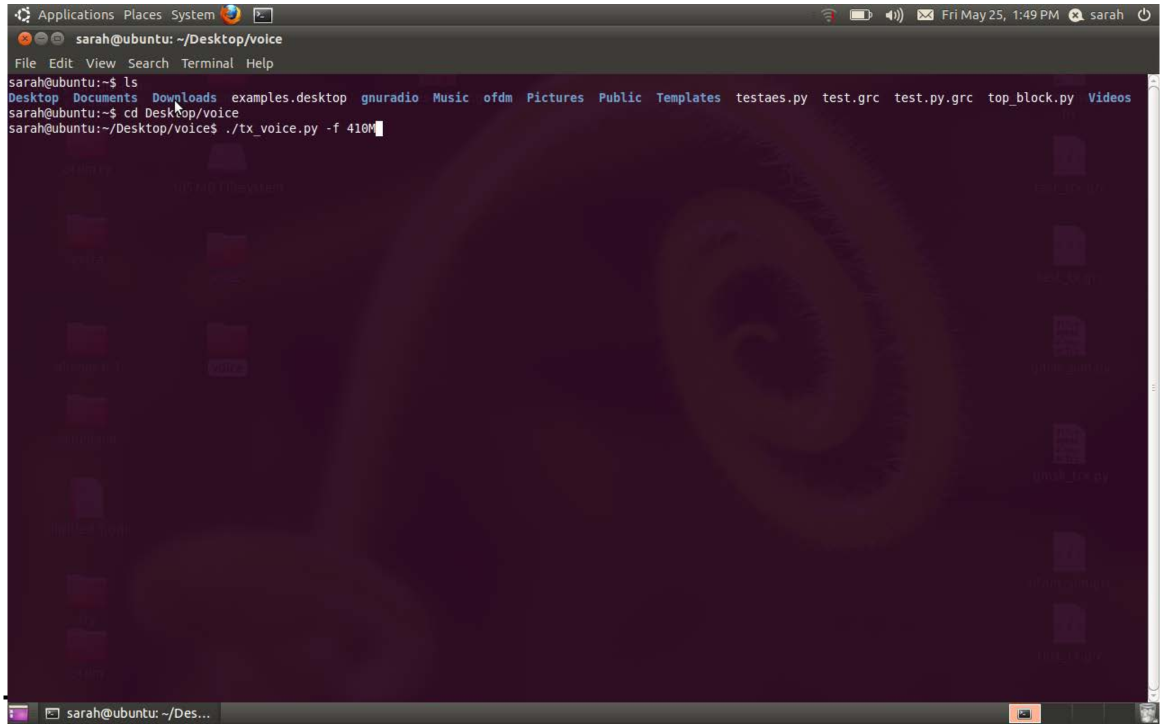
- To communicate through voice and video transmission using SDR

Equipment:

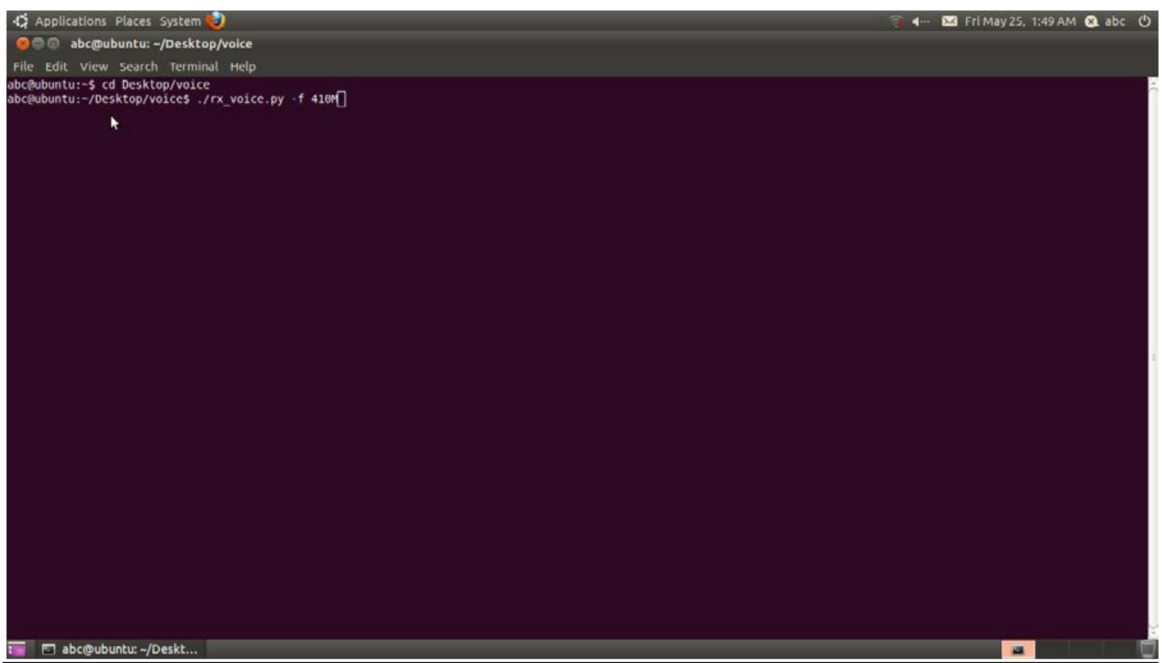
- 2 x Indigenously designed SDR platform
- 2 x LCD
- 2 x USB Keyboard
- 2 x USB Mouse
- 2 x 6V power cables
- 2 x platform power cables
- 2 x Headsets
- 2 x IP cameras

Installation and Operation:

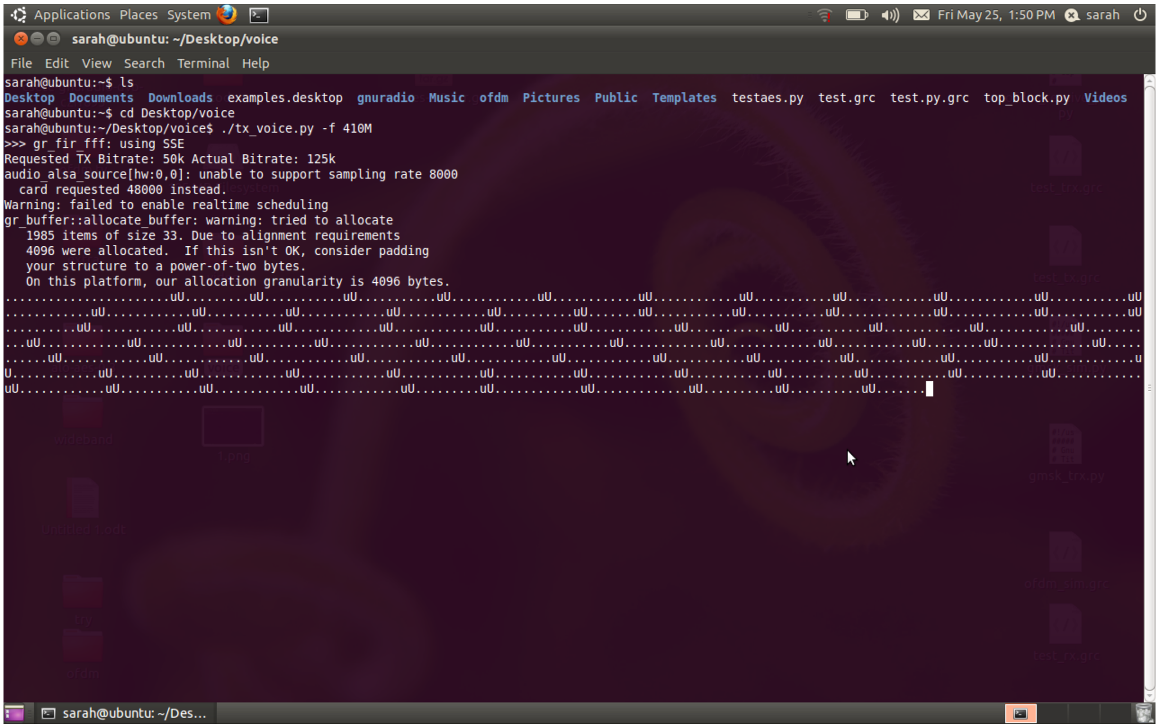
- Connect the LCD, Mouse, Keyboard, headset, camera and power cables to the SDR platform.
- Power up the two systems.
- Open terminal in Linux Ubuntu.
- For audio communication
  - Type the following commands for user A as shown



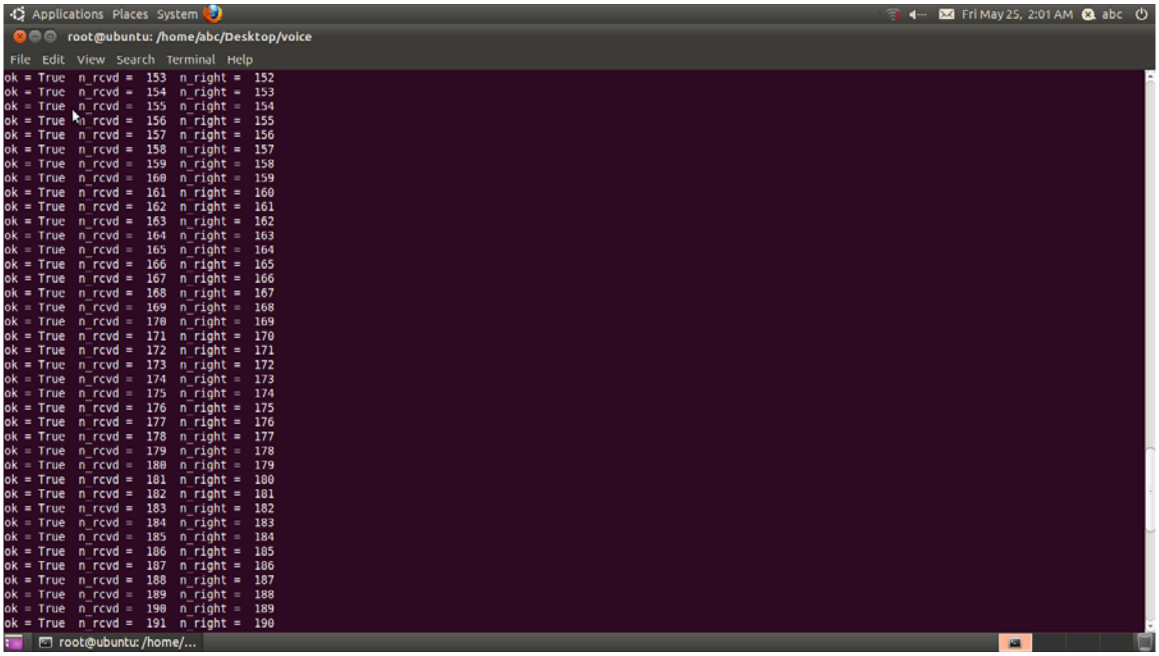
- For user B with system B, the commands in the terminal



- To initial communication enter the last command as seen in the above figures for both users
- The screen of user A should look like this



- The screen of user B will look like this

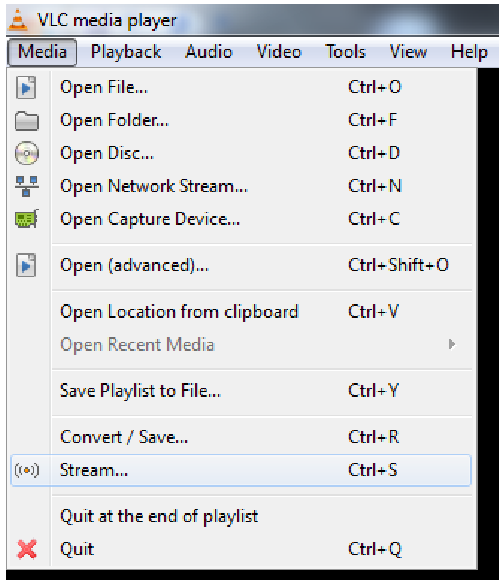


Successful audio transmission has started from user A to user B.

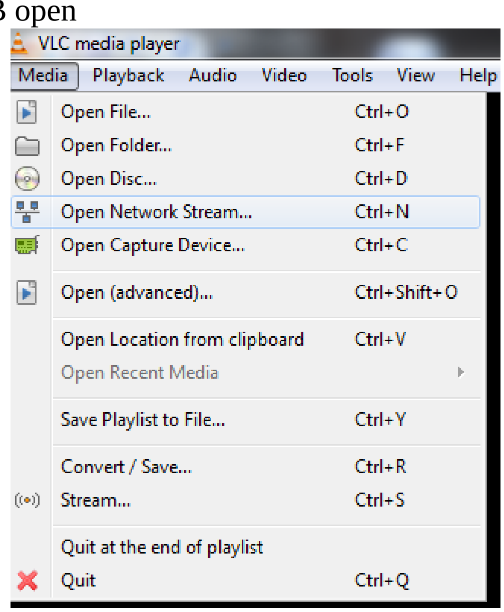
- For video transmission
  - For both users open two terminals each
  - For user A in one terminal type
    - Sudosu (enter)
    - ./taptun.py –tx-freq 410M –rx-freq 420M –bitrate 1M –c 50 (enter)
  - For user A in second terminal type
    - Sudoifconfig gr0 192.168.200.1 (enter)
  - For user B in one terminal type
    - Sudosu (enter)
    - ./taptun.py –tx-freq 420M –rx-freq 410M –bitrate 1M –c 50 (enter)
  - For user B in second terminal type
    - Sudoifconfig gr0 192.168.200.2 (enter)

A tunnel is established between the two systems it can be checked by ping.

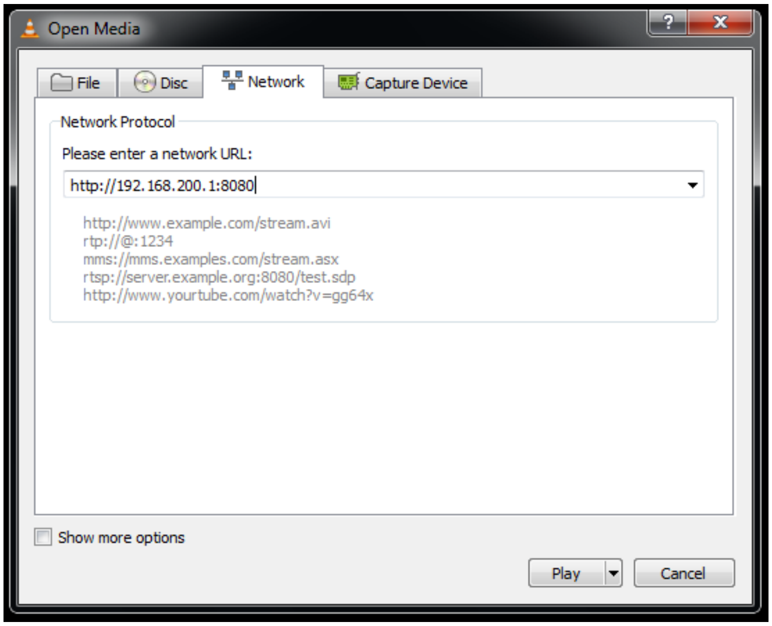
- Open Vlc in both the systems.
- User A open



- User B open



- Write the IP address of User A



Successful video transmission has started from user A to user B.

BIBLIOGRAPHY

BIBLOGRAPHY

[1] Software Radio: A modern approach to radio engineering by Jeffery H. Reed, Prentice Hall PTR, Upper Saddle River, New Jersey, 07458

[2] Software Defined Radio Certification in Europe:Challenges and Processes by GianmarcoBaldini Security Technology Assessment UnitJoint Research Centre, European CommissionIspra, Italy and DimitriosSymeonidisSecurity Technology Assessment UnitJoint Research Centre, European CommissionIspra, Italy.

[3] http://eda.europa.eu/Otheractivities/SDR/link_copy1

[4] Reconfigurable Radio Systems for Public Safety Based onLow-Cost Platforms by GianmarcoBaldini, Raimondo Giuliani, and DimitriosSymeonidisJoint Research Centre – European Commission.

[5] www.lyrtech.com (Lyrtech SFF SDR Platform)

[6] Blossom, E.: Exploring GNU Radio (last accessed September 16, 2008), http://www.gnu.org/software/gnuradio/doc/exploring-gnuradio.html

[7] http://www.spectrumsignal.com/category/products-services/integrated-systems/cpci-is/

[8] http://www.grc.nasa.gov/WWW/RT/2006/RC/RCD-kacpura1.html

[9] www.**sdr**forum.org/.../**SDR**F-08-P-0007-V1_0_0_**SCA**_Certification_Guide. pdf

[10] http://gnuradio.org/redmine/projects/gnuradio/wiki

[11] Intelligence and Security Informatics: European Conference, EuroISI 2008 by Daniel Ortiz-Arroyo

[12] Universal Software Radio Peripheral,The Foundation for Complete Software Radio Systems by Ettus Research

[13] GNU RADIO TESTBEDbyNaveenManicka

[14] http://www.vmetech.co.kr/datasheet/spectrum/sdrforcpci/sdr_4000.pdf

[15] http://gnuradio.org/redmine/projects/gnuradio/wiki/UbuntuInstall

[16] Digital Modulations Using the Universal Software RadioPeripheralByDanielKeithArtis

[17] SDR-Ready Standardized Waveforms for Tactical VHF and UHF Communications for NATO by Enrico Casini,PhilipVigneron, Rick Barfoot.

[18] http://en.wikipedia.org/wiki/Amplitude_modulation

[19] http://electrapk.com/14/

[20] http://www.radio-electronics.com/info/rf-technology-design/fm-frequency-modulation/what-is-fm-tutorial.php

[21] http://en.wikipedia.org/wiki/Phase_modulation

[22] http://en.wikipedia.org/wiki/Amplitude-shift_keying

[23] http://en.wikipedia.org/wiki/Phase-shift_keying