

IMPLEMENTATION OF A SOFTWARE DEFINED RADIO ON FPGAs  
USING SYSTEM GENERATOR

A Thesis  
Presented for the  
Master of Science Degree  
The University of Tennessee at Chattanooga

Tanvika M. Patel  
May 10, 2010

Certification of Final Defense of Thesis  
The Graduate School  
The University of Tennessee at Chattanooga

This is to certify that

Tanvika Patel  
Zgv565

A candidate for the Master of Science in Electrical Engineering

Passed

The defense of

IMPLEMENTATION OF A SOFTWARE DEFINED RADIO ON FPGAs USING  
SYSTEM GENERATOR

05/10/2010

Committee Names and Signatures

---

Name (Chairperson)

Signature

---

Name (Committee Member)

Signature

---

Name (Committee Member)

Signature

## **ABSTRACT**

The aim of this thesis is to implement a Software Defined Radio based wireless communication system using a Xilinx Spartan 3E Field Programmable Gate Array. Software Defined Radio refers to the class of reprogrammable radios in which the same piece of hardware can perform different functions at different times. Xilinx's System Generator for Digital Signal Processor tool is used to simulate and implement AM modulation on the Spartan 3E Starter Board.

This paper includes detailed procedure to create a radio design using Matlab Simulink and download the design onto the Spartan 3E board has been documented. The performance of a baseband radio transmitter is analyzed using waveforms for three different modulation techniques. The Modulation techniques include Amplitude Modulation, Amplitude Shift keying and Binary phase shift keying. The radio performance in real time is also analyzed by implementing these modulation techniques on the hardware using a Xilinx Spartan 3E board. By comparing the waveforms generated by implementing on the hardware and waveforms obtained by the Simulink, the system was validated.

## **ACKNOWLEDGEMENTS**

I would like to express my appreciation to my thesis advisor Dr. Stephen Craven for his support and guidance. He has been constant source of inspiration and has provided consistent support and valuable suggestion throughout this project without which this work wouldn't have been possible.

I would also like to thank Dr. Ahmed Eltom and Dr. Clifford Parten for their interest in the project and for being a part of my committee. I would also like to thank the Department of Electrical Engineering at University of Tennessee at Chattanooga for giving me the opportunity to do Master's degree in this honorable institution.

I would like to express my heart-felt gratitude to my family for their encouragement and support without which I wouldn't have come so far. Finally I would like to thank all my friends for their invaluable support and cooperation.

## LIST OF TABLES

<b>TABLE</b>	<b>PAGE</b>
1.1 Difference between Conventional Radio and Software Defined Radio .....	4

## LIST OF FIGURES

<b>FIGURE</b>	<b>PAGE</b>
1.1 (a) Block diagram of Conventional Radio.....	4
1.1 (b) Block Diagram of SDR.....	4
2.1 Basic block diagram of SDR System.....	8
2.2 USRP Hardware and Block diagram.....	12
2.3 Basic Architecture of GNU radio.....	13
3.1 Functional block diagram of digital transceiver .....	15
3.2 Demonstrating DDC On the Signal Lying In the Range of 39-40 MHz.....	17
3.3 Design flow using Xilinx system generator.....	19
3.4 Demonstrating DDC On the Signal Lying In the Range Of 39-40 MHz.....	21
3.5 System Generator dialog box.....	22
4.1 Radio Set Up.....	26
4.2 Simulation Model For AM Modulation.....	28
4.3 (a) Modulating Signal.....	29
4.3 (b) Carrier Signal.....	29
4.3 (c) Modulated Signal in Simulink.....	29
4.4 Modulated Waveform Viewed with Oscilloscope.....	30
4.5 Basic block Diagram of ASK.....	31
4.6 (a) ASK Modulated Signal.....	32
4.6 (b) OOK Modulated Signal in Simulink.....	32
4.7 OOK Modulated waveform viewed with Oscilloscope.....	33
4.8 Basic Block Diagram of BPSK Modulator.....	34

4.9 (a)	BPSK Waveform in Simulink.....	35
4.9 (b)	BPSK Modulated Waveform Viewed with Oscilloscope.....	

## LIST OF ACRONYMS

ADC	Analog to Digital Converter
AM	Amplitude Modulation
ASK	Amplitude Shift Keying
AGC	Automatic Gain Control
ASIC	Application Specific Integrated Circuit
BPSK	Binary Phase Shift Keying
BPF	Band Pass Filter
CDMA	Code Division Multiple Access
DDS	Direct Digital Synthesizer
DAC	Digital to Analog Converter
DSP	Digital Signal Processor
DDC	Digital Down Converter
DSB	Double Side Band
DUC	Digital Up Conversion.
FCC	Federal Communication Commission
FPGA	Field Programmable Gate Array
FM	Frequency Modulation
FIR	Finite Impulse Response
FFT	Fast Fourier Transform
GUI	Graphical User Interface
GPP	General Purpose Processors
HDL	Hardware Description Language



HR	Hardware Radio
ISDR	Ideal Software Defined Radio
IF	Intermediate Frequency
ISE	Integrated Software Environment
KHz	Kilo Hertz
LO	Local Oscillator
LUT	Look Up Table
MHz	Mega Hertz
MIMO	Multiple Input Multiple Output
OOK	On- Off Keying
PC	Personal Computer
PMOD	Peripheral Modules
RF	Radio Frequency
RSSI	Received Signal Strength Indication
RAM	Random Access Memory
SDR	Software Defined Radio
SCR	Software Controlled Radio
TDMA	Time Division Multiple Access
USRP	Universal software radio peripheral
USB	Universal Serial Bus
VHSIC	Very High Speed Integrated Circuit
VHDL	VHSIC Hardware Description Language
XST	Xilinx Synthesis Tool

## TABLE OF CONTENTS

CHAPTER	PAGE
I. ABSTRACT .....	i
II. ACKNOWLEDGEMENT.....	ii
III. LIST OF TABLE.....	iii
IV. LIST OF FIGURE.....	iv
V. LIST OF ACRONYMS.....	v
1.INTRODUCTION .....	1
1.1 Introduction.....	1
1.2 Software Defined Radio versus Conventional Radio.....	3
1.3 Outline of Thesis .....	5
2.BACKGROUND.....	6
2.1 Introduction.....	6
2.2 Definitions of Software Defined Radio.....	7
2.3 Characteristics of Software Defined Radio.....	8
2.4 Advantages and Disadvantages of Software Defined Radio.....	9
2.5 Implementation Platform.....	10
2.6 USRP.....	11
2.7 GNU Radio.....	12
2.8 System Generator.....	13
3. SDR DESIGN METHODOLOGY.....	15
3.1 Wireless Communication System Model for Software Defined Radio .....	15

3.1.1 DDC and DUC.....	15
3.1.2 Basic Transceiver Function.....	17
3.2 System Generator Design Flow.....	18
3.3 Simulation with System Generator and Simulink.....	20
3.4 Bitstream Generation .....	22
4. EXPERIMENTAL SET UP, SIMULATIONS AND RESULTS.....	24
4.1 Introduction.....	24
4.2 Basic Modulation Concept.....	24
4.3 Amplitude Modulation (AM).....	24
4.3.1 AM SDR Setup.....	25
4.3.2 System Generator Implementation.....	26
4.4 Amplitude Shift Keying.....	30
4.5 Binary phase shift keying (BPSK).....	33
5. CONCLUSION AND FUTURE WORK .....	35
5.1 Conclusion.....	35
5.2 Suggestion for future work.....	36
REFERENCES.....	37

# CHAPTER 1

## Introduction

### 1.1 Introduction

Wireless communication networks have become more popular in the past two decades since the advent of cellular communications. Today advancements in wireless technology and wireless applications require flexibility in the hardware. It is very expensive and time consuming to create new radios in response to changing wireless standards and applications [1]. Software radio can offer solutions to these problems by moving analog circuit components into the digital domain. Programmable logic devices, such as Field Programmable Gate Arrays (FPGAs) can be used to implement the radio functions.

Software Defined Radio (SDR) has gained much interest in recent years due to the advancements in processor and FPGA technology. FPGAs provide the capability of cheaply implementing functionality that previously was created using analog hardware components. FPGAs are built from one basic reconfigurable logic cell duplicated thousands of times. A logic cell is basically a small lookup table (LUT), a D flip-flop and a 2-to-1 multiplexer. The LUT is like a small RAM that can implement any logic function up to four inputs. Complex logic functions are created by connecting number of logic cells together through interconnect resources (wires and multiplexer placed around logic cell). Designs targeting FPGAs are typically described using Hardware Descriptions Languages (HDLs). However, in this thesis digital functional blocks that needed to be programmed in the FPGA core are designed and simulated using MATLAB and add-on programs.

“In a Software Defined Radio (SDR), functions that were formerly carried out solely in hardware, such as the generation of the transmitted signal and the tuning and detection of the received radio signal, are performed by software that controls high speed signal processors [6]”.

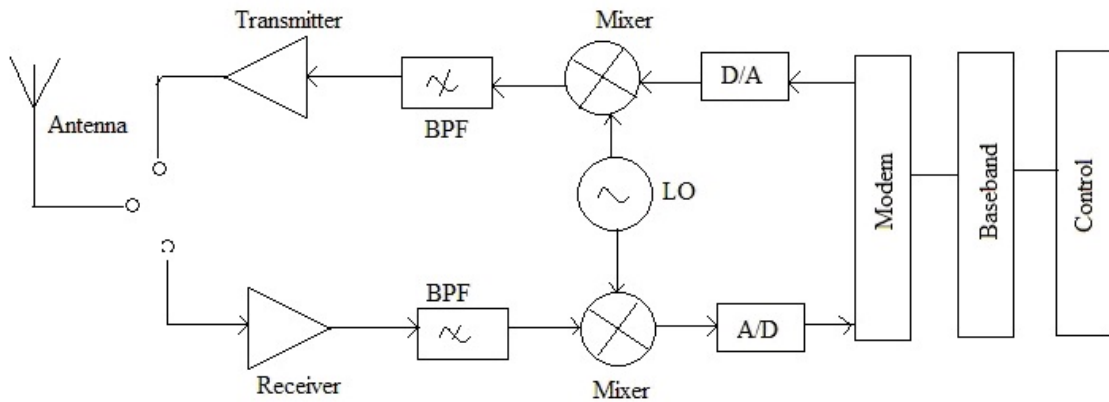
Reconfigurability in radio technology in radio development is not a new technique. In the 1980s, the first reconfigurable receiver was developed for radio intelligence to intercept and record enemy radio transmission and to determine their locations in the short wave range [1]. As per SDR forum discussion the difference between different levels of flexibility in a radio are as follows:

- 1) Hardware Radio (HR): Hardware Radio is defined as radio in which there is no software control of the hardware. The function of the hardware is set so it cannot be changed [13].
- 2) Software Controlled Radio (SCR): In this radio only the control functions are implemented in software. For example, the transmitter parameters like the transmitted power level are controlled by software, while the other functions are fixed in hardware [6].
- 3) Software Defined Radio (SDR): The name itself suggests that all radio functions are implemented by software. These functions include modulation, multiplexing, amplification, mixing, multiple access and other transmitter and receiver processes [6].
- 4) Ideal Software Defined Radio (ISDR): ISDR is same as SDR except that it does not include front end analog. Ideal SDR is one that has a transceiver that performs up conversion and down conversion between baseband and the Radio Frequency (RF)

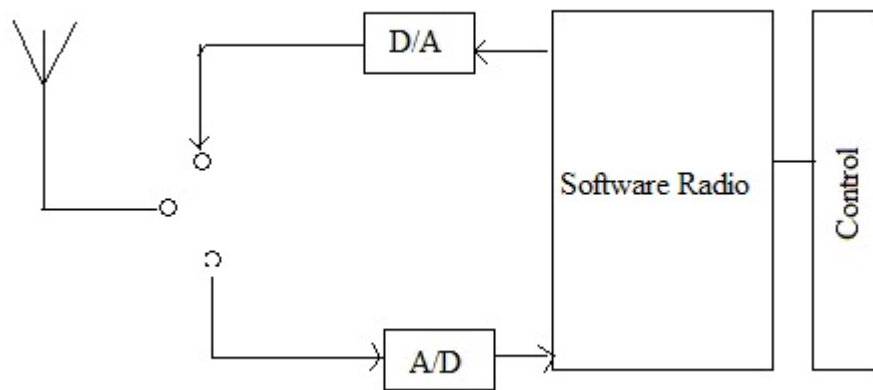
carrier exclusively in the digital domain, reducing the RF interface to a power amplifier in the transmit path, a low noise amplifier in the receive path, and little or no analog filtering. ISDR is currently unachievable due to the lack of very high frequency RF-to-Digital converters capable of converting carrier frequencies directly to digital data [6].

## **1.2 Software Defined Radio versus Conventional Radio**

Figure 1.1(a) shows the basic block diagram of a conventional radio. In a conventional radio's receive path, the radio RF signal is received by an antenna and it goes through a band pass filter. Frequency conversion from the transmitted RF to a lower, intermediate frequency (IF) is accomplished by multiplying the RF signal by a sinusoidal local oscillator (LO) in the mixer. An Analog to Digital Converter (ADC) then samples the output from the final IF stage and the digital data are processed by a Digital Signal Processing (DSP) circuit. The components from antenna to ADC are all analog circuits. If more stages of down conversion exist, then more analog components are needed. Analog components have limitations on signal processing capabilities and flexibility. And also analog components are expensive. If the number of analog components is reduced, it will result in simplification of the radio system, which in turn will result in higher reliability and reduced cost. It would be best if all the intermediate analog stages could be replaced by digital components, so that the antenna is directly connected to an ADC or DAC. This is shown clearly in Figure 1.1(b). The idea behind software defined radio is to move as much of the radio functionality as possible into software. For low frequency SDR, all the RF tasks (DUC,DDC) can be performed on the FPGA, allowing the ADC to sample the antenna directly.



(a)



(b)

**Figure 1.1 (a) Block Diagram of Conventional Radio (b) Block Diagram of SDR**

Air interface is the technology used for the radio transmission between base station and mobile units in a wireless network, such as, Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA). To compare the functionalities of conventional radio and SDR, A tabulation of their functions is provided in Table 1.1.

**Table 1.1 Difference between Conventional Radio and Software Defined Radio [19].**

<b>Conventional Radio</b>	<b>Software Defined Radio</b>
Radio functionalities are primarily defined in hardware with minimum configurability in software.	Radio functionalities are defined in software.
Upgrading of design is not possible.	Upgrading is easy because of software based architecture.
User has to use different mobile devices because of incapability of standards.	Global mobility can be achieved by downloading the appropriate air interface (TDMA, CDMA) thus overcoming the incapability of standards.
Less efficient	Reprogrammability makes SDR more efficient and compact

### **1.3 Outline of Thesis**

In this thesis Chapter 2 presents the background of software defined radio. This presents the fundamentals of software defined radio, general background information and various definitions of the software defined radio. It also presents the existing technologies in the SDR field. Chapter 3 presents a design methodology for implementation on FPGAs using the Xilinx System Generator software. Chapter 4 presents the experimental set up. Simulation results for the different modulation techniques such as AM modulation, Amplitude Shift Keying (ASK), On-Off Keying (OOK), Binary Phase Shift Keying (BPSK) modulation are analyzed. AM modulation is implemented on the Xilinx Spartan 3E Starter Kit. Chapter 5 summarizes the Thesis content and also discusses future work.



## **CHAPTER 2.**

### **BACKGROUND**

#### **2.1 Introduction**

In traditional architectures all modulation and demodulation is performed in the analog domain. Over the last few years, analog radio systems are being replaced by digital radio systems for various radio applications in military, civilian and commercial spaces. In addition to this, programmable hardware modules are increasingly being used in digital radio systems at different functional levels. SDR technology aims to take advantage of these programmable hardware modules to build open architecture based radio system software [12].

Traditional hardware based radio devices limit cross functionality and can only be modified through physical intervention. This results in higher production costs and minimal flexibility in supporting multiple waveform standards. Software Defined Radio technology provides an efficient and comparatively inexpensive solution to this problem, allowing multimode, multi-band or multi-functional wireless devices that can be enhanced using software upgrades [15].

Software Defined Radio refers to the class of reprogrammable radios in which the same piece of hardware can perform different functions at different times. A convenient approach is to use Field Programmable Gate Arrays (FPGAs) to implement physical layer signal processing for software defined radios. The FPGAs was first invented by Xilinx in 1984. Since its invention it has gone from being simple glue logic chips to actually replacing custom application-specific integrated circuits (ASICs) and processors for signal processing and control applications.

Currently the radio interface in a wireless system is usually implemented by dedicated hardware. SDR came out as reprogrammable architectures were developed with the throughput required to perform the signal processing operations common in radios. Many of the SDR developments have been increased by the need for reconfigurable radio receivers and transmitters [12]. For example, the radio system at a cell site might need to be reconfigured to implement new standards or protocols, bypass failed hardware, or reconfigure the network due to a change in the traffic pattern. By using SDR, these changes can be performed remotely, and without changing the radio's hardware, thereby reducing the need for visits to the site and increasing cost efficiency [15].

While commercial SDR products exist, they are typically geared toward military or telecommunication use and, as such, permit the implementation of high frequency and high-complexity radios. For simple research and educational purposes many of these products are simply too complex and too expensive. However, several SDR systems exist that provide limited functionality for a much reduced cost, making them appropriate for hobby and educational use. Two such systems are discussed below.

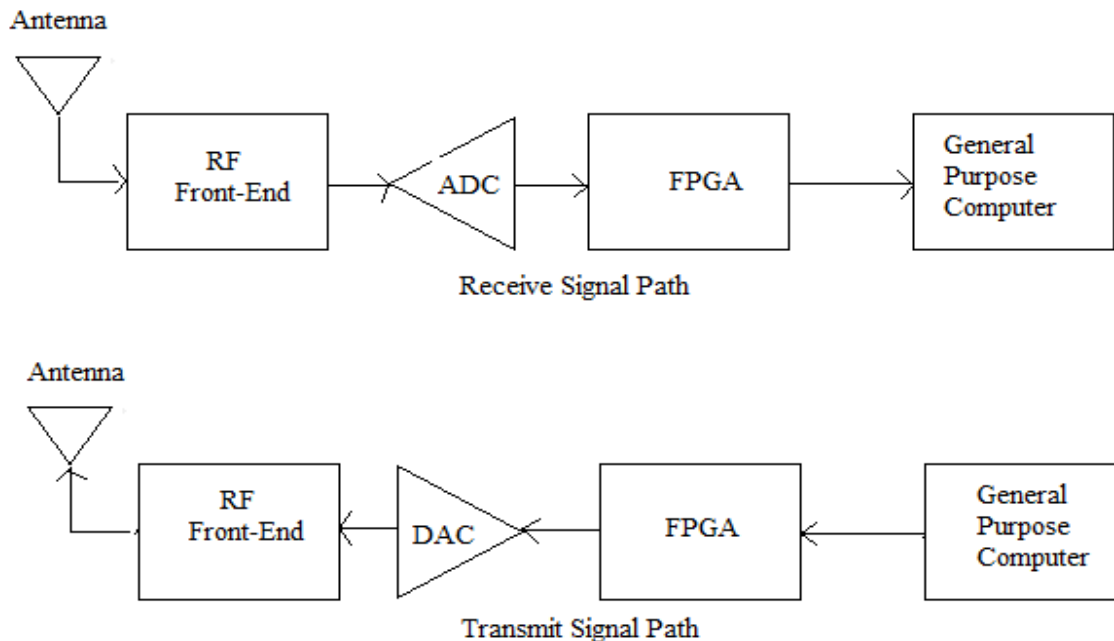
## **2.2 Definitions of Software Defined Radio**

Because of the many features of SDR, there are many definitions available. Radios that include microprocessors and digital signal processors do not necessarily qualify as a software radio. However a radio in which all the functions such as modulation, error correction, and encryption processes can be reprogrammed is called a software defined radio [11]. The most common definitions of Software Defined Radio are as follow [16]:

- Flexible transceiver architecture, controlled and programmable by software.
- Digital signal processor able to replace, as much as possible, radio functionalities.
- Transceiver where frequency band & radio channel bandwidth, modulation & coding scheme and radio resource and mobility management protocols can be defined by software.

### 2.3 Characteristics of Software Defined Radio

Consider the system model of a SDR shown in Figure 2.3. The signal transmission and reception is performed by the antenna. In the receiver's first section is the Radio Frequency (RF) front end where the signal is received at a carrier frequency and down converted to an Intermediate frequency (IF ) or to the baseband frequency by mixing the incoming frequency with a local oscillator frequency. The Intermediate Frequency (IF) section digitally samples the IF signal with the help of an Analog to Digital Converter (ADC) [9].



**Figure 2.3 Basic Block Diagram of SDR System. [7]**

Finally, the baseband section consists of either a processor or an FPGA, which demodulates and filters the signal. The software or the code is downloaded into the processor or FPGA hardware and it produces the output in accordance with the programmed parameters (modulation type and frequency band). For low frequency radios, the computational throughput of the FPGA is great enough to perform all of the RF front end tasks (down conversion, demodulation, etc.) in the FPGA itself, allowing the ADC to sample the antenna directly.

In the transmitter, the FPGA can be positioned between the DAC and the computer. Here the FPGA performs the computationally expensive signal processing which includes digital up conversion and interpolation filtering. The DAC converts the digital signal to an analog signal. The RF front end translates the outgoing signal from IF or baseband to the desire carrier frequency by mixing the incoming frequency to the local oscillator frequency.

#### **2.4 Advantages and Disadvantages of Software Defined Radio**

With SDR, the same piece of hardware will be rearranged to perform different functions [15]. By using the same piece of hardware, time and cost can be saved. Another advantage of SDR would be the possibility to improve the software in successive steps, and correcting errors and bugs discovered during the operation. SDR provides the benefits like reduced size, complexity and power consumption. The most important advantage of an SDR system is that it can support a variety of transmission standards, modulation schemes, and protocols simultaneously. While SDRs offer benefits as discussed above, there are drawback in the design and implementation of SDR. These include:

- The difficulty of designing software or hardware for various target systems or standards.
- The problem of poor dynamic range of the receiver in some communication system designs. The dynamic range of the receiver describes its ability to pick up weak signals.

## **2.5 Implementation Platform**

Real time software defined radio designs can be implemented using a variety of digital hardware platforms. These include FPGAs, digital signal processors, ASICs and general purpose processors. Each is discussed and compared below.

The DSP platform is essentially a microprocessor based system optimized for digital signal processing applications. High level languages such as C and MATLAB are used to program DSPs. One of the main disadvantages of DSPs are that when there are several computations to be performed, parallel executions of these computations will slow down the rate at which data is processed.

FPGAs are general purpose integrated circuits that are programmed by a hardware designer. An FPGA is programmed by downloading a bitstream into the static on-chip random access memory. The unique feature of FPGA is that it can be reprogrammed, even after it has been deployed in the system. Because of this unique quality, their configuration can be easily modified to upgrade the system.

ASICs, as the name implies, are used for only specific applications. ASICs implement circuits with fixed hardware and cannot be modified after manufacture. Typically ASIC design is very expensive and time consuming.

General purpose processors are similar to DSPs as a hardware platform. It offers flexibility and simplicity of design. Like DSPs, radio functionalities can be implemented in high level languages such as C and C++.

General purpose processors are most generalized hardware that can be programmed to perform various functions, while ASICs are designed for a specific application. FPGAs offer a compromise in flexibility between ASIC and processor-based platforms. There is a trade off between the maximum flexibility and high power consumption of processor platforms and the minimum flexibility and lower power consumption of ASICs with FPGAs lying in between. There are other advantages of using FPGAs instead of DSPs for signal processing in telecommunication system. FPGAs are small, faster, offer higher throughputs, while the DSPs are cheaper than FPGAs.

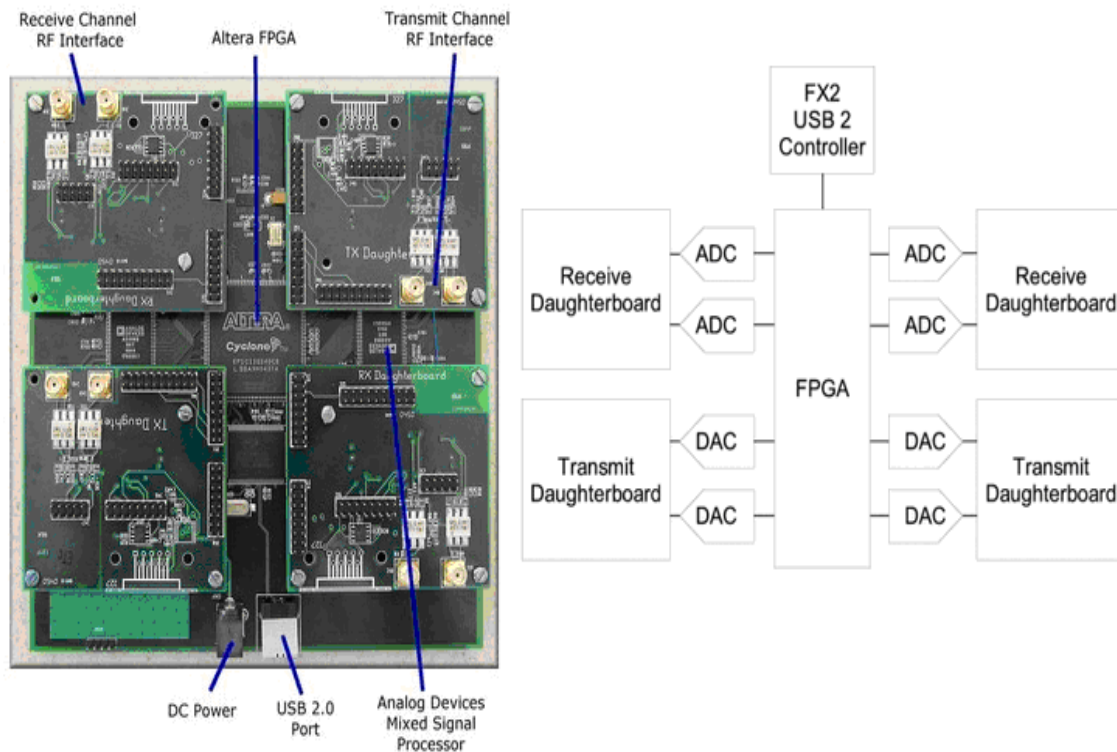
## **2.6 USRP (Universal Software Radio Peripheral)**

The universal software radio peripheral is responsible for the creation of a software defined radio using any computer with an USB 2.0 port. Usually the USRP board consists of one mother board and up to four daughter boards. Daughter boards operating from DC to 2.9 GHz are available [3]. Figure 2.1 shows the USRP hardware and block diagram.

Features of USRP include:

- Four 64 MS/s 12 bit analog to digital converters and four 128 MS/s 14 bit digital to analog converters.
- Four digital down converters with programmable decimation rates and two digital up converters with programmable interpolation rates.

- High speed USB 2.0 interface (480 Mb/s) and capable of processing a signal up to 16 MHz wide.
- Modular architecture supports wide variety of RF daughter boards.
- Auxiliary analog and digital I/O support complex radio controls such AGC.
- Fully coherent multi-channel systems (MIMO capable).



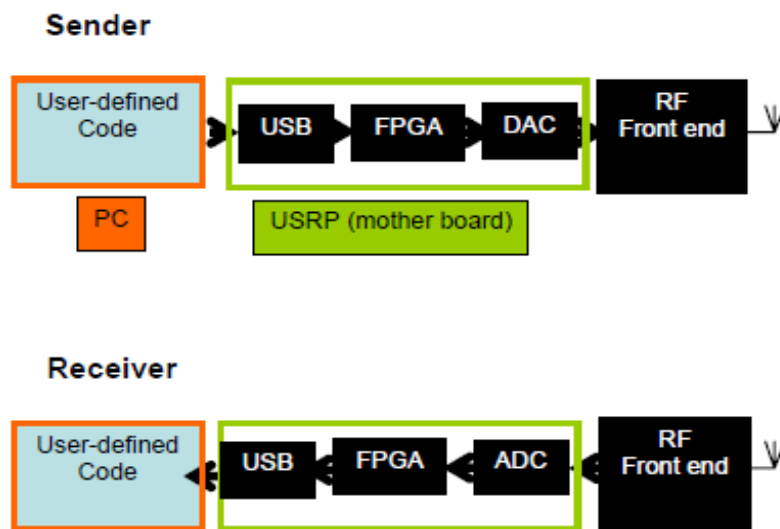
**Figure 2.1. USRP Hardware and Block Diagram. [3]**

## 2.7 GNU Radio

GNU radio is an open source software toolkit which provides a library of signal processing blocks and attaches these blocks together for building Software Defined Radios. In GNU radio the demodulation of the received waveform is achieved using software which also defines the transmitted waveforms. In short GNU radio is software defined radio that can implement practically any traditional radio just by changing the software [15]. GNU radio provides functions which can support implementing spectrum

analyzers, oscilloscopes, multichannel receivers, and an ever-growing collection of modulators and demodulators.

Figure 2.2 shows the basic architecture of GNU radio. It has three sections which includes an RF front end, USRP and PC. The user can develop and implement high throughput radios using the Python programming language and C++. The motherboard (USRP) includes four 12-bit 64M sample/sec ADCs, four 14-bit, 128 sample/sec DACs, a million gate Field Programmable Gate Array and a programmable USB 2.0 controller. The ADC and DAC are the bridge between the continuous-time analog signal and the discrete digital signal. At the receiver side an RF front end converts the received high frequency signal to a lower range [7].



**Figure 2.2 Basic Architecture of GNU Radio [7]**

## 2.8 System Generator

System Generator for DSP is a high-level tool for designing high-performance DSP systems using FPGAs [17]. It allows a user to develop highly parallel systems with advanced FPGAs. It provides system modeling and automatic code generation from



Simulink and MATLAB. It also integrates the Register Transfer Level (RTL) HDL, embedded, IP, MATLAB, and hardware components of a DSP system.

Features of System Generator include:

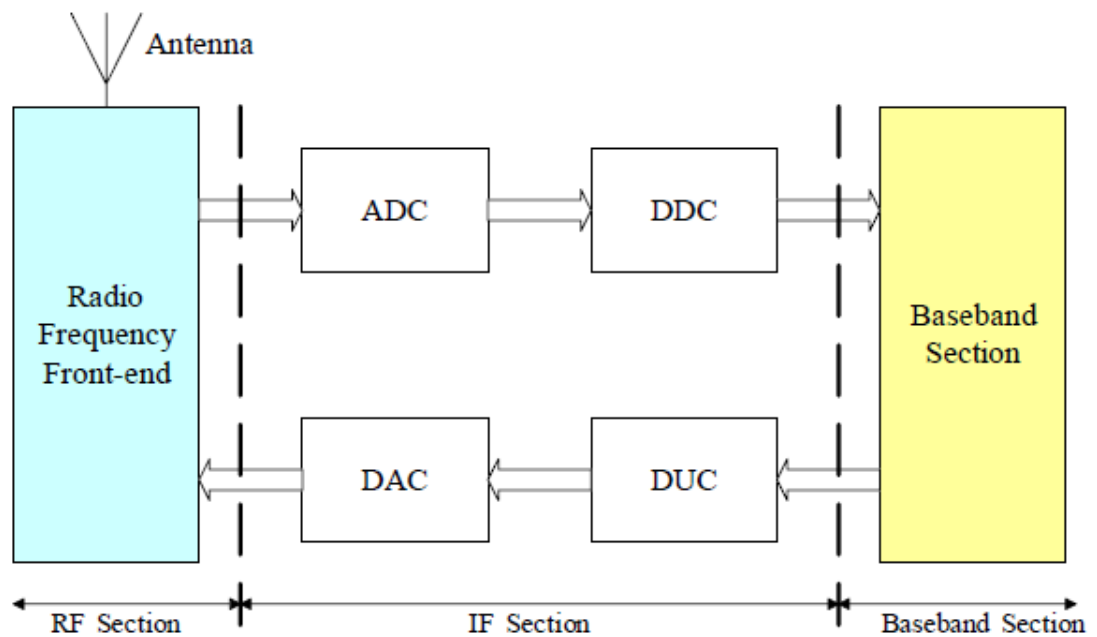
- **DSP modeling:** It builds and debugs high-performance DSP systems in Simulink using a special Xilinx Blockset that contains hardware descriptions of functions for signal processing (e.g., FIR filters, FFTs), error correction (e.g., Viterbi decoder, Reed-Solomon encoder/decoder), arithmetic, memories (e.g., FIFO, RAM, ROM), and digital logic.
- **Automatic code generation of HDL from Simulink:** It produces hardware designs using target-specific Xilinx IP cores from the Xilinx Blockset. System Generator, supports blocks generated from the AccelDSP synthesis tool, and supports custom HDL inclusion.
- **Hardware co-simulation:** It supports the execution of generated hardware modules on the FPGA, automatically importing the results into Simulink. Thus, results for the compiled System Generator blocks are computed on the FPGA rather than being emulated in software.
- **Hardware / software co-design of embedded systems:** It allows simultaneous design of both hardware and software to be implemented in a desired function. System Generator provides a shared memory abstraction of the HW/SW interface, automatically generating the DSP co-processor, the bus interface logic, software drivers, and software documentation for using the co-processor.

## CHAPTER 3

### SDR DESIGN METHODOLOGY

#### 3.1 Wireless Communication System Model for Software Defined Radio.

The standard wireless communication system consists of a transmitter, channel, and a receiver. Figure 3.1 shows the functional block diagram of the digital transceiver.



**Figure 3.1 Functional Block Diagram Of Digital Transceiver [20].**

##### 3.1.1 DDC and DUC

Fundamental parts of many digital communication systems are a Digital Down Converter (DDC) and a Digital Up Conversion (DUC). DDC and DUC are widely used in communication systems for changing the sample rate of the signals. The baseband signal is filtered and converted to a higher sampling rate before being modulated by the carrier frequency. Digital down conversion is a technique that takes

a band-limited high sample rate digitized signal, mixes the signal to a lower frequency and reduces the sample rate.

Digital receivers often have fast AD converters to digitize the band-limited RF or IF signal resulting in high data rates. To extract the desired frequency at this high sample rate would require a large filter. DDC allows one to move the desired frequency band down so that the sample rate can be reduced and ease the filtering requirements [21].

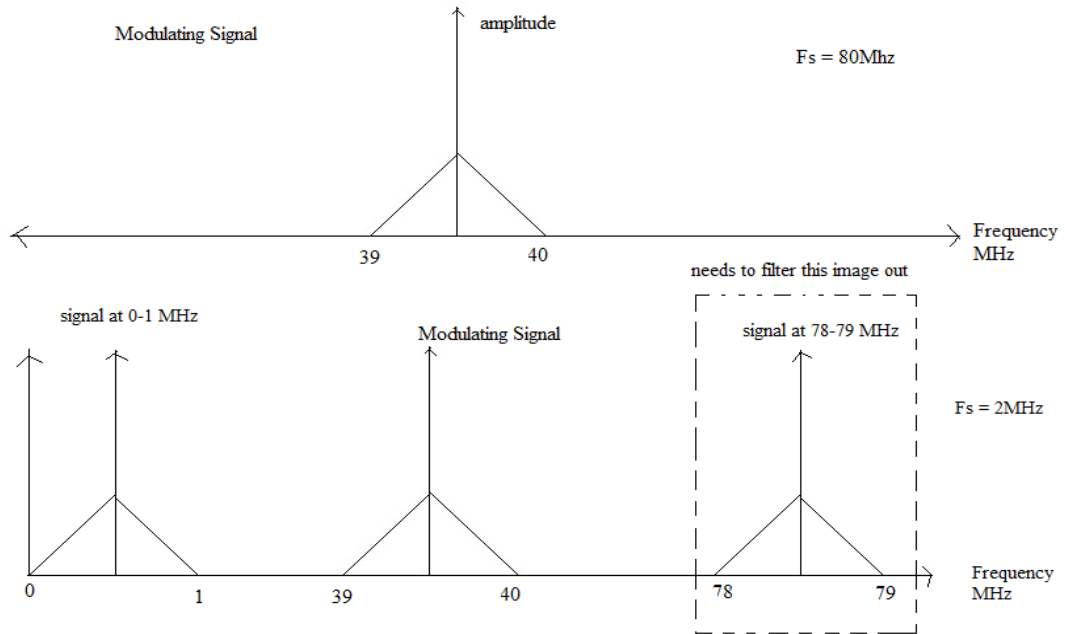
As an example, consider a radio signal lying in the range of 39-40 MHz with a bandwidth of 1 MHz. According to the Nyquist theorem, a sampling rate of over 80 M samples/sec would be required to correctly sample the signal. As shown in Figure 3.2, the DDC allows the selection of the 39-40 MHz band and shift its frequency down to baseband. The sample rate can then be reduced to just over 2M samples/sec. The basic equation for DDC is:

$$\text{Frequency (A)} * \text{Frequency (B)} = \text{Frequency (A-B)} + \text{Frequency (A+B)}$$

In the above example, if the signal is multiplied by 39 MHz thus,

$$\text{Input Signal} * 39\text{MHz} = \text{Signal at (0-1) MHz} + \text{Signal at (78-79) MHz}.$$

So the signal is shifted to the 0-1 MHz range and it needs at least a 2 MHz sample rate. The high frequency components (signal at 78-79 MHz) of the signal need to be filtered out.



**Figure 3.2. Demonstrating DDC on the Signal Lying in the Range of 39-40 MHz**

### 3.1.2 Basic Transceiver Function

The RF section consists of an antenna and some analog hardware like mixers and local oscillators to convert the RF signal into the intermediate frequency signal. The RF front end is designed in such a way to reduce interference and noise. The RF front end on the receiver performs amplification and down conversion from RF to IF. An RF front end on the transmitter performs up conversion and RF amplification [22].

The intermediate frequency stage includes an ADC followed by a DDC on the receive path and a Digital Up Converter (DUC) followed by a Digital to Analog Converter (DAC) on the transmit path [22]. This allows the receiver to reconstruct the original data in the presence of transmission errors.

The baseband section performs operations such as error correction, equalization, frequency hopping, modulation, demodulation, and timing recovery. Forward Error Correction (FEC) is a method of obtaining error control in data transmission in which the

transmitter sends redundant data allowing the receiver to reconstruct the original data in the presence of transmission errors. In a wireless communication system analog modulation techniques such as Amplitude Modulation (AM) and Frequency Modulation (FM) and digital communication techniques such as Binary Phase Shift Keying (BPSK), Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), etc. are used. In this thesis an implementation of AM modulation on an FPGA using System Generator is discussed in the next chapter [22].

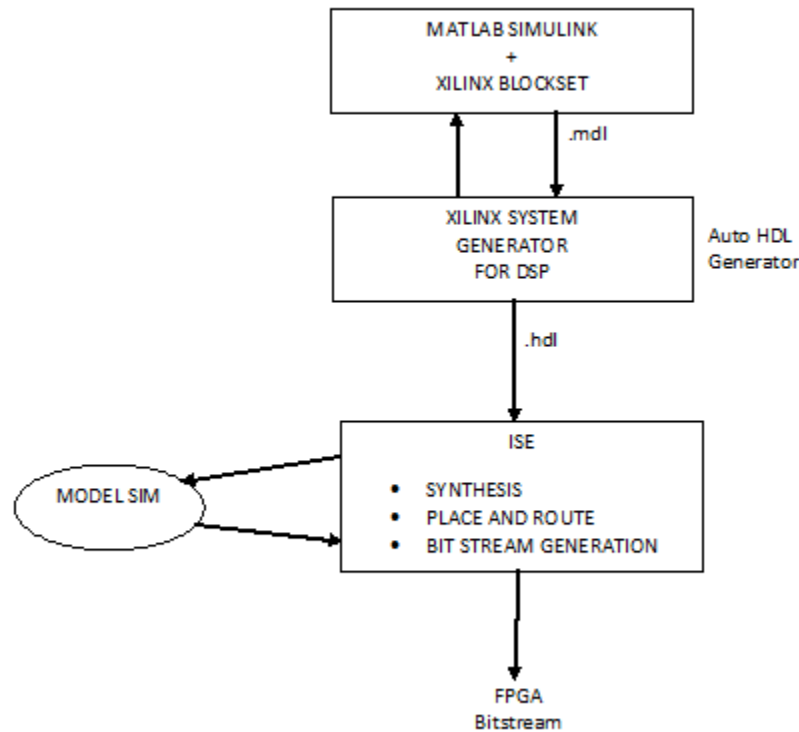
### **3.2 System Generator Design Flow**

By using FPGAs very high throughputs can be achieved in digital signal processing (DSP) applications. DSP application developers typically use Matlab to develop algorithms while FPGA developers use Hardware Description Languages (HDLs), such as Verilog and VHDL. This makes it difficult for DSP developers to transition their applications to FPGAs.

System blocks are shared however, between DSP designers and FPGA technology. With Xilinx, DSP designs can be implemented on FPGAs using MATLAB and Simulink from Mathworks combined with Xilinx's System Generator for DSP applications. The first step of the design process is simulation of the SDR system with Simulink. For the hardware-implementable representation of the radio, the Xilinx System Generator block set in Simulink is used. Figure 3.3 shows the general overview of the design flow using Xilinx system generator [24].

**Design Entry:** This is the first step in the design flow which consists in transforming the design ideas into some form of computerized representation. This can be achieved using Hardware Description Language (HDLs). The two most popular HDLs are Verilog and Very High Speed Integrated Circuit HDL (VHDL) [23].

**Synthesis:** The HDL itself is must first be compiled, or synthesized, into a gate level netlist before it can be placed on the FPGA. This netlist uses the logic gate primitives supplied by the vendor in order to satisfy the logic behavior specified in the HDL files. Thus, the synthesis step maps the HDL to the gate level representation [23].



**Figure. 3.3 Design Flow Using Xilinx System Generator [25]**

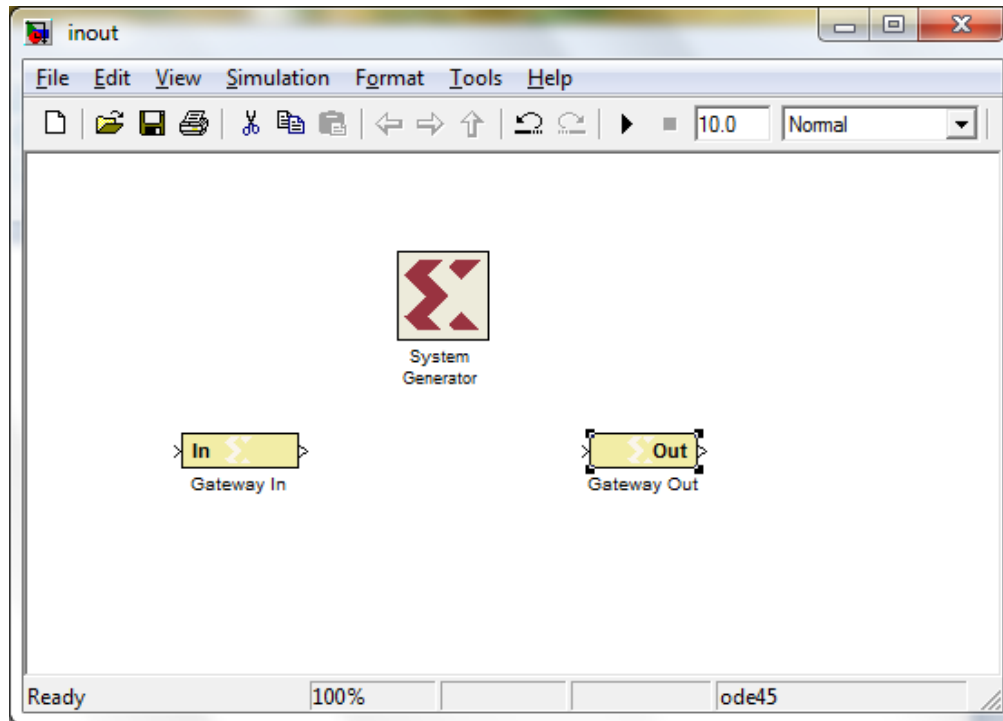
**Place and Route:** The placer program takes the synthesized netlist and chooses the place for each of the primitives inside the chip. The router program is then used to

interconnect all the primitives together to satisfy the timing constraints. This can be accomplished by Xilinx's ISE implementation programs. The most obvious constraint for the design is the system's clock frequency [23].

**Bit stream Generation:** Placing and routing is followed by the generation of the FPGAs programming file, called a bitstream. The design can then be downloaded into the target FPGA [23].

### **3.3 Simulation with System Generator and Simulink**

In this thesis, SDR algorithms are designed and simulated using Xilinx System Generator system level tool. For timing and logic-accurate simulation of the final hardware design, the Xilinx System Generator block sets within Simulink are used. The Xilinx block set enables bit true and cycle true modeling and includes common blocks such as Finite Impulse Response (FIR) filter, Fast Fourier Transform (FFT), Direct Digital Synthesizer (DDS), multiplier and more. Below a few steps are discussed for the processes of simulation using Simulink and System Generator [27].



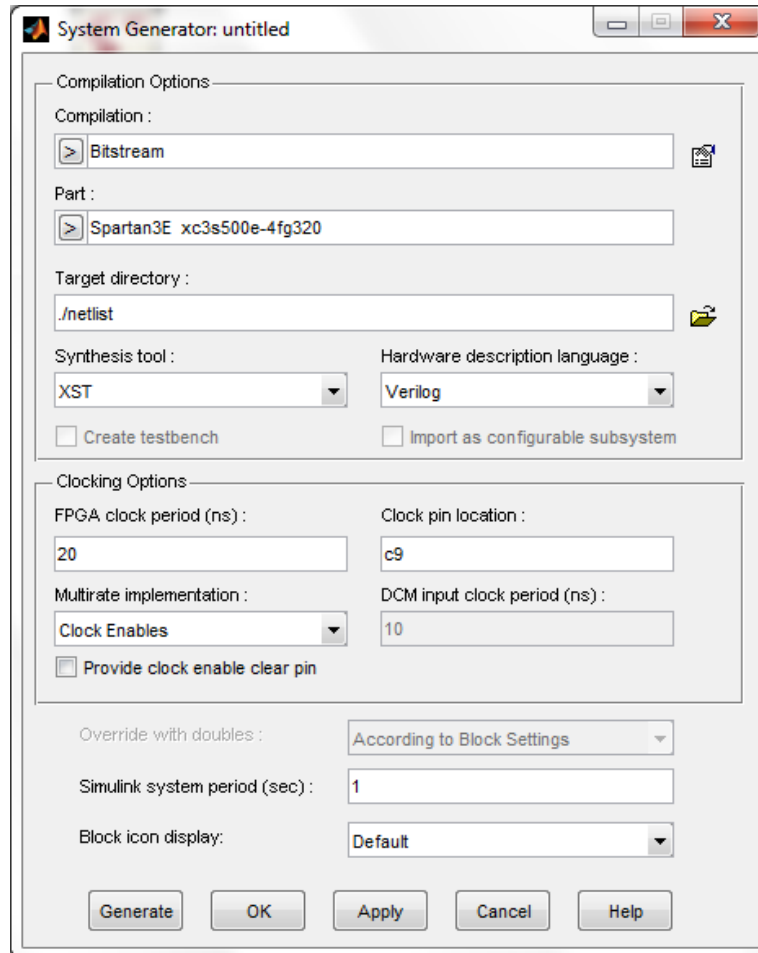
**Figure 3.4 Xilinx Gateway In, Gateway Out and System Generator Block**

1. As shown in figure 3.4, Start the design by implementing Xilinx blocks in the MATLAB Simulink program.
2. Select the Xilinx System Generator block and add it to the top of the design model.
3. “Gateway In “and “Gateway Out” blocks are use to define the inputs and outputs to the Xilinx design. These blocks automatically convert the double precision floating point value used in MATLAB to the fixed point value used in the FPGA. All the components located between these gateway blocks must be from the Xilinx block set only.
4. The design can be simulated and the output can be verified using visual output blocks.



### 3.4 Bitstream Generation

The System Generator system level design can be converted to a gate level representation through the steps listed below.



**Figure 3.5 System Generator Dialog Box**

- The System Generator block contains the hardware setting. This is illustrated in Figure 3.5. Xilinx XST is chosen for the Synthesis tool. HDL can be chosen as VHDL or Verilog. In this thesis Verilog is used.
- The next step is to run the System Generator by initiating the “Generate” button. It produces an FPGA configuration bit stream for the design that is suitable for hardware.

- Once a bit stream is generated then it is downloaded on the Spartan 3E Starter Kit board using the Xilinx ISE programming tool called Impact. [27]

## CHAPTER 4

### EXPERIMENTAL SET UP, SIMULATIONS AND RESULTS

#### 4.1 Introduction

This chapter describes the experimental set up, simulations and results for the different modulation techniques. Modulation techniques considered include analog techniques such as Amplitude Modulation (AM) and digital modulation techniques such as Amplitude Shift keying (ASK) and Binary Phase Shift Keying (BPSK). The system is modeled and simulated using MATLAB Simulink and System Generator. The system is then implemented on a Spartan 3E FPGA for real time measurements.

#### 4.2 Basic Modulation Concept

Modulation is the process of converting a message into a format that can be successfully transmitted through a medium. A sinusoid has three different parameters that can be varied: amplitude, phase and frequency. Depending on the chosen parameter we have modulation techniques such as amplitude modulation, phase modulation and frequency modulation. On the receiver side the modulated sine wave is converted back to the original information signal. In this chapter Amplitude Modulation (AM), Amplitude Shift Keying (ASK), Binary Phase Shift Keying (BPSK) are discussed.

#### 4.3 Amplitude Modulation (AM)

Amplitude modulation transmits information by modifying the amplitude of the carrier signal. Let the information signal  $M(t)$  be an arbitrary waveform, called modulating signal which is given by,

$$M(t) = M \cos(W_m t + \Phi) \quad 4.3.1$$

Where  $M$  is the maximum value,  $W_m$  is the modulating signal frequency and  $\Phi$  is the phase angle of the modulating signal. The carrier signal is also a sine wave given by,

$$C(t) = C \cos (W_c t + \Phi_c) \quad 4.3.2$$

Here  $C$  and  $\Phi_c$  are arbitrary constants representing the amplitude and phase of the carrier signal, respectively. For simplicity we consider the amplitude to be unity and phase to be zero. The standard carrier frequency in the U.S. is in the range of the 550 KHz to 1720 KHz. Generally it is assumed that  $W_m \ll W_c$ .

Amplitude Modulation is created by forming the product,

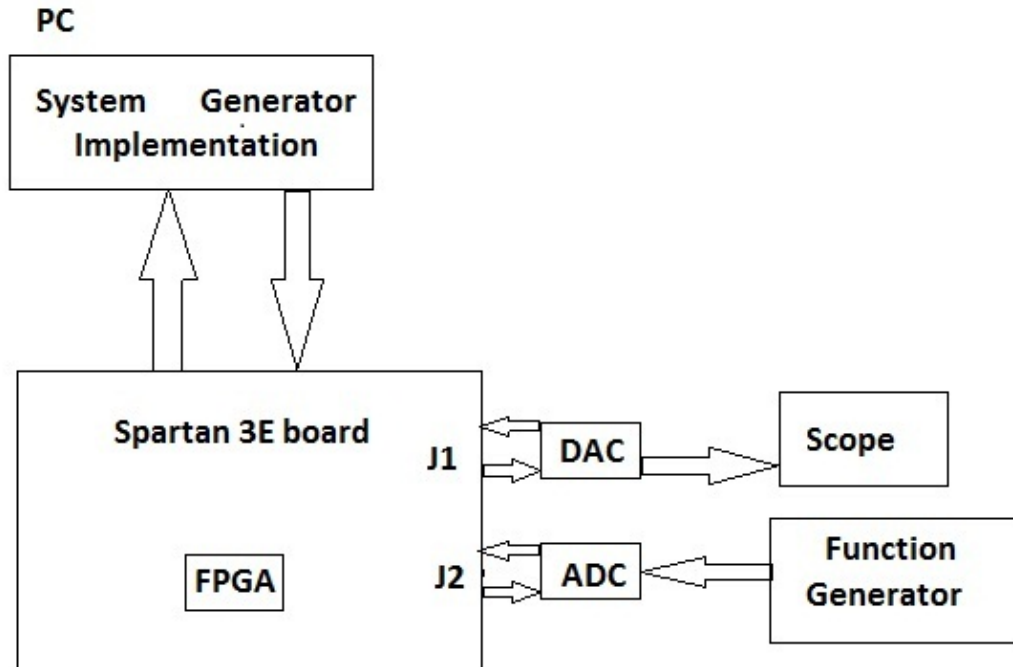
$$Y(t) = [A + M(t)] * C(t) \quad 4.3.3$$

Where  $A$  is constant and chosen to be unity in this discussion. A choice of  $A$  being zero eliminates the carrier components. That is the Double Sideband Suppressed Carrier (DSBSC) transmission mode. Here we choose  $A = 1$ . So it is called Double Sideband Amplitude Modulation (DSB-AM) with carrier [14].

### 4.3.1 AM SDR Setup

Figure 4.1 presents the basic idea of an implementation of SDR on the Spartan 3E Starter Kit. Peripheral Modules (PMODs) are made by Digilent in order to easily interface peripherals to their products using a simple standard connector.

The message signal is provided from a function generator to the 12-bit ADC housed in the peripheral board attached to the FPGA (PMOD AD1). As discussed in Chapter 3, the bitstream file which is generated by System Generator is downloaded on the Spartan 3E FPGA. The modulated output waveform from the 12-bit DAC peripheral board (PMODDA2) can be observed on an oscilloscope [29].



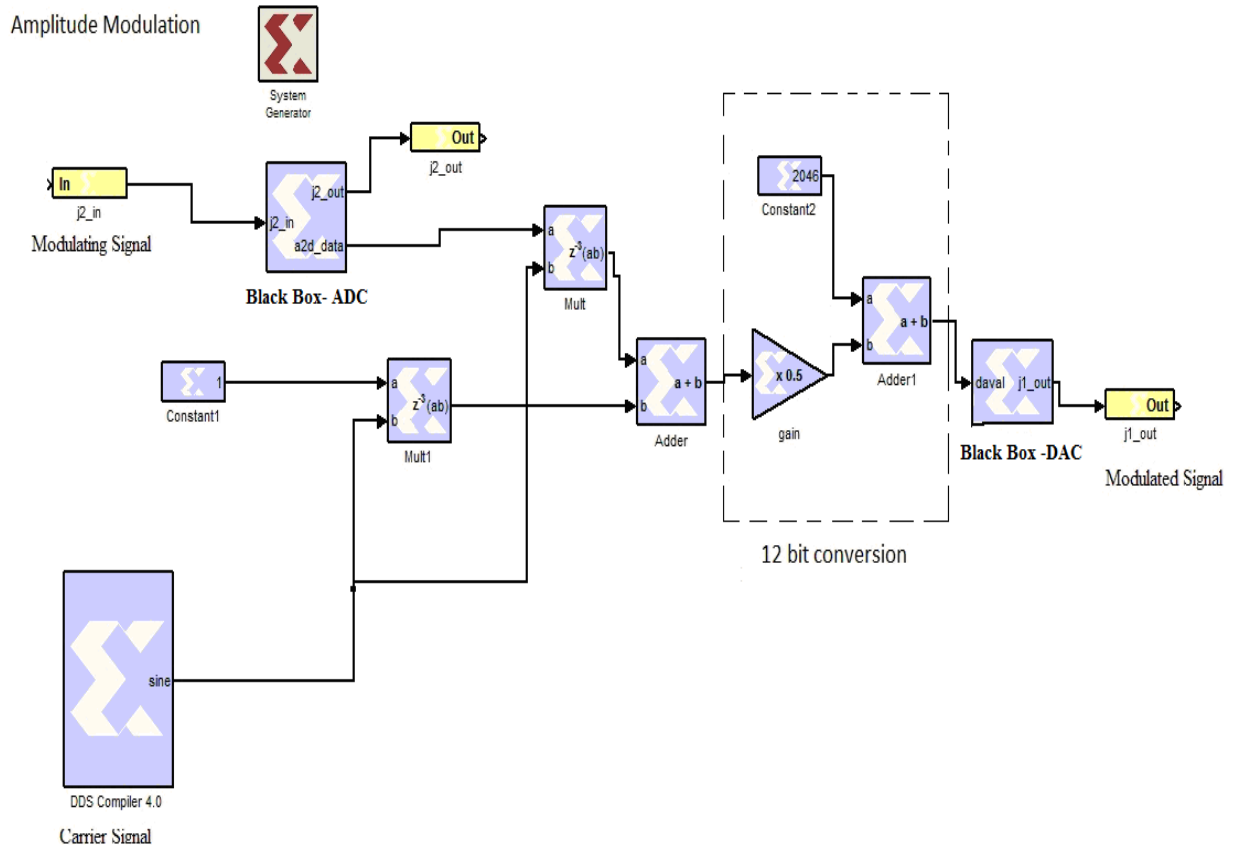
**Figure 4.1 Radio Set Up**

### 4.3.2 System Generator Implementation

The simulation model for the AM modulator is shown in Figure 4.2. This diagram is an implementation of equation 4.3.3. The message signal is given as an input to the Gateway In block. This block converts that data from a double precision floating point number to the Xilinx fixed point representation. The black box provides a way to include HDL models into System Generator. The black box can be used to incorporate Verilog files in the Simulink model. Here the first black box contains a Verilog model for the ADC and is labeled ADC in Figure 4.2. The second black box contains a Verilog model for the DAC and is labeled as DAC in Figure 4.2. During the hardware generation process, the associated HDL entity is automatically wired to the other block in the design. The output of the DAC (other black box in Figure 4.2) which contains the Verilog module for the DAC is a 12-bit unsigned value. The Direct Digital Synthesizer (DDS)

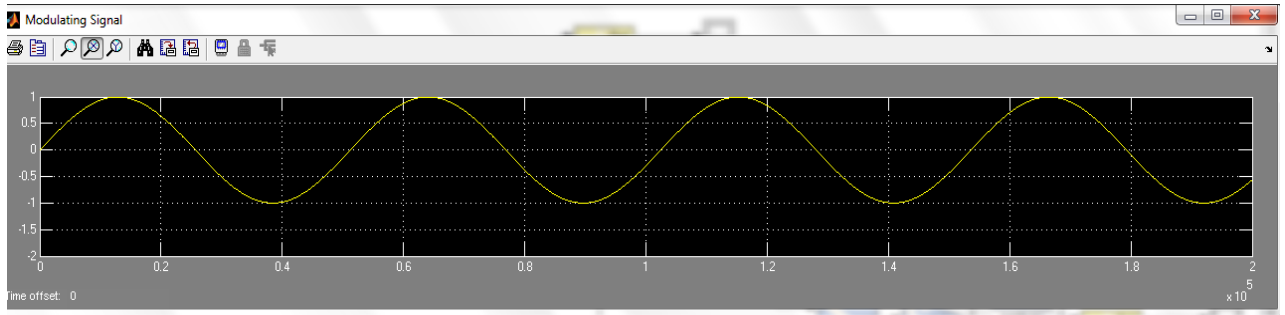
compiler block is used to generate the sine wave (carrier signal), or cosine wave, depending on the application. This capability allows users to custom build a DDS to fit individual application needs.

Here the DDS Compiler is used to generate a 10 KHz sine wave. The output of the DDS compiler is multiplied with constant (value of  $A$  in equation 4.3.3) using xilinx Mult block which is shown in the Figure 4.2. Mult blocks compute the product of the data on its two input ports. ADDSUB block performs the addition of the data on its two input ports. The next blocks are the gain operator, constant and ADDSUB block which convert the output of ADDSUB block to a positive 12-bit number which is a requirement of the DAC block.

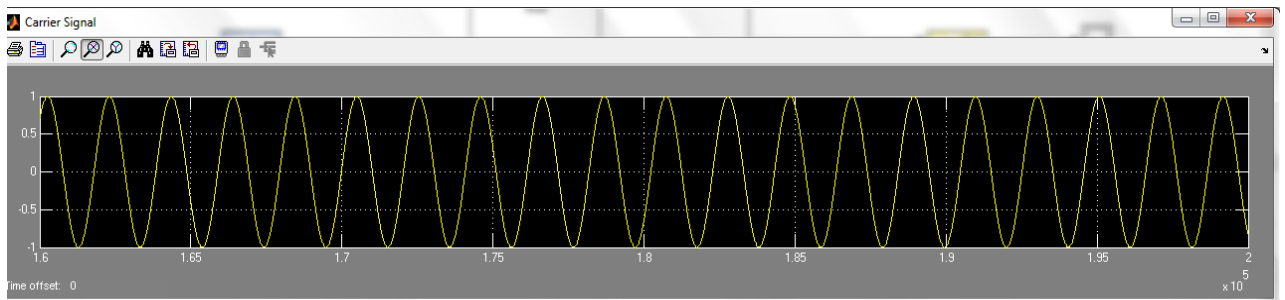


**Figure 4.2 Simulation Model for AM Modulation**

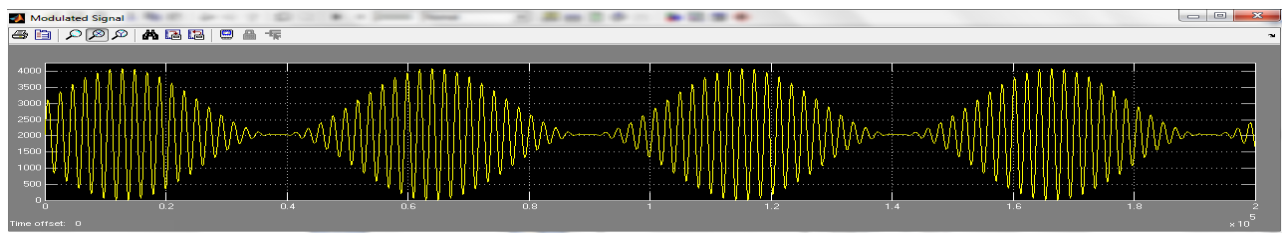
Figure 4.3 shows (a) the modulating signal, (b) the 10 KHz carrier signal and (C) the generated modulated signal using Simulink, and Figure 4.4 presents the hardware generated waveform. The radio design can be validated by comparing Figure 4.3 (c) and 4.4 [27, 28].



(a)



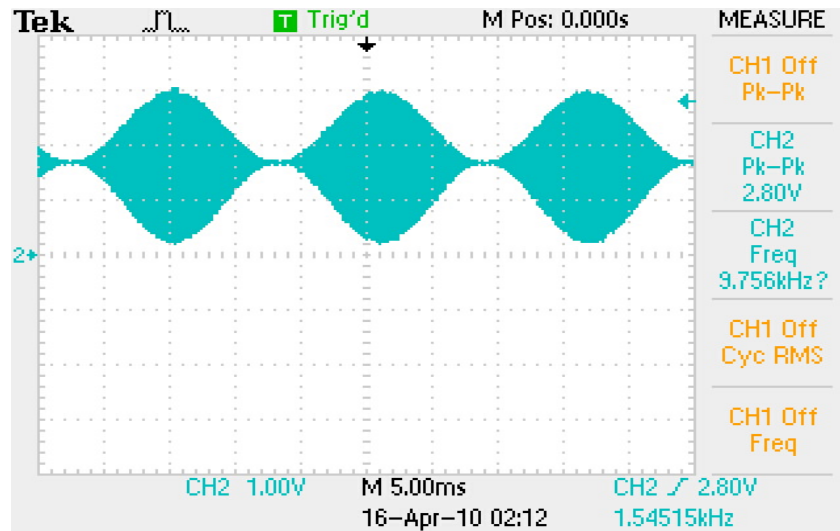
(b)



(c)

**Figure 4.3 (a) Modulating Signal (b) Carrier Signal (c) Modulated Signal in Simulink**





**Figure 4.4 Modulated Waveform Viewed with Oscilloscope**

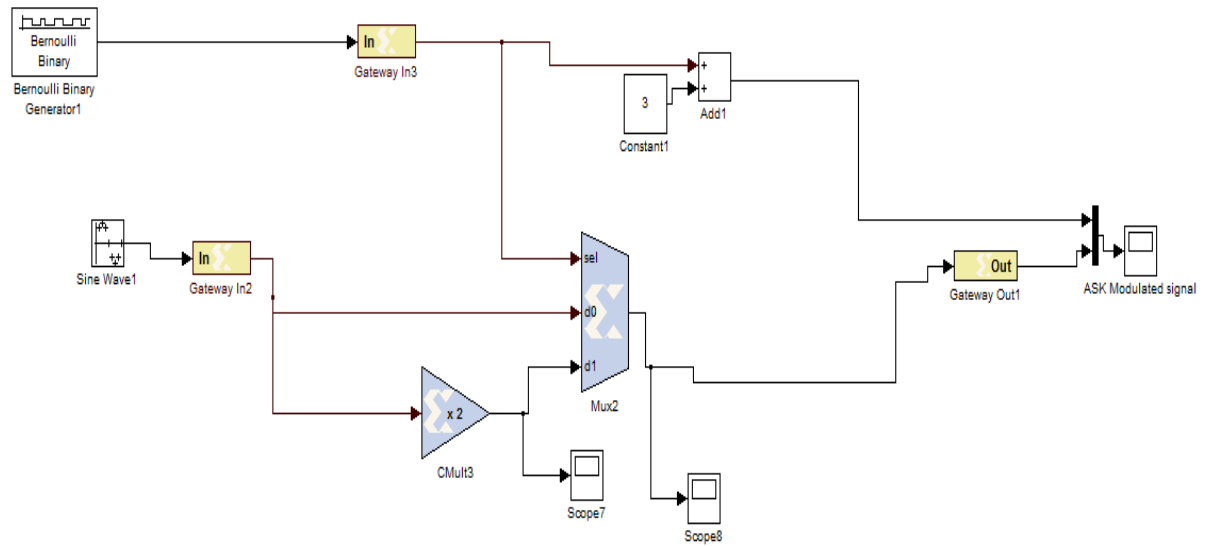
#### 4.4 Amplitude Shift Keying

Figure 4.5 shows the basic block diagram for ASK modulation. In ASK the amplitude of the carrier is changed in response to the digital data stream (information signal). The ASK signal can be defined as,

$$S(t) = A_1 m(t) \cos(2\pi f_c t) \quad \text{For Binary 1} \quad 4.4.1$$

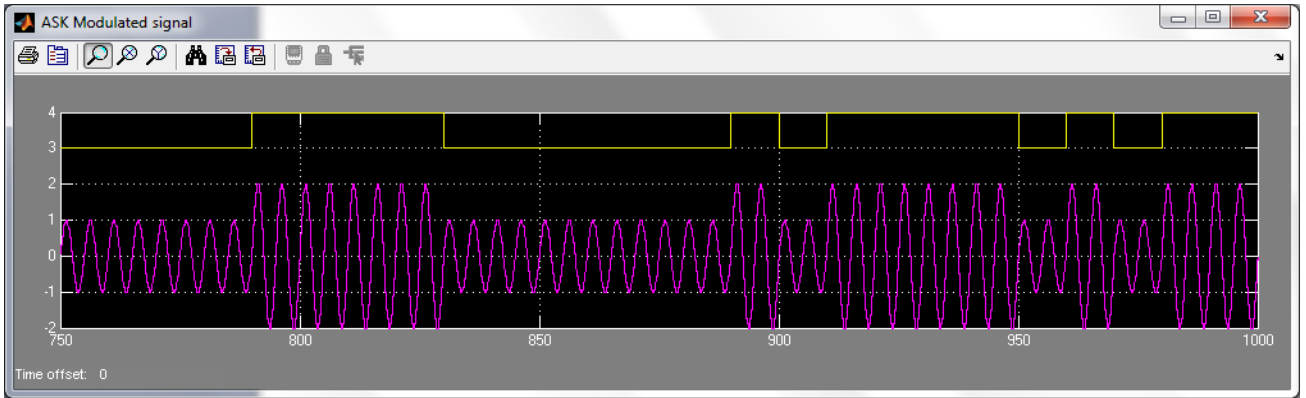
$$S(t) = A_2 m(t) \cos(2\pi f_c t) \quad \text{For Binary 0} \quad 4.4.2$$

Here  $A_1$  and  $A_2$  are two different constants representing the amplitudes of the two carriers and  $m(t)$  is an binary input bit stream. The level of the amplitude can be used to represent binary logic 0s and binary logic 1s.  $f_c$  is the carrier frequency which is constant. In ASK modulation a logic one is transmitted using one particular amplitude and logic zero is transmitted by different carrier amplitude without changing the frequency. Figure 4.6 (a) shows clearly that a logic one is transmitted using a carrier of amplitude 2 and a logic zero is transmitted by carrier of amplitude unity. Figure 4.6 (a) shows the generated waveform for ASK. OOK is a special form of ASK modulation where a logic zero is transmitted by carrier of amplitude zero [14].

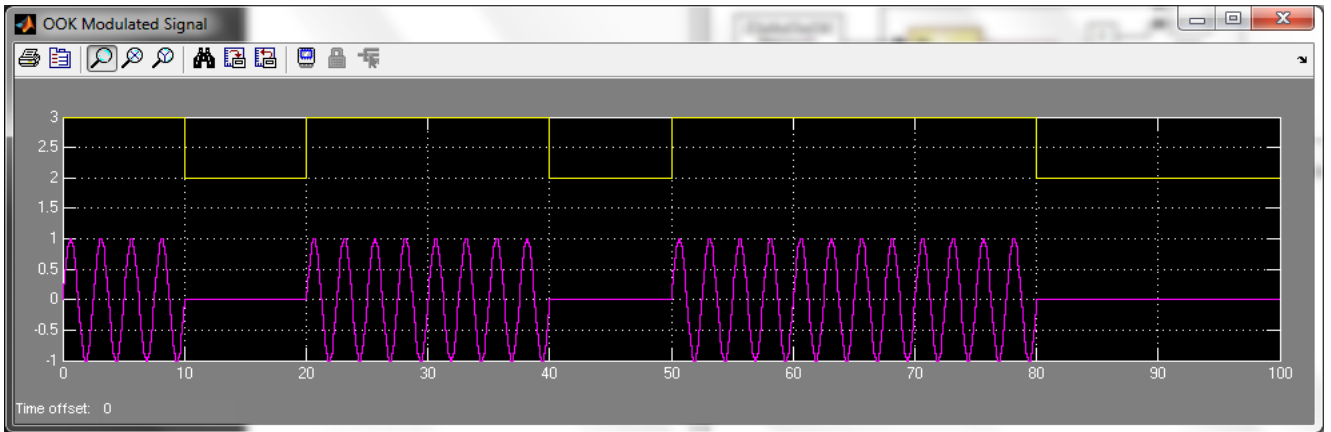


**Figure 4.5 Basic Block Diagram of ASK**

Figure 4.6 (b) shows the waveform for OOK modulation in Simulink. Figure 4.7 shows the Hardware generated waveform for ASK Modulation. The radio design can be validated by comparing Figure 4.6 (b) and 4.7.



(a)



(b)

Figure 4.6 (a) ASK Modulated Signal (b) OOK Modulated Signal in Simulink

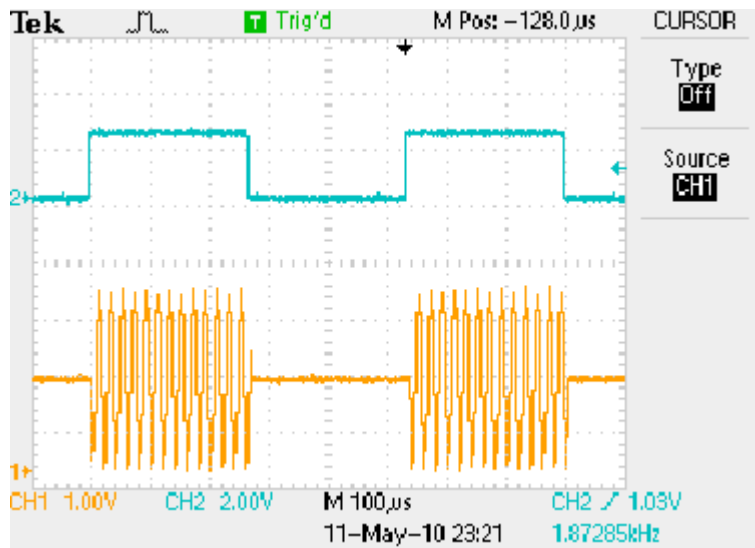
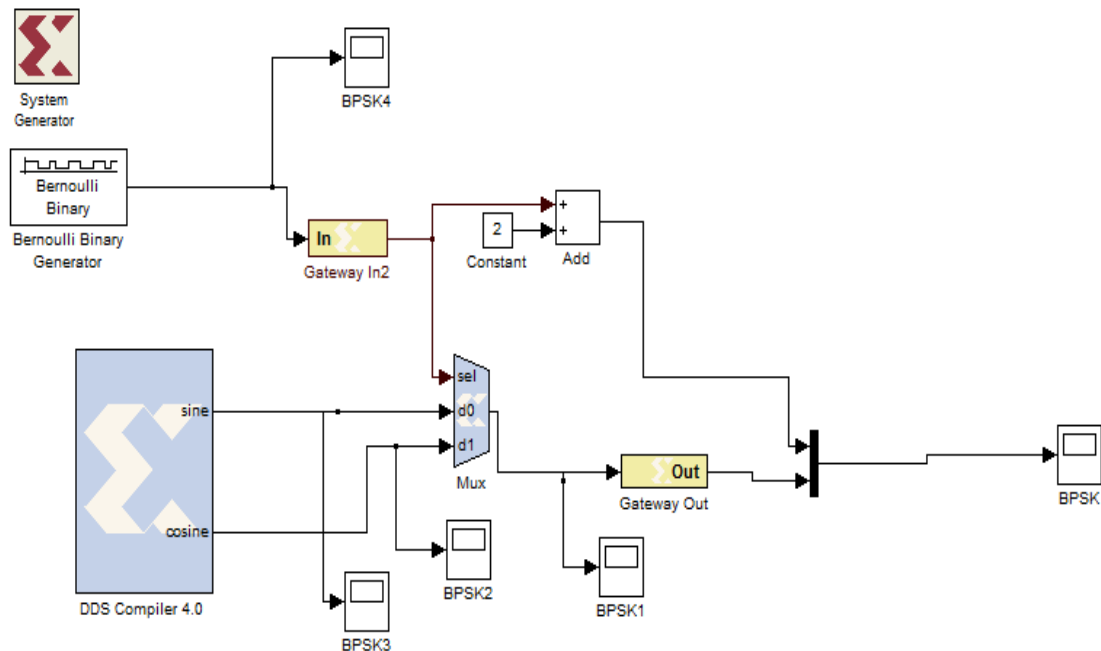


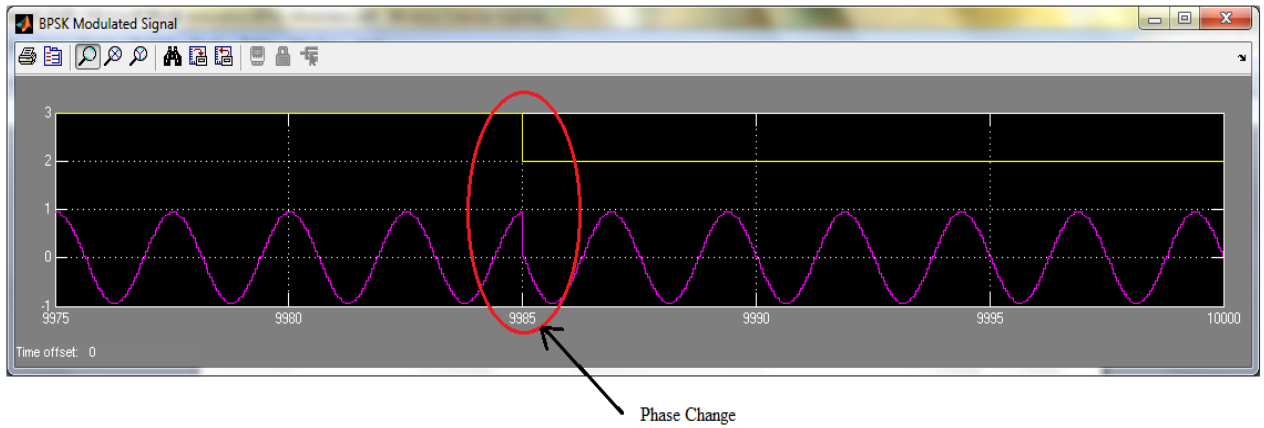
Figure 4.7 ASK Modulated waveform viewed with Oscilloscope.

## 4.5 Binary Phase Shift Keying (BPSK)

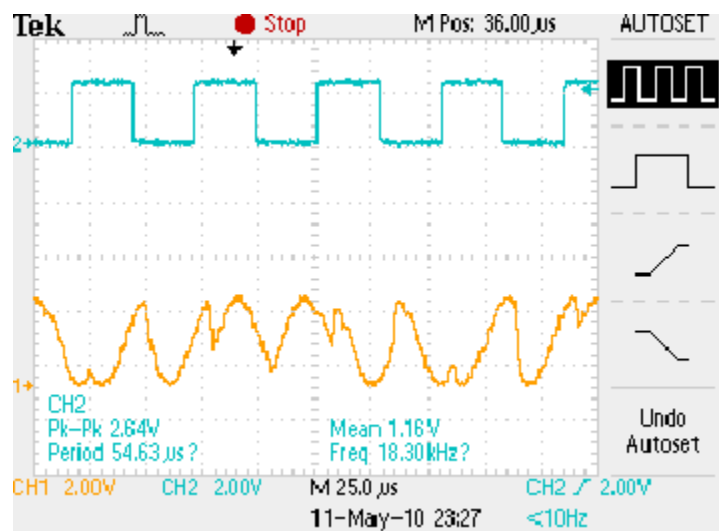
Figure 4.8 shows the basic block diagram of the BPSK modulator. The digital information signal (coded into digital signal) enters a multiplexer that converts the phase of the carrier signal according to the input bit stream (information signal). Depending on the logic condition of the input the carrier transferred to the output is either in phase or at  $90^\circ$  out of phase. Figure 4.8 shows clearly that a logic one is transmitted by a cosine wave and a logic zero is transmitted by a sine wave. Figure 4.9 (a) shows the waveform for a BPSK modulator [26]. Figure 4.9 (b) shows the Hardware generated waveform for BPSK Modulation. The radio design can be validated by comparing Figure 4.9 (a) and 4.9 (b).



**Figure 4.8 Basic Block Diagram of BPSK Modulator**



(a)



(b)

**Figure 4.9 (a) BPSK Waveform in Simulink (b) BPSK Modulated Waveform Viewed with Oscilloscope.**

## CHAPTER 5

### CONCLUSION AND FUTURE WORK

#### 5.1 Conclusion

This thesis presents a low cost SDR platform that leverages existing educational hardware and software. The Spartan 3E Starter Kit Board was chosen for implementing the SDR because it is cheap and easily available. Another advantage to choosing the Spartan 3E board is that it requires the least amount of external peripherals to implement the radios. In this thesis just an ADC and DAC are needed as external peripherals.

This thesis used the System Generator for DSP tool developed by Xilinx for implementing a digital signal processing application on the Xilinx FPGA platform. The Xilinx System Generator for DSP is compatible with MATLAB Simulink. Another advantage to choosing System Generator is that FPGA design and programming are easily performed with its model-based approach.

The first approach in the design process was to add System Generator components in order to simulate and implement AM modulation on the Spartan 3E Starter Board. Results were obtained using a function generator as an input signal and an oscilloscope to view the modulated waveform. These results were compared to simulations in System Generator with minimal error. Based on the comparison of the results and simulations, valid implementation was confirmed. ASK, BPSK and OOK modulation schemes were also simulated using System Generator but not implemented on the Spartan 3E Starter Board.

## **5.2 Suggestion for Future Work**

The SDR that has been introduced in this thesis is not fully complete. Only the baseband stage of the wireless communication system has been implemented. The other two stages (RF and IF) have not been implemented. Therefore this can be a focus point for future work.

This thesis could be extended by adding functionality such as channel coding, error correction techniques, etc. In this thesis the transmitter is simulated and implemented but not the receiver part. A typical SDR receiver involves complex techniques to recover the frequency and phase of the transmitter's carrier wave. The implementation of these techniques within System Generator is left for future work.

## REFERENCES

- [1] T. Rappaport, Wireless Communication - Principle and practice, 2<sup>nd</sup> Edition.
- [2] Software Defined Radio Forum. “About SDR”,  
<http://www.sdrforum.org/>
- [3] S.M.Shajedul Hasan, P. Balister, “ Prototyping a Software Defined Radio Receiver Based on USRP and SSIE” , Technical Report No. 1, Department of Electrical & Computer Engineering, Virginia tech, December 14,2005
- [4] A. Chandrasekhar, P.Banerjee, “TDMA Implementation using GNU Radio and USRP”, Department of Electrical and Computer Engineering, Cleveland State University.  
[academic.csuohio.edu/yuc/mobile09/avi.pdf](http://academic.csuohio.edu/yuc/mobile09/avi.pdf)
- [5] S. Naghmash, M. Ain, C. Hui,” FPGA Implementation Of Software Defined Radio Model based 16QAM“, European Journal of Scientific Research, Vol. 35, No.2 (2009), pp.301 – 310
- [6] Ke –Yu, Z. Chen, “GNU RADIO”, Department of Electrical Computer Engineering, University of Florida, Gainesville, Florida, 2006 ,Feb ,2008.  
<http://www.wu.ece.ufl.edu/projects/softwareRadio/>
- [7] M. Hicking, “New technology facilitates true software defined radio”, Retrieved in April 2005 from [www.rfdesign.com](http://www.rfdesign.com)
- [8] K. Patton, “A GNU Radio Based Software – Defined Radar”, Master Thesis, Wright State University, 2007.
- [9] J. Mitola, “Software Radio Architecture,” IEEE Communication Mag, May 1995.



- [10] H. Afshin, F. John, "Enabling Technology for Software Defined Radio", Software Defined Radio Technical Conference, 12 November 2002- San Diego, California.
- [11] K. Jondral, "Software Defined Radio Basics and Evolution to Cognitive Radio", EURASIP Journal On wireless Communication and Networking 2005:3, 275 – 283
- [12] Dr. Hikmat N. Abdullah, B.Sc. Hussein A. Hadi, "Design and Implementation of FPGA based Software Defined Radio Using Simulink HDL Coder" CUAS Journal.
- [13] J. Groati, G. Reehal, Nagarjuna, "Synthesizing FPGA Digital Modules for Software Defined Radio", National Aerospace and Electronics Conference, 16-18 July 2008, Ohio.
- [14] Ladimer S. Nagumey, "Software Defined Radio in the Electrical and Computer Engineering Curriculum", Frontiers in Education Conference, October 18-21, 2009, San Antonio, Texas.
- [15] R. Schiphorst," Demonstration of the Software – Radio Concept", Master thesis, University of Twente, Department Of Electrical Engineering ,Signals & System PO Box 217, 7500 AE Enschede, the Netherlands, June 14, 2000
- [16] Wipro Technologies, "Software-Defined Radio white paper," Aug. 2002.
- [17] D. Erik, P. Stefan, Communications Engineering Desk Reference, Academic press 2009-02-02.
- [18] P. Mannan,"Framework for the design and implementation of Software Defined Radio based wireless communication system", Master Thesis to the University of Akron, December 2005.
- [19] Hunt Engineering," The Theory of Digital down Converter".  
[www.hunteng.co.uk/pdfs/tech/ddctheory.pdf](http://www.hunteng.co.uk/pdfs/tech/ddctheory.pdf)

- [20] E. Ramon, j. Carrabina, “Using FPGAs for Software Defined Radio system: a PHY layer for an 802.15.4 transceiver”.
- [cephis.uab.es/resources/pdf/papers/JCRA\\_2005\\_SDR.pdf](http://cephis.uab.es/resources/pdf/papers/JCRA_2005_SDR.pdf)
- [21] J. Serrano, Digital Signal Processing using Field Programmable Gate Arrays”, Beam Instrumentation Workshop,2008, Geneva, Switzerland.
- [22] T. Saidani, D. Dia, M. Elhamzi and R. Tourki, “Hardware Co-simulation for video processing using Xilinx system generater”, WCE 2009 July 1 – 3 London, U.K.
- [23] Xilinx,”DSP co-processing in FPGAs: Embedding high performance, low cost DSP functions”, WP212 (v1.0) March 18, 2004.
- [24] J. Ruque, D. Ruiz, C. Carrion,” Simulation and implementation of the BPSK modulation on a FPGA Xilinx Spartan 3 xcs2004ftp256 using Simulink and the System Generator block set for DSP/FPGA”, Group of Electricity and Electronics System, Technical University Of Loja.
- [http://www.ece.unm.edu/xup/docs/collaboration/BPSK\\_Modulator.pdf](http://www.ece.unm.edu/xup/docs/collaboration/BPSK_Modulator.pdf)
- [26] Xilinx, “Products and Services: Design Tools,”
- <http://www.xilinx.com/tools/designtools.htm>
- [27] Math works, “Products for technical computing,”
- <http://www.mathworks.com/products/>
- [28] Digilent Inc., “Digital Designs Engineer’s Source.”
- <http://www.digilentinc.com/>