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Connected Me : Hardware for high speed BCC

Master thesis performed at Electronics Systems

by
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LiTH-ISY-EX--11/4503--SE

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Linköping, 29 August 2011
Abstract

Body coupled communication (BCC) is a hot topic in personal networking domain. Many works are published suggesting different architectures for BCC since its inception in 1995 by Zimmerman. The number of electronic gadgets used by a single person increases as time pass by. Its a tedious job to transfer data between them from a user point of view. Many of these gadgets can share their resources and save power and money. The existing wired or wireless networks does not meet the requirements for this network like scalable data rate, security etc. So here comes the novel idea of using human body as communication medium. The aim of this thesis is to realize a hardware for BCC based on wide band signaling as part of a big project.

The human body consists of 70% of water. This property makes the human body a fairly good conductor. By exploiting this basic property makes the BCC possible. A capacitance is formed if we place a metal plate near to the human body with the skin as a dielectric. This capacitance forms the interface between the human body and the analog front-end of the BCC transceiver. Any other metal structures near to the human body can attenuate the signal.

A first-order communication link is established in software by the human body model and the transceiver in the loop along with noise and interference. This communication link is used to verify the human body model and the base band model done as part of the same big project. Based on the results a hardware prototype is implemented. Measurements are taken in different scenarios using the hardware setup. The trade-off between design parameters are discussed based on the results. At the end, it suggests a road map to take the project further.

Keywords
Body-coupled communication, analog front end, IEEE 802.15.6, Body area network, Measurements, Connected Me,
To Appa, Amma and my little sister
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<td>Additive White Gaussian Noise</td>
<td>4</td>
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<td>AC</td>
<td>Alternating Current</td>
<td>6</td>
</tr>
<tr>
<td>AFE</td>
<td>Analog Front End</td>
<td>4, 5</td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary phase-shift keying</td>
<td>2</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
<td>2, 4, 5, 6</td>
</tr>
<tr>
<td>BCC</td>
<td>Body Coupled Communication</td>
<td>All Ch.</td>
</tr>
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<td>BSN</td>
<td>Body Sensor Networks</td>
<td>1, 2</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal Oxide Semiconductor</td>
<td>2</td>
</tr>
<tr>
<td>CRC</td>
<td>Cyclic Redundancy Check</td>
<td>2, 4</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
<td>All Ch.</td>
</tr>
<tr>
<td>DSSS</td>
<td>Direct Sequence Spread Spectrum</td>
<td>2</td>
</tr>
<tr>
<td>EO</td>
<td>Electro-Optic</td>
<td>2</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
<td>Details</td>
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<tr>
<td>ESD</td>
<td>Electrostatic Discharge</td>
<td>It is the discharge of the potential energy formed due to the separated electric charges</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field-Programmable Gate Array</td>
<td>It is an integrated circuit designed in a way such that the internal circuit connections can be modified after manufacturing</td>
</tr>
<tr>
<td>FDTD</td>
<td>Finite-Difference Time-Domain</td>
<td>It is basically a grid based numerical modeling technique</td>
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<tr>
<td>FEM</td>
<td>Finite Element Method</td>
<td>It is a numerical method to find approximate solutions for integral equations and partial differential equations</td>
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<tr>
<td>FM</td>
<td>Frequency Modulation</td>
<td>It is an analog modulation in which the instantaneous frequency of the carrier wave is modulated by the information signal</td>
</tr>
<tr>
<td>FSK</td>
<td>Frequency Shift Keying</td>
<td>It is a frequency modulation scheme in which the digital information is modulated as discrete frequencies of a carrier wave</td>
</tr>
<tr>
<td>LCD</td>
<td>Liquid Crystal Display</td>
<td>It is a kind of panel display which uses the light modulating properties of liquid crystals</td>
</tr>
<tr>
<td>OOK</td>
<td>On-Off Keying</td>
<td>It is an amplitude modulation scheme in which the digital information is modulated as presence or absence of a carrier wave</td>
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<tr>
<td>OCEAN</td>
<td>Open Command Environment for Analysis</td>
<td>A SKILL based command environment for configuring and controlling Virtuoso Analog Design Environment</td>
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<tr>
<td>op-amp</td>
<td>operational amplifier</td>
<td>It is an amplifier with high input impedance, low output impedance, high gain and bandwidth which can be used to realize comparators, filters, oscillators, mathematical functions etc</td>
</tr>
<tr>
<td>PER</td>
<td>Packet Error Rate</td>
<td>It is an unit-less performance measure in digital communication where the number of packet errors divided by the total number</td>
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<td>Acronym</td>
<td>Description</td>
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<tr>
<td>PAN</td>
<td>Personal Area Networks</td>
<td>Ch. 2</td>
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<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
<td>Ch. 4 and 5</td>
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<td>PPM</td>
<td>Pulse Position Modulation</td>
<td>Ch. 2</td>
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<tr>
<td>RC</td>
<td>Resistance Capacitance</td>
<td>Ch. 2 and 4</td>
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<td>RFID</td>
<td>Radio Frequency IDentification</td>
<td>Ch. 4</td>
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<tr>
<td>Rx</td>
<td>Receiver</td>
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<td>SNR</td>
<td>Signal to Noise Ratio</td>
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<td>Tx</td>
<td>Transmitter</td>
<td>Ch. 1 and 4</td>
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<td>UPS</td>
<td>Uninterpretable Power Supply</td>
<td>Ch. 6</td>
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<tr>
<td>USB</td>
<td>Universal Serial Bus</td>
<td>Ch. 1</td>
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<tr>
<td>WBS</td>
<td>Wide Band Signaling</td>
<td>Ch. 2</td>
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<td>WBAN</td>
<td>Wireless Body Area Network</td>
<td>Ch. 1</td>
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1 BACKGROUND

1.1 Introduction

Nowadays the portable electronic gadgets are very popular. The network used by them to interchange data are mainly wireless data transfer protocols like Bluetooth, Wi-Fi, Wireless USB, ZigBee, etc. These wireless protocols are mainly used to connect personal electronic gadgets which is known as Wireless Body Area Network (WBAN). WBAN also refers to the network of wearable and implanted devices for biomedical applications.

In entertainment field, think of an application which connects the wearable display with a keyboard and internet using a wireless network. As the number of personal gadgets increases the complexity of the network also increases. So it became a necessity in the modern world to have an efficient way to network all the electronic equipments in close proximity of a person.

In biomedical field, Body Sensor Network (BSN) is the major application of WBAN. BSN is defined as a network of wearable and implant sensors which collects data about the human body and send to an external network to monitor. The network of sensors measure blood pressure, cardiac activity (ECG), temperature, etc. Advanced BSN, which contains intelligent sensors, even take decisions upon the received data and take counter steps in the human body with the help of actuators.

1.2 Motivation

The main advantage of wireless networks is that they avoid wires to connect between them. But on the other hand the disadvantages of wireless network in the context of BAN are,

- Power consumption : It consumes more power than its wired counterpart. For eg., Bluetooth and wired headphones.
- Scalability : The gadgets in the network has different data rate. So the network standard should support a range of data rates with optimum performance.
- Pollution and Interference : These devices pollute its surroundings electromagnetically and interfere each other decreasing their performance.
- Security : Since these are basically broadcasting type of network, there is a
chance to eavesdrop.

- **Data rate**: Data rate vs Power characteristics of these networks does not meet the requirement of BAN.

Stefan Drude, a researcher at Philips has come up with a draft specification for BAN and positioned it among the popular wireless networks which is shown in Figure 1.1 [1]. From Figure 1.1, it is clear that none of the existing wireless networks does not serve the BAN requirements. A new wireless protocol for BAN will be having the disadvantages inherent to wireless network. So this thesis is investigating on the physical layer of Body Coupled Communications (BCC) for BAN. In BCC the human body itself is used as a communication link between devices. Zimmerman does his master thesis [2] on BCC which is the first study in this area.

![Figure 1.1: BAN draft specification vs other wireless networks](image)

### 1.3 Body Coupled Communication

There are two types of interactions between the human body and an electric field [3]. They are due to the low frequency electric field and the electromagnetic field. The time varying low frequency electric field induce a surface charge on the human body which can cause an electric current as well as formation and reorientation of electric dipoles on tissues. The conductivity of the human body determines the amount of flow of electric charge while permittivity governs the polarization. The conductivity and permittivity varies with different types of human tissue and frequency of the applied signal. Absorption of energy and an increase in body temperature can occur when it is exposed to electromagnetic field of frequencies above 100 kHz. Frequencies above 20 MHz causes relatively high absorption. Since the human body is a better conductor than air, an energy efficient communication method is possible.

In BCC the electric field is induced into the human body which is then received at any other part of the body. The transmission and reception can be done with a
transceiver which is in direct contact or in close proximity to the human body. A BAN consists of many electronic gadgets or on-body sensors which communicates each other through BCC technology and one or more than one node can be the central node. A central node is connected to external network through traditional wireless link.

BCC can be classified by the style with which the signal is applied to the body. They are differential approach [4] and single-ended approach [2]. Another classification is based on the type of coupling between the electrode and the human body such as galvanic and capacitive.

### 1.3.1 BCC classifications

In Figure 1.2, the BCC classification is shown with transmitter (Tx), receiver (Rx) and the human body. The position of electrode with respect to the human body is the criteria for classification. The recommended relative size of the electrodes and signal flow path through the human body and the environment is also shown in Figure 1.2.

![BCC Classifications](image)

Figure 1.2: BCC Classifications depicted with transmitter (Tx), receiver (Rx) and human body (a) Differential approach (b) Single-ended approach.
In a differential approach, the signal is applied and received differentially across two electrodes. Then the human body can be treated as a kind of transmission line. Figure 1.2a shows the signal path, return path and losses occurred to signal during its travel through the human body. The main drawback of this approach is the fairly high intra-electrode capacitance (between the signal and ground electrodes) of transmitter or receiver because they are physically placed near to each other. This will result in weakening of the signal. The surroundings has less effect in this scheme.

In the differential approach the relative placement of transmitter and receiver electrodes can be in longitudinal or parallel orientation which is shown in Figure 1.3. The path between $\text{Tx}_{\text{Signal}}$ and $\text{Rx}_{\text{Signal}}$ electrodes is the signal path and the path between $\text{Tx}_{\text{Return}}$ and $\text{Rx}_{\text{Return}}$ electrodes is the return path. In parallel mode the signal and the return path are having approximately similar transfer function mainly because of equal distance for the signal path and the return path which is shown in Figure 1.3a. In longitudinal mode the signal path has less attenuation than return path because the signal electrodes are near to each other which is shown in Figure 1.3b. This differential approach is also called as four electrode model in some literature because four electrodes are attached to the human body.

![Figure 1.3: Types of electrode orientation (a) Parallel (b) Longitudinal](image)

In single-ended approach, the signal is induced and received using one electrode through the human body. The return path is through the surroundings as well as the body using ground plane or electrode. Figure 1.2b illustrates the possible return paths. The main drawback of this approach is the dependency of surroundings in signal strength. For example, conductive floor, metallic objects near to the human body etc weakens the signal. Another person, who is in direct contact or close proximity of the subject will also weakens the signal. The main advantage is that...
1.3 Body Coupled Communication

the electrode does not need a direct coupling with the human body. A loosely coupled electrode means air, textile, plastic etc in between with the human body and the electrode can be used. This single-ended approach is also called as two electrode model in some literature because two electrodes are attached to the human body.

Galvanic coupling means the electrode is in direct contact with the human body. Even though it is referred as galvanic the skin can be practically considered as an insulator with high relative permittivity [5].

Capacitive coupling means that there is no direct contact between the electrode and the human body. The space between them can be air, plastic, textile, etc. The coupling is weaker than galvanic because of the less permittivity of the space between the electrode and the human body.

In differential approach it is recommended to have the galvanic coupling because it will increase the electrode to body capacitance than intra-electrode capacitance. This results in more signal to get coupled to the body than getting shorted between electrodes. In single-ended approach either galvanic, capacitive or both coupling can be used.

1.4 Outline of the project

Ericsson AB has a vision called “The Networked Society” which can be be fulfilled by 50 billion connections. These connections are classified as “Machine to Machine” and “Machine to Nature” which are collectively known as “Machine to Anything”. “Machine to Nature” category involves humans being as the channel for communication. As a first step to prove the feasibility three sub-projects are formed such as

1. The Connected Me - Proof of concepts
2. Connecting the human body - models, connections, competition
3. Connected Me : Hardware for high speed BCC

The sub-project 1 deals with the communication base-band which is a digital one. It recommends the modulation or encoding scheme for the human body communication. The sub-project 2 deals with the human body and Analog Front End (AFE) modeling. It consists of the detailed analysis of the prerequisites for communication base-band. The sub-project 3 deals with building a hardware prototype for the human body communication and evaluate the human body model and communication base-band.

The thesis registration number for sub-project 1 is LiTH-ISY-EX—11/4504--SE and the thesis registration number for sub-project 2 is LiTH-ISY-EX—11/4505--SE.
1.5 Outline of the thesis

This thesis is about sub-project 3. It strongly overlaps with other sub-projects. The main objectives of this thesis are,

- Investigate the requirements for the electrode.
- Creating a software loop which contains the human body model, AFE, communication base-band, noise and interference to evaluate the whole system.
- A hardware prototype which can be used to study the human body communication.
- Take measurements using the prototype which can be used to investigate the dependency of environmental factors on BCC.
- Tuning the hardware for high speed and low power consumption.

Initially to understand the state of the art, document survey and initial measurements are needed. After that a system architecture has to be finalized for the whole project. Then this architecture which are modeled by other sub-projects are integrated and evaluated by creating a software loop. Based on the results of this evaluation the system is iterated till a prototype can be built based on it. Then a prototype will be realized to study deeper about the BCC. To study about the various factors that affects the functionality and performance a lot of measurements will be taken. Based on the measurements the hardware will be upgraded for high speed as well as low power consumption.

1.6 Anticipated results

During the early stage of the project, a fully integrated and customizable software loop will be done for the evaluation. The purpose of this plug and play software test bench is to find the range of values for the system parameters. Then a first-order communication link will be realized with existing FPGA, discrete component AFE and electrodes. Measurements will be taken on this prototype to plot the graphs of BER against various physical as well as electrical parameters. The anticipated bit rate of the prototype is 10 Mbps with a BER less than $1.0 \times 10^{-5}$.


2 STATE OF THE ART

2.1 Introduction

In this chapter the main papers discussing BCC is reviewed. Since there is no approved standard for BCC, different papers approach it in different ways. This chapter is introducing and comparing different publications.

2.2 Zimmerman, 1995

The first published paper regarding BCC is by Zimmerman [2] in 1995. In his work of Personal Area Network (PAN), the single-ended approach with capacitive coupling is investigated. The human body is considered as a perfect conductor beneath the skin. The skin is taken as an insulator and three capacitors are defined with respect to the human body. They are to transmitter, receiver and environment from human body.

The physical layer for BCC is developed and is used to perform measurements on the human body. Transmitter and receiver are having separate isolated ground. Hardware design issues like cost, power, size, channel capacity and different location are studied. Different sizes and positions for the electrode are considered based on the commonly used personal belongings like watch, shoes, belt, etc. The human body and electrode capacitances are measured. Experiments shows that feet are the best location for PAN because the return path has less attenuation.

On the base-band side, a linear on-off keying (OOK) and a nonlinear direct sequence spread spectrum techniques are examined. Spread spectrum has the higher received signal. Even though the tank resonator circuit increases the received signal for OOK, still it is inferior to spread spectrum by 60%. But OOK is selected because of its simplicity in implementation. This study resulted in a carrier frequency of 333 kHz and a data rate of 2.4 kbps.

2.3 Fuji, et al., 2002-2006

Publications [6, 7, 8, 9, 10] mainly focus on the transmission mechanisms. The authors of [6] studied different electrode structures in terms of the difference in transmission power. The electric field distribution of arm and the transmitter is studied using finite-difference time-domain (FDTD) models for a transmitter with and without ground electrode. The results show that when the ground electrode is not present, the electric field does not penetrate into the arm. This is concluded as because of the presence of large input capacitance in the input impedance in the
absence of ground electrode which causes the power mismatch.

The papers [7], [8] and [9] explains very important aspects about the BCC mechanisms. The authors compared four different types of electrode combination. They are (a) both transmitter and receiver with ground, (b) only transmitter is with ground, (c) only receiver is with ground and (d) both transmitter and receiver without ground. It is concluded that the ground electrode of transmitter is very important in propagating wave along the surface of the body. Then the receiver signal level is plotted against frequency ranging from 10 MHz to 100 MHz. The received voltage decreases as the frequency is increased but not very much. It is also found that the size of the transmitter electrodes have significant effect on the received signal. The authors then tried two different orientation of the transmitter electrodes with respect to the receiver signal electrode and found that transverse is better than longitudinal. They also concluded that the primary path of signal is along the surface of arm as surface waves and not through inside of it.

In the publication [10], the authors extend the plotting of electric field for the whole body. The results prove the feasibility of data communication by our daily natural actions.

2.4 Hachisuka, et al., 2003-2005

Publications [11] and [12] are two of the earliest to talk about galvanic coupling. One of the publication [6] investigates about only differential approach while the other [7] considers both approaches. Initial experiments were carried on a human body. The input sine wave frequency is varied from 1 to 40 MHz to find the optimized one for BCC. The results shows that the signal propagation through the human body is superior than through air up to 30 MHz and 10 MHz is the optimized frequency for BCC. They also proves that surroundings has no effect on differential approach. They also proved that the impedance between electrode and the human body is independent of the metal or alloy used for electrode.

They made a human phantom arm for reproducible results. A wearable FM transmitters and receivers of 10.7 MHz as carrier frequency were assembled. The experiment results shows that still in the presence of noise sources like mobile phone, microwave etc, the signal is received correctly. Then they transmitted the digital data using FSK with another hardware. A data rate of 9.6 kbps is reported without any bit error rate (BER).

They modeled the BCC system with six impedances which is the maximum possible impedances between four electrodes. They calculated gain for both four electrode and two electrode model for different frequencies and distances. For two electrode model the calculated and measured values are in agreement, but for the four electrode model there is a difference between values as the frequency increases. They concluded it as the frequency goes high in four electrode model the signal propagates as electromagnetic waves. They conducted an interesting
experiment with one transceiver on the foot and the other placed at arm. Of the different arm positions for the measurement the arm held up or arm held horizontally have better gain than arm held down which is concluded as because of the interference due to the direction inversion at shoulder.

2.5 Shinagawa, et al., 2004

In this publication [13], the authors introduce a novel method of signal detection replacing electrical sensors with electro-optic (EO) crystals and laser light. The merits of EO sensor is that it has high input impedance and ultra wide band of detection. They developed a near-field transceiver with a data rate of 10 Mbps. Transverse EO sensor is selected against longitudinal EO sensor because of its high sensitivity. The measured signal of EO sensor shows a 65% improvement over its electrical counterpart.

They successfully tested the BCC physical layer both galvanic and capacitive with textile in between electrode and the human body. The receiver is able to detect it the signal even after passing through two persons in series generated by a 25 V transmitter. The packet error rate (PER) of the communication within a single human body is about 0.04% with a bit error rate (BER) of $4.7 \times 10^{-8}$. But the PER for communication between two human bodies is 3% which is considerably high.

2.6 Wegmueller, et al., 2005-2007

In these works [14], [15] and [16], a differential and galvanic coupling approach is investigated. This galvanic approach is best suitable for on-body sensors in biomedical monitoring systems. They analyzed the attenuation to signal transmission of human tissue with finite-element methods (FEM) and measurements on the human body. The human body is modeled as different layers of dedicated tissues like skin, fat, muscle, etc. The dependency of joints in the human body, distance between transmitter and receiver and size and type of electrodes on attenuation factor are studied. A stimulus waveform of 10 kHz, 100 kHz, 500 kHz and 1 MHz are used. The clinical trial has been conducted on 20 subjects with an average age of 47.2 years. The measurements are taken along the arm, leg and through the thorax. They represent the model as a simple electronic impedance network with four terminals. It includes the body-electrode impedance, the input and output impedance, the longitudinal impedance and the cross impedance.

The conclusions are

- The receiver electrode size has negligible impact on attenuation while the attenuation increases with decrease in transmitter electrode size.

- The attenuation increases as the distance between the transmitter and receiver increases.
• The larger the joint in the human body the higher the attenuation.

• A low resistive muscle tissue short circuits the signal while a low resistive fat leads to lower attenuation.

• Attenuation through the thorax is less compared to legs and arms.

• Motion of the human body has no effect on attenuation.

Digital modulation techniques like frequency-shift keying (FSK) and binary phase-shift keying (BPSK) are used for data transmission. A maximum data rate of 255 kbps is achieved with a carrier frequency of 600 kHz.

2.7 Song, et al., 2006-2007

In paper [17], a low power BCC receiver analog front end (AFE) is presented. This receiver uses wide band signaling (WBS) as the scheme. The receiver consists of a direct current (DC) biasing circuit, a preamplifier and a schmitt trigger. A low power wide band op-amp is used as the preamplifier. The narrow low amplitude pulse is amplified to the thresholds of schmitt trigger by the op-amp.

The op-amp uses low voltage fully complementary folded cascode topology and is fabricated in 0.18 \( \mu \)m standard CMOS technology. This results in a low power, high slew rate, wide band op-amp even though under a stringent condition of 1 V supply voltage. The AFE is tested on a human arm from wrist to fingertip of about 25 cm length and resulted in a data rate of 10 Mbps.

In another paper [18] the authors adopted wide band signaling along with direct sequence spread spectrum (DSSS) technique for interference rejection and faster code acquisition. The AFE performs three level pulse shaping for the pulse position modulation (PPM). This transceiver is tested in BSN over the shared human body channel and it is scalable. This scheme uses packet based communication with a synchronization header, an address field, a variable length data part and a cyclic redundancy check (CRC). The transceiver is fabricated in 0.18 \( \mu \)m standard CMOS with a maximum data rate of 10 Mbps and lower energy per bit.

According to the studies done in paper [19], the human body has the potential capability of being a channel for a data rate of up to 125 Mbps with WBS. In their study the human body behaves like a bandpass filter in single-ended approach. This receiver AFE is manufactured with a 0.25 \( \mu \)m standard CMOS technology which has a data rate of 2 Mbps and input sensitivity of 10 mV. They achieved a BER of \( 1.1 \times 10^{-7} \) on a distance of 100 cm with a power consumption of 5 mV from a 1 V supply.
2.8 Cho, et al., 2007-2009

The authors of the paper [20] developed a distributed RC model of the human body to analyze the BCC. Each RC block corresponds to a length of 10 cm in the human body approximated as a cylinder. They claim that with high frequency a higher data rate is possible by exploiting the strong return path but with interference. They used a battery powered signal generator and an oscilloscope and a spectrum analyzer to take measurement to validate the RC model. They empirically formed an equation consists of distance between transceivers, ground plane size, frequency of signal, transmitting power and receiver sensitivity.

An adaptive-frequency-hopping transceiver is discussed by the authors of [21]. The authors claim that for BCC signal to interference (SIR) is more important than signal to noise ratio (SNR). The motivation behind this scheme is because the strength of interference signal depends on location and time. So this transceiver selects a band with less interference and starts communication with a data rate according to the requirement of the BER. They tested this transceiver in the presence of in-band interferences generated by cordless phone, FM transmitter and walkie-talkie. The result shows a low power, low BER and scalable data rate transceiver from 60 kbps to 10 Mbps.

2.9 Conclusion

The publications discussed above proves the capability of the human body as a communication link. Since many of the publication results are based on measurements taken on human phantom they are contradicting with other works which took measurements on the real human body. Most of the authors who studied about the size of electrodes conclude that a larger area on transmitter side improves the signal strength. They also concluded that a larger ground plane will improve the communication in lower frequencies by decreasing the impedance in the return path.

To study about BCC, a digital modulation scheme is selected for simplicity. So Manchester encoding is selected as the modulation scheme. Based on the above observations, in this thesis a transmitter and receiver AFE which supports the digital modulation will be implemented to study the BCC. The AFE will be realized with off the shelf components. In this work the parasitic capacitances will be modeled and studied. The possible range of values for these capacitances will be measured.
3 INITIAL MEASUREMENTS

3.1 Introduction

The main aim of taking initial measurements is to fine tune the human body model. It is also useful in studying the approximate signal strength in various practical conditions and design AFE according to it. The DC characteristics of the human body is needed to design the receiver AFE.

3.2 Frequency response test

The main aim of this test is to plot the received power through a human body against frequency when a predefined signal is applied. This is to study the basic frequency response of the human body. The signal from the function generator is applied directly to one hand of the human body through an electrode. It is then measured on the other hand through an electrode by using spectrum analyzer. A sinusoidal signal of power 0 dBm is generated using a function generator of an output impedance of 50 Ohm. An ESD strap as shown in Figure 3.1 is used as the electrode. A spectrum analyzer of input impedance 50 Ohm is used to measure the received power. This measurement is a best case scenario but can be taken as a proof that BCC is possible in higher frequencies. The plot is shown in Figure 3.2.

Figure 3.1: ESD strap as electrode
3.3 Different practical scenario test

The aim of this test is to study how different types of electrode to the human body coupling affect the BCC. From the frequency response curve in Figure 3.2, a frequency band of 10 to 15 MHz is found very suitable for the BCC. This test is about sending a continuous pulse signal from a source directly to one hand of the human body and measuring it on the other side by a spectrum analyzer through electrodes. A 10 MHz pulse is passed through the human body under different use-case scenarios and received power is studied. A pulse signal of peak-to-peak voltage of 2 V is generated using a pulse generator with an output impedance of 50 Ohm. An ESD strap as shown in Figure 3.1 is used as the electrode. A spectrum analyzer of input impedance 50 Ohm is used to measure the received power.

The fundamental tone and six harmonic tones both even and odd are measured and plotted. For bench-marking these readings, a 50 Ohm cable is used for taking the first measurement. Then the different scenarios are created and tested including direct coupling and capacitive coupling. Capacitive coupling uses textile and air as dielectric in between the human body and electrode. Fine cotton is used as the textile. The results are shown in Figure 3.3. It is observed that a good coupling on transmitter side gives a slight better performance than at the receiver side. This is again verified in Chapter 6. Among the dielectrics, textile couples more power than air.
3.4 DC test

A DC test is performed to study how the human body response to zero frequency. For this test the human body is approximated as shown in Figure 3.4. Since a DC is applied to the human body, a galvanic coupling is needed. So all the capacitors in the human body model are neglected and the torso is not at all grounded. By measuring V1 and V2 and with a known value for R6, the sum of R1, R2, R3 and R5 can be calculated. Since capacitances are involved in the circuit, V2 is measured after settling it to the steady state value. The total series resistance of the human body and contact resistance at the human body and electrode interface is calculated as 170 kOhm. The electrode used is a copper plate with the dimension 11.5 cm x 5.5 cm.
Chapter 3. INITIAL MEASUREMENTS

3.5 Conclusions

The results from the frequency response test shows that the frequency range from 10 MHz to 60 MHz is desirable for BCC. In this frequency range 10 MHz to 20MHz can be selected for the hardware prototype as a trade-off between hardware capability and the human body channel response. These readings are also used in the human body modeling.

The practical scenario test has been performed to prove the feasibility of different use-cases. By measuring the received power at different scenarios, the potential applications of BCC are verified. The authors [22], measured the dielectric constant of fine cotton textile as 2.012 approximately. Since it is double the dielectric value of air, textile is a good dielectric than air. As the dielectric value increases, the capacitance between the electrode and the human body increases which results in good coupling. This explains the better performance of BCC through textile as more power is coupled to the human body as well as received by the receiver. This in turn will make the BCC possible between devices which are inside your shirt or trouser pockets.

The DC resistance value is needed to design the input resistance of receiver AFE. If we apply 5V at the transmitter side and ground the node V2 at the receiver side, the maximum DC that flows through the body is approximately 30 $\mu$A. Since the expected input resistance of the receiver is around 100 Ohm, receiving the voltage

![Figure 3.4: DC test circuit.](image-url)
by galvanic coupling will change the input DC bias voltage level only by a few mV. This gives the possibility to use the same hardware for galvanic as well as capacitive coupling communication.
Chapter 3. INITIAL MEASUREMENTS
4 SOFTWARE MODELS

4.1 Introduction

In order to realize an AFE for BCC, the architecture need to be validated in software. For validation, a software environment is needed where the human body and the surrounding are modeled. This chapter describes how the models in different tools are integrated and tested.

4.2 The human body model

The distributed RC model of the human body presented in the publication [20] is the accurate one till now. The approximation of the human body as a perfect conductor [2] is valid when the carrier frequency is in the kHz range. This is because the return path has very high impedance compared to the human body in lower frequency range. As the frequency goes higher the impedance of the human body and return path is comparable. So for higher frequency operation distributed RC model of the human body is very accurate.

![Diagram of BCC model with electrode and parasitic capacitances](image-url)

Figure 4.1: A capacitive coupling single ended approach of BCC model with electrode and all parasitic capacitances.
HB_Gnd_Cc represents the coupling between human feet with the real ground. Since the signal electrode is a plane, it forms a capacitance together with its own ground plane. Tx_Self_Cc and Rx_Self_Cc represents the self coupling or intra-electrode capacitance of transmitter and receiver respectively. The transmitter and receiver are battery powered devices which operates with respect to their own local ground. These local grounds has coupling to the real ground. Tx_Gnd_Cc and Rx_Gnd_Cc represents the coupling between local ground and real ground of transmitter and receiver respectively. When the transmitter and receiver are close enough there is a coupling between the local grounds which is represented by Tx_Rx_Cc. More details about the human body model is available with sub-project 2.

To study the impact of reverse path on the BCC, a truly grounded scenario is also considered for simulations which is shown in Figure 4.2.

![Figure 4.2: A capacitive coupling single ended approach of BCC model in grounded scenario.](image)

### 4.3 Electrode model

When an electrode comes in close proximity to the human body a capacitance is formed between them with air as dielectric. Tx_HB_Cc and Rx_HB_Cc represents the capacitive coupling between the human body and the signal electrodes of
4.3 Electrode model

transmitter and receiver respectively. But when an electrode is in direct contact with the human body it is called galvanic coupling. In galvanic coupling DC will pass through the human body but it will not in capacitive coupling. For galvanic coupling the electrode and the human body interface is modeled as a parallel RC circuit. It represents the contact resistance and the capacitance between the metal plate and the conductive inner human body with the skin as dielectric. The value of capacitance in galvanic coupling is around 500 times higher than in capacitive coupling. This is because of the permittivity of skin is higher than air. So a strong signal is transferred to the human body in galvanic coupling.

4.4 Base-band model

This thesis focuses on digital wide band signaling on the human body because of its low power profile. The data is transmitted in logical packets which consists of a preamble (62-bit), delimiter (2-bit), source and destination address field (8-bit), length field (16-bit), raw data and CRC (16-bit) of the data. The whole packet then is Manchester encoded by the transmitter base-band. Because of its regular bit transition, the Manchester encoded packet helps with clock recovery in the receiver base-band. The preamble is used to synchronize the receiver clock and detect the presence of a new packet. The receiver over-samples the pulse initially to synchronize with the preamble. Once synchronized and the delimiter is detected, the receiver starts to decode the data by sampling the value at a particular pulse of the over sampled clock. More details about the base-band model is available with sub-project 1.

4.5 Transmitter AFE model

The basic requirement for AFE is that it should support wide band signaling. The transmitter AFE gets the manchester encoded data packet from the base-band.
Since the electrode and the human body interface creates a high impedance, the transmitter need not to be capable of driving high current. The transmitter AFE can be modeled as shown in Figure 4.3.

TX is a pulse voltage source with data input and voltage amplitude control. $R_{\text{Tx}}$ represents the finite internal resistance of voltage sources. $Tx_{\text{SelfCc}}$ represents the intra-electrode capacitance. $I_{\text{Tx}}$ represents the stray inductance of the PCB and the the off-board wire connections.

### 4.6 Receiver AFE model

The receiver AFE for wide band signaling should be able to detect the narrow pulse from the human body and reconstruct it to pulse with proper duty cycle. The minimum functional blocks needed are amplification and pulse shaping which is shown in Figure 4.4. This is similar to the AFE proposed by Song, et al. in [17]. For amplification, a wide band, high slew rate op-amp in non-inverting configuration is used and a schmitt trigger for pulse shaping. A single supply op-amp is used for simplicity but traded off with a DC bias circuit at both the inputs. Again for simplicity, a resistor divider is used but it will result in draining more current.
4.6 Receiver AFE model

Rx_Self_Cc represents the intra-electrode capacitance and the input capacitance of the op-amp. R_Rx is the DC bias resistance. R_Rx || R_Rx || Rx_Self_Cc forms the input impedance for the AFE. R1 and R2 forms the feedback path for op-amp which determines the gain. The positive and negative going thresholds are the important design parameters for the schmitt trigger. C1 and C2 represents the input capacitance of schmitt trigger and base-band respectively. The initial values used for simulations for R_Rx is 200 Ohm. The op-amp has given a gain of 20 which is split into two stages of equal gain.

4.7 Test bench

The human body is modeled in Cadence®. The base-band model is in Simulink. So MATLAB is used to integrate both Cadence and Simulink. Simulink and MATLAB are products of MathWorks®. The main challenge of this test bench is to integrate analog and digital signals.

4.7.1 MATLAB-Cadence co-simulation

![Diagram of MATLAB-Cadence co-simulation](image)

Figure 4.5: MATLAB-Cadence co-simulation.
MATLAB-Cadence co-simulation is the best solution for mixed signal simulations. The data exchange between MATLAB and Cadence is through writing and reading files. MATLAB can read from and write to a file using dlmread and fprintf functions respectively. Cadence can read from and write to a file using fscanf and fwrite functions respectively. Virtuoso can be controlled and configured by scripting language called OCEAN. It can be executed from a terminal by using the command ocean. The OCEAN script for a particular simulation can be generated by MATLAB. So the internal simulation variables of the Cadence can be controlled from MATLAB. The co-simulation flow is shown in the Figure 4.5.

4.7.2 Test bench overview

The overview of the test bench is given in Figure 4.6. The simulation test bench has its frame work written in MATLAB. MATLAB and Simulink can share the same workspace for data exchange. So it coordinates the data exchange between different tools. This is a plug and play test bench where each component can be added or removed by configuration switches.
4.7 Test bench

4.7.3 Test bench description

This section describes in detail about the different models and how the data flow is happening in the test bench. The MATLAB code for the test bench is in Appendix A.

4.7.3.1 Configuration inputs

The configuration inputs are to select which of blocks need to be included in the simulation. The list of it is shown in Table 4.1.

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SimulationLevel</td>
<td>1</td>
<td>Grounded scenario</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Non-grounded scenario</td>
</tr>
<tr>
<td>RxTx_Level</td>
<td>0</td>
<td>No base-band present</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Base-band detailed in sub-project 1</td>
</tr>
<tr>
<td>AFE_Level</td>
<td>0</td>
<td>No AFE present</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>AFE detailed in Section 3.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>AFE detailed in sub-project 2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>AFE detailed in sub-project 2</td>
</tr>
</tbody>
</table>

Table 4.1: Configuration input list.

4.7.3.2 Simulation inputs and initialization

The other inputs needed to run the simulation are listed in Table 4.2. From these inputs, MATLAB calculate the simulation time need for the Simulink and Cadence as per the Equation 4.1.

\[
simtime = \left( \frac{2 \cdot (C + \text{no_data_bits_in_a_packet}) \cdot \text{no_of_packets}}{2 \cdot \text{bit_rate}} \right) + E_{\text{time}}
\]

Equation 4.1: Simulation time calculation.

In Equation 4.1, C is the total size of preamble, delimiter, source and destination address field and CRC which is substituted as 104. For more details refer sub-project 1. \(E_{\text{time}}\) is the extra time added to make sure that all packets are simulated which is usually substituted as 5 μsec.
Chapter 4. SOFTWARE MODELS

MATLAB generates the random data needed for transmitter base-band model from the input. For RxTx_Level = 0, the raw data is send to the human body model without packet structure. For RxTx_Level = 1, the test bench generates the preamble and delimiter for transmitter base-band model. By using the `sim` command MATLAB invoke the Simulink which can read the data from the same workspace.

### 4.7.3.3 Data from Simulink to Cadence

Simulink generates the manchester encoded packet consists of preamble, delimiter, source and target address, raw data and CRC of the data. This stream of data is written into a file by MATLAB. MATLAB then invokes the transmitter AFE and the human body model in Cadence through the method described in Section 4.7.1. The MATLAB is controlling the internal variables of Cadence by generating the OCEAN file. Cadence take its input data packet from the file written by MATLAB.

### 4.7.3.4 Interference and white noise

After the simulation the Cadence write the time stamped voltage and current outputs into a file where MATLAB reads it. The model in Cadence is terminated with the input impedance of receiver AFE. MATLAB then adds the noise and interference to the data and write into another file. The interference signal details are shown in Table 4.3 and spectrum is shown in Figure 4.7.

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>bit_rate</code></td>
<td>The maximum speed at which data can transmit</td>
</tr>
<tr>
<td><code>Vin_Pk2Pk</code></td>
<td>The peak to peak voltage output of the transmitter</td>
</tr>
<tr>
<td><code>Tx_trisefall</code></td>
<td>The rise and fall time adjustment variable for transmitter, if zero the inherent circuit RLC alone will determine the value</td>
</tr>
<tr>
<td><code>no_data_bits_in_a_packet</code></td>
<td>Number of data bits in a packet</td>
</tr>
<tr>
<td><code>no_of_packets</code></td>
<td>Number of packets needed for simulation</td>
</tr>
<tr>
<td><code>OSR</code></td>
<td>Over sampling ratio for the data which is written from Cadence human body model</td>
</tr>
<tr>
<td><code>OSR_AFE</code></td>
<td>Over sampling ratio for the data which is written from Cadence receiver AFE model</td>
</tr>
</tbody>
</table>

Table 4.2: Simulation input list.

The additive white gaussian noise (AWGN) spectrum is shown in Figure 4.8. The power spectral density of AWGN is calculated by using the Equation 4.2. MATLAB also calculate the received power from current and voltage.
In equation 4.2, $V_n^2$ is the power spectral density with unit $V^2$/Hz. $K_B$ is the Boltzmann constant, $1.38 \times 10^{-23}$ J K$^{-1}$. $T$ is the temperature in Kelvin which is taken as 373 K. $R$ is the input resistance of the receiver which is 50 Ohm. By substituting these values, $V_n^2$ is obtained as 1.014 nV$^2$/Hz.

$$V_n^2 = 4 \cdot K_B \cdot T \cdot R$$

Equation 4.2: Thermal noise.
4.7.3.5 Data from MATLAB to Cadence

If receiver AFE is present in the simulation configuration, MATLAB will call that model in Cadence as described in Section 4.7.1. After simulation, Cadence writes the voltage output of AFE with time stamp into a file. If it is not present, MATLAB convert the output voltage to digital data by modeling a comparator. The shape of narrow pulse output from the human body is shown in Figure 4.9.
4.7 Test bench

4.7.3.6 Data from Cadence to Simulink

If receiver AFE is present in the simulation configuration, MATLAB will read the output file from Cadence. This voltage is then converted to digital data for receiver base-band in Simulink by modeling a flip-flop. If it is not present, the comparator output from MATLAB workspace will read by receiver base-band in Simulink.

4.7.3.7 Data from Simulink to MATLAB

If base-band is present in the simulation configuration, the digital data is read with its time base. This packet is decoded and data part is recovered. This raw data and CRC is sent to MATLAB for BER calculation. If base-band is not present in the simulation configuration, MATLAB takes the raw data from Cadence to calculate BER.

4.7.3.8 Logging of results

The MATLAB receives the decoded data from Simulink and compare it with the random data generated by MATLAB to calculate the BER. It also receive the number of good packets received and compare it with those transmitted to calculate PER. Before the simulation completes, the test bench logs all the configuration inputs, simulation inputs along with BER and PER for further reference.

4.7.4 Results

The results obtained along with important inputs and configuration is shown in Table 4.4.

<table>
<thead>
<tr>
<th>SimulationLevel</th>
<th>RxTx_Level</th>
<th>AFE_Level</th>
<th>bit_rate (bps)</th>
<th>BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>15 M</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>15 M</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>10 M</td>
<td>&lt; 10^-5</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>3</td>
<td>40 M</td>
<td>6 x 10^-2</td>
</tr>
</tbody>
</table>

Table 4.4: Results of software in loop simulation.

4.8 Conclusion

A first-order BCC link is established in test bench. The software loop is tested with different configurations and inputs to evaluate the wide band signaling architecture. The communication link is stressed with AWGN and interference. Based on the BER results, the transmitter AFE in Section 4.5 and receiver AFE in Section 4.6 are prototyped in hardware which is described in Chapter 5. More details about AFE_Level 2 and 3 is described in sub-project 2.
5 HARDWARE

5.1 Introduction

Based on the results from the software simulation, the wide band signaling for BCC is feasible. To prove this in hardware, a prototype is needed. Since it need a lot of tuning in the hardware, off-the-shelf components are used. A printed circuit board (PCB) is made based on the software models for transmitter and receiver AFE.

5.2 Digital base-band

The digital base-band is implemented in Altera® Cyclone® II 2C70 FPGA which is a part of Altera DE2-70 development board. The transmitter and receiver base-band consists of a physical layer and an application layer. The applications selected to prove the concept on a use case basis are short messaging, audio and image file transfer. For evaluation of the concept, a layer to calculate the BER is also implemented. The physical layer receives the data from application layer and embed it the packet. Then it is manchester encoded and outputs to AFE for transmission. Upon receiving the digital data from AFE, the receiver decodes it and extract the data. More details of it is reported in sub-project 1.

5.3 Transmitter AFE

The transmitter AFE gets input from FPGA in development board. The total output capacitance of the board and the connection wire is approximately 100 pF. So a schmitt trigger is used to shape the pulse. A schmitt trigger is preferred over comparator to remove false triggering due to noise or interference. But due to higher capacitance a buffer is used in between them. Another buffer is used in between the electrode and schmitt trigger to drive the input impedance of the human body. The schematic of the transmitter AFE is shown in Figure 5.1.

The impedance seen from transmitter is in kilo Ohm range for capacitive coupling [sub-project 2]. The worst case maximum current through the human body occurs during galvanic coupling and for short distance. The transmission pulse peak to peak voltage is selected as 4.5 V. So the maximum current through the human body is less than 1 mA which is well within the safe range [3]. The direct current passing through the human body is calculated as less than 30 µA for this architecture by DC test in Section 3.4.
Chapter 5. HARDWARE

The AFE is assembled in a general purpose PCB and is powered by battery. Latest chips from leading manufacturers are used as buffers and schmitt trigger. The photograph of the transmitter AFE is shown as Figure 5.2. More details are in Appendix B.

![Diagram of Transmitter AFE](image)

Figure 5.1: Transmitter AFE.

![Photograph of Transmitter AFE](image)

Figure 5.2: Photograph of transmitter AFE.
5.4 Receiver AFE

The schematic of receiver AFE is shown in Figure 5.3. It gets narrow width pulses shown in Figure 4.9 from the human body. For capacitive coupling, there is no DC content in the received signal. Since a single supply op-amp is used for amplification, a DC bias is needed at the input. This is realized by a resistor divider circuit. A similar circuit is also used at the other input of op-amp to eliminate the DC offset. From the DC test explained in Section 3.4, the total resistance is 170 kOhm. So a low resistance value does not affect the DC bias at the input. For an input resistance of 50 Ohm, the change in DC voltage is 1.3 mV. But for short distance communication this can increase only slightly, because the contact resistance is still the same which is 200 times higher than body resistance. Another method to avoid the DC offset is to put an input series capacitance, but it will attenuate the signal.

For wide band signaling, a high bandwidth op-amp is needed. But it will result in low gain. The minimum gain for op-amp depends on the threshold voltages of the schmitt trigger and minimum input voltage. The minimum input voltage for 10 MHz is measured as 200 mV for an electrode area of 5.5 cm x 5.5 cm. The positive-going and negative-going thresholds of the schmitt trigger are 1.7 V and 1 V respectively. So the minimum gain needed is 700 mV / 200 mV which is 3.5 at 10 MHz. The
feedback path resistance values are fixed according to this. The gain versus frequency plot of the op-amp is given in Figure 5.4. The photograph of receiver AFE is given in Figure 5.5.
5.4 Receiver AFE

The AFE is assembled in a PCB shown in Figure 5.6 and is powered by battery. Latest chips from leading manufacturers are used as op-amp and schmitt trigger. All the resistances are realized by potentiometer such that it gives the flexibility for tuning the values later. More details are in Appendix B.

![Figure 5.6: Receiver AFE PCB.](image)

5.5 Electrodes

A copper plane on a PCB is used as the electrode. The dimension of the electrodes varies from 11.5 cm x 5.5 cm to 2.5 cm x 2.5 cm. The photograph of the electrode is shown in Figure 5.7.

![Figure 5.7: Photograph of an electrode.](image)
5.6 Hardware setup

All hardware units are tested individually before integration. More details about the testing and measurements are in Chapter 6. The schematic of whole setup is shown in Figure 5.8. This hardware setup is used to demonstrate three types of data transfer which are short message service, audio streaming and file transfer. The short message service is performed by transmitting the data from the keyboard through the body to be displayed on an LCD. The size of the data is 8 bit in the packet. For audio streaming, the external audio signal is converted to digital format and transmitted in the real time. The data size can be varied among 1024, 256, 64 or 32 bytes based on the BER of the channel. A stored image file is transferred through the body to demonstrate the file transfer. Since it is an image file, one can see the file downloading in a display screen packet by packet in real time. For testing purpose a BER application layer is also developed. The BER is measured for different scenarios to evaluate the whole system. For more details about the application layer refer sub-project 1. The photograph of the test setup is shown in Figure 5.9.

Figure 5.8: Schematic of hardware setup.
5.7 Conclusion

By developing the hardware, it is possible to test the real scenarios and compare with the software model. The measurement results can be used to iterate the software model and test bench. The performance is evaluated by the BER application layer. The measurements and results are discussed in Chapter 6.
6 MEASUREMENTS AND RESULTS

6.1 Introduction

The measurements are done with the hardware setup described in Chapter 5. The measurement system used here are taking power from the AC outlet. So to decouple the earth ground, an UPS is used to power them. This will not imitate the exact scenario but it is good enough to evaluate the system. The input impedance of the measuring equipments are kept in high impedance to avoid any signal distortion by the equipments itself. Since the equipments are not portable the measurements are taken at the lab itself. The experiments are repeated on different days to check the repeatability of the measurements.

6.2 Waveforms at 2.5 MHz

Figure 6.1: Waveforms at 2.5 MHz.
Figure 6.1 shows the waveforms at 2.5 MHz at different stages in the whole system. The transmitter is giving pulse output with a peak to peak of 4 V. When it passes through body it is attenuated to 300 mV which is amplified to 3 V by op-amp. It is observed that the pulse width get narrowed when it passed through the human body. Further band limitation is applied by the op-amp. It is also observed that high frequency noise is eliminated by op-amp due to the finite bandwidth. So op-amp acts as both an amplifier and as well as a low pass filter. Finally the schmitt trigger reconstructs the pulse from the op-amp output. So from this study it is proved that till 2.5 MHz the duty cycle of the pulse is not varied.

6.3 Waveforms at 6 MHz

Figure 6.2 shows the waveforms at 6 MHz at different stages in the whole system. The transmitter is giving pulse output with a peak to peak of 4 V. When it passes through body it is attenuated to 500 mV which is amplified to 2 V by op-amp. Finally the schmitt trigger reconstructs the pulse from the op-amp output. So from
6.3 Waveforms at 6 MHz

In this study, it is proved that till 6 MHz, the duty cycle is not varied much.

6.4 Tuning of Hardware

By comparing the waveforms at these frequencies, it is certain that the human body attenuates 2.5 MHz more than 6 MHz. So higher the frequency, better the response from the human body. But the op-amp has low gain in higher frequency due to its low pass behavior. So the extra gain given by the human body is compensated here. So by this amplitude response of op-amp, the system cannot operate at higher frequencies. So the gain of op-amp is reduced at lower frequencies to get a wide bandwidth. After tuning, the op-amp has a gain versus frequency plot shown in Figure 5.4. With this tuned hardware, a maximum frequency of 12 MHz is achieved along with the duty cycle constrains. The waveforms are shown in Figure 6.3.

After analyzing the waveforms, a band limitation to the signal at the transmitter output causes a low amplitude at the human body output. This band limitation is caused by the intra-electrode capacitance at the transmitter output. So as the frequency goes up, the intra-electrode capacitance acts as a short circuit path for...
the signal.

6.5 Hardware limitation

In manchester encoding one is encoded as “01” and zero as “10”. So the data stream of “111...” or “000...” encodes to a high frequency pulse and “101010....” encodes to a low frequency pulse. This low frequency signal is exactly half in frequency of the high frequency signal. So it is a mixture of pulses of two frequencies. In ideal case, for any time interval which is a multiple of the low time period (high frequency) signal, the pulse high-amplitude time should be equal to the pulse low-amplitude time. This is shown in Figure 6.4 for a 300 kHz and 600 kHz manchester encoded waveform.

![Figure 6.4: A 300 kHz and 600 kHz manchester encoded waveform](image1)

But as the frequency goes up, even-though the ratio between two frequency components remain same but the difference in frequency between them increases. So the higher frequency attenuates more when it passes through op-amp. This

![Figure 6.5: A 3 MHz and 6 MHz manchester encoded waveform](image2)
results in high rise and fall times. This is shown in Figure 6.5 for a 3 MHz and 6 Hz waveform. But when it reaches 6 MHz and 12 MHz it will result in BER as shown in Figure 6.6. Continuous stream of either zero or one will result in high frequencies when it is Manchester encoded and it might result in BER.

Consider the data stream “101110”. An ideal Manchester encoded waveform of this data stream looks likes as the pulse(transmitted) in Figure 6.7. When it is transmitted through the human body and received by the AFE, it will get distorted and get noisy. The reconstructed pulse is also shown in Figure 6.7. SP1, SP2, ..., SP6 are the sampling points where the receiver base-band samples the received pulse and decode the data. Due to the non-equal rise and fall time, the decoded data is “1010101”. The time delay between the transmitted and recovered pulse is not shown here. The receiver base-band adjusts the sampling point and correct it to an extend. This explains the hardware limitation as well as one of the major cause of BER.
6.6 Area of electrode Vs BER

The contact area of the electrode to the human body is crucial in galvanic or capacitive coupling. As it is mentioned previously, for galvanic coupling the area is indirectly proportional to contact resistance while directly proportional to capacitance. For capacitive coupling also area is directly proportional to capacitance. So as area increases, the signal strength increases and thus the BER decreases. But the intra-electrode capacitance increases with area which is the trade-off. As the frequency of operation increases, the BER increases as mentioned in Section 6.5. So in order to compensate that we need more area of contact which is shown in Figure 6.8. The measurements in Figure 6.8 is taken with a transmitter peak-to-peak voltage of 4.3 V.
The transmitter peak-to-peak voltage has influence on BER. As the transmitter voltage decreases the voltage at the input of receiver also reduces which in turn affect the pulse output. The aim is to perform the experiment with a constant area of electrode and the human body interface and measure the BER. The plot is shown in Figure 6.9. It is found that as the transmitter voltage decreases the BER increases logarithmically.
6.8 Different coupling Vs BER

As an extension to the initial measurements in Section 3.3, different coupling scenarios are compared in terms of BER. The different scenarios are distinguished in terms of the coupling between the electrode and the human body and the dielectric used between them. The reading are shown in Table 6.1. The aim is to compare between different scenarios and not on the actual BER itself. The major conclusion is that a good or galvanic coupling at the transmitter side results in low BER than it is at the receiver side. A textile in between electrode and the human body results in low BER promises that the BCC device can communicate with each other when it is in the user's pocket.

<table>
<thead>
<tr>
<th>Transmitter Coupling</th>
<th>Receiver Coupling</th>
<th>Dielectric of capacitive coupling</th>
<th>BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galvanic</td>
<td>Galvanic</td>
<td>--</td>
<td>1.0 x 10^7</td>
</tr>
<tr>
<td>Galvanic</td>
<td>Capacitive</td>
<td>FR4</td>
<td>3.3 x 10^6</td>
</tr>
<tr>
<td>Capacitive</td>
<td>Galvanic</td>
<td>FR4</td>
<td>4.8 x 10^6</td>
</tr>
<tr>
<td>Capacitive</td>
<td>Capacitive</td>
<td>FR4</td>
<td>2.1 x 10^3</td>
</tr>
<tr>
<td>Galvanic</td>
<td>Capacitive</td>
<td>Cotton textile</td>
<td>5.5 x 10^6</td>
</tr>
<tr>
<td>Capacitive</td>
<td>Galvanic</td>
<td>Cotton textile</td>
<td>3.3 x 10^4</td>
</tr>
<tr>
<td>Capacitive</td>
<td>Capacitive</td>
<td>Cotton textile</td>
<td>5.2 x 10^4</td>
</tr>
<tr>
<td>Galvanic</td>
<td>Capacitive</td>
<td>Paper</td>
<td>4.0 x 10^7</td>
</tr>
<tr>
<td>Capacitive</td>
<td>Galvanic</td>
<td>Paper</td>
<td>2.0 x 10^6</td>
</tr>
<tr>
<td>Capacitive</td>
<td>Capacitive</td>
<td>Paper</td>
<td>4.0 x 10^6</td>
</tr>
</tbody>
</table>

Table 6.1: BER for different scenarios.

6.9 Power consumption

The transmitter consists of two buffers and one schmitt trigger. The power consumption of one buffer is calculated as 8.5 mW and one schmitt trigger as 7.5 mW. So the total power consumption of the transmitter AFE is 24.5 mW at a supply voltage of 4.2 V and a frequency of 12 MHz. The power consumption of digital transmitter base-band is 3.3 mW from sub-project 1. So total power consumption is 27.8 mW. The extra buffer and the schmitt trigger is introduced due to the long trace from base-band to AFE. So considering it as a single unit, the extra power can be avoided and the final power can be estimated as 11.8 mW.

The receiver consists of two resistor divider circuit, one op-amp and a schmitt trigger. The total current consumption is 38 mA. Of this, 24 mA is consumed by
resistor dividers which is 91.2 mW. So the rest 14 mA is consumed by op-amp and schmitt trigger at a supply voltage of 3.8 V and a frequency of 12 MHz which is 53.2 mW. The power consumption of digital transmitter base-band is 3.2 mW from sub-project 1. So total power consumption is 147.2 mW. The resistor divider is the main power consuming circuit which is selected because of simplicity. If we replace it by efficient circuits it can be reduced by 70%. The schmitt trigger has to drive the connection wire to FPGA as well as the input capacitance of the FPGA. So considering these two aspects, power can still be reduced to around 50 mW. So as a transceiver it consumes around 62 mW which proves that wide band signaling approach for BCC results in a low power architecture.

6.10 Conclusion

Once the hardware setup is finalized, the measurements are taken on similar conditions for comparison. The conditions or variables which are mainly taken care here are the type of coupling between the electrode and the human body, area of the coupling electrode and voltage levels of the power supply and signal. In order to study the impact of one variable, all the other variables are kept constant and measurements are taken for the whole range of the interested variable. The parameter used here to compare among all the measurements is BER for simplicity.

The hardware prototype contains a general purpose FPGA board which contains the digital base band and a custom PCB which contains the AFE. There are interconnections between them as well as to the electrode. These factors make the hardware environment easy to modify but more power will be consumed for this. So the power estimation results given here are at least ten times higher, if we consider an ASIC for the transceiver.

The main aim of the waveform study is to find the hardware limitation. As the frequency of pulse increases, the rise and fall times also increases which results in BER. This trade-off is explained in Section 6.5. Thus the hardware can be tuned for low as well as high bandwidth application. The maximum data rate of the hardware is 12 Mbps with a BER of $1.0 \times 10^{-7}$. It can go as low as 600 kbps with a BER of $1.0 \times 10^{-7}$. The scalable data rate is to support the whole range of multimedia.
7 CONCLUSION

7.1 Conclusion

In this thesis an extensive literature study on different BCC architectures and implementations are done. Based on that, wide band signaling architecture with manchester encoding is selected for simplicity. The whole communication link is modeled including the human body, environment and transceiver as part of the other theses. In this thesis a first-order communication link has been established in software and is proved feasible by co-simulation. A random digital input data is generated and passed through the link and the output data is recorded. BER is calculated by comparing the input and output digital data and is used for the evaluation of the models. The design variables are tuned according to the BER. Some initial measurements are also done as inputs to modeling.

After observing a stable and safe BER of $1 \times 10^{-7}$ during simulation, a hardware prototype was made with the wide band signaling architecture. Basic initial testing was done on each hardware module before the integration was done. After integration the hardware loop is tested without the human body. Then measurements are done with the human body using the whole hardware setup to find the trade-off in the design. It is found that at low frequencies the human body attenuates the signal more than in the higher frequencies. The return path also has higher impedance in the lower frequencies.

As the frequency goes up the the intra-electrode capacitance shorts the signal more but the return path and the human body has less impedance. Since the signal is manchester encoded, as the frequency goes up the receiver needs more bandwidth to extract all the information. The op-amp in the receiver front end which is used for amplification attenuates high frequency signal more than the lower frequency signal because of its low-pass behavior. This creates a variation in the pulse high-amplitude time to low-amplitude time which causes bit error. Another source of bit error is the environment in which the system operates. The flooring, big metal structures etc. influence the signal through the human body. The metals will form a capacitance with the human body which attenuates the signal. A good isolation between the human body and the floor is needed for better signal transfer.

Different types of coupling between the human body and the electrode are plotted against BER. Galvanic coupling results in maximum signal transfer but capacitive coupling is more convenient in terms of use cases. Better coupling at the transmitter results in low BER than at the receiver. It is also proved that the BCC device can communicate by just being in the pocket of your attire. The relation
between transmitter voltage and electrode area with BER is investigated which helps in low power, low size variation of the current one. The power analysis proves this architecture as low power one. The hardware is tuned to have a maximum possible frequency of 12 MHz with a low BER of $1 \times 10^{-7}$. Since the hardware works in 600 kHz with the same BER, the requirement of scalable data rate is achieved.
8 FUTURE WORK

8.1 Future Work

The hardware prototype is made to prove that with wide band signaling high data rates are possible in BCC. Since it is achieved, the following can be done to take it further.

• Make the hardware as a stand alone unit which can act as a transceiver as well as a performance evaluator. As a transceiver it should contain transmitter and receiver base-band and AFE.

• Make the prototype size and weight comparable to the target product because the form factor does affect the performance a lot.

• Add the necessary extra hardware to measure the signal strength. This should avoid the situation of using external measuring equipments which is actually destroying the signal.

• A single switch operation to control all the tests from outside such that after that the stored results should be able to retrieve and process later.

• Perform the tests on people with different physique and on different noisy environment conditions.

• After collecting all the data from tests, design an optimized adaptation algorithm. The algorithm should contain how to adjust the circuit parameters by its own based on the physique of different people, environment and distance between the devices which are communicating.

• Design a better DC bias circuit for receiver AFE to reduce power consumption.

• Design a network layer such that more than two devices can communicate in the same network.

The future of this technology as a stand alone device may not be bright. If it can be integrated into a smart phone platform, it could find a lot of applications in daily life. This will lead to the release of smart phone applications in the market which makes this technology popular. The applications which combines BCC technology with other sensors in the smart phone can be a breakthrough in the smart phone arena.
It can also be integrated with the gesture recognition technology. One of the potential application will be pointing at a part on the screen and transfer data to or from a particular folder. It can also be the new way of doing old things like having the key within the mobile to avoid physical keys, shop by just touching the photograph of a product displayed anywhere without going to a shop etc. These are just some application examples and the actual possibilities are endless.


[23] Private Communication, Ericsson AB : Appendix B
A.1 Test bench top layer

% Run the Body Link Demo using Cadence-Matlab co-simulation
% User: bibba123
% Project name: bodyLink
% Project area: /site/edu/es/EXJOBB/bodyLink/bodyLinkDemo/m
% Department of Electrical Engineering
% Linkoping University
% Fri Mar 04 02:15:41 CEST 2011
%%%%%%%%%%%%%%%%%%%%%%%%%
% This function is the top level of the test bench in which the system
% parameters are % configured and all the sub functions are called. This is
% explained in Section 4.7
%%%%%%%%%%%%%%%%%%%%%%%%%
%function bodyLinkDemo_Top(SimulationLevel, AFE_Level,RxTx_Level)

% Table 4.1 in Section 4.7.3.1 explains about the configuration switches
% below
SimulationLevel = 2 % 1 = Grounded scenario, 2 = Non-grounded scenario
AFE_Level = 3 % 0 = No AFE, 1 = Basic AFE, 2 or 3 = Advanced AFE
RxTx_Level= 1 % 0 = No base-band, 1 = Baseband supporting wide band
signaling

close all;
fprintf('*******************************\n');
fprintf('Simulation level: %d \n', SimulationLevel);
fprintf('AFE level: %d \n', AFE_Level);
fprintf('RxTx_Level level: %d \n', RxTx_Level);
fprintf('*******************************\n');

%%
% Table 4.2 in Section 4.7.3.2 explains about the simulation inputs below
Appendix A. TEST BENCH CODE

bit_rate=40e6 % The maximum speed at which data can transmit
Vin_Pk2Pk = 3.3 % The peak to peak voltage output of the transmitter
Tx_trisefall = 5e-9 % The rise and fall time adjustment variable for transmitter, if zero the inherent circuit RLC alone will determine the value
no_data_bits_in_a_packet = (32*8) % Number of data bits in a packet
no_of_packets = 1 % Number of packets needed for simulation
OSR = 32 % Over sampling ratio for the data which is written from Cadence human body model
OSR_AFE = 32 % Over sampling ratio for the data which is written from Cadence receiver AFE model

% Section 4.7.3.4 explains about the interference
% Interference Signals
f1 = 13.56e6; % Frequency
dBm1 = -69; % Power in dBm
A1 = sqrt( 10^((dBm1/10)*10^(-3)*50)*sqrt(2) ); % Amplitude
f2 = 46e6; % Frequency
dBm2 = -48; % Power in dBm
A2 = sqrt( 10^((dBm2/10)*10^(-3)*50)*sqrt(2) ); % Amplitude
f3 = 80e6; % Frequency
dBm3 = -30; % Power in dBm
A3 = sqrt( 10^((dBm3/10)*10^(-3)*50)*sqrt(2) ); % Amplitude

%FFT parameters
fs = bit_rate*2*OSR; % Sampling frequency
fftLength = 16384; % No of FFT points

% Data for one packet
% if RxTx_Level == 0 % Sending raw data without simulink transmitter and receiver

    %tx_in=[1;0;1;0;1;1;0;0;0;1;0;1;0;1;1;0;1;1;0;0;1;0;1;0;0;1;0;0;1;0;1;1;0;1;1;0;1;0;1;1;0;0;1;0;1;1;0;1;0;1;0;0;1;0;1;1;0;0;1;0;1;1;0;0;1;0;1;1;0;1;0;1;0;0;1;0;1;1;0;1;0;1;0;0;1;0;1;1;0;0;1;0;1;1;0;1;0;1;0;0;1;0;1;1;0;1;0;1];
tx_out = tx_in;
    sizeof_tx_out = size(tx_out);
else

    options=simset('srcworkspace','current');
    preamble=[1;0;1;0;1;0;1;0;1;0;1;0;1;0;1;0;1;0;1;0;1;0;1;0;1;0;1;0;1;0;1;0;1;0;1;0;1;0;1;0;1;0;1;0;1;0;1;0;1;0];
    % Interfere[0 1]);
    sizeof_tx_in = size(tx_in);
    simtime=((2*(104+sizeof_tx_in(1)))*no_of_packets)/(2*bit_rate)+5e-6
        % The simulation time is calculated as per Equation 4.1 which is
        % explained in Section 4.7.3.2

        %Calling transmitter in Simulink
    sim('EXJOBB_connectedme_txv0_1',simtime,options);
    sizeof_tx_out = size(tx_out);

    % Plotting FFT
    bodyLinkDemo_FFT(tx_out,fftLength,fs);
    title('Magnitude Response in Log Scale at the TX output');

    end

if AFE_Level == 2 || AFE_Level == 3
    inv_tx_out = ~tx_out; % Receiver AFE 2 and 3 are inverting the data. so
to compensate the inverting the actual data is inverted at the transmitter
    tx_out = inv_tx_out;
end

% The environmental parameters (file paths) for the simulation are calculated
% based on the Simulation level variable
[data_from_FPGA_filepath simLog_filepath ocnScript_filepath runScript_filepath]= bodyLinkDemo_GetEnvParameters(SimulationLevel);

% The ocean script to give simulation inputs and configuration inputs for
% Cadence simulation is generated using this function and it is explained in
% Section 4.7.1
bodyLinkDemo_GenerateOceanScript(ocnScript_filepath,
SimulationLevel,bit_rate,sizeof_tx_out(1),VinPk2Pktx_trisefall,OSR);

% The script to run simulation is generated using this function
bodyLinkDemo_GenerateRunScript(simLog_filepath, ocnScript_filepath,
runScript_filepath);

% Cadence Human body model execution
bodyLinkDemo_CadenceModel_HumanBody(tx_out,data_from_FPGA_filepath,runScript_filepath)

%! Read data from Cadence to AFE

fprintf('Receiving data from Human body model...
');
fprintf('*******************************
');
basePath = strcat('/site/edu/es/EXJOBB/bodyLink');
data_from_HB_filepath = strcat(basePath,
'/bodyLinkModel/m/Voltage_from_HB.txt');
data_from_HB = dlmread(data_from_HB_filepath);
% Reading from the file
voltage_from_HB = data_from_HB (:, 1); % data is in column #1
time_base_from_HB = data_from_HB (:, 2); % data is in column #2
volt_samples_from_HB = size(time_base_from_HB);

data_from_HB_filepath = strcat(basePath,
'/bodyLinkModel/m/Current_from_HB.txt');
data_from_HB = dlmread(data_from_HB_filepath);
current_from_HB = data_from_HB (:, 1); % data is in column #1
time_base_from_HB = data_from_HB (:, 2); % data is in column #2
current_samples_from_HB = size(time_base_from_HB);
samples_from_HB = min(volt_samples_from_HB,current_samples_from_HB)
voltage_from_HB = voltage_from_HB(1:samples_from_HB(1)-1,1);
time_base_from_HB = time_base_from_HB(1:samples_from_HB(1)-1,1);
figure;
plot(time_base_from_HB*1e-9,voltage_from_HB);
title('Voltage at the AFE input before adding noise');

% Plotting FFT
bodyLinkDemo_FFT(voltage_from_HB,fftLength,fs,2);
title('Magnitude Response in Log Scale at the HB output');

% calculating power of received signal removing DC if it is there
if SimulationLevel == 1
    DC_level = 1.3;
else
    DC_level = 0;
end

voltage_from_HB = voltage_from_HB-DC_level;
total_power = 0;
for i = 1:((8*sizeof_tx_out(1))-5) %Considering the oversampling ratio and discarding initial junk values
    inst_power(i) =abs(current_from_HB(i))*abs(voltage_from_HB(i));
    total_power = total_power+inst_power(i);
end

power_avg = total_power/((8*sizeof_tx_out(1))-5);
power_dBW = 10*log(power_avg);
power_dBm = 10*log(power_avg/1e-3);
fprintf('Received signal power = %d W\n',power_avg);
fprintf('Received signal power in decibells = %d dBm\n',power_dBm);
fprintf('Received Pk to Pk voltage = %d mV\n',(max(voltage_from_HB)+abs(min(voltage_from_HB)))/1e-3);

% Section 4.7.3.4 explains about the interference
% Generating AWGN
fn = 100*10^6;
t = [ 0 : 1 : (samples_from_HB(1)-2) ];
NoiseGen = 0.6e-7 * sin(2*pi*fn/fs*t);
SNR = 0;
NoiseGen_with_noise = awgn(NoiseGen,SNR,'measured','db');
difft = NoiseGen_with_noise - NoiseGen;
Noise = difft';

% Noise Analysis
figure;
plot(time_base_from_HB*1e-9,Noise);
plot(Noise);
title('Noise');
bodyLinkDemo_FFT(Noise,fftLength,fs,2);
title('Spectrum in Log Scale of noise');
bodyLinkDemo_FFT(Noise,fftLength,fs,1);
title('Spectrum in Linear Scale of noise');
ylabel('V_n^2','color','black','FontName','DejaVu Sans','Fontsize',12);
xlabel('Frequency(Hz)','color','black','FontName','DejaVu Sans','Fontsize',12);

% Adding AWGN white noise to the received signal
voltage_from_HB_with_noise = voltage_from_HB+Noise;
voltage_from_HB_with_noise = voltage_from_HB_with_noise+DC_level;

figure;
plot(time_base_from_HB*1e-9,voltage_from_HB_with_noise);
title('Noisy Voltage at the AFE input');

% Plotting FFT
bodyLinkDemo_FFT(voltage_from_HB_with_noise,fftLength,fs,2);
title('Magnitude Response in Log Scale at the HB output with noise');

%Adding interference
t = [ 0 : 1 : (samples_from_HB(1)-2) ];
x1 = A1 * sin(2*pi*f1/fs*t);
A.1 Test bench top layer

\[
x_2 = A_2 \cdot \sin(2\pi f_2/fs \cdot t);
\]
\[
x_3 = A_3 \cdot \sin(2\pi f_3/fs \cdot t);
\]
\[
x = x_1 + x_2 + x_3;
\]

bodyLinkDemo_FFT(x',fftLength,fs,2);
title('Spectrum in Log Scale of the Interference signal added at the AFE input');
ylabel('Power(dBm)', 'color', 'black', 'FontName', 'DejaVu Sans', 'Fontsize', 12);
xlabel('Frequency(Hz)', 'color', 'black', 'FontName', 'DejaVu Sans', 'Fontsize', 12);
bodyLinkDemo_FFT(x',fftLength,fs,1);
title('Spectrum in Linear Scale of the Interference signal added at the AFE input');
figure;
plot(time_base_from_HB*1e-9,x);
title('Interference signal added at the AFE input');
voltage_from_HB_with_noise_interference = voltage_from_HB_with_noise + x;
figure;
plot(time_base_from_HB*1e-9,voltage_from_HB_with_noise_interference);
title('Noise and interference added to Voltage at the AFE input');
bodyLinkDemo_FFT(voltage_from_HB_with_noise_interference,fftLength,fs,2);
title('Magnitude Response in Log Scale at the HB output with noise and interference');

%Noise and Interference file generation
NI = diff + x;
NI_filepath = ('/site/edu/es/EXJOBB/bodyLink/bodyLinkModel/m/NI.txt');
NI_fileId = fopen(NI_filepath,'w+');
fprintf(NI_fileId, '%d
', NI);

%Cadence AFE model initialization and execution
if AFE_Level ~= 0
    [data_to_AFE_filepath  simLog_filepath  ocnScript_filepath runScript_filepath]= bodyLinkDemo_AFE_GetEnvParameters(AFE_Level);
BodyLinkDemo_AFE_GenerateOceanScript(ocnScript_filepath, AFE_Level, bit_rate, sizeof_tx_out(1), samples_from_HB, OSR, OSR_AFE);

BodyLinkDemo_AFE_GenerateRunScript(simLog_filepath, ocnScript_filepath, runScript_filepath);

BodyLinkDemo_AFE_CadenceModel(voltage_from_HB_with_noise, data_to_AFE_filepath, runScript_filepath);

fprintf('Receiving data from AFE...
');
fprintf('*******************************
');
basePath = strcat('/site/edu/es/EXJOBB/bodyLink', '/bodyLinkModel/m/Voltage_out_from_AFE.txt');
data_from_AFE_filepath = strcat(basePath);data_from_AFE = dlmread(data_from_AFE_filepath);
voltage_from_AFE = data_from_AFE(:, 1); % data is in column #1
time_base_from_AFE = data_from_AFE(:, 2); % data is in column #2

samples_from_AFE = size(time_base_from_AFE)
digital_data = voltage_from_AFE(1:samples_from_AFE(1), 1);
time_base_from_AFE = time_base_from_AFE(1:samples_from_AFE(1), 1);

% Plotting FFT
BodyLinkDemo_FFT(digital_data, fftLength, fs, 2);
title('Magnitude Response in Log Scale at the AFE output');

else

% AFEComparator thresholds
Comp_posThreshold = 1e-3;
Comp_negThreshold = -1e-3;
digital_data = zeros (samples_from_HB(1)-1, 1);

for j = 1:samples_from_HB(1)-1
    if voltage_from_HB_with_noise(j) > Comp_posThreshold
        digital_data(j) = 1;
    else
        if voltage_from_HB_with_noise(j) < Comp_negThreshold
            digital_data(j) = 1;
        else
            digital_data(j) = 0;
        end
    end
end

A.1 Test bench top layer

digital_data(j) = 0;
else
    if j == 1
        digital_data(j) = 0;
    else
        digital_data(j) = digital_data(j-1);
    end
end
end
end

figure;
plot(time_base_from_AFE*1e-9,digital_data);
title('Digital output data from AFE');

% Modeling a FF
for k = 1:OSR_AFE*sizeof_tx_out(1)+17
    if digital_data(k) <= 1.65
        digital_data(k) = 0;
    else
        digital_data(k) = 1;
    end
end
digital_data_for_Rx= digital_data;

if RxTx_Level ~= 0
    digital_data_for_Rx = digital_data_for_Rx (1:
    (OSR_AFE*sizeof_tx_out(1)),1);
    time_base_from_AFE = time_base_from_AFE (1:(OSR_AFE*sizeof_tx_out(1)),1);
    rx_in = [(time_base_from_AFE*1e-9),digital_data_for_Rx];
    options=simset('srcworkspace','current');
    packetsize= size(tx_in,1)+32;
    delays=7;
    masterclk=10*bit_rate
Appendix A. TEST BENCH CODE

```matlab
sim('EXJOBB_connectedme_rxv0_1',simtime,options);

max_of_goodpacket = max(no_goodpackets);
PER = ((no_of_packets-max_of_goodpacket)/no_of_packets);
fprintf('*******************************
');
fprintf('PER of Received data: %d 
', PER);
fprintf('*******************************
');
end

%    digital_data = digital_data (6:(OSR_AFE*sizeof_tx_out(1)+5),1);
%    digital_data = digital_data (5:(OSR_AFE*sizeof_tx_out(1)+4),1);
digital_data = digital_data (18:(OSR_AFE*sizeof_tx_out(1)+17),1);%2,2,1 or 1,2,1 10mbps
for k = 1:OSR_AFE*sizeof_tx_out(1)
    digital_data_grouped(floor((k-1)/OSR_AFE)+1,rem((k-1),OSR_AFE)+1)  =
    digital_data(k);
end
for k = 1:sizeof_tx_out(1)
    one = 0;
    for j = 1:OSR_AFE
        if digital_data_grouped(k,j) == 1
            one = one + 1;
        end
    end
    if one >= OSR_AFE-4
        rx_in_for_BER(k) = 1;
    else
        rx_in_for_BER(k) = 0;
    end
end
rx_in_for_BER = rx_in_for_BER';
rx_in_for_BER = rx_in_for_BER (2:sizeof_tx_out(1),1);
tx_out = tx_out (2:sizeof_tx_out(1),1);
time_base = 0:1:samples_from_AFE;
```
time_base = time_base';
time_base = time_base (2:sizeof_tx_out(1),1);
figure;
sizeof_rx_out  = size(rx_out);
rx_out_for_BER = rx_out_for_BER (1:sizeof_rx_out(1),1);
subplot (2,1,1);
plot(tx_out_for_BER);
subplot (2,1,2);
plot(rx_out);
title('BER Calc');
BER = bodyLinkDemo_BERCalc(rx_out,tx_out_for_BER);
currTimeStr = datestr(now,'yyyyymmdd_HHMMSS');
Sim_Result_filepath = strcat('/site/edu/es/EXJOB/Link/bodyLinkPhy/lab/SimulationResults/bodyLinkSIL_', currTimeStr, '.txt');
Sim_Result_fileId = fopen(Sim_Result_filepath,'w+');
fprintf(Sim_Result_fileId, 'Switch Config : %d  %d  %d 
',SimulationLevel, AFE_Level,RxTx_Level);
fprintf(Sim_Result_fileId, '*******************************************************
');
fprintf(Sim_Result_fileId, 'Input  Pulse  Peak  to  Peak  voltage  :  %d V
',Vin_Pk2Pk);
fprintf(Sim_Result_fileId, 'Input  Pulse  Rise/Fall  time:  %d ns
',Tx_trisefall/1e-9);
fprintf(Sim_Result_fileId, 'Bit rate : %d Mbps
',bit_rate/1e6);
fprintf(Sim_Result_fileId, 'Simulation time : %d us
',simtime/1e-6);
fprintf(Sim_Result_fileId, '*******************************************************
');
fprintf(Sim_Result_fileId, 'No  of  data  bits  in  a  packet  : %d
',no_data_bits_in_a_packet);
fprintf(Sim_Result_fileId, 'No of bits in a packet : %d
', (2*(72+sizeof_tx_in(1))));
fprintf(Sim_Result_fileId, 'No of packets transmitted : %d
',no_of_packets);
fprintf(Sim_Result_fileId, 'Total No of bits transmitted : %d
',sizeof_tx_out(1));
fprintf(Sim_Result_fileId, '*******************************************************\n');
fprintf(Sim_Result_fileId, 'Frequency of the interference signal= %d MHz\n', (f1/1e6));
fprintf(Sim_Result_fileId, 'Peak to peak of the interference signal= %d V\n', (A1*2));
fprintf(Sim_Result_fileId, '*******************************************************\n');
fprintf(Sim_Result_fileId, 'Received signal power at the input of AFE= %d W\n', power_avg);
fprintf(Sim_Result_fileId, 'Received signal power in decibells = %d dBm\n', power_dBm);
fprintf(Sim_Result_fileId, 'Received Pk to Pk voltage = %d mV\n', (max(voltage_from_HB)+abs(min(voltage_from_HB)))/1e-3);
fprintf(Sim_Result_fileId, '*******************************************************\n');
fprintf(Sim_Result_fileId, 'No of error bits : %d\n', floor((BER*sizeof_tx_out(1))));
fprintf(Sim_Result_fileId, 'No of good packets received: %d\n', max_of_goodpacket);
fprintf(Sim_Result_fileId, 'No of packets that has error in data or CRC: %d\n', max(crc_error));
fprintf(Sim_Result_fileId, 'No of packets that has error in delimiter: %d\n', max(sfd_error));
fprintf(Sim_Result_fileId, '*******************************************************\n');
fprintf(Sim_Result_fileId, 'BER of Received data: %d \n', BER);
fprintf(Sim_Result_fileId, 'BER of Received data in percentage : %d \n', (BER*100));
fprintf(Sim_Result_fileId, '*******************************************************\n');
fprintf(Sim_Result_fileId, 'PER of Received data: %d \n', ((no_of_packets-max_of_goodpacket)/no_of_packets));
fprintf(Sim_Result_fileId, 'PER of Received data in percentage : %d \n', (((no_of_packets-max_of_goodpacket)/no_of_packets)*100));
fprintf(Sim_Result_fileId, '*******************************************************\n');
fprintf('Simulation Completed.\n');
fprintf('*******************************\n');
A.1 Test bench top layer

A.2 Function to get environmental parameters for human body model

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This function is used to generate the file paths to save or read data as %well as to save scripts which is based on the simulation level
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [data_from_FPGA_filepath  simLog_filepath  ocnScript_filepath runScript_filepath] = bodyLinkDemo_GetEnvParameters(currentLevel)

currTimeStr = datestr(now,'yyyymmdd_HHMMSS'); % to create the time log
currLevelStr = num2str(currentLevel);
demoPath  =  strcat('/site/edu/es/EXJOBB/bodyLink/bodyLinkDemo/m', currLevelStr, '/', currTimeStr);
basePath = strcat('/site/edu/es/EXJOBB/bodyLink');
mkdir(demoPath);

data_from_FPGA_filepath  =  strcat(basePath, '/bodyLinkModel/m/digital_datain.txt');
simLog_filepath  =  strcat(demoPath, '/bodyLinkDemo_simLog_level', currLevelStr, '_', currTimeStr, '.log');
ocnScript_filepath  =  strcat(demoPath, '/bodyLinkDemo_ocnScript_level', currLevelStr, '_', currTimeStr, '.ocn');
runScript_filepath  =  strcat(basePath, '/bodyLinkDemo/bin/runScript_level', currLevelStr, '.sh');

A.3 Function to generate ocean script file for human body model

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This function generates the ocean script to control the cadence which is described in Section 4.7.1
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function bodyLinkDemo_GenerateOceanScript(ocnScript_filepath, SimulationLevel, bit_rate, sizeof_tx_out, Vin_Pk2Pk, Tx_trisefall, OSR)
    sim_time = sizeof_tx_out(1)/(2*bit_rate);
Appendix A. TEST BENCH CODE

OceanScript_fileId = fopen(ocnScript_filepath,'w+');
fprintf(OceanScript_fileId, 'ocnWaveformTool( ''awd )\n');
fprintf(OceanScript_fileId, 'simulator( ''spectre )\n');
fprintf(OceanScript_fileId, 'design( "/site/edu/es/EXJOBB/bodyLink/bodyLinkModel/sim/bodyLinkModel_Distributed_RC_TB/spectre/schematic_Trans_Int_InitialDemo/netlist/netlist")\n');
fprintf(OceanScript_fileId, 'resultsDir( "/site/edu/es/EXJOBB/bodyLink/bodyLinkModel/sim/bodyLinkModel_Distributed_RC_TB/spectre/schematic_Trans_Int_InitialDemo" )\n');
fprintf(OceanScript_fileId, 'modelFile\n'("/sw/cadence/IC5141_USR5/tools/dfII/samples/artist/mixSig/models/spectre/cds_msdev.scs" "")\n');
fprintf(OceanScript_fileId, 'analysis( ''tran ?stop "%d" ?errpreset "conservative" )\n',(sim_time+5e-6));

% The variables controlled below are explained in Section 4.2

fprintf(OceanScript_fileId, 'desVar( "Tx_Period" "1/ %d" )\n', bit_rate);
fprintf(OceanScript_fileId, 'desVar( "Tx_trisefall" "%d" )\n', Tx_trisefall);
fprintf(OceanScript_fileId, 'desVar( "samples" %d )\n', (sizeof_tx_out(1)));
fprintf(OceanScript_fileId, 'desVar( "Explicit_Feet_Cap" 1p )\n');
fprintf(OceanScript_fileId, 'desVar( "R_Tx" 50 )\n'); %50
fprintf(OceanScript_fileId, 'desVar( "R_Rx" 200 )\n'); %200
fprintf(OceanScript_fileId, 'desVar( "Tx_Rx_Cc" 100f )\n');
fprintf(OceanScript_fileId, 'desVar( "Tx_Gnd_Cc" 10f )\n');
fprintf(OceanScript_fileId, 'desVar( "Rx_Gnd_Cc" 10f )\n');
fprintf(OceanScript_fileId, 'desVar( "Rx_Self_Cc" 1p )\n');
fprintf(OceanScript_fileId, 'desVar( "Rx_HB_Cc" 1p )\n');
fprintf(OceanScript_fileId, 'desVar( "Tx_HB_Cc" 10p )\n');
fprintf(OceanScript_fileId, 'desVar( "amp1" -20 )\n');
fprintf(OceanScript_fileId, 'desVar( "Rt" 7 )\n');
fprintf(OceanScript_fileId, 'desVar( "Ra" 60 )\n');
fprintf(OceanScript_fileId, 'desVar( "Ct" 310p )\n');
A.3 Function to generate ocean script file for human body model

```c
fprintf(OceanScript_fileId, 'desVar("Cct" 5p )\n');
fprintf(OceanScript_fileId, 'desVar("Cca" 2p )\n');
fprintf(OceanScript_fileId, 'desVar("Ca" 48p )\n');
fprintf(OceanScript_fileId, 'desVar("Tx_Self_Cc" 10p )\n'); %50p
fprintf(OceanScript_fileId, 'desVar("preamp1_ip_vref" 2.6 )\n');
fprintf(OceanScript_fileId, 'desVar("Vin_pk2pk" %d ), Vin_pk2pk);%d
fprintf(OceanScript_fileId, 'desVar("Vin_PK2Pk" %d ), Vin_PK2Pk);%d
    fprintf(OceanScript_fileId, 'desVar("Vin_PK2Pk" %d ), Vin_PK2Pk);%d
else if (SimulationLevel == 2)
    OceanScript_fileId = fopen(ocnScript_filepath, 'w+');
    fprintf(OceanScript_fileId, 'ocnWaveformTool( ''awd )\n');
    fprintf(OceanScript_fileId, 'simulator( ''spectre )\n');
    fprintf(OceanScript_fileId, 'design( ''/site/edu/es/EXJOBB/bodyLink/bodyLinkModel/sim/bodyLinkModel_Distributed_RC_TB/spectre/schematic_Trans_Int_FinalDemo/netlist/netlist" )\n');
    fprintf(OceanScript_fileId, 'resultsDir( ''/site/edu/es/EXJOBB/bodyLink/bodyLinkModel/sim/bodyLinkModel_Distributed_RC_TB/spectre/schematic_Trans_Int_FinalDemo" )\n');
    fprintf(OceanScript_fileId, 'modelFile( ''/sw/cadence/IC5141_USR5/tools/dfII/samples/artist/mixSig/models/spectre/cds_msdev.scs" "")\n''("/site/edu/es/DAISY/pdk/gpdk045_v_2_0/gpdk045/../models/spectre/gpdk045.scs" "mc")\n');
    fprintf(OceanScript_fileId, 'analysis( ''tran ?stop %d ?errpreset "conservative" )\n', (sim_time+5e-6));
    fprintf(OceanScript_fileId, 'analysis( ''dc ?saveOppoint t )\n');
    fprintf(OceanScript_fileId, 'desVar("Vin_PK2Pk" %d ), Vin_PK2Pk);%d
    fprintf(OceanScript_fileId, 'desVar("Vin_PK2Pk" %d ), Vin_PK2Pk);%d
    fprintf(OceanScript_fileId, 'desVar("Vin_PK2Pk" %d ), Vin_PK2Pk);%d
    fprintf(OceanScript_fileId, 'desVar("Vin_PK2Pk" %d ), Vin_PK2Pk);%d
    fprintf(OceanScript_fileId, 'desVar("Vin_PK2Pk" %d ), Vin_PK2Pk);%d
    fprintf(OceanScript_fileId, 'desVar("Vin_PK2Pk" %d ), Vin_PK2Pk);%d
    fprintf(OceanScript_fileId, 'desVar("Vin_PK2Pk" %d ), Vin_PK2Pk);%d
    fprintf(OceanScript_fileId, 'desVar("Vin_PK2Pk" %d ), Vin_PK2Pk);%d
    fprintf(OceanScript_fileId, 'desVar("Vin_PK2Pk" %d ), Vin_PK2Pk);%d
    fprintf(OceanScript_fileId, 'desVar("Vin_PK2Pk" %d ), Vin_PK2Pk);%d
```
fprintf(OceanScript_fileId, 'desVar(  "R_Tx" 50 )\n');% 
fprintf(OceanScript_fileId, 'desVar(  "R_Rx" 50 )\n');% 
fprintf(OceanScript_fileId, 'desVar(  "Tx_Rx_Cc" 100f\n'); 
fprintf(OceanScript_fileId, 'desVar(  "Tx_Gnd_Cc" 10f\n'); 
fprintf(OceanScript_fileId, 'desVar(  "Rx_Gnd_Cc" 10f\n'); 
fprintf(OceanScript_fileId, 'desVar(  "Rx_Self_Cc" 10p\n'); 
fprintf(OceanScript_fileId, 'desVar(  "Rx_HB_Cc" 5p\n'); 
fprintf(OceanScript_fileId, 'desVar(  "Tx_HB_Cc" 5p\n');% 
fprintf(OceanScript_fileId, 'desVar(  "amp1" -20\n'); 
fprintf(OceanScript_fileId, 'desVar(  "Rt" 7\n'); 
fprintf(OceanScript_fileId, 'desVar(  "Ra" 60\n'); 
fprintf(OceanScript_fileId, 'desVar(  "Ct" 310p\n'); 
fprintf(OceanScript_fileId, 'desVar(  "Cct" 5p\n'); 
fprintf(OceanScript_fileId, 'desVar(  "Cca" 2p\n'); 
fprintf(OceanScript_fileId, 'desVar(  "Ca" 48p\n'); 
fprintf(OceanScript_fileId, 'desVar(  "Tx_Self_Cc" 10p\n'); 
fprintf(OceanScript_fileId, 'desVar(  "preampl_ip_vref" 2.6\n');% 
fprintf(OceanScript_fileId, 'desVar(  "OSR" "%d"\n', OSR); 

elseif (SimulationLevel == 3)
elseif (SimulationLevel == 4)

end

fprintf(OceanScript_fileId, 'temp( 70 )\n'); 
fprintf(OceanScript_fileId, 'run()\n'); 
fprintf(OceanScript_fileId, 'selectResult(  "dcOp")\n'); 
fprintf(OceanScript_fileId, 'selectResult(  "tran")\n');

close(OceanScript_fileId);

A.4 Function to generate script file to run cadence

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This function generates the script to run the cadence in background using
% ocean script
A.4 Function to generate script file to run cadence

```
function bodyLinkDemo_GenerateRunScript(simLog_filepath, ocnScript_filepath,
runScript_filepath)

RunScript_fileId = fopen(runScript_filepath, 'w+');
fprintf(RunScript_fileId, '#!/bin/tcsh\n\n');
fprintf(RunScript_fileId, 'source ~/.bodyLink_rc\n');
fprintf(RunScript_fileId, 'cad\n');
fprintf(RunScript_fileId, 'ocean < %s >! %s\n', ocnScript_filepath,
simLog_filepath);
fclose(RunScript_fileId);
```

A.5 Function to run cadence human body model

```
function bodyLinkDemo_CadenceModel_HumanBody(tx_out, data_from_FPGA_filepath, runScript_filepath)

Data_from_FPGA_fileId = fopen(data_from_FPGA_filepath, 'w+');
fprintf(Data_from_FPGA_fileId, '%d\n', tx_out);
% Transmitting data to body...
fprintf('Transmitting data to body...\n');
fprintf('*******************************\n');
%data_from_FPGA = dlmread(data_from_FPGA_filepath);
%data_from_FPGA = data_from_FPGA (:, 1); % data is in column #2
data_from_FPGA = tx_out;
figure;
plot(data_from_FPGA);
title('data from FPGA');

% Call Script
fprintf('Running simulation in Cadence...\n');
unix('chmod +x /site/edu/es/EXJOBB/bodyLink/bodyLinkDemo/bin/runScript_level1.sh');
```
Appendix A. TEST BENCH CODE

errorCode = unix(runScript_filepath);
if (errorCode == 0)
    fprintf('Cadence simulation completed.
');
else
    error('Error during Cadence simulation');
end

A.6 Function to plot FFT

function bodyLinkDemo_FFT(tx_out,fftLength,fs,sw)

sigLength = length(tx_out);
win = rectwin(sigLength)';
ff = fft(tx_out'.*win,fftLength);
figLength = fftLength/2 + 1;
if sw == 1
    % Plot the Magnitude Response in Linear Scale
    figure;
    plot(fs/2*linspace(0,1,figLength),(abs(ff(1:figLength))/6786));
else
    % Plot the Magnitude Response in Log Scale
    figure;
    plot(fs/2*linspace(0,1,figLength),
         ((log(((abs(ff(1:figLength))/6786)/sqrt(2)^2)/50)*1000)*10));
end

A.7 Function to get environmental parameters for receiver AFE model

function [data_to_AFE_filepath simLog_filepath ocnScript_filepath
         runScript_filepath] = bodyLinkDemo_AFE_GetEnvParameters(AFE_Level)

currTimeStr = datestr(now,'yyymmdd_HHmmss');
currLevelStr = num2str(AFE_Level);
demoPath = strcat('/site/edu/es/EXJOBB/bodyLink/bodyLinkDemo/AFE',
currLevelStr, '/', currTimeStr);
basePath = strcat('/site/edu/es/EXJOBB/bodyLink');
mkdir(demoPath);
A.7 Function to get environmental parameters for receiver AFE model

data_to_AFE_filepath = strcat(basePath, '/bodyLinkModel/m/data_to_AFE.txt');
simLog_filepath = strcat(demoPath, '/bodyLinkDemo_simLog_level', currLevelStr, '_', currTimeStr, '.log');
ocnScript_filepath = strcat(demoPath, '/bodyLinkDemo_ocnScript_level', currLevelStr, '_', currTimeStr, '.ocn');
runScript_filepath = strcat(basePath, '/bodyLinkDemo/bin/runAFEScript_level', currLevelStr, '.sh');

A.8 Function to generate ocean script file for receiver AFE model

function bodyLinkDemo_AFE_GenerateOceanScript(ocnScript_filepath, AFE_Level, bit_rate, sizeof_tx_out, samples_from_HB, OSR, OSR_AFE)

sim_time = sizeof_tx_out(1)/(2*bit_rate);

if (AFE_Level == 1)

OceanScript_fileId = fopen(ocnScript_filepath, 'w+');
fprintf(OceanScript_fileId, 'ocnWaveformTool( ''awd '')\n');
fprintf(OceanScript_fileId, 'simulator( ''spectre '')\n');
fprintf(OceanScript_fileId, 'design( ''/site/edu/es/EXJOB/bodyLink/bodyLinkModel/sim/bodyLinkPhy_AFE1_INITIALDemo/spectre/schematic/netlist/netlist'')\n');
fprintf(OceanScript_fileId, 'resultsDir( ''/site/edu/es/EXJOB/bodyLink/bodyLinkModel/sim/bodyLinkPhy_AFE1_INITIALDemo/spectre/schematic'' )\n');
fprintf(OceanScript_fileId, 'modelFile( ''/sw/cadence/IC5141_USR5/tools/dfII/samples/artist/mixSig/models/spectre/cds_msdev.scs'' )\n');
fprintf(OceanScript_fileId, 'analysis( ''tran ?stop "%d" ?errpreset "conservative" ''(sim_time+2e-6))\n');
fprintf(OceanScript_fileId, 'desVar( ''samples'' %d )\n', (samples_from_HB(1)+20));
fprintf(OceanScript_fileId, 'desVar( ''schmitt_trig_ip_cap'' 1p )\n');
fprintf(OceanScript_fileId, 'desVar( ''preamp2_cap'' 1p )\n');
fprintf(OceanScript_fileId, 'desVar( ''preamp1_cap'' 1p )\n');
fprintf(OceanScript_fileId, 'desVar( ''preamp_gnd2'' 1.3 )\n');
fprintf(OceanScript_fileId, 'desVar( ''preamp_gnd1'' 1.303 )\n');
fprintf(OceanScript_fileId, 'desVar( ''preamp1_ip_vref'' 2.6 )\n');
fprintf(OceanScript_fileId, 'desVar( ''R'' 50 )\n');
fprintf(OceanScript_fileId, 'desVar("scht_trise" 13n)\n');
fprintf(OceanScript_fileId, 'desVar("scht_trigL" 1.05)\n');
fprintf(OceanScript_fileId, 'desVar("scht_trigH" 1.6)\n');
fprintf(OceanScript_fileId, 'desVar("scht_tdel" 0)\n');
fprintf(OceanScript_fileId, 'desVar("scht_outL" 0)\n');
fprintf(OceanScript_fileId, 'desVar("scht_outH" 3)\n');
fprintf(OceanScript_fileId, 'desVar("preamp_vsoft" 0)\n');
fprintf(OceanScript_fileId, 'desVar("preamp_vinoffset" 3m)\n');
fprintf(OceanScript_fileId, 'desVar("preamp_ubf" 230M)\n');
fprintf(OceanScript_fileId, 'desVar("preamp_rout" 10)\n');
fprintf(OceanScript_fileId, 'desVar("preamp_rin" 33M)\n');
fprintf(OceanScript_fileId, 'desVar("preamp_R2" 10K)\n');
fprintf(OceanScript_fileId, 'desVar("preamp_R1" 1K)\n');
fprintf(OceanScript_fileId, 'desVar("preamp_iin_max" "(970*3.5e-6)")\n');
fprintf(OceanScript_fileId, 'desVar("preamp_ibias" 0.9u)\n');
fprintf(OceanScript_fileId, 'desVar("preamp_gain" 1G)\n');
fprintf(OceanScript_fileId, 'desVar("pramp_slewrate" 970M)\n');
fprintf(OceanScript_fileId, 'desVar("hyst_state_init" 0)\n');
fprintf(OceanScript_fileId, 'desVar("Tx_Rise_time" 4n)\n');
fprintf(OceanScript_fileId, 'desVar("R_electrode_cable" 5)\n');
fprintf(OceanScript_fileId, 'desVar("Tx_Pulse_Low_Voltage" 0)\n');
fprintf(OceanScript_fileId, 'desVar("Tx_Pulse_High_Voltage" 2)\n');
fprintf(OceanScript_fileId, 'desVar("Tx_Period" "1/ %d")\n',bit_rate);
fprintf(OceanScript_fileId, 'desVar("Cin_FPGA" 1p)\n');
fprintf(OceanScript_fileId, 'desVar("scht_tfall" "scht_trise")\n');
fprintf(OceanScript_fileId, 'desVar("OSR" "%d")\n', OSR);
fprintf(OceanScript_fileId, 'desVar("OSR_AFE" "%d")\n', OSR_AFE);

elseif (AFE_Level == 2)

OceanScript_fileId = fopen(ocnScript_filepath,'w+');
fprintf(OceanScript_fileId, 'ocnWaveformTool(\n');
fprintf(OceanScript_fileId, 'simulator(\n');
A.8 Function to generate ocean script file for receiver AFE model

\[
\begin{align*}
\text{fprintf(OceanScript_fileId,} & \quad \text{'design( }/\text{site/edu/es/EXJOBB/bodyLink/bodyLinkModel/sim/bodyLinkPhy_AFE2} \\
& \quad \text{_Receiver_rel1/spectre/schematic/netlist/netlist")\n')}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'resultsDir( }/\text{site/edu/es/EXJOBB/bodyLink/bodyLinkModel/sim/bodyLinkPhy_AFE2} \\
& \quad \text{_Receiver_rel1/spectre/schematic\n')}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'modelFile\n'))("/sw/cadence/IC5141_USR5/tools/dfII/samples/artist/mixSig/mod} \\
& \quad \text{els/spectre/cds_msdev.scs" \\
& \quad "")\n'); \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'analysis('['\text{tran} \ ?\text{stop} \ "%d" \ ?\text{errpreset} \\
& \quad \"conservative\" \ )\n'])); \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"samples" \ %d \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"AFE2_Opamp_Rout" \ 3 \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"AFE2_Opamp_Rid" \ 1M \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"AFE2_Opamp_R1" \ 1K \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"AFE2_Opamp_C1" \ 1p \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"AFE2_Opamp_Avdiff" \ 40 \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"receiver_vdc" \ 1.65 \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"AFE2_Opampin_max" \ 1m \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"AFE2_opampvsupply_p" \ 3.3 \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"AFE2_opampvref" \ 1.65 \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"AFE2_Opampufreq\" \ 230M \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"AFE2_Opampslewrate\" \ 900M \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"AFE2_Opampoutres\" \ 2 \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"AFE2_Opampinres\" \ 1M \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"AFE2_Opampbias\" \ 10m \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"AFE2_Opampgain\" \ 20 \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"nand2_vtrans\" \ 1.65 \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"nand2_vlogic_low\" \ 0 \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"nand2_vlogic_high\" \ 3.3 \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"nand2_trise\" \ 1n \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"nand2_tfall\" \ 1n \ )\n'}}; \\
\text{fprintf(OceanScript_fileId,} & \quad \text{'desVar( \\
& \quad \"nand2_tdel\" \ 1n \ )\n'}}; 
\end{align*}
\]
fprintf(OceanScript_fileId, 'desVar(      "nand1_vtrans" 1.65   )\n');
fprintf(OceanScript_fileId, 'desVar(      "nand1_vlogic_low" 0   )\n');
fprintf(OceanScript_fileId, 'desVar(      "nand1_vlogic_high" 3.3   )\n');
fprintf(OceanScript_fileId, 'desVar(      "nand1_trise" 1n   )\n');
fprintf(OceanScript_fileId, 'desVar(      "nand1_tfall" 1n   )\n');
fprintf(OceanScript_fileId, 'desVar(      "nand1_tdel" 1n   )\n');
fprintf(OceanScript_fileId, 'desVar(      "LNA_S22" -15  )\n');
fprintf(OceanScript_fileId, 'desVar(      "LNA_S12" 15   )\n');
fprintf(OceanScript_fileId, 'desVar(      "LNA_S11" -15  )\n');
fprintf(OceanScript_fileId, 'desVar(      "LNA_REF_IMP_PORT2" 50    )\n');
fprintf(OceanScript_fileId, 'desVar(      "LNA_REF_IMP_PORT1" 50    )\n');
fprintf(OceanScript_fileId, 'desVar(      "LNA_OUTPUT_CAP" 1p   )\n');
fprintf(OceanScript_fileId, 'desVar(      "LNA_NF" 10   )\n');
fprintf(OceanScript_fileId, 'desVar(      "LNA_INPUT_CAP" 1p    )\n');
fprintf(OceanScript_fileId, 'desVar(      "LNA_IIP3" -10   )\n');
fprintf(OceanScript_fileId, 'desVar(      "LNA_GAIN" 20  )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv3_vtrans" 1.65   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv3_vlogic_low" 0   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv3_vlogic_high" 3.3   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv3_trise" 1n   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv3_tfall" 1n   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv3_tdel" 1n    )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv2_vtrans" 1.45    )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv2_vlogic_low" 0   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv2_vlogic_high" 3.3    )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv2_trise" 1n   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv2_tfall" 1n   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv2_tdel" 1n    )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv1_vtrans" 1.85    )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv1_vlogic_low" 0   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv1_vlogic_high" 3.3    )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv1_trise" 2n   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv1_tfall" 2n   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv1_tdel" 2n    )\n');
A.8 Function to generate ocean script file for receiver AFE model

```matlab
fprintf(OceanScript_fileId, 'desVar( "R" 50 )\n');
fprintf(OceanScript_fileId, 'desVar( "Tx_Rise_time" 10n )\n');
fprintf(OceanScript_fileId, 'desVar( "R_electrode_cable" 0 )\n');
fprintf(OceanScript_fileId, 'desVar( "Tx_Pulse_Low_Voltage" 0 )\n');
fprintf(OceanScript_fileId, 'desVar( "Tx_Pulse_High_Voltage" 3.3 )\n');
fprintf(OceanScript_fileId, 'desVar( "Tx_Period" "(1/ %d)" )\n', bit_rate);
fprintf(OceanScript_fileId, 'desVar( "Explicit_Feet_Cap" 1p )\n');
fprintf(OceanScript_fileId, 'desVar( "R_Tx" 50 )\n');
fprintf(OceanScript_fileId, 'desVar( "R_Rx" 50 )\n');
fprintf(OceanScript_fileId, 'desVar( "Rx_Self_Cc" 10p )\n');
fprintf(OceanScript_fileId, 'desVar( "Tx_Rx_Cc" 100f )\n');
fprintf(OceanScript_fileId, 'desVar( "Tx_Gnd_Cc" 10f )\n');
fprintf(OceanScript_fileId, 'desVar( "Rx_Gnd_Cc" 10f )\n');
fprintf(OceanScript_fileId, 'desVar( "Rx_HB_Cc" 5p )\n');
fprintf(OceanScript_fileId, 'desVar( "ampl" -20 )\n');
fprintf(OceanScript_fileId, 'desVar( "Rt" 7 )\n');
fprintf(OceanScript_fileId, 'desVar( "Ra" 60 )\n');
fprintf(OceanScript_fileId, 'desVar( "Ct" 310p )\n');
fprintf(OceanScript_fileId, 'desVar( "Cct" 5p )\n');
fprintf(OceanScript_fileId, 'desVar( "Cca" 2p )\n');
fprintf(OceanScript_fileId, 'desVar( "Ca" 48p )\n');
fprintf(OceanScript_fileId, 'desVar( "Tx_Pulse_width" "(Tx_Period/2)-Tx_Rise_time" )\n');
fprintf(OceanScript_fileId, 'desVar( "OSR" "%d" )\n', OSR);
fprintf(OceanScript_fileId, 'desVar( "OSR_AFE" "%d" )\n', OSR_AFE);

elseif (AFE_Level == 3)

OceanScript_fileId = fopen(ocnScript_filepath, 'w+');
fprintf(OceanScript_fileId, 'ocnWaveformTool( 'awd )\n');
fprintf(OceanScript_fileId, 'simulator( 'spectre )\n');
```
Appendix A. TEST BENCH CODE

```matlab
fprintf(OceanScript_fileId, '%design( "/site/edu/es/EXJOBB/bodyLink/bodyLinkModel/sim/bodyLinkPhy_AFE2_Receiver_test/spectre/schematic/netlist/netlist")
');
fprintf(OceanScript_fileId, '%design( "/site/edu/es/EXJOBB/bodyLink/bodyLinkModel/sim/bodyLinkPhy_AFE2_Receiver_rell1/spectre/schematic/netlist/netlist")
');
fprintf(OceanScript_fileId, '%resultsDir( "/site/edu/es/EXJOBB/bodyLink/bodyLinkModel/sim/bodyLinkPhy_AFE2_Receiver_test/spectre/schematic" )
');
fprintf(OceanScript_fileId, '%resultsDir( "/site/edu/es/EXJOBB/bodyLink/bodyLinkModel/sim/bodyLinkPhy_AFE2_Receiver_rell1/spectre/schematic" )
');
fprintf(OceanScript_fileId, '%modelFile("sw/cadence/IC5141_USR5/tools/dfII/samples/artist/mixSig/models/spectre/cds_msdev.scs"")
');
fprintf(OceanScript_fileId, '%analysis(''tran ?stop "%d" ?errpreset "conservative" "")
');
fprintf(OceanScript_fileId, '%desVar( "samples" %d )
');
fprintf(OceanScript_fileId, '%desVar( "AFE2_Opamp_Rout" 3 )
');
fprintf(OceanScript_fileId, '%desVar( "AFE2_Opamp_Rid" 1M )
');
fprintf(OceanScript_fileId, '%desVar( "AFE2_Opamp_R1" 1K )
');
fprintf(OceanScript_fileId, '%desVar( "AFE2_Opamp_C1" 1p )
');
fprintf(OceanScript_fileId, '%desVar( "AFE2_Opamp_Avdiff" 40 )
');
fprintf(OceanScript_fileId, '%desVar( "receiver_vdc" 1.65 )
');
fprintf(OceanScript_fileId, '%desVar( "AFE2_Opampin_max" 1m )
');
fprintf(OceanScript_fileId, '%desVar( "AFE2_opampvsupply_p" 3.3 )
');
fprintf(OceanScript_fileId, '%desVar( "AFE2_opampvref" 1.65 )
');
fprintf(OceanScript_fileId, '%desVar( "AFE2_opampugf" 230M )
');
fprintf(OceanScript_fileId, '%desVar( "AFE2_opamp slewrate" 900M )
');
fprintf(OceanScript_fileId, '%desVar( "AFE2_Opampoutres" 2 )
');
fprintf(OceanScript_fileId, '%desVar( "AFE2_Opampinres" 1M )
');
fprintf(OceanScript_fileId, '%desVar( "AFE2_Opampbias" 10m )
');
fprintf(OceanScript_fileId, '%desVar( "AFE2_Opampgain" 20 )
');
fprintf(OceanScript_fileId, '%desVar( "nand2_vtrans" 1.65 )
');
fprintf(OceanScript_fileId, '%desVar( "nand2_vlogic_low" 0 )
');
```
fprintf(OceanScript_fileId, 'desVar(      "nand2_vlogic_high" 3.3   )\n');
fprintf(OceanScript_fileId, 'desVar(      "nand2_trise" 0.2n   )\n');
fprintf(OceanScript_fileId, 'desVar(      "nand2_tfall" 0.2n )\n');
fprintf(OceanScript_fileId, 'desVar(      "nand2_tdel" 0.2n )\n');
fprintf(OceanScript_fileId, 'desVar(      "nand1_vtrans" 1.65   )\n');
fprintf(OceanScript_fileId, 'desVar(      "nand1_vlogic_low" 0  )\n');
fprintf(OceanScript_fileId, 'desVar(      "nand1_vlogic_high" 3.3   )\n');
fprintf(OceanScript_fileId, 'desVar(      "nand1_trise" 0.2n   )\n');
fprintf(OceanScript_fileId, 'desVar(      "nand1_tfall" 0.2n )\n');
fprintf(OceanScript_fileId, 'desVar(      "nand1_tdel" 0.2n )\n');
fprintf(OceanScript_fileId, 'desVar(      "LNA_S22" -15 )\n');
fprintf(OceanScript_fileId, 'desVar(      "LNA_S12" 15   )\n');
fprintf(OceanScript_fileId, 'desVar(      "LNA_S11" -15 )\n');
fprintf(OceanScript_fileId, 'desVar(      "LNA_REF_IMP_PORT2" 50   )\n');
fprintf(OceanScript_fileId, 'desVar(      "LNA_REF_IMP_PORT1" 50   )\n');
fprintf(OceanScript_fileId, 'desVar(      "LNA_OUTPUT_CAP" 1p   )\n');
fprintf(OceanScript_fileId, 'desVar(      "LNA_GAIN" 20   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv3_vtrans" 1.65   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv3_vlogic_low" 0  )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv3_vlogic_high" 3.3   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv3_trise" 0.2n   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv3_tfall" 0.2n )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv3_tdel" 0.2n )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv2_vtrans" 1.45   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv2_vlogic_low" 0  )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv2_vlogic_high" 3.3   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv2_trise" 0.2n   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv2_tfall" 0.2n )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv2_tdel" 0.2n )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv1_vtrans" 1.85   )\n');
fprintf(OceanScript_fileId, 'desVar(      "inv1_vlogic_low" 0  )\n');
fprintf(OceanScript_fileId, 'desVar( "inv1_vlogic_high" 3.3 )\n');
fprintf(OceanScript_fileId, 'desVar( "inv1_trise" 0.2n )\n');
fprintf(OceanScript_fileId, 'desVar( "inv1_tfall" 0.2n )\n');
fprintf(OceanScript_fileId, 'desVar( "inv1_tdel" 0.2n )\n');
fprintf(OceanScript_fileId, 'desVar( "R" 50 )\n');
fprintf(OceanScript_fileId, 'desVar( "Tx_Rise_time" 10n )\n');
fprintf(OceanScript_fileId, 'desVar( "R_electrode_cable" 0 )\n');
fprintf(OceanScript_fileId, 'desVar( "Tx_Pulse_Low_Voltage" 0 )\n');
fprintf(OceanScript_fileId, 'desVar( "Tx_Pulse_High_Voltage" 3.3 )\n');
fprintf(OceanScript_fileId, 'desVar( "Tx_Period" "(1/ \%d)" )\n', bit_rate);
fprintf(OceanScript_fileId, 'desVar( "Explicit_Feet_Cap" 1p )\n');
fprintf(OceanScript_fileId, 'desVar( "R_Tx" 50 )\n');
fprintf(OceanScript_fileId, 'desVar( "R_Rx" 50 )\n');
fprintf(OceanScript_fileId, 'desVar( "Rx_Self_Cc" 1p )\n');
fprintf(OceanScript_fileId, 'desVar( "Tx_Rx_Cc" 100f )\n');
fprintf(OceanScript_fileId, 'desVar( "Tx_Gnd_Cc" 10f )\n');
fprintf(OceanScript_fileId, 'desVar( "Rx_Gnd_Cc" 10f )\n');
fprintf(OceanScript_fileId, 'desVar( "Rx_HB_Cc" 5p )\n');
fprintf(OceanScript_fileId, 'desVar( "amp1" -20 )\n');
fprintf(OceanScript_fileId, 'desVar( "Rt" 7 )\n');
fprintf(OceanScript_fileId, 'desVar( "Ra" 60 )\n');
fprintf(OceanScript_fileId, 'desVar( "Ct" 310p )\n');
fprintf(OceanScript_fileId, 'desVar( "Cct" 5p )\n');
fprintf(OceanScript_fileId, 'desVar( "Cca" 2p )\n');
fprintf(OceanScript_fileId, 'desVar( "Ca" 48p )\n');
fprintf(OceanScript_fileId, 'desVar( "Tx_Pulse_width" "(Tx_Period/2)-Tx_Rise_time" )\n');
fprintf(OceanScript_fileId, 'desVar( "OSR" \%d )\n', OSR);
fprintf(OceanScript_fileId, 'desVar( "OSR_AFE" \%d )\n', OSR_AFE);

elseif (AFE_Level == 4)
A.8 Function to generate ocean script file for receiver AFE model

```matlab
fprintf(OceanScript_fileId, 'temp( 70 )\n');
fprintf(OceanScript_fileId, 'run()\n');
fprintf(OceanScript_fileId, 'selectResult( ''tran '')\n');
fclose(OceanScript_fileId);
```

A.9 Function to generate script file to run cadence receiver AFE model

```matlab
function bodyLinkDemo_AFE_GenerateRunScript(simLog_filepath,
ocnScript_filepath, runScript_filepath)

RunScript_fileId = fopen(runScript_filepath, 'w+');
fprintf(RunScript_fileId, '#!/bin/tcsh\n');
fprintf(RunScript_fileId, 'source ~/.bodyLink_rc\n');
fprintf(RunScript_fileId, 'cad\n');
fprintf(RunScript_fileId, 'ocean < %s >! %s\n', ocnScript_filepath,
simLog_filepath);
fclose(RunScript_fileId);
```

A.10 Function to run cadence receiver AFE model

```matlab
function bodyLinkDemo_AFE_CadenceModel(voltage_from_HB_with_noise,
data_to_AFE_filepath, runScript_filepath)

Data_to_AFE_fileId = fopen(data_to_AFE_filepath, 'w+');
fprintf(Data_to_AFE_fileId, '%f\n', voltage_from_HB_with_noise);
fprintf('Transmitting data to AFE...\n');
fprintf('*******************************\n');

% Call Script
fprintf('Running simulation in Cadence...\n');
unix('chmod +x /site/edu/es/EXJOBB/bodyLink/bodyLinkDemo/bin/runScript_level1.sh');
errCode = unix(runScript_filepath);
if (errCode == 0)
A.11 Function to calculate BER

function BER = bodyLinkDemo_BERCalc(digital_data, tx_out)

BER=0;
errorbits=0;
no_bits_tx=size(tx_out);
no_bits_rx=size(digital_data);
if no_bits_tx <= no_bits_rx
    for (i=1:no_bits_tx)
        error= tx_out(i,1) == digital_data(i,1);
        if error ~= 1
            errorbits=errorbits+1;
        end
    end

    BER=errorbits/no_bits_tx(1);
else
    for (i=1:no_bits_rx)
        error= tx_out(i,1) == digital_data(i,1);
        if error ~= 1
            errorbits=errorbits+1;
        end
    end

    BER=errorbits/no_bits_rx(1);
end

fprintf('*******************************
');
fprintf('BER of Received data: %d
', BER);
fprintf('*******************************
');