# STUDY OF DUAL BAND WEARABLE ANTENNAS USING COMMONLY WORN FABRIC MATERIALS

By

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STUDY OF DUAL BAND WEARABLE ANTENNAS

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Abstract: In recent years, body-centric communication has become one of the most attractive fields of study. The versatile applications of body-centric communication not only being used for health monitoring, but also for real-time communication purposes in special occupations. They are important for supporting a population with increasing life expectancy and increase the probability of survival for the people suffering from chronic illness.

For both wearable and implantable form of body-centric communication, characterizing the system electromagnetically is very important. Given the constraints in power, size, weight and conformity, one of the most challenging parts become the designing antenna for such communication systems. Wearable antennas are the most popular option regarding these issues.

Wearable antennas are easier and simpler to mount on clothing when they are made of textile materials. In the process of designing a textile antenna, the availability of the fabrics is pivotal to mount on regularly worn clothes. In this report, several designs of a co-planar waveguide microstrip patch antenna are presented. Instead of felt fabric, the antenna was modified using 100% polyester and cotton fabric for the substrate material. A parasitic patch slot was created on the co-planar ground plane to achieve the dual band resonance frequencies at 2.4 GHz and 5.15 GHz. The geometrical modifications of the antennas were described and their performances were analyzed. The antenna achieved resonating frequency with a thinner substrate as the dielectric constant went higher for the fabrics. The design with different fabric materials was first simulated in CST Microwave Studio, then fabricated and measured in regular environment. They were also mounted on a 3-D printed human body model to analyze the bending effect. The design of the antennas shows satisfactory performance with a good -10dB bandwidth for both the lower and higher desired resonating frequency band.

TABLE OF CONTENTS

Chapter Page

Chapter Page

LIST OF TABLES

LIST OF FIGURES

# CHAPTER I

## INTRODUCTION

The ever-growing miniaturization of electronics has been forming the demand of devices that can be attached to the users' body [1] - [3]. In recent years, a great amount of development was seen by the miniaturized computer technology. The revolution in microelectronics has made it possible to have mobile devices, such as PDAs (personal digital assistants), smartphones, and smart watches. These technologies can be considered as a continuation of the last few decades of immense development in the size and functioning ability of mobile phone. Alongside this trend, researchers have made it possible to have special wearable communication system for people of special occupation, such as paramedics, firefighters, and astronauts, as well as for military personnel. The demand of having these communication systems has largely arisen from user satisfaction and/or dependency on mobile phones. People have become more uncomfortable to lose their mobility even for a short time, which motivated greater demand of having wearable devices for communication. Although a number of breakthroughs in this field have been experienced, many obstacles remained there seeking time and attention of researchers.

Wearable health monitoring systems (WHMS) are said to be one of the most emerging areas pursuing a lot of attention and exploration from the researchers. In recent years, we have seen smart watches that can sufficiently work as a substitution of our smartphone along with a number of medical applications, smart clothes that can gather vitals of a human body, process and to some extent take decision depending on the data. To make these things possible, research has been conducted to make antennas suitably fit in the devices. In order to get used in a wearable device, an antenna needs special attention while designing. Flexibility, conformity, power consumption, size, and weight are few of the most important constraints that must be addressed. Researchers have been looking into this for a long time to come up with suitable antenna designs that will be flexible, small, lightweight and can conformable to various shapes. Since antenna performance directly depends on the size of the antenna in order to ensure high performance and efficiency, a tradeoff has to be made between design parameters such as return loss, radiation pattern, and bandwidth.

The first ever design of an antenna for wearable applications was published in 1999. A dual-band planar inverted F antenna was printed on a flexible substrate. Although success were seen since that time, but still there has been issues concerning the antennas' flexibility and performances under conformal conditions. A solution to these issues was drawn when it was proven by some researchers that textile fabrics can be used as substrate and conductive materials for an antenna. Since textile materials are limited in their dielectric and conductive properties compared to the regular materials used in antenna design, the characteristics of the textile materials have to be explored in order to determine their usability in designing an antenna.

A few designs have been proposed using fabrics in recent years. Many varieties in antenna types can be found in the literature. Different types of patch antennas, such as circular patches, patch arrays for astronauts' suits have demonstrated [4] useful performance. Aperture coupled antenna and planar inverted F antennas (PIFAs) are discussed in [5-7]. Apart from these, loop antennas, spirals, and FM (frequency modulation) reception antennas were designed using fabric materials. These studies demonstrated that textile antennas are significantly suitable and efficient due to their comfortability, simple and eco-friendly process of design.

Taking into account that the antenna needs to be mounted in the vicinity of human body for wearable applications, lossy dielectric like human tissue has to be considered in analysis of electric fields excited by an antenna. A study [8] shows that, electric fields excited by a short dipole on the surface of human tissue are due to two possible types of surface waves, TM (transverse magnetic) and TE (transverse electric) modes. Material types also have a great impact on these fields. It was shown that, antennas with vertical polarization such as monopole, PIFA, and patch are much more efficient than the loop, and dipole which are horizontally polarized. The material type also less effects vertically polarized antennas. Among various types, microstrip patch antennas are proven to be very convenient for on-body applications due to their small thickness and light weight. Their ability to radiate strongly in the direction of away from the surface makes them suitable for off-body channels.

## 1.1 Research Objectives

Before going to the design and performance of an antenna, it is necessary to distinguish the applications that are the focus of wearable antennas. Considering that the main intention for this antenna is to mount in the close proximity of a human body for WHMS, it was suitable to choose the wireless local area network (WLAN) band for resonating frequency. The antenna was designed to resonate in two very important frequency band, 2.4 GHz, which can serve for Bluetooth, ISM (industrial, scientific and medical radio) band and for bands around 5.1 GHz, which have comparatively low interferences.

The other concern before starting the design was to select right dielectric fabric material. In the literature, felt is found to be very popular as a dielectric substrate material for fabric antennas. However, felt lacks in its flexibility and conformity on regularly worn garments. Considering flexibility, resistance towards crumpling and conformity, 100% Polyester and Cotton fabric are also candidate dielectric materials. As a conductive fabric, pure copper taffeta and nickel copper ripstop were chosen because of their higher conductivity comparing to other conductive fabric available.

An existing dual-band WLAN antenna [1] was picked from the literature which was designed on a felt substrate. CST (Computer Simulation Technology) Microwave studio was used to tweak the design according to the change of material properties. The objective of this research is to develop a modified design that serves the purpose for WLAN frequency. Once the simulated results show good agreement with the expectations and standards, the antennas were physically designed using the laser cutting facility over at the Apparel Design and Production Department of Oklahoma State

University and measurements were taken in REFTAS (Robust Electromagnetic Field Testing And Simulation) lab. The designs and performance of the antennas are described in this study after assuring good agreement of the measurements with simulated results.

## 1.2 Thesis Organization

Chapter 2 introduces the concept of body-centric wireless communication and its applications. In order to deploy a communication system, it is very necessary to consider electromagnetic properties of the human body. Also, it has been stated that simulations were done before going for measurements, Chapter 3 gives a brief on EM characteristics and modeling of human body along with a brief on the numerical techniques that can be used for simulating such designs and also how numerical methods were implemented in CST Microwave Studio. In Chapter 4, literature was reviewed regarding wearable antennas in order to find design constraints, EM characterization of textile materials, how antennas work in close proximity to the human body and their applications. The design procedure of the antennas is described in Chapter 5. After acquiring confidence on the simulated designs, the methods and characteristics of the antenna performance is described in Chapter 6. The characteristics of the antenna and its achieved goal are discussed in the conclusion. Future work will also be described.

# CHAPTER II

# BODY-CENTRIC WIRELESS COMMUNICATION SYSTEM

## 2.1 Body-centric Communication System

If we look a few decades back, it was quite impossible to even think of carrying a computer with us. The size of the computers was so big that they used to occupy a whole room of our house or work place. With time and dedication from many researchers, the size and weight of computer became smaller. We now have laptop computers, which can be carried along with us and necessarily. When mobile phones were invented and became popular among people of all ages and occupation, it became more achievable to think of a communication device that can be carried in the pocket or attached to the body. Gradually, smart phones were introduced that satisfied many users' technological needs. Starting from the very basic usage of mobile phone that is communication via audio call, video call or text messaging, a smart phone can be used to take pictures, video, browse the internet or using different applications through internet, even some case storing and processing very important data, such as monitored biomedical vitals. In short, to some extent smart phones are able to serve the need of having a computer. Shoes were invented having biomedical sensors to measure our blood pressure or heart bit rate and instantaneously transmit those data to a smart phone for processing. By the time, the next big invention in the world of electronics, smart watch, was available for mass people, there have been a number of body centric communication systems were developed for specialized occupations, such as paramedics, firefighters and astronauts. Body worn equipment is also being used for health monitoring. In the last decade, studies have concentrated on medical implants for health monitoring, and diagnosis [9-10]. Developed nanotechnology and micro technology have opened up new possibilities of using body centric communication for health monitoring and implantation in much more widespread applications. In addition to that, communication plays a vital role in implementation of sensors and drug delivery operations. Communication channels are also needed for monitoring internal body conditions and takings actions as warranted. Fig. 2.1 depicts an ordinary construction of a wearable medical support network.

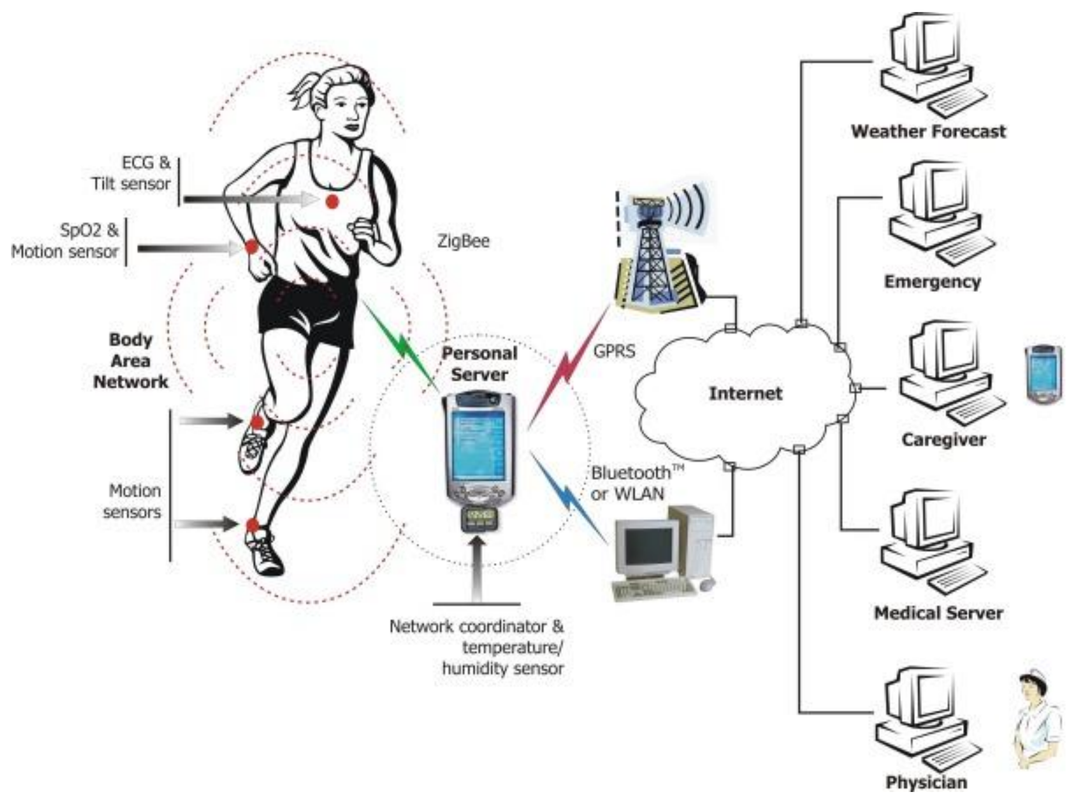



Fig. 2.1 Wearable medical support network [11]

Body-centric communication systems are constructed around the domain of personal area networks (PANs) and body area networks (BANs). These two specific structures of communication have their own protocols and requirements. Overall, the body-centric communication systems can be classified as [8]:

- Off-body: Channel of communication is off the body. Antenna of transmission end is on the body.
- On-body: Channel is on the body surface; both transmission and receiving antennas are mounted or attached to the body.
- In-body: Major part of the communication channel is inside the body.

These subdomains are not neatly defined in literature, yet they resembles the shorthand nomenclatures that will be used to explain the body centric communication in this work. Fig. 2.2 demonstrates these subdomains all together.

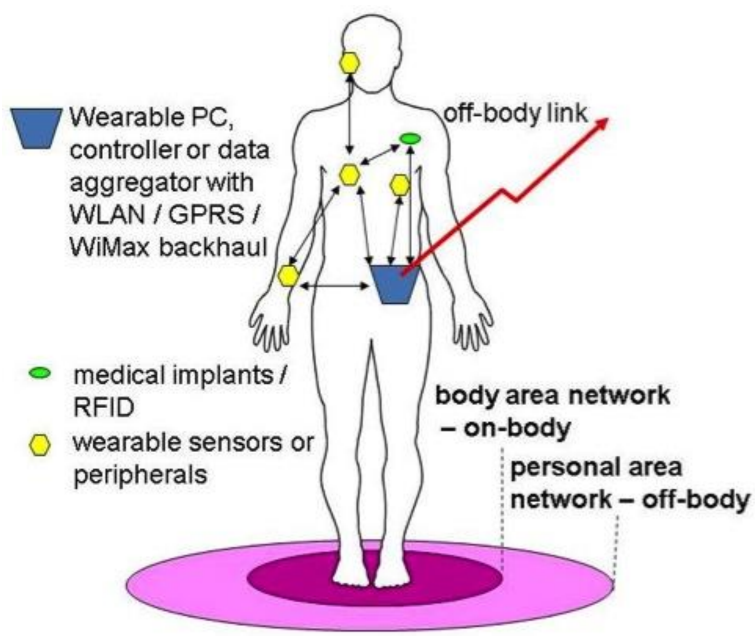



Fig. 2.2. Subdomains of Body-centric Communication [11]

### 2.1.1 Off-body Communication

Off-body communication refers to the scenario where the communication system is constructed with a node on a human body and another node far away from the body. Typically, this type of communication can be seen when a base station or multiple broadcast stations are involved. In that sense, off-body communications can also be referred as Off- to- On-Body Communications. Communications involving this type of scenarios have been extensively studied [12-14]. Off-body communication system refers to both wired and wireless communication. A good example of off-body communication is ECG (electrocardiogram) sensors with a base node connected through wire (Fig. 2.3). In bio-medical world, this idea has been used in order to not only for echocardiogram applications, but also for other expect of human health monitoring, such as glucose level and, heart bit rate monitoring.


Fig. 2.3. ECG using off-body communication [15]

For a wired network, the reliability becomes an issue due to the constant flexing of cables and connectors. In addition, the weight of such cables causes inconvenience to the user.

Wireless off-body networks provide a solution to the inconvenience and reliability issues regarding wired networks. Antennas can be used as the communication node mounted on body to transmit the data to a wireless router to reroute or directly to a storing device. Therefore, the antenna needs to radiate data at a distance from the wearer that requires the design to be characterized specifically for off-body communication. Most wearable health monitoring systems have been developed using wireless off-body communication systems. Fig. 2.4 demonstrates a generic structure of wireless off-body communication system for health monitoring.

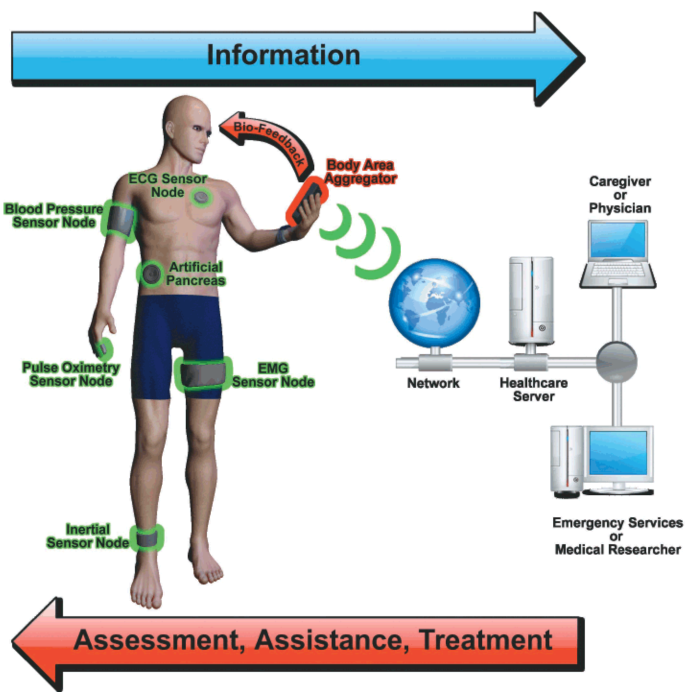



Fig. 2.4 WHMS using Off-Body Communication [11]

Not only in WHMS, off-body communication can be used for communicating with firefighters to get video feed. Using off body communication, smart clothes have been designed to monitor firefighters' physiological parameters. Using these smart protective clothing, toxic chemicals in the environment can be detected, location of the first responders can be tracked and communication among members of the team can be processes that can decrease the possibility of harm to firefighters [16]. Fig 2.5. Shows a standard smart firefighters' suit using off-body communication.


Fig. 2.5 Smart Protective Suit for Firefighters [23]

NASA is also using off-body communication systems for continuous health monitoring of astronauts using sensors on their spacesuit [17].

### 2.1.2 On-Body Communications

Body centric communication systems are considered on-body systems when both the transmitting and receiving nodes are attached to or carried by human body. Such wireless communication systems are an attractive option for connecting various electronic devices that can be attached or carried by a person on their body. The whole network may include sensors, data processing unit and several I/O units. This system of communication can be exploited to use several devices that are carried by human on a regular basis to monitor physiological readings and so many other applications. Some of those applications can readily adopt existing standards of communication, such as UWB, Bluetooth, ISM or ZigBee.

For on-body communication, the human body becomes the crucial part while adopting and/or constructing the system. At low frequencies, electromagnetic energy has a significant penetration depth [18] On the contrary, penetration depth decays drastically in higher frequency. For example, at 2.45 GHz the penetration depth is approximately 25 mm for muscle and 120 mm for fat while at 10 MHz depths are 200 mm and 1 m respectively [19-21]. Therefore, in order to reduce the potential for harm, higher frequency communication becomes more practical.

Moreover, while thinking of on-body communication, a few criterions have to be considered. Since the system may be used for data and video feed, it must support a high data rate. Secondly, the devices must be small and light weight in order for a human to carry them. In addition, the power consumption has to be minimum. In [22], the author demonstrated a near-field intra-body communication system to monitor physiological data. The proposed ECG monitoring system is shown in fig. 2.6.

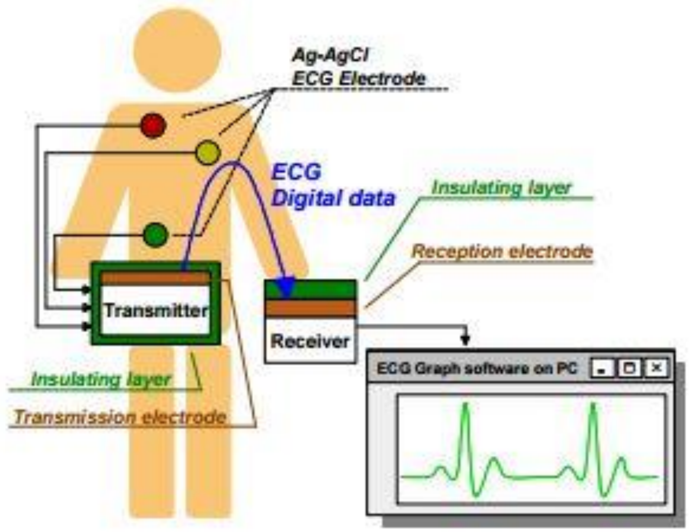



Fig. 2.6. Wireless ECG monitoring system [22]

### 2.1.3 In-body Communications

Although in-body communication generally indicates to those networks where most part of the network remain inside the body, but in reality in-body networks are typically medical implants and sensor networks. Recent developments in nanotechnology and microelectromechanical systems (MEMS) have had a profound impact on medical implants and sensor-based solutions to medical needs. Because of these technologies, it is possible to construct intelligent microscopic implantable sensors, mobile robots, and drug release devices that can perform in vivo diagnostic and therapeutic intervention [8].

However, implantable devices are not new to the biomedical world. In 1958, Ake Senning implanted a heart pacemaker into a human body (Fig. 2.7). The device was designed and built by a Swedish cardiac surgeon Rune Elmqvist [24]. Since then a lot of efforts has been made to modernize the technology which led to an industry producing 600,000 pacemakers per year [25].

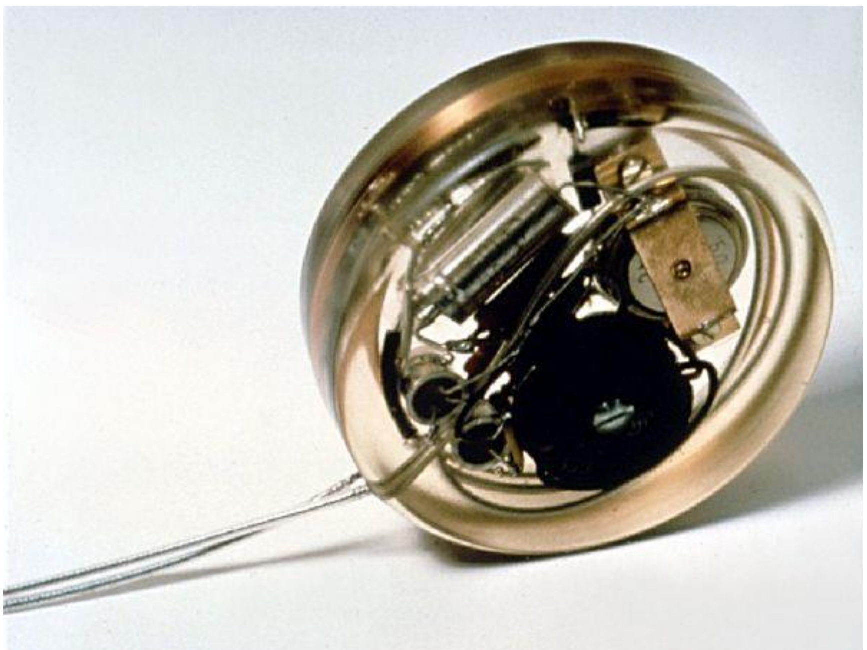


Fig. 2.7. First pacemaker built and implanted in 1958 [26]

Normally, a patient with pacemaker implanted inside his/her body has to go through checkups on regular basis to ensure the functionality of the pacemaker as well as his/her well being. A RF connection with the pacemaker makes it easier and more secure for the patient as the data can be collected and processed without having the patient physically in the medical facility.

Apart from this, a number of other implants are being used or under development. For example, brain pacemakers for the treatment of Parkinson’s decease, implantable drug delivery system, cochlea implants, artificial eyes, muscle stimulators, and nerve signal recorders to use with robotic prostheses. [27]

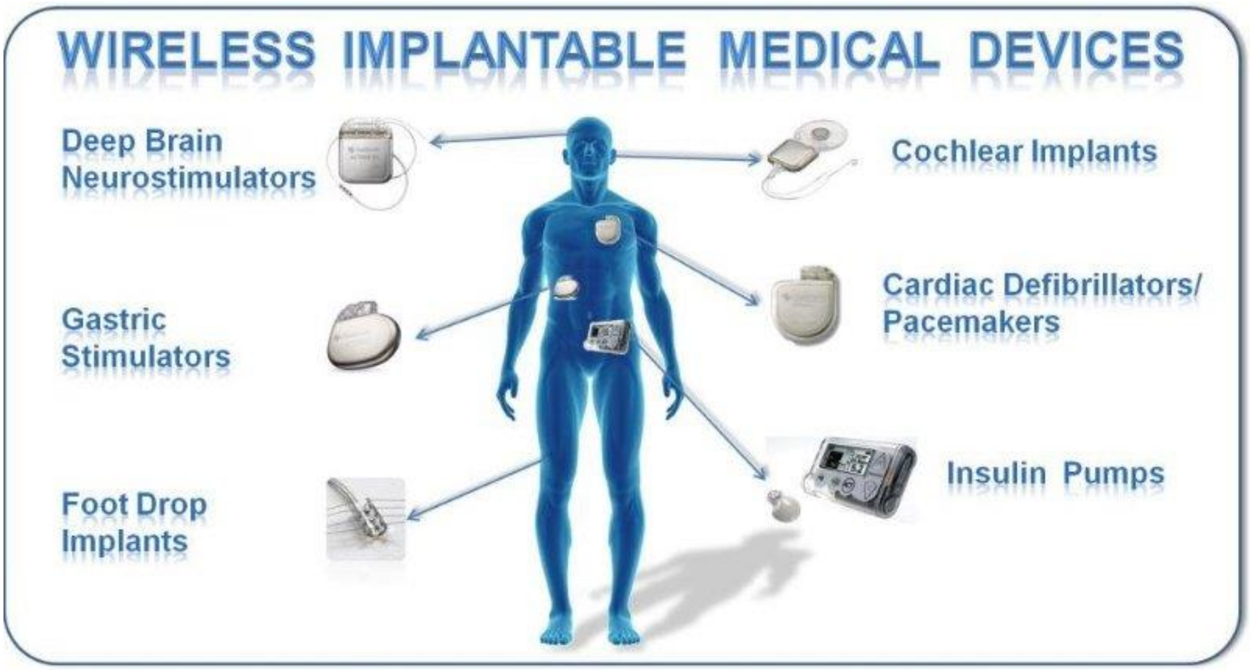



Fig. 2.8. Medical Implants and Sensors [11]

However, the technologies are not sufficiently efficient yet to be used practically. Many problems must be overcome if these technologies are intended to widely exploit. Researches on Nano-system and microsystems are being conducted to make progress in overcoming these issues [28-29].

## 2.2 Overview of Systems

Body centric wireless communication systems are constructed around body area networks (BANs) and personal area networks (PANs) that are capable of operating in several bandwidths. Therefore, it becomes challenging to define or distinguish the operating bands in specific groups. However, based on the operating frequencies, two classifications can be constructed; narrowband and wideband systems.

Table. 2.1 summarizes the selection of frequency bands for Body centric wireless communications.

Table 2.1. Summary of Frequency Bands in Body-centric Wireless Communication [30]

| Standard | Frequency (MHz) | Data Rate (max.) | Power Consumption (max.) | Range (m) |
|---|---|---|---|---|
| **UHF/VHF** | ~10 | Very low | Very low | <=0.5 |
| **Medical Implant Communications Service (MICS)** | 402-405 | 500 Kbps | 25μW | <=2 |
| **Wireless Medical Telemetry Services (WMTS)** | 420-429<br>440-449<br>(Japan)<br>608-614<br>1395-1400<br>1427-1429.5<br>(USA) | Low | Low | ~10 |
| **IrDA** | Infrared | 16 Mbps | - | 1 |
| **BodyLAN** | 900 | 32 Kbps | 0 dBm | 2-10 |
| **ZigBee** | 868<br>915<br>2400 | 20 Kbps<br>40 Kbps<br>250 Kbps | 30mW | 10-75 |
| **Bluetooth** | 2400-2480 | 1 Mbps | 0dBm | 0.1-10 |
| **WLAN** | 2400, 5200 | 10-50 Mbps | 0dBm | 30-50 |
| **UWB** | 3100-10,600 | 1 Gbps | -41 dBm/MHz | 10 |

### 2.2.1 Narrowband Systems

Different classifications of narrowband systems are described below,

- UHF/VHF bands: Using carrier frequencies between 9-315 KHz, with a data rate upto 512 Kbps, constraints imposed on the range of communication for pacemakers and implantable RFID networks. The range of communication becomes so low that it can be referred to "touch" range, which limits the usefulness. The issue can be slightly eased by using a higher frequency of ~ 10MHz but still provides very low data rate compared to the need of body-centric communication systems.
- Implant and telemetry bands: The frequency band from 402-405 MHz is called the Medical Implant Communication System (MICS) band [30]. The Wireless Medical Telemetry Services (WMTS) band operates on various frequencies between 420 and 1430 MHz depending on the region of operation [31]. The medical implants and swallow able sensors mainly use these bands. These technologies show very distinctive nature in channel behavior.

European Telecommunications Standards Institute (ETSI) listed two principal fields of applications for MICS; telecommunication between a base station and an implanted device, and between medical implants between same body. The ITU-R recommendation sets a level of 25 µW [32] equivalent isotropic radiated power (EIRP) which is 2.5 dB lower than ETSI standard for MICS. FCC in USA and Australia follow the ITU-R recommended standard.

- ISM, Bluetooth, ZigBee, and WLAN: In body area network (BAN), the most active standards are IEEE 802.15.1 (Bluetooth) and IEEE 802.15.4 (ZigBee). These standards are originally part of IEEE 802.15 group for wireless personal area network (WPAN).

  The ZigBee standard [33] provides communication with low cost, low data rate and less complexity. The operations of ZigBee occur in 16 different channels in 2.4 GHz ISM band, 10 channels in 915 MHz band and in 1 channel in 868 MHz.

  Bluetooth can be characterized as a low cost, low power RF standard, which operates on unlicensed industrial 2.4 GHz spectrum. It uses 79 channels in the ISM band to provide up to 1 Mbps data rate with a range of 10 m. (3 Mbps in enhanced mode with 100m range).

  Wireless Local Area Network (WLAN) is based on IEEE 802.11 standard. Sometimes it is referred as Wi-Fi. The most upgraded standard 802.11b can provide highest of 11 Mbps of data rate in 2.4 GHz frequency. The 802.11g increases the data rate up to 54 Mbps while existing 802.11a can provide up to 54 Mbps in the 5 GHz spectrum. 5.15 GHz to 5.825 GHz band may also be referred to WLAN band as FCC has set it aside from licensing since 1997.

### 2.2.2 Wideband Systems

As per FCC's approval, the UWB band resembles 7.5 GHz of bandwidth between 3.1 GHz to 10.6 GHz frequency with a maximum power spectral density of -41 dBm/MHz and maximum transmit power of -2.5 dBm [34-37]. UWB offers flexibility, robustness and high precision. On top of that, low power consumption, high data rates, high throughput and extended range makes it more suitable for many applications. It is the extreme case of spread spectrum technology. Also, jamming is extremely difficult in UWB communication as the devices work below the noise floor. UWB has become the most suitable standard for on-body applications and endoscopic devices. As UWB provides very accurate positions, it becomes most desirable for patient-centric applications.

Spatial movement or trajectory of an implant can be monitored using UWB technology, which can be pivotal in healing process as the implant can non-invasively update its condition. Finally, UWB can also be used in monitoring vital statistics of a patient. In case of on-body communication systems, it is evident that none of the applications requires a high data rate. But, if the system is using several WBAN application devices together (listed in Table 2.2), the aggregated data rate becomes very high which is higher than the data rate provided by any low frequency operating band standard. Giving a viable solution to this issue, UWB emits signals based on the generation of short pulses over a very wide bandwidth (3.1GHz-10.6 GHz), which not only resolves the issue with data rate but also becomes susceptible to noise or jamming because of its reduced average power output.

Table 2.2 A few commonly used medical WBAN applications [38]

| Application | Data Rate | Bandwidth (Hz) |
|---|---|---|
| ECG (12 leads) | 288 Kbps | 100-1000 |
| ECG (6 leads) | 71 Kbps | 100-500 |

| | | |
|---|---|---|
| EMG | 320 Kbps | 0-10000 |
| EEG (12 leads) | 43.2 Kbps | 0-150 |
| Blood Saturation | 16 bps | 0-1 |
| Glucose Monitoring | 1.6 Kbps | 0-50 |
| Temperature | 120 bps | 0-1 |
| Motion Sensor | 35 Kbps | 0-500 |
| Cochlear Implant | 100 Kbps | - |
| Artificial Retina | 50-70 Kbps | - |
| Audio | 1 Mbps | - |

Aiming UWB radar device at a human body, organic motion related signals can be obtained which leads to another very useful application of UWB technology. They can be used as a cardio vascular monitor attached to heart detecting cardiac contractions, arterial wall motion and respiratory movements through monitoring breathing of a human. As worn garments do not influence electromagnetic signals in UWB frequency, with a few meters of communicating range,UWB radar in cardio vascular monitoring provides a nice complement to electrocardiogram (ECG) [39].

## 2.3 mmWAVE Wireless Body-centric Communication

In recent years, the 60 GHz band has become the next big thing regarding improvement in the data rate of telecommunication. The frequency band around 60 GHz which is normally referred as the mmWave communication band is now in the pinnacle of scientific and industrial interest since the allocation of a 7 GHz unlicensed band was done by Federal Communications Commission (FCC) in 2001 [40]. This band was set aside because of the large-scale attenuation due to the resonance of the oxygen molecule until it was reconsidered because of its huge and continuous available spectrum and very high data rate (in Gbps) in small range communication. These features of mmWave communication also grabbed interest worldwide, which resulted many countries other than USA to allocate 60 GHz band for communications [41-44]. Fig. 2.9 shows the worldwide allocations of unlicensed bands around 60 GHz frequency.

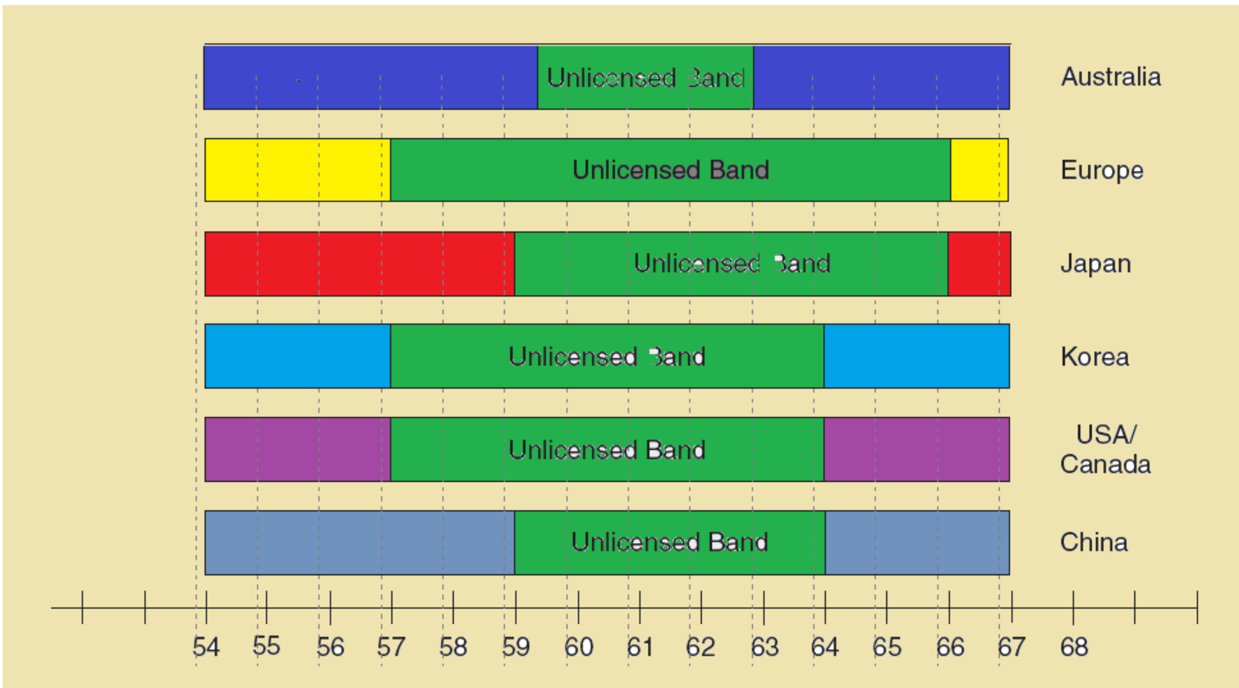



Fig. 2.9. Worldwide 60- GHz band allocations [45]

With this very high data rate, 60 GHz communications can avail high-resolution video monitoring systems for elderly patients and those who need constant surveillance. In [46], authors have considered low-power mmWaves as communication technology in evolution of brain electrodes, neuro stimulators and other implantable devices. A MRI profile is formed with several hundred slices of MRI scans. mmWave shows prospectus in transferring these high quality images with its high speed data rate for further analysis remotely.

Among all these applications, the most interesting would be the research outcome supported by VISION ERC [48] on potential application of mmWave in cognitive behavioral systems [47]. It was shown that, implanting sensors on those people who have difficulties in communicating verbally, such as communicative impaired children who sends non-verbal messages that cannot be immediately captured, could be relayed in real time, which may be pivot for the special people in our society.

## 2.4 Applications of Body-centric Communication Systems

Body centric communication intend to provide such systems that will be constantly available, reconfigurable, and unobtrusive. High data rate, low power consumption, low weight and small sized devices offers a vast amount of applications. Immense prospects around this system led to increased amount of research activities with the main interest being healthcare, patient monitoring, military applications, and applications for specialized occupations, navigations, and personal multimedia entertainment. A summary of a few of those applications are listed below:

- Medical applications: patient monitoring, diagnosis, drug delivery, cognitive behavioral systems.
- Wireless monitoring: position monitoring for firefighters and astronauts, tracking elderly and children.

- Real-time applications: real time video feed from firefighters, communicative impaired children, astronauts etc.
- Military applications: Recognizing team mates position, real-time communications with base and other members of the team, battlefield personnel care and intelligence.
- Specialized occupations: smart suits for firefighters and astronauts. Biosensors for their health monitoring.

This chapter has discussed the different types of body-centric communication systems. Before going into depth of a special element of body-centric communication system, such as antenna, it is very important to be familiar with different types of systems. Every applications have their individual requirements, thus it is also important to have idea about the applications of body-centric communication to narrow down the goal and proceed accordingly.

However, now that different types of body-centric communication systems have been discussed, it is intended to discuss what makes this kind of system very different from other communication system. The answer would be human body. To have a complex structure like human body inside the system, it becomes challenging to maintain the quality of the system and ensure harmless communication to human cells. This is why, in the next chapter, EM characteristics of human body will be discussed. Also, different types of body phantoms are used to simulate and measure the quality of the communication system in presence of human body. The modeling techniques of these physical and numerical phantoms will also be discussed. Apart from that, it is very important to simulate the system before going into physically building it. Several numerical methods are historically being used for simulation purpose. Some of them will be briefly discussed. Alongside, as CST Microwave Studio was used for this particular work, the numerical methods used in CST Microwave Studio will also be discussed.

# CHAPTER III

## HUMAN BODY MODELING AND NUMERICAL METHODS FOR BODY-CENTRIC COMMUNICATION

Body-centric communication systems are structured around human body, which makes the electromagnetic interaction between the body and the communication system most important. However, human body is not a simple structure. More than 37.2 trillion body cells of four major tissue types makes the EM characterization very complex for human body [50-51]. Yet, without understanding the behavior of any communication system around human body, it would be very immature to expect to work on the field. To explore interaction of communication systems located on or near the body, key step is to understand the electromagnetic characteristics of human body. Electromagnetic properties of human body significantly varies depending upon the tissue type and the frequency of operation. The interaction also depend on the surface form of human body. The entire variety of the human body surfaces can be roughly distinguished in two kinds, i.e., flat and curved surfaces. However, the surfaces considered as flat also have some curvature, which can be neglected considering the practical point of view. In order to explore the properties of the variations and enabling the development of antennas and transceiver for body centric communications, modeling of the body can be very helpful.

Physical body phantoms can be structured with solid, liquid or gel materials. On the other hand, numerical phantoms may refer to either theoretical phantoms or the models of voxel family. The modeling of these body models and the basic electromagnetic properties of body tissues are addressed in the first part of this chapter. The last part of the chapter will briefly overview the numerical methods that have been used in body centric communication. As for this project, the simulations were done using CST Microwave Studio, later this chapter, the numerical techniques used in CST MW Studio will also be discussed.

## 3.1 Electromagnetic Characteristics of Human body Tissue

Electromagnetic behavior of body tissues vary with the characteristics of electromagnetic field. It also depends on the type of the tissue. Therefore, while discussing dielectric properties of biological tissue, the properties of electromagnetic fields must be taken into account. Several authors have examined the dielectric properties of body tissue so far [52-56]. Dielectric properties of tissue are tabulated in some of these works. The frequency range normally considered is from 10 kHz to 10 GHz [54]. Most recently, a comprehensive study is presented in [57]. However, obtaining tissue samples has always been the biggest challenge in determining the tissue behaviors. It is not possible to perform measurements on living tissue cell. That is why most of the researches have been done depending on the measurements obtained from freshly killed animals and human autopsy [57].

However, before getting into the discussion regarding human tissue behavior, it is very important to revise the basics of electromagnetic wave propagation.

### 3.1.1 Overview of EM Wave Propagation

In EM wave propagation, both the conductivity and dielectric property significantly depend on the frequency of the propagation. In a lossy medium,

$$\varepsilon_r = \varepsilon_r' - j\varepsilon'' ,$$

where, $\varepsilon_r'$ is the relative permittivity of the material and ε" is the out of phase loss factor.

$$\varepsilon'' = \sigma/\varepsilon_0\omega ,$$

σ is the total conductivity of the material. The conductivity may include a frequency independent ionic conductivity, $\sigma_i$. $\varepsilon_0$ refers to the permittivity of free space and ω is the angular frequency of the EM field.

In tissue, these properties changes with frequency because of their differences in water content [58]. Due to the interaction of tissue's components in cellular and molecular level with the electromagnetic field, the dielectric characteristics of the biological tissue occurs. In a literature survey on dielectric properties of biological tissues [59], authors have mentioned following features of the biological tissue's dielectric spectrum:

- For a frequency < 100 Hz, relative permittivity of tissue may reach up to the value of $10^7$.
- At three main steps known as α, β, and γ dispersions, the relative permittivity decreases for higher frequency.

- Because of the ionic diffusion of cellular membrane, α dispersion occurs in low frequency.
- At kilohertz region, β dispersion mainly occurs due to the polarization of the cellular membranes, protein and other organic macromolecules.
- On the other hand, polarization of water molecules results γ dispersion in gigahertz region.

For numerical analysis of dispersive media, evidence of using different formulation methods can be found in literature, such as Debye [60-63], Lorentz [64-66], or Cole-Cole models [67-69].

Historically, it is evident that Debye and Cole-Cole model have been conveniently used in formulation of dielectric dispersive media.

In [70], authors have adopted a formulation technique from the basic Debye formulation, which is given in [71], as,

$$\varepsilon_r^*(\omega) = \varepsilon\infty + (\sigma_i/j\omega\varepsilon_0) + (\varepsilon_s - \varepsilon\infty)\sum_{n=1}^{N}\left(\frac{An}{1+j\omega\tau n}\right),$$

Where,

$\varepsilon\infty$ = relative permittivity at $\omega\tau_n >> 1$,

$\varepsilon_s$ = relative permittivity at $\omega\tau_n << 1$,

$\sigma_i$ = static ionic conductivity,

Rest are Debye coefficients.

On the other hand, dielectric constant of biological tissue can be expressed by Cole-Cole model as [74] :

$$\varepsilon = \varepsilon\infty + \frac{\varepsilon s - \varepsilon\infty}{1+(j\omega\tau)^{\wedge}(1-\alpha)}$$

Where, $\varepsilon\infty$ and $\varepsilon_s$ are the relative permittivity of material at infinite and zero frequencies respectively. $\alpha$ is a distribution parameter in,

$$0 \leq \alpha < 1 \text{ [10]}$$

### 3.1.2 Dielectric Properties of Human Body Tissue

Now that the basic properties of EM wave and formulation of properties in dispersive media have been discussed, the next step would be to explore the properties of human body tissue. As discussed earlier, different amount of water molecules in different tissue types, the values of the parameters changes according to tissue type for a same frequency. In [56], a model based on 4-Cole-Cole expression is used to formulate various parameters needed to find $\varepsilon(\omega)$. Based on the found parameters and 4-Cole-Cole expression [72], authors have generated a list of conductivity, relative permittivity, loss tangent, and penetration depth for different tissue types at a frequency of 2.5 GHz [72].

However, with the brief knowledge about the complexity of human body, we can move forward to the modeling of body phantom that is a necessity to analyze the performance and comprehend the shortcomings of any body-centric communication system. The rest of this chapter will be describing different types of physical body phantoms as well as numerical phantoms.

## 3.2 Physical Body Phantoms

The microwave systems and devices that have electromagnetic interaction with the human body demands explicit validation of the performance around human body to be eligible for implementation. A numerical model of the environment can be easily designed and simulated, but that cannot be sufficient in order to have an idea about the realistic environment that is exposed to various electromechanical and environmental interferences. Hence, it becomes a necessity for validation of any wearable devices to have measured in an environment with presence of a human body. However, testing a newly designed device that is expected to have significant amount of interaction with human body may put the living human in danger, sometimes even impossible. For example, many implantable devices are used for imaging of human body from inside. Without assuring the safety of the organs from the EM interaction, it would be very risky to implant such devices. Moreover, some experiments such as antennas used in wearable technology needs verified specific absorption rate (SAR) to ensure that the radiation is not going to do any harm to human body cell. Engaging living human body in such experiments will put the entire test procedure in exposure of many inherent uncertainty. In addition, even if the researchers somehow manage permission from the human subject, it would be highly inhumane to put their life at risk. These are the reasons why it becomes important to have physical body phantoms or artificial tissue emulating (ATE) phantoms. A phantom can refer to a simulated biological body (numerical phantoms) and/or physical model that is capable of simulating the characteristics of biological tissues.

In general, a phantom is expected to emulate human organs and tissues. In order to do that, it is expected that a phantom will have the features of being anatomically realistic, have dielectric precision across the frequency band and long lifetime. It is possible to classify phantoms from several points of view. Frequency range may be considered as the most important among them. Another important criterion is the tissue type the phantom emulate. Amongst the variety of human tissues, most important types can be determined based on the water content of the tissue cells. Low-water content tissue, such as bones and fats that features low permittivity and low loss. On the other hand, the high-water content tissue such as brain, muscle, and skin with higher permittivity and loss [72-75]. Based on these criterions, a phantom can be classified based on the manufacturing material, which can be either liquid, gel, semisolid (jelly), or solid (dry).

## 3.3 Numerical Phantoms

Having the discussion above, it would not be tough to imagine that enabling any wearable device or antenna with a proper physical phantom can be difficult, which leads to the desire of having a virtual phantom for numerical analysis. Several numerical phantoms are available for theoretical analysis and computational simulation. This part of the chapter discusses some of the models available. Generally, simple shaped phantoms are used for theoretical analyses whereas more realistic numerical phantoms composed of many voxels are used for computational simulation in order to get more viable results compared to physical body phantom. Next sections show examples of theoretical and voxel phantoms.

### 3.3.1 Theoretical Phantoms

The most basic and simplest theoretical phantoms are homogenous, or layered flat phantoms [88] to evaluate EM dosimetry. In these phantoms, energy is radiated form plane wave, half-wave dipole antenna, small dipole antenna and other simple sources. Spherical models are mainly used for EM dosimetry inside the human head [74-77] and eyes. Cylindrical shaped phantoms [78,79] are used as whole body model.

Results of EM interaction can also be found using finite-domain time difference (FDTD) method [31, 32] and the method of moment (MOM) [34]. The phantoms can be used in validating the results from these numerical methods. Other canonical models have also been used. For instance, in [33], $200^3$ $mm^3$ cube and 200mm diameter sphere have been used at 900 MHz and 1800 MHz which is shown in Fig. 3.1 [33].

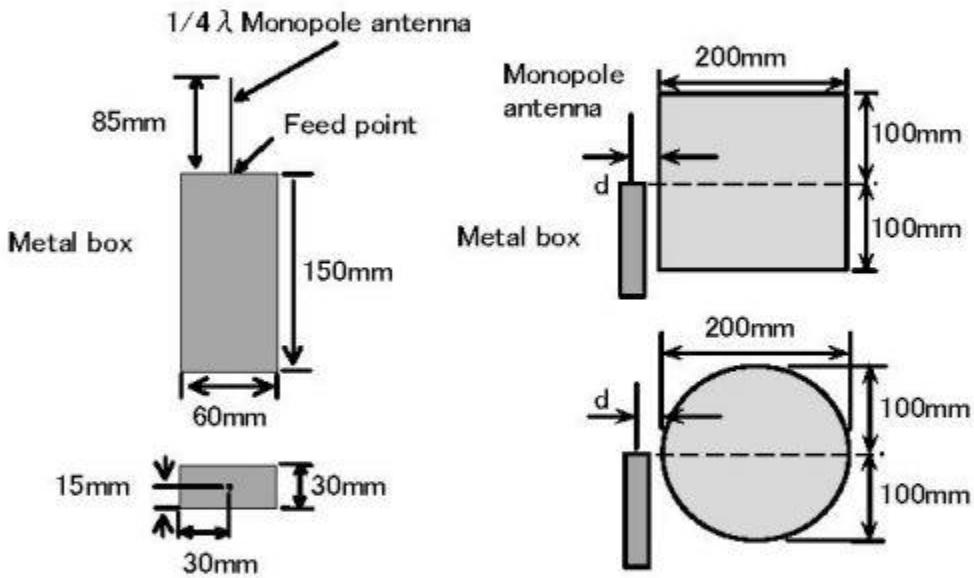



Figure 3.1. Canonical phantoms with monopole antenna on metal box [33]

### 3.3.2 Voxel Phantoms

Recent progress in medical imaging technologies, such as magnetic resonance imaging (MRI) and x-ray computed tomography (CT) and huge advancement in computational capability regarding time and complexity encouraged the development of precision head and whole body voxel models.

With the development in computation and tomographic imaging technologies, the history launched a new era of Voxel phantoms in late 1980s. For measuring EM dosimetry and antenna characteristics for cellular phone when placed in human ears, human-head models are used [83, 84]. In addition, SAR is also measured for different applications [85-87]. However, SAR inside the head model can vary for different age group [87].

Dimbylow developed an anatomically realistic voxel model of an entire body of height 170 cm with a weight of 70 Kgs [88]. This model was named NORMAN which stands for “normalized man”. This adult male model NORMAN was segmented into 37 different tissue types. Dimbylow later also developed the female voxel model [89]. This adult female human model had segments of 41 different tissue types. A very high spatial resolution whole body voxel model was proposed in [90]. Acquiring data from visible human project (VHP), this model was classified with over 40 different tissue types. Fig. 3.2  shows a high spatial resolution whole body voxel model. Later Nagaoka et al. [91] developed very high-resolution, whole body model of a Japanese male and female of almost same height classifying 51 different tissue types which are shown in Fig. 3.3.

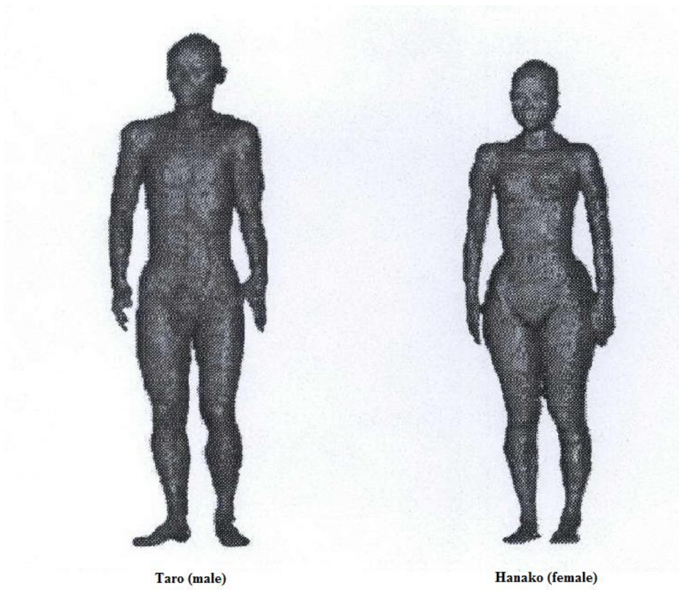



Figure 3.2. Japanese human voxel model [91]

## 3.4 CST Body Phantoms

CST Microwave Studio offers a variety of human body model for numerical analysis. The models can be distinguished in two major part, homogeneous phantoms and detailed heterogeneous voxel models. Homogeneous phantoms can serve the purpose of analyzing bending effect, but fails to provide reliable measurements for SAR and temperature distribution.

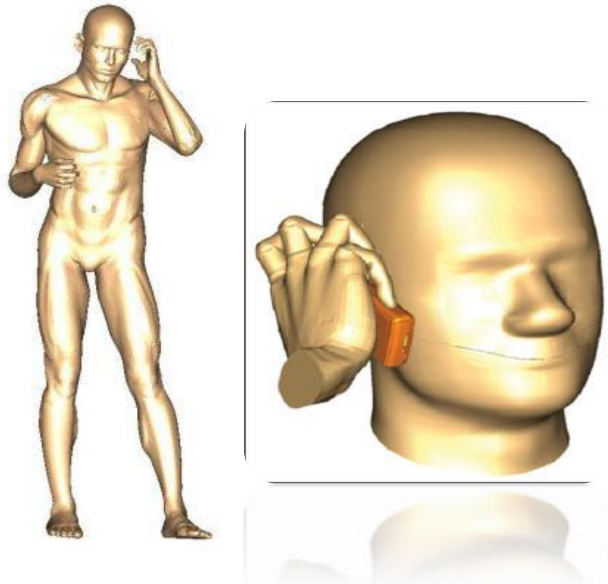


Fig. 3.3 Homogeneous SAM Phantom and Head model [92]

This is the reason biological models are offered for SAR or EMI simulation. CST offers a vast collection of biological body model, not only human body model, also some animal body model. Fig. 3.5 shows the versatile collection of CST Voxel Family.

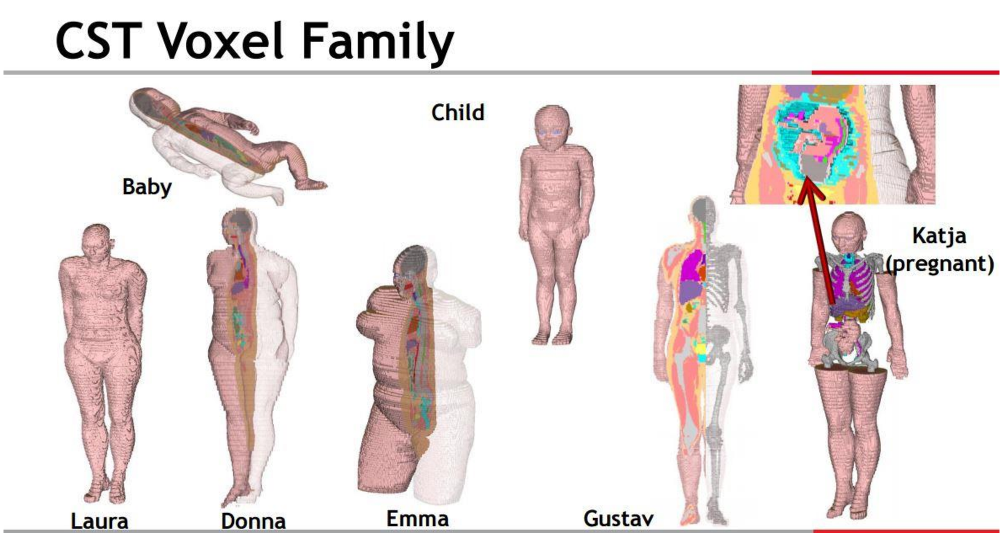



Fig. 3.4 CST Voxel Family [92]

These voxel human body models are made of different age, height, weight and resolution. CST avails the option to the users to explore material properties for any desired frequencies. Table. I shows the detail of every models available in CST Voxel Family acquired from CST website.

Table 3.1. CST Voxel Family details [92]

| MODEL | AGE/SEX | SIZE (CM) | MASS (KG) |
|---|---|---|---|
| **BABY** | 8 week/female | 57 | 4.2 |
| **CHILD** | 7 years/female | 115 | 21.7 |
| **DONNA** | 40 years/f | 176 | 79 |
| **EMMA** | 26 years/f | 170 | 81 |
| **GUSTAV** | 38 years/m | 176 | 69 |
| **LAURA** | 43 years/f | 163 | 51 |
| **KATJA** | 43 y/pregnant | 163 | 62 |

So far, the major parts of a body-centric communication system have been discussed. However, designing the systems and simulating using numerical techniques plays a pivotal role in developing any communication systems. In case of body-centric communication, simulating the system becomes more important because of the diversity of the elements. The next part of the chapter will be a discussion about a few of the most popular numerical methods along with a brief overview of the methods that have been used in the designing process of this particular work.

### 3.5 Numerical Techniques for Body-centric Communication

Numerical approaches have been taken mostly in calculating specific absorption rate (SAR) for cellular networks and RFIDs. However, for body-centric communication systems, implementation of numerical modeling techniques are very much distinctive. At microwave frequencies, a human body not only changes the boundary condition for the antennas, also used as a transmission medium that guides the surface waves and reflects the space waves. In body-centric communication systems, it is usual to have on body communication nodes. In case of on-body communication, two or more communication node can be seen on or near proximity to the human body. Presence of the human body changes the polarization and alignment of the antennas used for the system. Moreover, due to the non-planar characteristic of human body surface, bending of antenna changed the performance of an antenna. The postures of human body also plays a significant role in changing radio propagation channel causing a large variation in channel gain. Additionally, the dimensions of a human body are much larger than the wavelength of the antenna, which demands an approximation of the human body.

Several numerical methods have been developed over time to analyze EM fields in different conditions. A list of such methods with their constraints and how they combine with each other can be found in [93], which can depicted as follows:

- Method of Moments (MoM)
  Ideal for radiation and coupling analysis.
- Multi-level Fast Multipole Method (MLFMM)
  Ideal for electrically large, full-wave analysis.

- Finite Element Method (FEM)
  Ideal for inhomogeneous medium and waveguides.
- Geometrical Optics (GO)
  Ideal for electrically very large analysis.
- Finite Difference Time Domain (FDTD)
  Ideal for inhomogeneous, complex boundary conditions and wideband problem.
- Uniform Theory of Diffraction (UTD)
  Ideal for electrically very large conductive structure

### 3.5.1 Method of Moments (MoM)

Method of moment can be used in both frequency and time domain to analyze thin-wire structures. This method basically reduces the complex integral equations by solving them to a system of simpler linear equations. 'Weighted residuals' technique introduced by Harrington [95] is used in this process. The fundamental procedure of this technique can be elaborated as following:

- Derivation of the appropriate integral equation has to be done.
- Next step would be conversion or discretization of the IEs into a matrix equation. In this process weighting functions and basis functions are used.
- The elements of the matrix equation are evaluated.
- Solving the matrix equation gives the parameters of interest.

However, for arbitrary configurations involving complex geometries and inhomogeneous dielectrics, this technique evidences to be ineffective. Apart from this issue, a number of significant research regarding body centric communication can be found in literature. In [105-107], an extensive study of the computer simulated results on the influence of human body on a circular loop antenna used for pager communication has been presented. A hybrid technique of FEM and MoM was adopted in [108] to calculate SAR on a human body phantom positioned in near field of a GSM base-station antenna. In this study, MoM was used to model the metallic surfaces whereas heterogeneous human body phantom was modeled using FEM. The advantages of these frequency domain techniques were exploited to construct a highly efficient numerical method for analyzing bio-electromagnetic problems.

Other than these, a Green's function approach was proposed in [109] to analyze on-body antennas and radio channels. Authors have approximated human body as a cylindrical lossy medium and obtained Green's function by solving Helmholtz wave equation with required boundary conditions.

### 3.5.2 Finite Element Method (FEM)

Finite element method generally applies to the electrically large or inhomogeneous dielectric bodies where MoM fails in efficiency. The basic idea of FEM follows [110-111]:

- Divide the electromagnetic structures into a number of rectangular and triangular shaped elements.
- Using a set of basis polynomials, each element is expanded.
- The expanded field is substituted with function for Maxwell's equation and the function are set to zero.

- A matrix eigenvalue equation is derived with the field values at the element nodes as the unknowns.
- Eigenvalues and eigenvectors are determined by solving the equation.

The matrix solution is very time consuming which can be considered as a major drawback of FEM technique.

As it is evident that FEM requires huge amount of computer memory, it is often applied in solving problems at low frequency, mostly in lower MHz range, for medical applications. An approach based on FEM was adopted in [120] to calculate eddy current effects on human body. Authors have demonstrated the feasibility of  FEM-techniques for calculating the effects of eddy currents using two different ways using linearly polarized RF-field at 64 MHz frequency. They have considered several organs of human body, such as skin, fat, bone, muscle, marrow, spinal cord, kidney, liver, bowels and bladder. A coarser discretization of the innermost organs was proved to be sufficient.

### 3.5.3 Finite-Difference Time-Domain Method (FDTD)

Finite-Difference is best known for its ability to efficiently solve boundary value problems. Similar to FEM, this technique also requires the division of the EM structures into small cell structures which is why it is very suitable for modeling inhomogeneous medium and complex boundary conditions.

This very popular numerical method was first proposed by Yee in 1966 [113]. Since then, several extensions and enhancements techniques of FDTD have been proposed [114]. In early 90’s, FDTD became very popular among the researchers in calculating SAR for mobile applications [115]. In [116], an application of FDTD method was proposed to compute electromagnetic field distribution of human body. A number of applications of the method in dosimetry of various cellular base station antennas were also demonstrated. FDTD method has also been used to demonstrate mesh model of human body [114], which can be useful in predicting antenna patterns and rough estimation of electromagnetic field inside a human body. More realistic FDTD meshes were obtained from MRI scan data in order to provide more accurate estimation of electromagnetic fields in [115].

However, FDTD also has a few weaknesses. For instance, it requires a complete mesh of the entire computational domain, which makes larger structure to be very difficult to compute. In addition to that, a stair-case approximation has to be done because of the rough edges of the small structure of the elements. This approximation may require very small grid size and minor step.

Historically, FDTD is seen to be applied in human body phantoms including visible human [116], Japanese man and woman [117], Korean human model [118]. Various parameters, such as resonance frequency, radiation pattern, directivity of antennas, specific absorption rate (SAR) were calculated using FDTD. In [119], a numerical experiment based on FDTD was demonstrated to simulate a 2.4 GHz transmission between two on body device along with the SAR computation in the fetal brain of a pregnant woman at 900 MHz frequency. This method was also applied to compute SAR, temperature rise, near fields and far fields in four different frequencies for 21 different scenarios including seven positions and three orientations of wireless implant in two separate human models [120]. FDTD method has also been used to characterize in-body radio channels for wireless implants [121].

### 3.6 Numerical Methods in CST Microwave Studio

CST microwave studio offers both time-domain and frequency domain analysis. For time domain analysis, Transient solver and TLM solver are offered [92],

Transient Solver:

- Finite Integration Technique
- Efficient calculation for both lossless and lossy structures
- Direct time-domain analysis.
- Automatic waveguide port mesh adaption.
- PBA Mehsing

TLM (time domain transmission-line matrix method) Solver:

- Octree-based meshing
- Efficient for both lossy and loss-free structures.
- Ideal for EMC/EMI applications.
- Users can define excitation signals.

On the other hand, frequency domain analysis can be done by using frequency domain solver or integral equation solver [92],

Frequency Solver:

- Only single frequency excitation is allowed.
- Applicable for electrically small structures.
- Tetrahedral mesh is used.
- Multiple ports can be used for feeding purpose.
- Simulation performed at steady state.

Integral Equation Solver:

- Uses MoM, surface triangulation and MLFMM.
- Suitable for RCS calculation.
- Surface mesh discretization.
- User defined frequency sweeping available.

Other than these solvers, multilayer solver, asymptotic solver and Eigen mode solvers are available in CST.

- The idea behind the discussion on human body modeling and numerical techniques was to understand the effect of human body in a communication system and the techniques used in simulating the elements of any communication system. This understanding will reflect on the next chapters where several designs of wearable antennas will be presented. While designing the antennas, this knowledge about human body interaction plays a very crucial part. The designs ought to be constructed taking into account that they are going to be mounted on some part of human body. The knowledge of different numerical techniques becomes pivotal in while simulating the designs. They help in understanding how the antenna geometry effects the design and also which method will be appropriate for the specific simulation. Now that a long discussion has been done on the human body modeling and numerical methods, next chapter aims to narrow down the vast area of body-centric communication to wearable antennas and discuss different requirements and aspects of wearable antennas through reviewing literature.

# CHAPTER IV

## BODY-CENTRIC WIRELESS COMMUNICATION: WEARABLE ANTENNAS

Until this chapter, it has been mostly a discussion about different fragments and aspects of body-centric communications. After introducing body-centric communications briefly, we have discussed different types of body-centric wireless communication and their applications. We have also discussed the complexity of human body, how they can be electromagnetically characterized and portrayed through body phantoms. Not only that, we also discussed various methods of numerical analysis that can be applied to body-centric communication systems. However, all of it becomes futile without the most important segment of any wireless communication network, Antenna.

Merriam-Webster dictionary defines an antenna as “a usually metallic device (such as a rod or wire) for radiating or receiving radio waves” [122]. The IEEE Standard for Definitions of Terms for Antennas (IEEE Std 145-2013) [123] defines the antenna or aerial as “the part of a transmitting or receiving system that is designed to radiate or to receive electromagnetic waves.” However, when a general person is asked about an antenna, it will not be very much wrong to expect the response to be similar to Webster dictionary. That would not be wrong. Mostly when one hears the word “antenna”, a picture of a TV antenna appears to our imagination.

However, in the course of recent years, antenna technology has seen evolutionary changes in their size, structure, materials and usability. One of major driving factor behind this transformation is body-centric wireless applications. Ranging from commercial sports and entertainment systems to security and healthcare applications. It may be supporting a body sensor network for health monitoring, or drug release, and may be sending real time video feed of space from an astronaut, or the situational update of a hazardous fire scene from a firefighter. It may be updating the base on the vitals of a soldier on field, or an elderly person who is very important in our life. In these processes, a part of the system that cannot be neglected even a bit is the antenna. In the course of changes in applications, antennas have also seen many changes. Size has become small to equip mobile technologies, weight has reduced so they can be carried with us, and building material has become flexible so that it is possible to deploy them on non-planar surfaces. Not only that, conventional conductive or dielectric materials changed to fabric to avail the antennas to fit into our wearing garments.

From the title of this thesis and the preface, it should be quite predictable for the discussion to lead to wearable antennas. In this chapter, it is intended to review the literature of wearable antennas and gradually move on to a special kind of wearable antennas, which is “textile/fabric antenna”. Upon making this kind a little more familiar, the design constraints will be discussed. After a brief discussion on the electromagnetic behavior of textile materials, attention will be focused on the antenna performance issues in different environments, such as in the vicinity of human body, and the effect of ice, water, or snow.

## 4.1 Wearable Antennas

Before we jump straight into reviewing the literature on wearable antennas, it would be more appropriate to rekindle our understanding of the very definition of wearable antenna. There is a possibility we might mix up wearable antennas with textile antennas.

In [124], authors have defined the wearable antenna as, “an antenna that is designed to be part of clothing. It is optimized to perform in the close proximity to human body and it can be rigid or flexible.”  Nevertheless, in practice, wearable antennas refer to any antenna that is designed to be fully functional when worn, not just in clothes, but also be in devices we wear. For instances, smartwatches typically have integrated Bluetooth antennas, GoPro action cameras and google glasses have Wi-Fi and GPS antenna on them, and even the Nike+ sensor has an antenna placed in user’s shoe to communicate with smartphones via  Bluetooth antenna.


Fig. 4.1 Diversity of wearable antenna’s applications [23]

Even though wearable antennas have attracted research interested significantly in the last decade, the earliest work on wearable antenna was published in 1999 where authors presented a low profile PIFA (planar inverted- F antenna) constructed from a combination of monopole antenna and a PIFA [125]. A U-shaped slot was etched to obtain dual band operating frequency for wearable and ubiquitous computing equipment working on GSM band. The proposed antenna was intended to be placed on the sleeve of clothing. Conventional types of antennas, such as planar dipoles, monopoles, PIFAs, and microstrip patches were used in many researches in designing antennas for wearable applications. However, because of their low cost and ease of fabrication made microstrip patches a very suitable type to be used. The ground plane of a patch antenna can be used as a shield for the backward scattering. In other words, the ground plane reflects back antenna radiation, which can prevent any damage to the human body. Another design of a flexible PIFA was presented in [126] for Bluetooth operated smart clothes. In [127], a broadband dipole and spiral antenna were proposed for body wearable applications. The necessity of having omni-directional radiation pattern was also discussed with the consequences of having side lobe in the close proximity to human body. However, in [128-128], authors have compared the performances of different antennas in on-body channels. In literature, so many types of antennas were demonstrated for wearable applications. For instances, loops and omnidirectional antennas were proposed in [129,130]. A cavity slot antenna was proposed in [131]. Antennas with performance enhancement techniques such as antennas on electromagnetic band gap materials [129, 122,123] can be found.

However, microstrip patch antennas seems to be very convenient for on body applications. With their small thickness and flexibility, they become one of most suitable type of antenna for on-body applications. The characteristic of having strong radiation in the direction away from surface makes them even more suitable for off-communications. Examples of such antennas can be found in [124-126]. Some conformal designs of UWB antennas were proposed in [127,128]. Very recently, an aperture coupled miniature feeding network for wearable antennas was proposed in [129].

However, the desire of having antennas that completely fits with our clothing and more flexible compared to conventional ones led to the invention of fabric-based antennas. Even though, this kind of antennas is often referred as a fabric antenna, the conventional and proper name would be “textile antennas”. The main idea behind a textile antenna is to design an antenna with conventional or industrial fabrics. Finding suitable conductive fabric was not hard as they were being used in other applications already, such as antennas for satellite systems [130-132] and search and rescue [133]. With these works and knowledge gathered from some other research work, such as [134], the electromagnetic properties of commonly available textile materials were explored. The first textile antenna with circular polarization is claimed to be the work published in [132]. Since then, a lot of research was concentrated on the integration of antennas in protective clothing such as autonomous communication for firefighters and other emergency personnel [132-137].

So many types of antennas were modified with fabric materials. Rectangular microstrip patches [138-140], circular patches [141-142], and arrays of patches were described. Patch arrays for spacesuit applications were proposed in [144]. In addition to theese, designs of aperture coupled patch antennas [5], PIFAs [6-7], loop antennas [147], spirals [148] and button antennas [150] were found in literature. Electromagnetic band gap (EBG) materials were also applied on textile antennas to enhance their performance and reducing specific absorption rate (SAR). Most recently, a PIFA embroidered on woven made conductive textiles operating in ISM 2.4 GHz band was presented [128]. Another interesting design was proposed in [129]. In their work, authors have presented a button antenna for dual band WLAN applications. This antenna was designed with textile materials to work for both on and off-body communication systems. The antenna showed both a monopole and a broadside type radiation pattern in 2.4 GHz and 5 GHz bands, respectively.

## 4.2 Designing Textile Antennas

Wearable antennas are not exactly like other antennas. They demand special approaches in designing. Although, the requirements vary according to the specific applications, some common requirements irrespective of applications can be listed as,

- Light weight,
- Low-cost,
- Low maintenance,
- No set-up requirements, and
- Robust.

Several features regarding the design of these antennas have to be addressed. In [8], the authors made a step diagram of wearable antenna designing, which is illustrated in Fig 5.2.

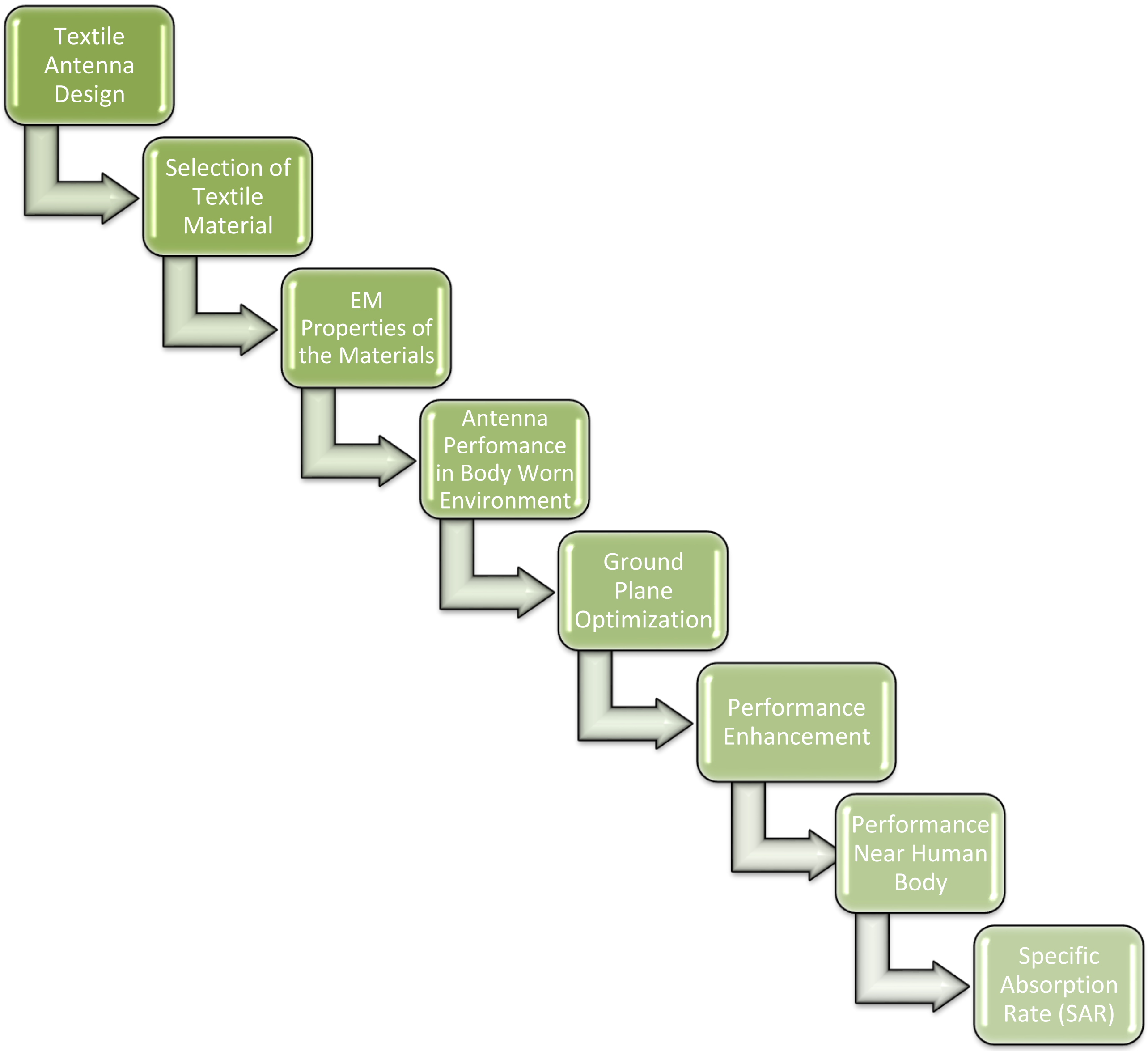



Fig. 4.2 Steps in Textile Antenna Designing [8]

In next few sections, these design features are intended to be discussed.

## 4.3 Textile materials and Their EM Characterization

Textile materials are not similar to the conventional materials used in antenna designing. Their properties are different then the orthodox materials in several ways. Moreover, the material properties directly affect the performance of an antenna. For example, the thickness of the substrate and relative permittivity mainly determine the bandwidth and efficiency of a planar microstrip antenna. Therefore, these properties of a material are often used in manipulating the antenna performance. That is why, in order to use textile material in antenna, it is required to characterize their properties. It is also important to consider the materials' availability. Textile materials that are used in wearable antennas can be divided into two main categories: - Dielectric and Conductive.

### 4.3.1 Dielectric Fabrics

In general, fabric do not demonstrate high dielectric constant. Their very low dielectric constant reduces the loss of surface wave and increases the impedance bandwidth of the antenna. They also exchange water molecules with the environment continuously, which plays a pivotal role in changing their EM properties. Textiles are rough, porous and heterogeneous material. The density of the fibers, air volume and size of the pores necessarily determines the general behavior of the materials, such as air permeability and thermal insulation. In addition, low air pressure can change their thickness and density. All these characteristics are very difficult to control in real life applications.

The permittivity of a dielectric material, $\varepsilon$ is a complex value parameter.

It is characterized with relative permittivity, $\varepsilon_r$,

$$\varepsilon = \varepsilon_0\, \varepsilon_r = \varepsilon_0(\varepsilon_r' - j\, \varepsilon_r''), \qquad \varepsilon_0 = \text{permittivity of vacuum.}$$

The real part, $\varepsilon_r'$ is called the dielectric constant while the ratio of the imaginary to real part is called loss tangent, $\tan\delta = \varepsilon_r''/\varepsilon_r'$. However, the so called dielectric constant is not constant in frequency. Generally, the frequency, surface roughness and temperature determines the dielectric properties [139]. It also depends on the moisture content, purity and homogeneity of the material [140].

In some research, the dielectric properties of textile materials have been studied [143-144]. Different experimental techniques have been used in this process. For instances, Cavity Perturbation Method [126,132], MoM-segment Method [131], Resonance Method [142], Free Space Method [146] and Transmission Line Method [143-144] were used in exploring the dielectric properties of various textile materials. Table. 5.1 shows the dielectric properties of some very commonly used fabrics [146] obtained using waveguide cavity model under 2.6 GHz.

Table 4.1 Dielectric Properties of Some Commonly Used Fabric Tested in [146]

| **Nonconductive Fabric** | **Dielectric Constant ($\varepsilon_r''$)** | **Loss Tangent ($\tan\delta$)** |
|---|---|---|
| Cordura | 1.90 | 0.0098 |
| Cotton | 1.60 | 0.0400 |
| 100% Polyester | 1.90 | 0.0045 |
| Quartzel Fabric | 1.95 | 0.0004 |
| Lycra | 1.50 | 0.0093 |

As mentioned earlier, the bandwidth and efficiency performance of a planar microstrip antenna mainly depends on the thickness of the dielectric material. Therefore, changing in thickness results variations in the antennas bandwidth, input impedance and resonance frequency.

The influence of thickness on the bandwidth of the antenna can be more conveniently explained through the concept of antenna quality factor, Q.

Antenna bandwidth is often characterized through the equation below,

$$BW \sim 1/Q$$

Where,

$$1/Q_t = (1/Q_{rad}) + (1/Q_c) + (1/Q_d) + (1/Q_{sw}) \ [32]$$

$Q_t$ = Total Q,

$Q_{rad}$ = space wave losses,

$Q_c$ = conductive ohmic losses,

$Q_d$ = dielectric losses,

$Q_{sw}$ = surface wave losses.

For thin substrates ($h \ll \lambda_0$), $Q_{rad}$ dominates the Q factor and inversely proportional to the height of the substrate [146]. Hence, increasing $h$ of substrate lowers the Q factor which increases the span of antennas bandwidth.

### 4.3.2 Conductive Fabrics

Fabrics are planar materials; therefore, surface resistivity can be used to characterize their electrical behavior. For antenna designing purpose, it is important to consider the fabric's conductivity in order to be used as patch and ground material. The conductivity (σ) of a fabric depends on its surface resistivity ($\rho_s$) and its thickness (t). Using the equation below, the conductivity of a fabric can be determined [146],

$$\sigma = 1/ (\rho_{s * t})$$

To be used in a textile antenna, a fabric has to satisfy following requirements [151]:

- a low and stable electrical resistance (≤ 1 `Ω/ square meter);
- the material must be homogenous;
- the fabric should be flexible so that it does not lose its properties when the antenna is deformed while worn;
- It has to be inelastic so that the electrical properties do not change when stretched or bent.

Although, surface resistance is expected to be constant over the area of the antenna [146], some heterogeneities, such as some discontinuities in the electric current may be experienced in the area of the antenna. The electromagnetic field will not be interfered if these discontinuities are parallel to the surface current [152]. Otherwise, the fabric resistance will increase. In [153], the authors found better performance in conductive fibers than coated fabrics. Another study [154] showed that woven fabric with higher density of conductive threads results higher effective conductivity.

## 4.4 Wearable Antenna Performances: In Close Proximity of Human Body

The name itself justifies the necessity of the study of wearable antenna performance while mounted on a human body. To serve the purpose of body-centric communication, regardless whether on-body or off-body communication, an antenna has to perform up to the mark to ensure good communication links.

However, while designing a wearable antenna, a few conditions have to be considered, as the human body is not a planar surface and the mobility of body parts is very much expected. The effects of bending and crumpling have to be taken into account. Other than that, specific absorption rate (SAR) is a very essential parameter that needs to be considered while designing a wearable antenna.

### 4.4.1 Bending Effect

In most cases, flat surfaces cannot be provided for antenna placement in wearable systems. Therefore, it is necessary to make sure that the antenna is fully functional in bending conditions. In different bending conditions, a change in antenna bandwidth is expected. A shift in resonating frequency is also anticipated. In a study [155], a patch antenna was taken under test in two different bending conditions. It was bended towards two plastic cylinders with diameter of 70 and 150 mm which are typical for different human body parts, such as arm, leg, and shoulder. Antennas were bent along the principal xz and yz plane. It was observed that, yz plane bending has minor effect on antenna performance whereas xz plane bending results significant changes in resonating frequency.

In another study, the bending effects on antenna radiation pattern and efficiency were studied [155]. It was clear from the study that antenna bending broadens the radiation pattern in bending plane resulting a decay in antenna gain. In addition, a slight reduction in antenna efficiency was noticed from the study.

### 4.4.2 Crumpling Effect

As textile antennas are made of fabrics, crumpling in the antenna becomes very much anticipated. In [155], authors have investigated the crumpling effect on a textile antenna in two principal planes, y-z and x-z planes. A significant change in resonance frequency was observed in every cases. In some extreme cases, the radiated power was even lost at some angles and the efficiency decayed almost 26% for the worst cases.

However, a decay of 16% in antenna efficiency was observed when the antenna was placed on human body. A increment in forward gain was however noticeable in this condition which was predictable because crumpling leads to less interaction between antenna and the human body compared to planar condition.

### 4.4.3 Specific Absorption Rate (SAR)

Generally, an antenna measurement indicates the conventional parameters, such as return loss, radiation pattern, gain and efficiency. However, these parameters are not sufficient for wearable/textile antennas. As wearable antennas are designed to operate in the vicinity of human body, SAR becomes an essential factor to evaluate when antenna is excited on the body.

The concern of health effect due to the radiation demands the measurement and control over the power absorbed by the human body. This need led to the specifications of SAR limit for wearable devices. Two most commonly used standards are IEEE [156] and ICNIRP (International Commission on Non-ionizing Radiation Protection [157]). As per IEEE, SAR limit is 1.6W/kg for any 1g tissue whereas ICNIRP limits 2W/kg for any 10g of tissue. As it can be easily imagined that SAR measurements cannot be done experimentally by mounting the antenna on human body, there are a few ways of measuring this. Simulation of human voxel model can provide an approximate idea. SAR measurement systems, such as DASY4 are also available and used in several researches [158].

## 4.5 Wearable Antenna Performances: Effects of Nature

As discussed earlier, textile materials do not behave like conventional materials. The nature, i.e. ice, water or snow has a significant effect on the fabric materials. For a body worn antenna, it is highly anticipatable to be exposed to these natural situations, which demands the discussion elaborated in this section of the chapter.

Although, it depends on the salinity, temperature and frequency, the permittivity of pure water is approximated to 81. This permittivity, however, interestingly drops to 3.15 [159] for frozen water and becomes nearly independent of frequency. The same goes for the snow too as this can be considered as a mixture of ice and air. But the density of snow affects the propagation of EM wave significantly.

Water, having a much higher dielectric constant compared to the fabric used as substrate, dramatically changes the antenna performance. When water is absorbed by an antenna, the moistness reduces the resonant frequency. As body worn antenna has high possibility of getting wet, it would be a viable solution to use water resistant fabric materials or a water tight cover bag which will help retaining the antenna operable in harsh environmental conditions.

So far, this thesis has covered the concept of body-centric wireless communications, how human body effects the communication network, modeling of such communication networks and wearable antennas for body centric communication. The intention behind this prolonged discussion was to clarify every aspect of a body-centric wireless communication system in order to move on to the designing antennas for such system. It was necessary to understand the system, which is very different from the conventional networks and identify the constraints and requirements in order to design antennas for such systems. The next part of the thesis will concentrate on the heart of the thesis, which is the designing and measurements of an antenna for wearable applications.

# CHAPTER V

## DUAL BAND TEXTILE ANTENNA DESIGNING

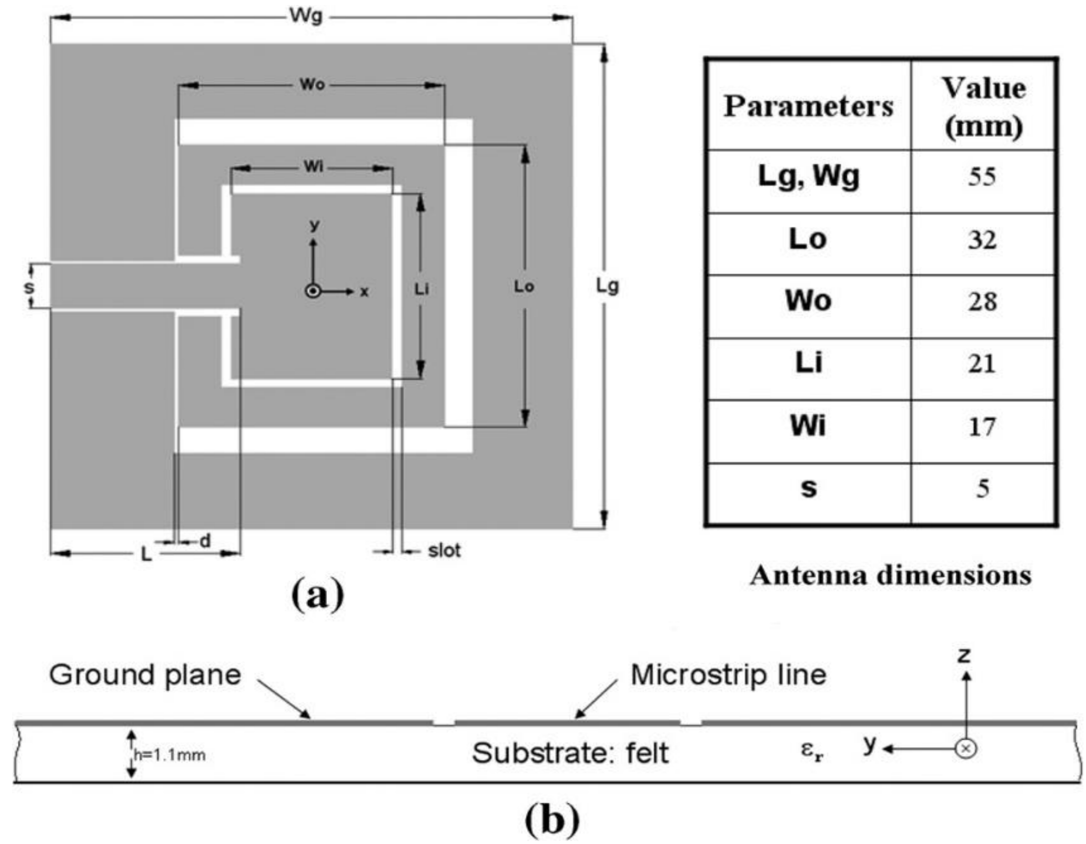
In the previous chapter, examples of various antennas were discussed for wearable applications. The effects of human body on antennas was discussed. In this chapter, it is intended to present two different textile antenna designs for wearable applications. Determining the desired resonating frequency was very important before starting with the designing process. The bandwidth around the resonating frequency was also very important in order to make sure quality communication channel. After considering several options, 2.4 GHz WLAN frequency band seemed to be most suitable frequency band for wearable applications. Along with this frequency, 5 GHz WLAN band and some other indoor frequency band around 5.1- 5.6 GHz used in many countries including North America, Europe and Japan seemed to be very appealing for prospective body centric communication systems. Considering the intention is to design a dual band microstip patch antenna, the selection and characterization process of dielectric and conductive fabrics will be discussed. Finally, the design of the antennas was simulated with CST Microwave Studio and the simulated antenna parameters are demonstrated in this chapter.

## 5.1 Background Study

A number of textile antennas were studied. For instance, a higher mode microstrip patch antenna was described in [160] using Taconic TLY-3 PTFE woven glass substrate for 2.45 GHz frequency. Another dual-band button antenna over Denim substrate [161] was evaluated and compared with the core design without fabric. A cavity slot antenna that shows PIFA like performance for the ISM band [162] and other modified designs of antennas for wearable applications where different performance enhancement techniques, such as placing buttons or EBG (Electromagnetic band gap) substrates were also studied [163-164].

After studying the literature, the basic design for this research was chosen from [165]. Originally, this coplanar waveguide antenna was designed using “felt” fabric of 1.1mm thick and “zelt” as conductive layer. A parasitic patch ring was implemented in between the patch and ground plane to obtain the dual band frequency. The geometry of the original design is shown in Fig. 1.

Authors reported a 2% bandwidth achievement at 2.45 GHz frequency band whereas 12% bandwidth at higher frequency of 5.15-5.825 GHz band. However, this design was modified for this project using different fabric materials and the designs were simulated using CST Microwave Studio. The selection of fabrics and the simulated antenna performances are discussed in next sections.




| Parameters | Value (mm) |
|---|---|
| Lg, Wg | 55 |
| Lo | 32 |
| Wo | 28 |
| Li | 21 |
| Wi | 17 |
| s | 5 |

**Antenna dimensions**

Fig. 5.1 Dual-band CPW fed antenna geometry [164]

## 5.2 Fabric Selection and their characterization

The main reason of designing antennas with textile fabrics are not just their flexibility, their capability of blending in with the regularly worn clothes also plays a pivotal role in the process. It has always been one important requirement for textile antennas to become a part of the clothing without affecting the users' fashion in dresses. It is also important to make sure the size and the weight do not make the user feel the antenna as a parasite in his/her body. The main idea behind this project was to overcome the odd presence of thick, rarely used 'felt' like substrate and make the antenna look like a part of the regularly worn garments. Not only that, it was also important to consider the availability of the fabrics. It was necessity for the fabrics to be very much available for the users to make sure they can blend in with their dresses.

### 5.2.1 Dielectric Fabric

Considering all these requirements drawn above, a few number of regularly worn fabrics were considered for the dielectric substrate material. The dielectric characteristics of the fabrics were found in literature. Based on [164,166], a list of fabrics with their permittivity and loss tangent was drawn while choosing the perfect fabrics for this project. The initial selections are listed below in Table. 5.1.

Table 5.1 Selections of Textile Fabrics and Their Properties [166]

| Fabric Materials | Relative Permittivity | Loss Tangent |
|---|---|---|
| **Silk** | 1.75 | 0.012 |
| **100% Polyester** | 1.90 | 0.0045 |
| **Cordura/Lycra** | 1.50 | 0.0093 |
| **Cotton** | 1.60 | 0.0400 |

Among these fabrics in access, silk was discarded because of its thickness whereas cordura/lycra was found to be mostly unavailable in departmental stores and clothing outlets. Because of these reasons, the 100% polyester and cotton fabrics were initially selected for the antenna substrate.

### 5.2.2 Conductive Fabric

Conductive fabrics are industrially produced for many purposes. Company like Technical Textile Inc. and Less EMF Inc. offers a selection of conductive materials which can be obtained very easily in very low price. The fabrics used in this project were obtained from Less EMF Inc. Along with every fabric they also provide the detail characteristics of the specific material. As it has been discussed in chapter 4 that the surface resistivity has to be stable and ≤ 1Ohm/square, this criterion was strongly maintained in the selection process. Pure Copper Taffeta with resistivity of 0.05 ohm/sq and Nickel Copper RipStop with < 0.03 ohm/sq of resistivity were chosen.

As the selections of fabrics are done, the next step was to design the antennas and simulate them in CST Microwave Studio. The designs were modified several times to get the desired frequency bandwidth.

## 5.3 Antenna Design

### 5.3.1 Design I

The first antenna was modified using 100% Polyester fabric instead of felt as substrate. Change in the substrate material results a shift to right in $S_{11}$ characteristics. To achieve the resonating frequency in lower band, substrate thickness was reduced to 1 mm. The higher resonating frequency was accomplished by modifying the parasitic patch. The length of the parasitic patch ($L_0$) was reduced to 31 mm from 32 mm. The modified design assures good agreement to the expected resonating frequencies with fair bandwidth. The design was also modified for both the conductive fabrics, nickel copper ripstop and pure copper taffeta. Fig 2. Shows the simulated S11 for the both design.

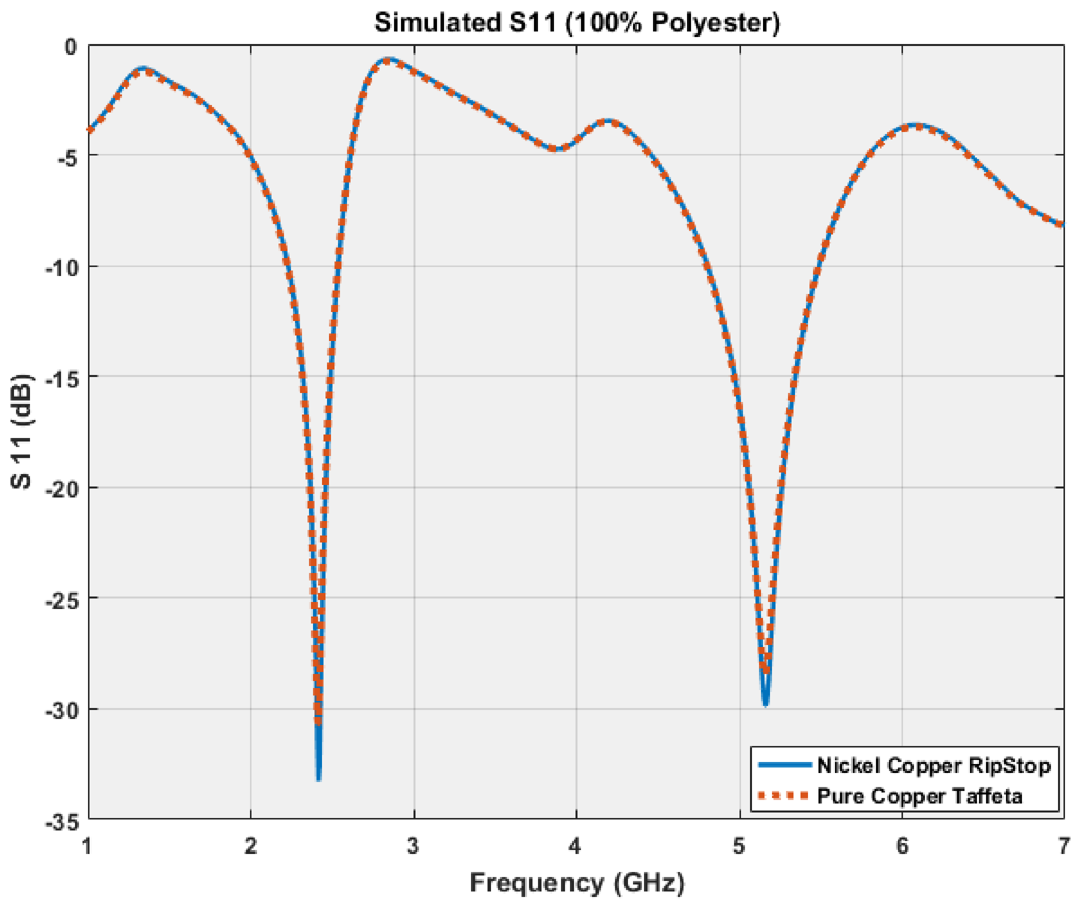
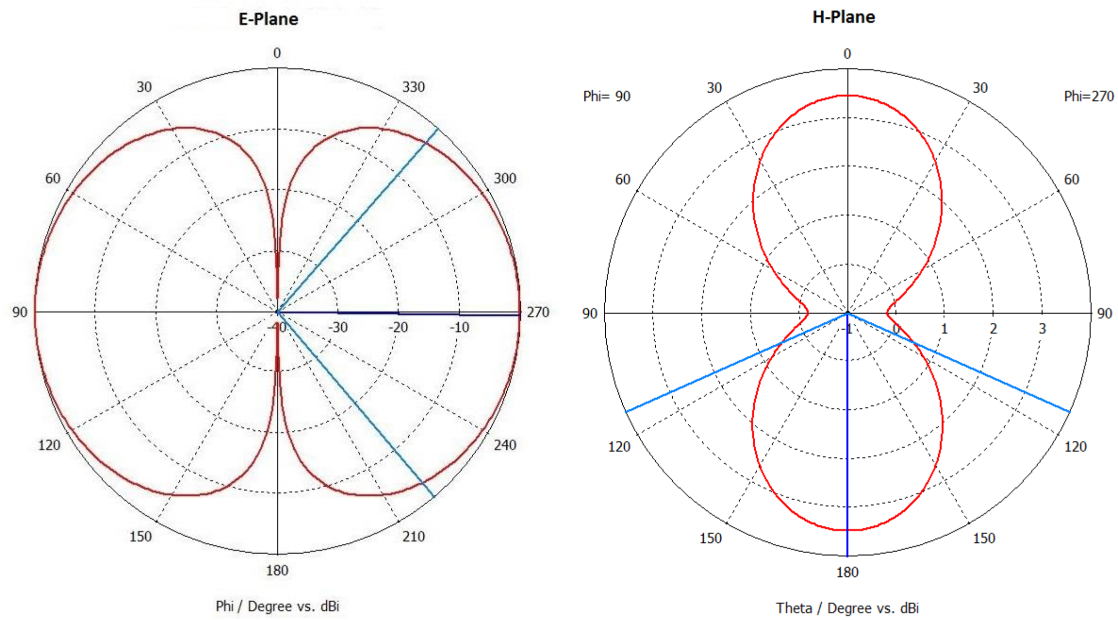


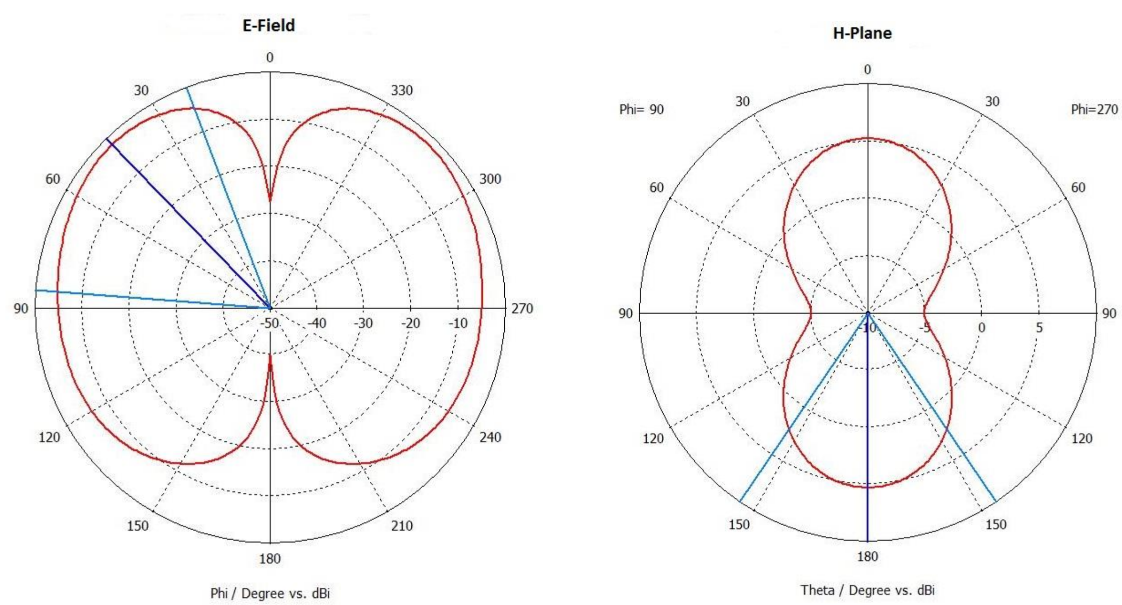

Fig. 5.2 $S_{11}$ for the 100% Polyester based antenna

From the figure, it can be realized that, even though the change in conductive fabric causes a tiny bit of reduction in S11 but that can be considered as negligible. The designed antenna covers the lower frequency band around 2.4 GHz with 12.9% of -10 dB bandwidth and upper band at 5.1 GHz with around 13.6% bandwidth.

The far field radiation patterns of the antenna was also simulated for 2.4 GHz and 5.1 GHz frequency, which are shown below in fig. 3.




(1) Far-field radiation pattern at 2.4 GHz




(2) Far-field radiation pattern at 5.1 GHz

Fig. 5.3. Far-field radiation pattern of 100% Polyester based antenna

For a coplanar patch antenna, it is highly expected that the radiation pattern would be in both forward and reverse direction, which seems to be met with this design.

5.3.2 Design II

The second design presented here is based on a Cotton substrate. The initial geometry was changed to achieve the resonating frequencies. The substrate thickness was changed to 1.76 mm as per easily accessible cotton fabric's thickness. The length of the slot in the ground plane was changed to 37.8 mm instead of 37.24 mm. As like as the first design, this design was also simulated for both the conductive materials. Fig. 4 shows the simulated $S_{11}$ obtained from CST Microwave Studio.

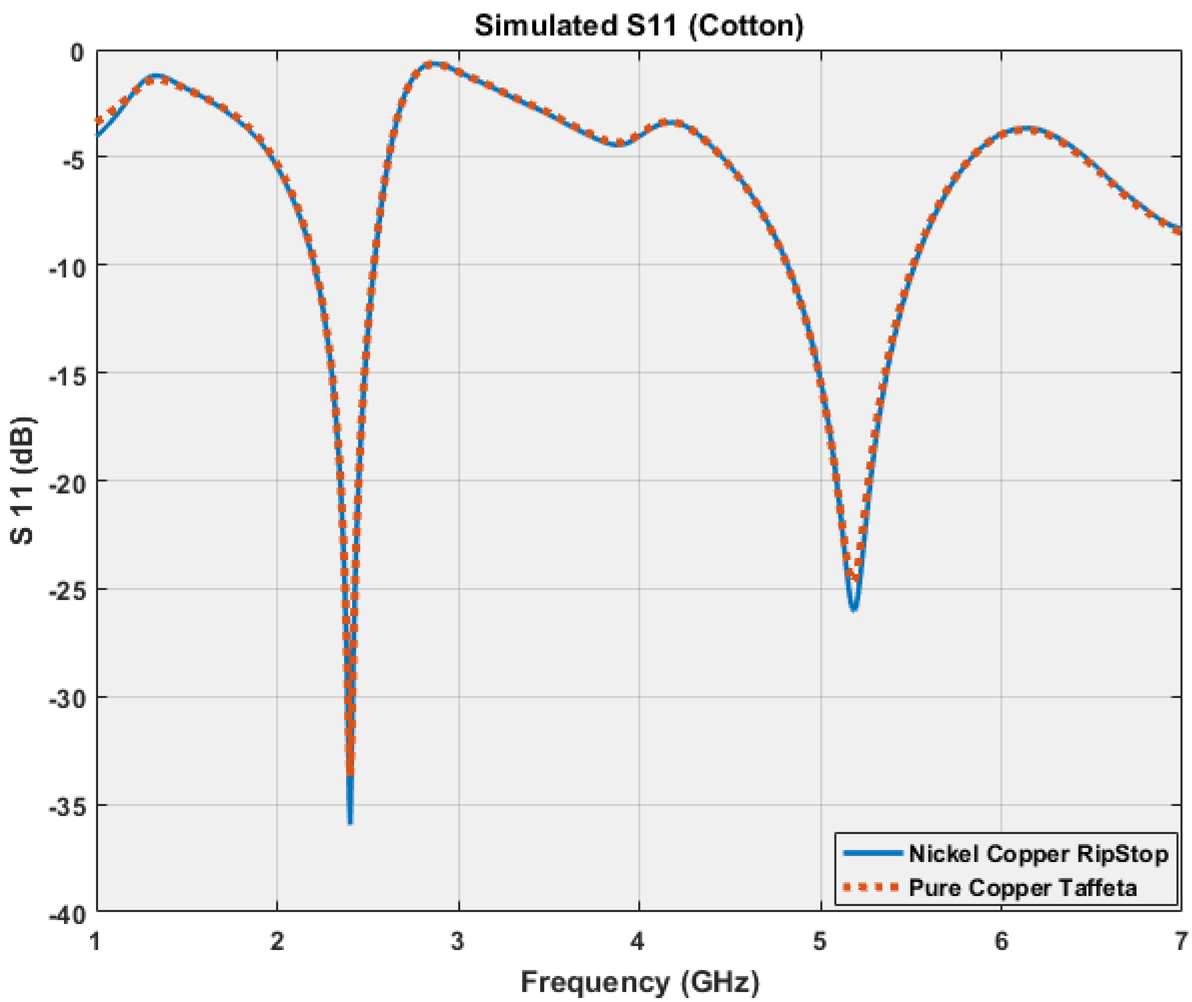
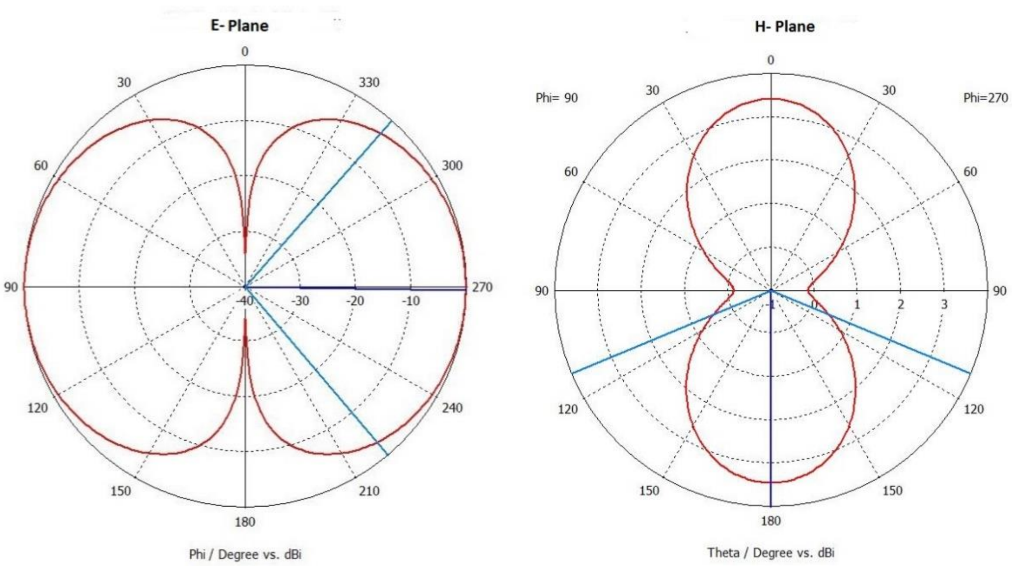
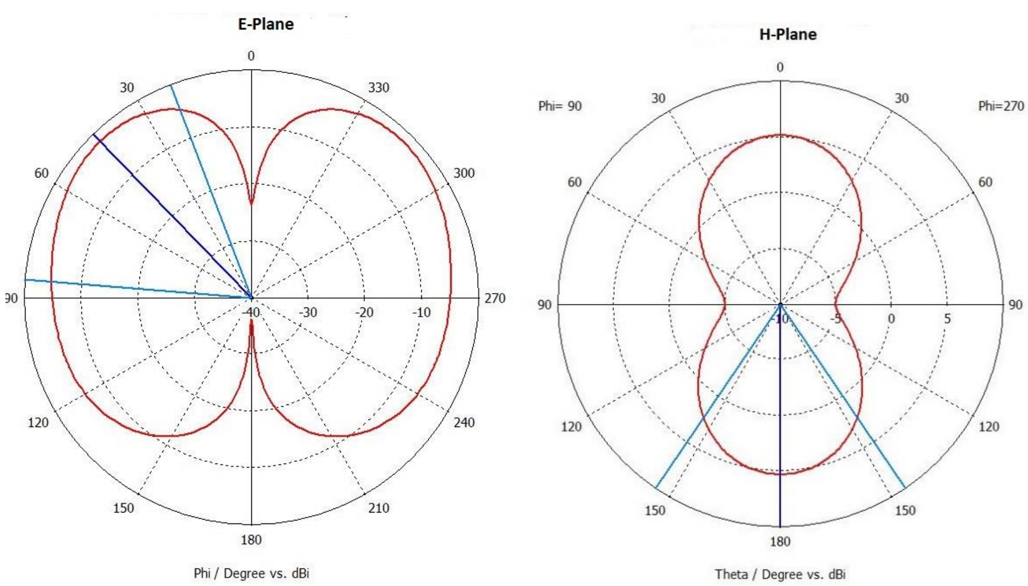



Fig. 5.4 Simulated $S_{11}$ for Cotton based design

From this plot, most noticeable thing is that, the change in conductive material still does not cause any significant changes. However, this design also satisfies the desirable bandwidth for both low and high resonating frequency. In higher band, this design achieves a 13.5% of bandwidth around 5.15 GHz whereas in lower band it achieves bandwidth of 13.75% which is a little more compared to Design I.




(a) Far field radiation pattern at 2.4 GHz




(b) Far field radiation pattern at 5.15 GHz

Fig. 5. Far-field radiation pattern of Cotton based antenna

The simulated far field radiation pattern also follows the previous design. Thus, it can be concluded from the simulated outcomes that these designs shows reasonable amount of prospectus for the purpose of body worn applications using WLAN bands. Therefore, it would be more viable to proceed with fabrication and measurements to check whether the parameters agree with the simulated results. This is why the next chapter elaborates on the fabrication process and discusses the measured data of the antennas.

# CHAPTER VI

## DUAL BAND TEXTILE ANTENNA: FABRICATION AND MEASUREMENTS

Designing the antennas using CST MW Studio were crucial. Several designs had to be simulated to accomplish the goal regarding resonating frequency and bandwidth. However, fabricating the antenna and feeding for measurements became harder than that because of the delicacy and unorthodox nature of the fabric materials. From cutting the materials to feeding the antennas, so many obstacles had to be overcome to carry out the measurement process. This chapter will discuss the details of fabrication and measurement process.

### 6.1 Fabrication of Dual-band Antenna

The first step of fabrication process was to gather the fabric materials according to the design simulated in CST Microwave Studio. It was hard to find fabrics of exact same thickness. Therefore, the designs had to be modified according the available materials. The designs discussed in previous chapter were the result of these modifications. Below is a list of materials and their thickness that were available in this process.

Table 6.1: Fabric Materials and Their Thickness

| Fabric Materials | 100 % Polyester | Cotton | Nickel Copper RipStop | Pure Copper Taffeta |
|---|---|---|---|---|
| Thickness (mm) | 0.5 | 0.88 | 0.06 | 0.08 |

The thickness of each material was measured in the DHM (Design, Housing & Merchandising) Lab using a digital thickness gauge shown in Fig. 6.1. However, the dielectric fabrics' thickness was insufficient for the design and so two layers of each fabric had to be glued together using all purpose adhesive spray. The conductive layer was also attached to the dielectric layers using same adhesive spray.


Fig. 6.1. Thickness Gauge

The next step was to cut the conductive layer according to the design. As the design is, a coplanar waveguide fed microstrip patch design and very small, it was not possible to hand cut the design on conductive layer. This issue was solved with the help of DHM plotter, which is a laser-cutting machine with the ability to embroider the trace with exact thickness. Therefore, the conductive layer was attached to the layers of dielectric fabric and the whole design was duplicated using Adobe Illustrator in order to print with the Trotec Speedy 300 i.e. DHM plotter. Fig. 6.2. Shows the cutting process along with the facility of Apparel Designing and Production Department at Oklahoma State University.


Fig. 6.2: DHM Plotter and Embroidery Process

## 6.2 Feeding the antenna

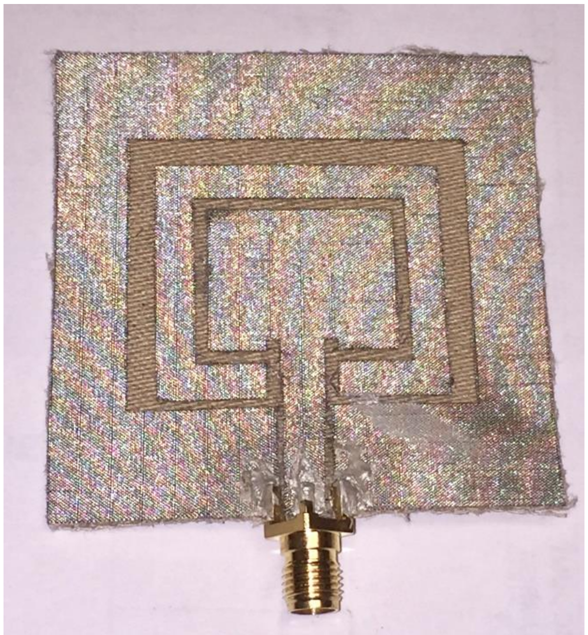
The next big obstacle was to feed the antenna. If it were a normal antenna, an SMA connector could have been attached by soldering as soldering cannot be done on fabric materials. Gluing with regular adhesive was not possible since its not conductive. The solution of this problem was reached through using CW 2400 Conductive Epoxy manufactured by Circuit Works. The silver epoxy provided excellent electrical conductivity.

## 6.3 Antenna Measurements

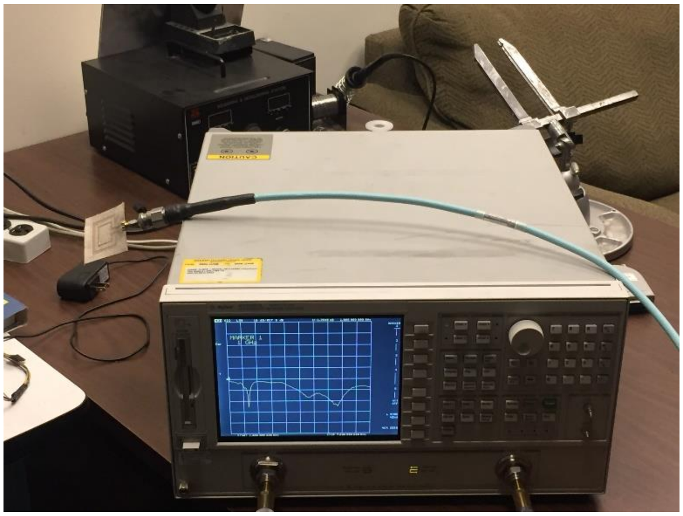
Five different prototypes were fabricated and $S_{11}$ was measured for each of them using an Agilent 8722 ES S-Parameter Network Analyzer. For prototype I and Prototype II, $S_{11}$ was measured in both REFTAS Lab and Anechoic Chamber facility at Oklahoma State University.

### 6.3.1 Prototype I

The first design was fabricated on 100% Polyester substrate using Nickel Copper RipStop as a conductive layer, which will be referred as Prototype I for rest of the discussion. Fig. 6.3 shows the antenna and a picture of measurement process.



(a) Prototype I



(b) $S_{11}$ Measurement of Prototype I

Fig. 6.3 $S_{11}$ Measurement of Prototype I

The measurement was taken in REFTAS lab. The measured $S_{11}$ was compared to the simulated $S_{11}$ in Fig. 6.4.

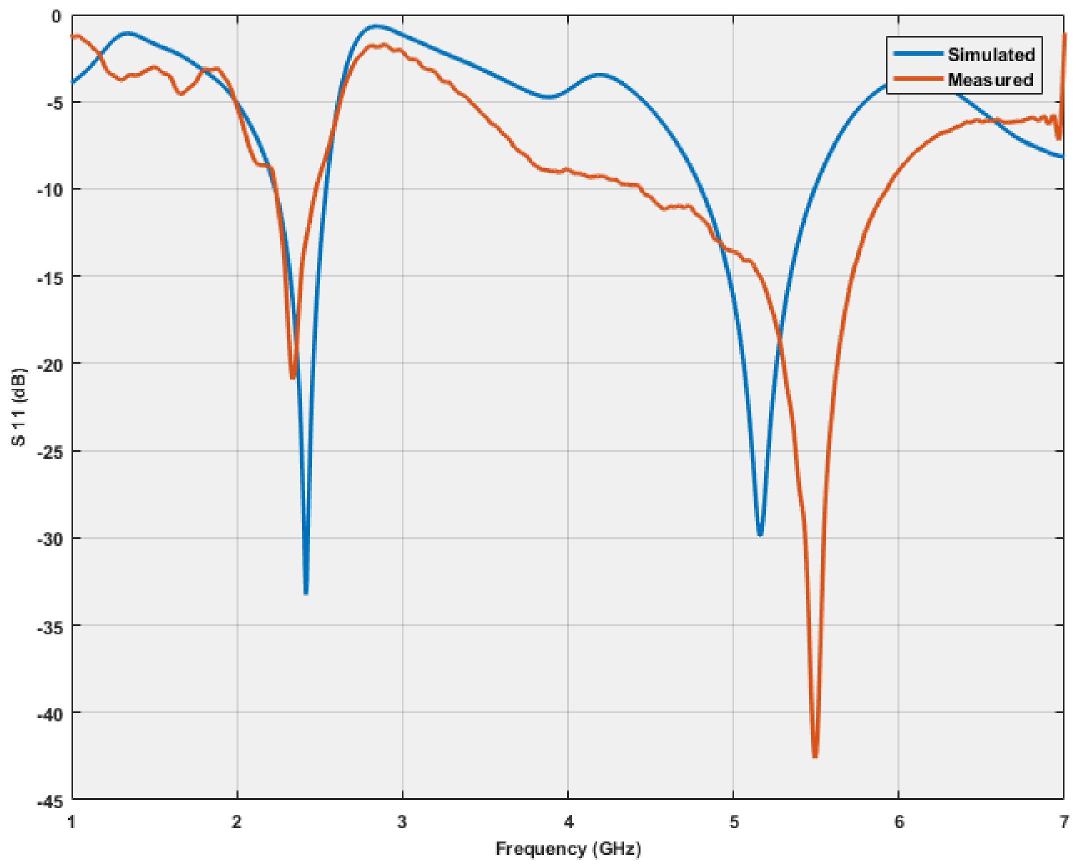



Fig. 6.4. Measured $S_{11}$ of Prototype I

Although, a major difference can be observed in higher frequency band, yet the antenna satisfies the bandwidth requirements for both the frequency band.

### 6.3.2 Prototype II

Second design was fabricated on cotton fabric using the same conductive material as Prototype I, shown in fig. 6.5. The fabric was taken from a denim material.

Fig. 6.5. Prototype II

$S_{11}$ for this one was measured in REFTAS Lab. Fig. 6.6 shows the comparison between measured $S_{11}$ and simulated $S_{11}$ for this antenna. In the measured one, a decay in return loss with a slight right shift in lower band can be observed. However, for higher frequency band the opposite happens. The resonating frequency shifted to right with major increment in return loss. Other than these minor changes, the antenna shows good agreement to required bandwidth.

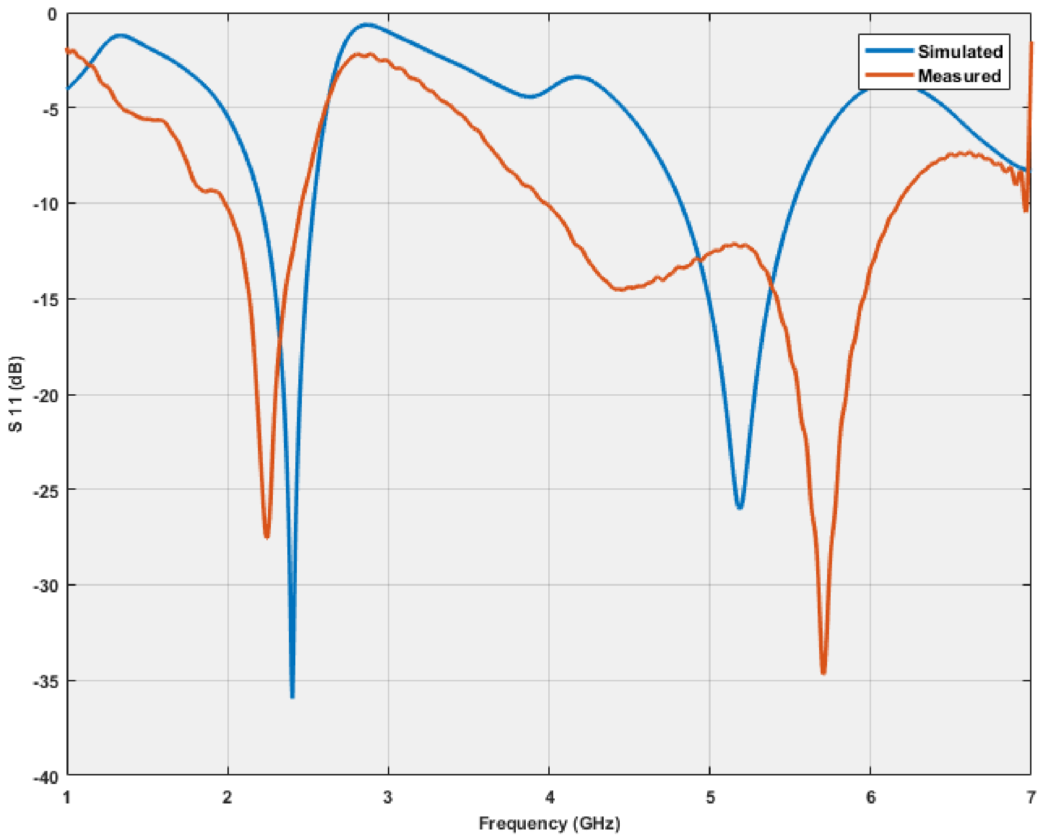



Fig. 6.6. Measured $S_{11}$ for Prototype II

### 6.3.3 Prototype III

Prototype III was fabricated on 100% Polyester fabric too. The difference from prototype I is that this antenna used Pure Copper Taffeta as conductive layer. Even though simulated results did not show any significant difference in $S_{11}$ for nickel copper ripstop and pure copper taffeta, the measured $S_{11}$ begs to differ with it. Major difference can be witnessed at around 1.7-1.9 GHz frequency range. Apart from that, a major decay in return loss was also noticed in higher frequency band. Fig. 6.7 and fig. 6.8 respectively shows the antenna and the measured $S_{11}$ in REFTAS Lab.

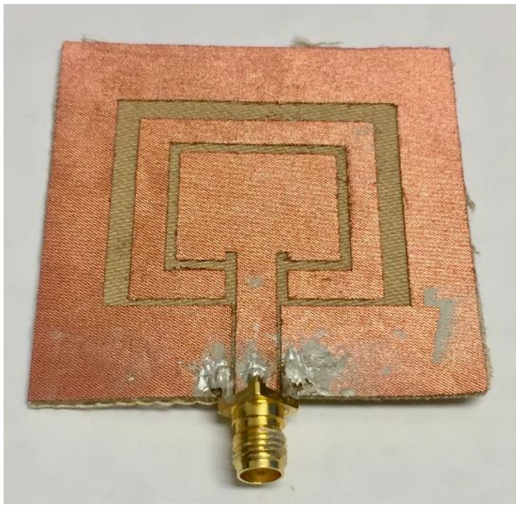


Fig. 6.7. Prototype III

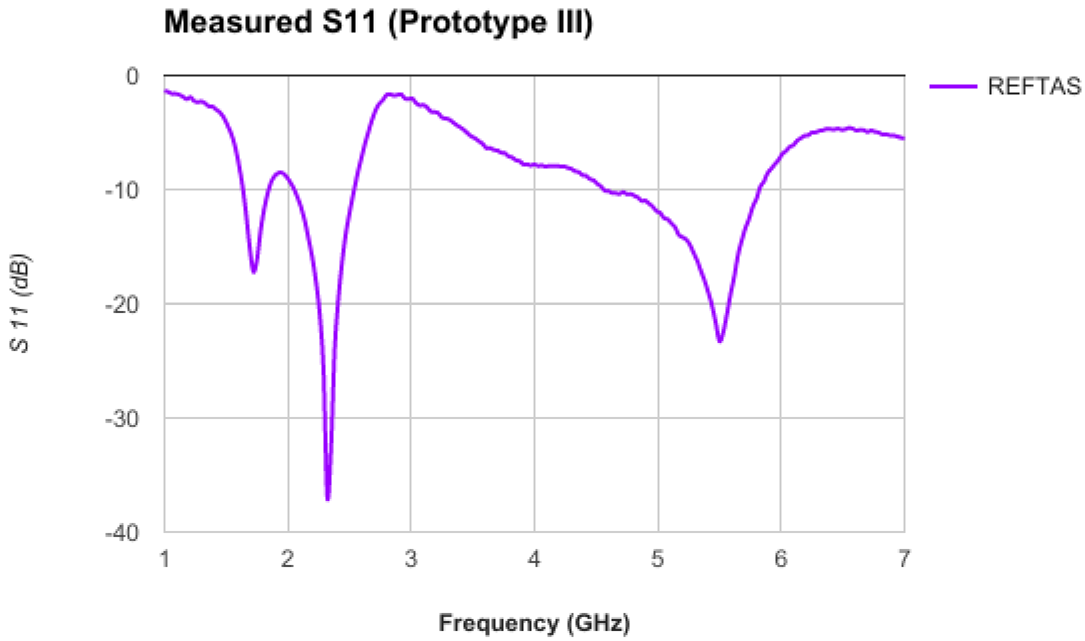



Fig. 6.8. Measured $S_{11}$ in REFTAS Lab for Prototype III

6.3.4 Prototype IV

This design is almost similar to Prototype II. It is also fabricated on fabric taken from a Jeans. Instead of being 100% cotton, this fabric consisted 80% cotton and 20% polyester. The main purpose behind fabricating this antenna was to explore the change results from the cross of two dielectric materials. The antenna and measured $S_{11}$ are shown in Fig. 6.9 and Fig. 6.10 respectively.

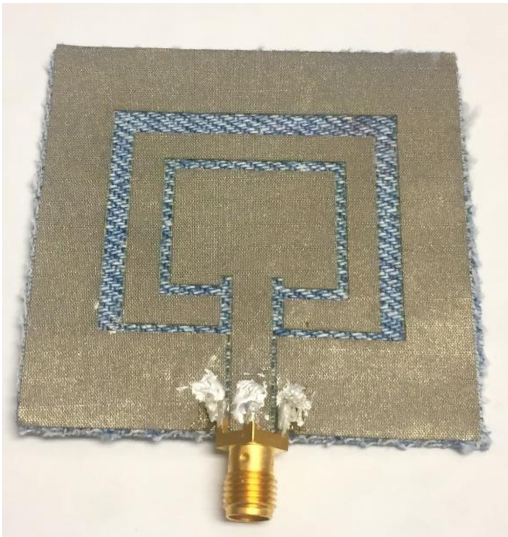


Fig. 6.9. Prototype IV

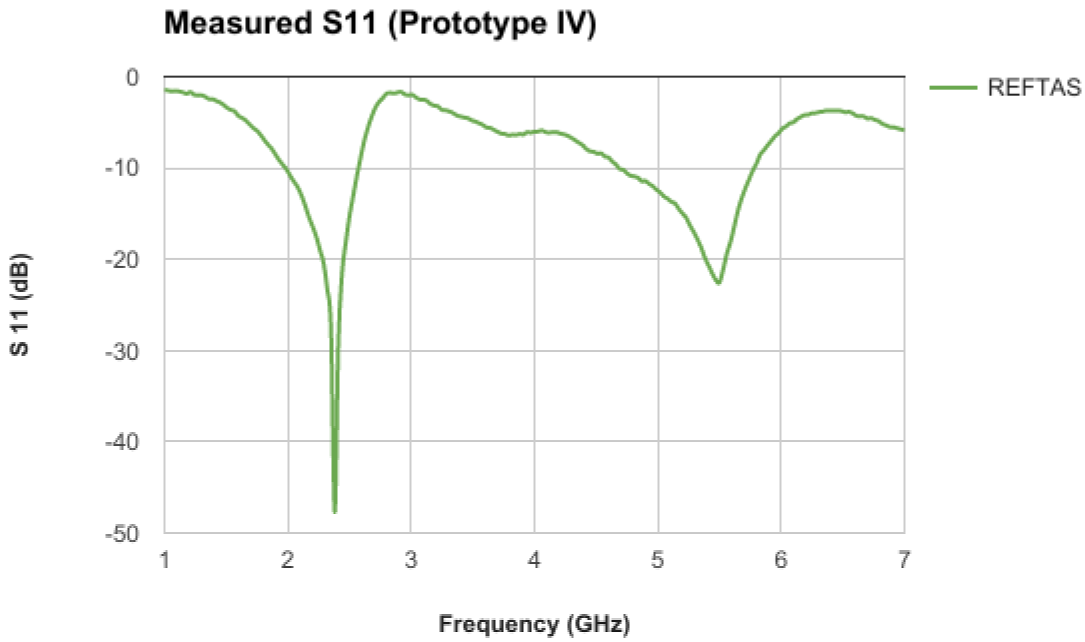



Fig. 6.10. Measured $S_{11}$ in REFTAS Lab for Prototype IV

From the measured $S_{11}$, the only change was observed is the decay in return loss at higher frequency band. Other than that, a very sharp resonating frequency was observed at 2.4 GHz frequency.

### 6.3.5 Prototype V

Among all the antennas were made, this turns out to be most interesting because of the origin of its dielectric material. Although the dielectric fabric used in this antenna is cotton, but the pieces of the fabrics were taken from a floor rug, shown in fig. 6.11. This antenna helps in exploring prospects of using wearable antennas in floor rugs, which can be used in a pressure sensor based burglar prevention system. The S-parameter for this antenna was also measured in REFTAS Lab.

Fig. 6.11. Prototype V using floor rug

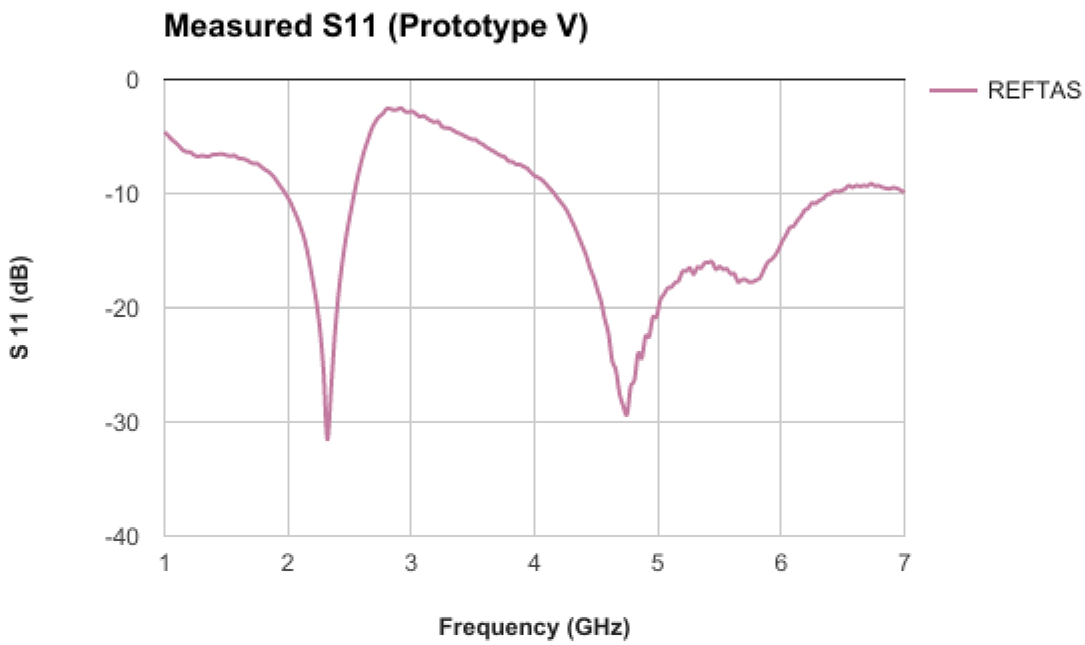



Fig. 6.12. Measured $S_{11}$ for Prototype V

From the measured $S_{11}$, a drastic change in higher frequency can be observed. The resonating frequency significantly shifted towards left whereas return loss improves quite a bit.

### 6.4 Antennas on Body Phantom

Until wearable antennas are not mounted on body, the analysis of performance remains incomplete. In body worn condition, antenna experiences different bending effects. In addition, the boundary condition changes because of the EM characteristics of human body. In this project, antennas were not able to be mounted on any of the physical phantoms with similar characteristics as human body. Yet, a body phantom 3D printed with PLA material was availed to the antennas for observing the bending conditions. Prototype III and IV were placed on chest and shoulder of the phantom and $S_{11}$ was measured.

#### 6.4.1 Prototype III on Body Phantom

The antenna made of 100% Polyester and Pure Copper Taffeta was placed on the phantoms chest and shoulder shown in Fig. 6.13.

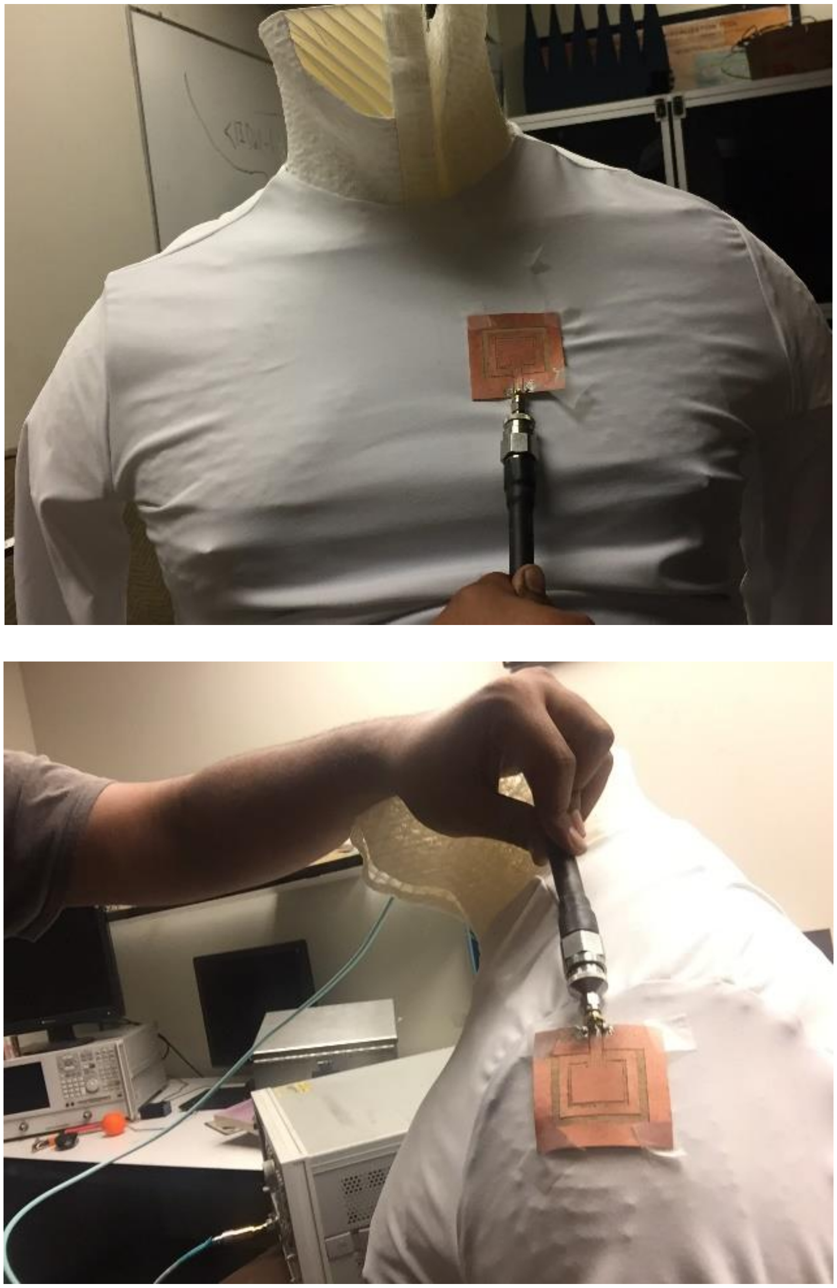


Fig. 6.13. Prototype III on Body Phantom

Measured $S_{11}$ for both the situations were compared with the previous off-body result, shown in fig. 14.

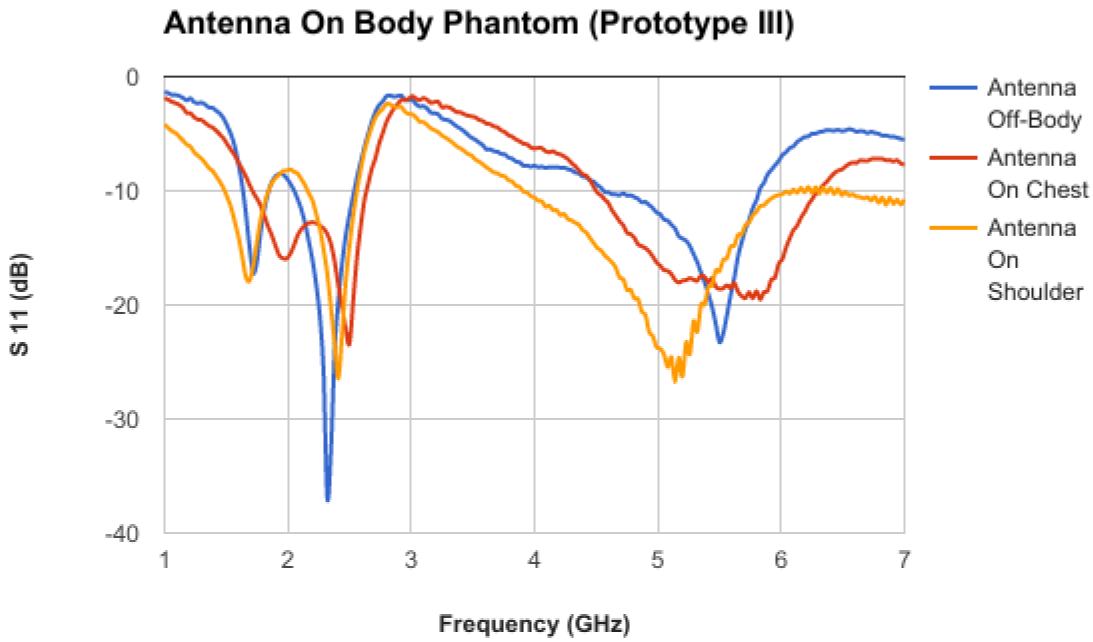



Fig. 6.14. Comparison between $S_{11}$ measured in different condition (Prototype III)

A right shift in lower frequency band with decay in return loss can be observed. On the other hand, in higher frequency band, the bandwidth became wider with a slight shift when placed on the shoulder.

### 6.4.2 Prototype IV on Body Phantom

Prototype IV was also placed on the body phantom in same parts of the body, chest and shoulder. Because of the higher weight of the cable connecting the antenna and network analyzer, the cable had to be held to maintain the position of the antenna on body surface. The pictures of the antenna on body are shown in Fig. 6.15.

Fig. 6.15. Prototype IV on Body Phantom

The measured $S_{11}$ were also compared with the previously measured $S_{11}$ without placing on body. The results show similar characteristics as prototype III. For lower band, the resonating frequency decays quite a bit whereas shifts on left in higher band with a gain in bandwidth. The comparison between the measured results are shown in Fig. 6.16.

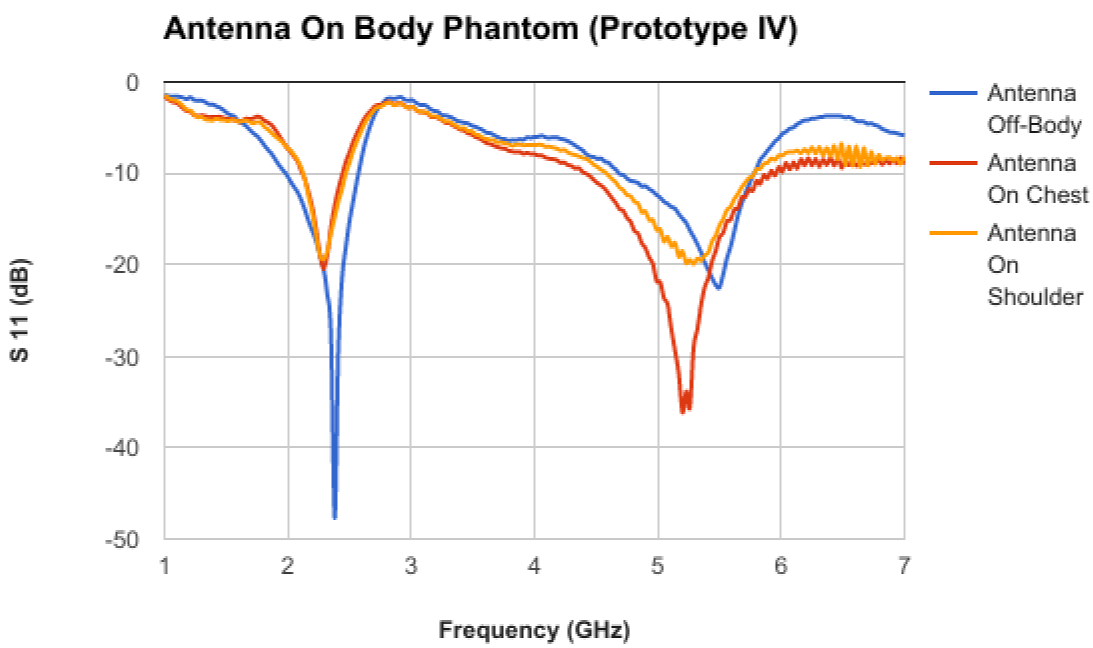
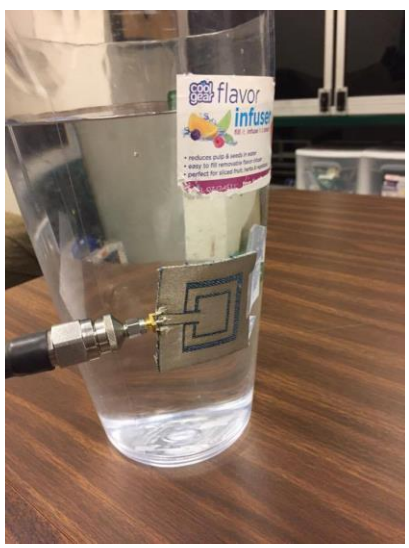



Fig. 6.16. Comparison between $S_{11}$ measured in different condition (Prototype IV)

## 6.5 Prototype II in Near Proximity of Water

As the main purpose of these antennas are to perform in close proximity of human body, it is very important to consider the dielectric properties of human body as boundary condition. However, it was not possible for this study to measure the return loss or SAR for these antennas while mounted on human body because of lack in resources. In order to get an approximate idea about the performance of these antennas, one of the prototypes, Prototype II was mounted on a cylindrical shaped Jug. $S_{11}$ was measured for two different condition, when the jug was empty and also when the jug was full of normal temperature water. The human body shows different dielectric properties depending on the tissue type of the specific body region. However, the dielectric constant varies from approximately 20 to 68 (appendix A) while in room temperature of around 298 K, water has dielectric about 78 of dielectric constant value [167], which leads to this specific effort to explore how this particular antenna performs in an environment that has dielectric properties not so different than human body. The measurement set up and the measured $S_{11}$ are shown in Fig. 6.17 and Fig. 6.18 consequently.


(a) Empty Jug




(b) Jug Full of Water

Fig. 6.17 Prototype II Mounted on a Jug

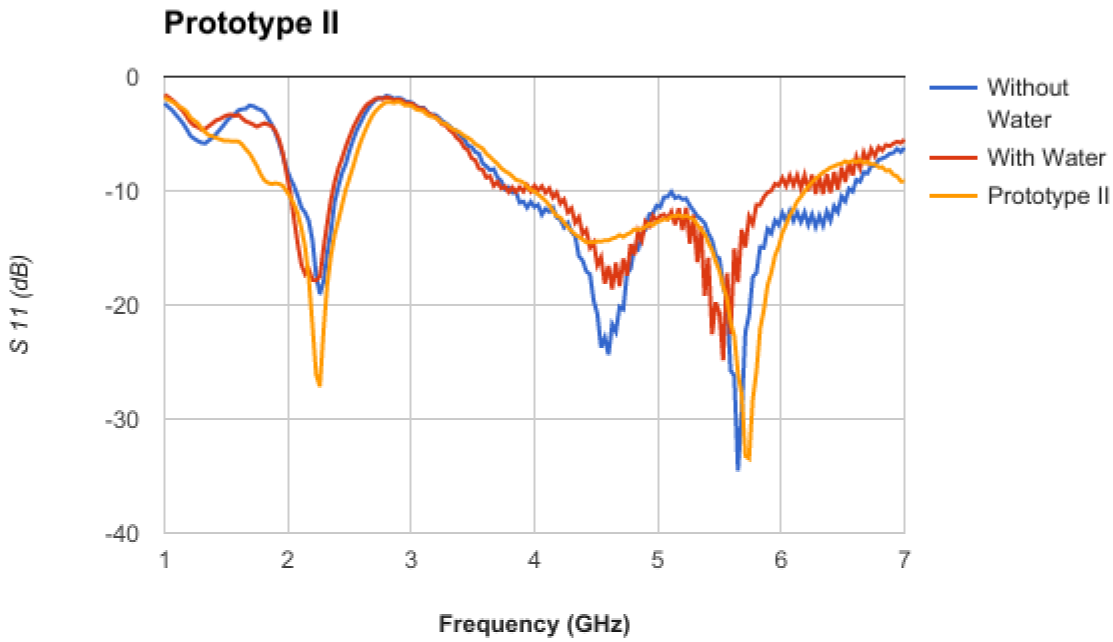



Fig. 6.18 Measured $S_{11}$ for Prototype II

From the plot, we can see the return loss in lower frequency experiences a decay without any major shift in resonating frequency because of the change in surroundings. However, in higher frequency, resonating frequency shows slight shift to left as the boundary condition changes. For the situation with a jug of water, the $S_{11}$ experiences around 10 dB decay, which can be explained by assuming water absorbs the power.

The $S_{11}$ from the measurements of all the prototypes show fair agreement with the requirements considering the bandwidth. Bandwidth is defined as the frequency range that shows $S_{11}$ below -10 dB. The aim was to have at least 2% in lower band as in around 2.4 GHz and 12% in higher band that is 5.15 GHz. Below is table that shows the bandwidth achieved by each of the prototypes.

Table 6.2. Prototypes and Their Specifications

| **Antenna Prototypes** | **Dielectric Fabric** | | **Conductive Fabric** | | **Bandwidth** | |
|---|---|---|---|---|---|---|
| | Fabric | Thickness | Fabric | Thickness | 2.4 GHz | 5.15 GHz |
| **I** | 100% Polyester | 1 mm | Nickel Copper RipStop | 0.06 mm | ~ 10% | ~ 28% |
| **II** | 100% Cotton | 1.76 | Nickel Copper RipStop | 0.06 mm | ~ 21% | ~ 42% |
| **III** | 100% Polyester | 1 mm | Pure Copper Taffeta | 0.08 mm | ~ 18.75 | ~ 24% |
| **IV** | 80% Cotton + 20% polyester | 1.76 mm | Nickel Copper RipStop | 0.06 mm | ~ 24% | ~ 21% |
| **V** | Cotton (Floor Mat) | 1.74 mm | Nickel Copper RipStop | 0.06 mm | ~ 22% | ~ 43% |

# CHAPTER VII

## CONCLUSION

Body-centric wireless communications, the most iterated few words throughout the whole thesis. With its applications having major impact in areas like, health monitoring, position monitoring, real-time video feed networks, military and specialized occupations make body-centric wireless communication one of most attractive research area. However, having the human body in the network, the system becomes more complex. Each element of the system demands special attention in designing and implementation process.

The main purpose of this thesis was to demonstrate designs of dual wearable antennas that are made of textile materials and suitable for wearable applications. As these antennas were designed to serve in close proximity of human body being a part of body-centric communication system, consideration of human body while designing is necessary. The earlier chapters in this thesis discuss about the EM characterization of human body and their effect on an antenna performance. For the simulation purpose, modeling of human body phantoms was also discussed. The designs were simulated using CST Microwave Studio. To draw a basic understanding on numerical techniques that can be used for body-centric communication, some of techniques were also discussed briefly.

However, for the designing process, a few criterions had to be met. After the desired frequencies were selected as 2.4 GHz and 5.15 GHz after considering several frequency bands, an existing antenna was picked from the literature in order to modify for two different fabrics, 100%% polyester and cotton. Several designs were simulated to ensure the resonating frequency and fair amount of bandwidth around them, in this case which were at least 2% in lower band and 12% in higher frequency band. The fabrics were chosen based on their relative permittivity and availability.

Going into the fabrication revealed so many obstacles to overcome. Firstly, the thickness of the designed substrate was not available. Therefore, modification had to be made in the designs and simulate again to ensure the available thickness satisfies the design requirements. Furthermore, hand cutting the conductive layer was impossible because of the size of the antenna. Hence, help was taken from the Apparel Designing and Production Department to use the DHM plotter in cutting the conductive layers. The next issue was to attach SMA connector in order to feed the antenna. That was solved using conductive epoxy.

After all these issues were solved, the prototypes were ready for measurements. Five different prototypes' $S_{11}$ were measured in different condition. At first all of them were measured in regular environment at REFTAS lab. $S_{11}$ for Prototype I and II were also measured in anechoic chamber. Furthermore, Prototype III and IV were mounted on a 3D printed human body phantom to observe the bending effects. Two separate body position were considered, chest and shoulder. The measured $S_{11}$ for all the designs show satisfactory -10dB bandwidth in the resonating frequencies, which assures the suitability of these prototypes for being used for wearable applications.

## 7.1 Future Work

Even though the constraints were overcome and the initial requirements were met, yet there remains a few more requirements have to be addressed. For instance, specific absorption rate (SAR) has to be measured for each of the designs and standards have to be met. Meeting SAR measurements requires a few step, at first the antennas has to be simulated on a voxel model in CST Microwave Studio to get initial idea. Considering the designs are co-planar waveguide microstrip patch, which has both forward and backward radiation pattern, electromagnetic band gap (EBG) substrate has to be attached to minimize the backward scattering. Designing that EBG substrate would be the second and very important step of the future work. Next, SAR for the antennas have to be measured in close proximity to physical heterogeneous body phantom with proper SAR measuring equipment. Once the SAR standards are met, the antennas will be ready for deployment in appropriate body-centric communication system.

REFERENCES


[1] S. Zhu and R. Langley, "Dual band wearable textile antenna on an EBG substrate," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 4, April 2009.

[2] B. Sanz-Izquierdo, J. C Batchelor, M.I. Sobhy, "Button antenna on textiles for wireless local area network on body applications," *IET Microwaves, Antennas & Propagation*, vol. 4, p. 1980-1987, 2010.

[3] S.J. Chen, and D.C. Ranasinghe, "A modular textile antenna design using snap-on buttons for wearable applications," *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 3, March 2016.

[4] T. Haagenson, N. Sima, L., Pablo, and Y. Chang, "Textile antennas for spacesuit applications," *IEEE Antennas and Propagation Magazine*, August 2015.

[5] Hertleer, C., et al., "Aperture coupled patch antenna for integration into wearable textile systems," Antennas and Wireless Propagation Letters, IEEE, Vol. 6, 2007, pp. 392-395

[6] Soh, P.J., et al, "Characterization of a simple broadband textile planar inverted-F antenna for on body communication," *ICECom, 2010 Conference Proceedings*, 2010, pp. 1-4.

[7] Cibin, C. et al., "Modified E-shaped PIFA antenna for wearable systems," *URSI International Symposium on Electromagnetic Theory*, Pisa, Italy, 2004.

[8] P. Hall, and Y. Hao, Antennas and Propagation for Body-centric wireless Communication, 2nd Edition, Artech House, 2012.

[9] Yang, G., Z., Body Sensor Networks, Springer, 2006.

[10] IMEC Human : Body Area Networks, www.imec.be/scientificreport/sr2008.

[11] www.google.com/wearablemedicaldevice

[12] Famolari, D., and P. Agarwal, "Architecture and Performance of an Embedded IP PAN," IEEE ICPWC, 2000.

[13] Stratis, G., S. Sibecas and R. Kipp, "Composite Antenna Pattern for Realistic Ray Tracing Simulations," IEEE APS International Symposium,2003.

[14] Schwendener, R., "Indoor Radio Channel Model for Protocol Evaluation of Wireless Personal Area Networks," 13th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, 2002.

[15] www.google.com/ecg

[16] Hertleer, C, and H. Rogier, “A textile antenna for off-body communication integrated into protective clothing for firefighters”, IEEE Transactions on Antennas and Propagation, April 2009.
[17] Taj-eldin, M. and E. Nelson, “Wireless Propagation Measurements for astronaut body area network,” WiSEE, 2013.
[18] Hall. P, Y. Hao, “Antennas and propagation for body centric communications,” EuCAP 2006.
[19] T. G. Zimmerman, “Personal Area Networks: Near-Field intra body communictions,” IBM Systems Journal, 1996.
[20] T. G. Zimmerman, J. R. Smith,” Appling E-field sensing to human computer interfaces,” Proc. Of CHI’95.
[21] K. Fujii, K. Ito,” A study on the receiving signal level in relation with the location of electrodes for wearable devices using human body as a transmission channel,” 2003 IEEE Int Symp on APS.
[22] T. Kobayashi, M. Kyoso, “Application of Near-field intra-body communicaton and spread spectrum technique to vital-sign monitor,” 34 th International Conference of the IEEE EMBS, 2012.
[23] www.google.com
[24] C. Brunckhorst, R. Candinas, and S. Furman, “Obituary : Ake Senning 1915-2000,” Journal of Pacing and Clinical Electrophysiology, 2000.
[25] W. Greatbatch, “The making of the Pacemaker,” rometheus Books, 2000.
[26] www.google.com/first+pacemaker+1958.
[27] J. Cavouto, “Neural Enginnering’s image problem,” IEEE spectrum, 2004.
[28] www.healthyaims.org.
[29] Figeys, D., “Lab-on-a-chip: a revolution in biological and medical sciences,” Ann Chem, may 2000.
[30] www.fcc.gov
[31] FCC: The Medical Implant Communication Service (MICS).
[32] Falcon, C., “Wireless medical devices: satisfying radio requirements,” Medical Decvice and diagnostic industry, 2004.
[33] Zigbee alliance. www. Zigbee.org
[34] Opperman, I, UWB theory and aplications, John Wiley and sons, 2004.
[35] Porcino, D, “ UWB radio Technology’” IEEE Communications Magazine, 2003
[36] Gerrits, J, “Design and performance analysis of UWB communication system for low data rate’” PACWOMAN, Oct 2003
[37] For, A., “An UWB Body area prop channel model,” Transaction on Microwave theory and tech, april 2006.
[38] Latre, A, “survey on wireless body area networks,” Wireless Networks, 17, 2011.
[39] W. Rhee, “Low power, non invasive UWB systems for WBAN app,” ICTC, 2010.
[40] Federal Communications Commission. Code of Federal Regulation, title 47, cha 1, 2001.
[41] www.tele.soumu.go.jp
[42] ACMA. Radio Communication class license variation 2005.
[43] Ministry of information communication of Korea.
[44] ETSI DTR/ERM-RM-049, March 2006.
[45] www.google.com/mmwave
[46] Htttp://nyuwireless.com/VTSPlenary.pdf.

[47] L. Berardinelli, “Vision as a support to cognitive behavirioual systems.”EUCOgII-SSPnet-COST2102- Lectture Notes in Computer Science, springer, 2012.
[48] www.vision-ercproject.eu.
[49] http://www.smithsonianmag.com/smart-news/there-are-372-trillion-cells-in-your-body-4941473/
[50] https://www.msnucleus.org/membership/html/k-6/lc/humanbio/4/lchb4_3a.html
[51] Durney, C.H., H. Massoudi, and M.F. Iskander, Radiofrequency Radiation Dosimetry Handbook, Brooks Air Force Base- USAFSAM-TR-85-73, 1986.
[52] Geddes, L.A., and L.E. Barker, “The specific resistance of biological material- a compendium of data for the biomedical engineer and physiologist,” Medical and biological engineering, 1967, pp. 271-293.
[53] Stuchly, M.A., and S.S. Stuchly, “dielectric properties of biological substances,” The Journal of Microwave Power, Vol. 15, No. 1, 1980, pp. 19-26.
[54] Foster, K.R., and H.P. Schwan, “Dielectric properties of tssues and biological materials: a critical review,” Critical Reviews in Biomedical engineering, Vol. 17, No.1, 1989.
[55] Duck, F.A., Physical Properties of Tissue: A comprehensive Reference book, Academic press, Harcourt Brace Jovanovich, 1990.
[56] Gabriel, C., “Compilation of the dielectric properties of body tissues at RF and microwave frequencies,” Brooks Air Force Technical Report, 1996.
[57] Das, R, “Transmission of Electromagnetic Power Through A biological Medium,” 2003.
[58] Gabriel, C., T.Y. Chan, and E.H. Grant, “Admittance Models for Open ended Coaxial Probes and their Place in dieletric Spectroscopy,” Physics in Medicine and Biology, Vol. 39, No.12, 1994, pp. 2183-2200.
[59] Om. P., B. Gao, and J. Chen, “A frequency-dependent FDTD formulation for dispersive media,” IEEE Tans. Mircowave theory and Technique, vo. 41, No. 4, pp. 658-665, April 1993.
[60] O. P. Gandhi and C. M. Furse, “Currents induced in the human body for exposure to UWB EM pulses,” IEEE Trans. Of EMC, Vol. 39, No. 2, pp. 174-180, May 1997.
[61] C. M. Furse, “the use of FDTD method for induced current and SAR calculations for a heterogeneous model of the human body,” IEEE Trans EMC, vol36, No.2 , pp 128-133, May 1994.
[62] J.L. Yound, “Propagation in linear dispersive media,” IEEE Trans APS, Vol 43, No. 4, pp. 422-426, April 1995.
[63] R. Siushansian and J. LoVetri, “A comparison of numerical techniques for modeli of electromagnetic dispersive media,” IEEE Microwave theory tech. Vo. 5, No.12, Pp. 426-428, December 1995.
[64] P.G. Petropoulos, “Stability and phase error analysis of FDTD in dispersive dielectrics,” IEEE APS, Vol.42, No. 1, pp. 62-69, Jan 1994.
[65] M. Mrozowski and M.A. Stuchly, “Parameterization of media dispersive properties for FDTD,” IEEE APS, Vol. 45, No. 9, pp. 1438-1439, Sep. 1997.
[66] S. Gabriel, and C. Gabriel, “The dielectric properties of biological tissues,” Physics Medical Biology, 1996.
[67] M. Eleciwa, and A.Z. Elsherbeni, “Accurate FDTD Simulation of Biological tissues for bio-electromagnetic applications,” IEEE Tans EMC, 2001.

[68] C. Andreas, et. Al, “The dependence of EM far field absorption on body tissue composition in the frequency range from 300MHZ to 6 GHz,” IEEE Transaction of Microwave theory and techniques, 2006.
[69] Y. Hao, and P.S. hall, Antennas and Propagation for body centric communication, 2nd edition, 2014.
[70] K. Ito, “Numerical and Experiental human body phantoms,” IET Seminar on Antennas and Propagation for Body-Centric Wireless Communications, 2007.
[71] C. C. Johnson and A. W. Guy, “Nonionizing electromagnetic wave effects in biological materials and systems,” *Proc. IEEE*, vol. 60, no. 6, pp. 692-718, June 1972.
[72] S. Watanabe, M. Taki, T. Nojima, and O. Fujiwara, “Characteristics of the SAR distributions in a head exposed to electromagnetic fields radiated by a handheld portable radio,” *IEEE Trans. Microw. Theory Techn.*, vol. 44, no. 10, pp. 1874-1883, Oct. 1996.
[73] S. Gabriel, R. W. Lau, and C. Gabriel, “The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz,” *Phys. Med. Biol.*, vol. 41, no. 11, pp. 2251-2269, Nov. 1996.
[74] S. Gabriel, R. W. Lau, and C. Gabriel, “The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues,” *Phys. Med. Biol.*, vol. 41, no. 11, pp. 2271-2293, Nov. 1996.
[75] M. Lazebnik, L. McCartney, D. Popovic, C. B. Watkins, M. J. Lindstrom, J. Harter, and S. C. Hagness, “A large-scale study of the ultrawideband microwave dielectric properties of normal breast tissue obtained from reduction surgeries,” *Phys. Med. Biol.*, vol. 52, no. 10, pp. 2637-2656, Oct. 2007.
[76] K. R. Foster and H. P. Schwan, “Dielectric properties of tissues and biological materials: a critical review,” *Crit. Rev. Biomed. Eng.*, vol. 17, no. 1, pp. 25-104.
[77] Supplement C to bulletin 65, "Evaluating compliance with FCC guidelines for human exposure to radiofrequency electromagnetic fields," (2001).
[78] M.Y. Kanda, M. Ballen, C.-K. Chou, and Q. Balzano, "Formulation and characterization of tissue equivalent liquids used for RF densitometry and dosimetry measurements," IEEE Trans. Microwave Theory Tech., Vol. 52, No. 8, pp.2046-2056, (2004).
[79] G. Hartsgrove, A. Kraszewski, and A. Surowiec, “Simulated biological materials for electromagnetic radiation absorption studies,” *Bioelectromagnetics*, bol.8, pp. 29–36, 1987.
[80] C. K. Chou, G. W. Chen, A. W. Guy, and K. H. Luk, “Formulas for preparing phantom muscle tissue at various radiofrequencies,” *Bioelectromagnetics*, vol. 5, pp. 435 – 441, 1984.
[81] Ito,K.K., Y. Okano, and L. Hamada, “Development and characteristics of a Biological tissue-equivalent Phantom for Microwaves,” Electronics Communicationa JPN. Pt.2001
[82] Kobayashi, T., T. Nojima, “Dry Phantom Composed of Ceramics and its application to SAR estimation, “IEEE Trans Microwave Theory Tech, 1993”
[83] A. Mobashsher and A. Abbosh, “Three dimensional human head phantom with realistic electrical properties and anatomy,” *IEEE Antennas Wireless Propag.Lett*., vol. 13, pp. 1401–1404, July 2014.
[84] T. Nojima, T. Kobayashi, K. Yamada, and S. Uebayashi, “Ceramic dry-phantom and its application to SAR estimation,” in *Proc. IEEE MTT-S Int. Microw.Symp. Dig*., July 1991, pp.189-192.

[85] Nikawa, Y. , M. Chino, and K. Kikuchi, "Soft and Dry Phantom Modeling Material Using Silicone Rubber with Carbon Fiber," IEEE Trans EMC, 1997.
[86] Chang, j. T, M. W. Fanning, P. M. Meaney and K.D. Paulsen, "A conductive plastic for simulating biological tissue at microwave frequencies," IEEE Trns on EMC, 2000.
[87] Weil, C. M. , " Absorption characteristics of multi-layered sphere models exposed to microwave radiation," IEEE trans biomed eng., 1975.
[88] P.J. Dimbylow, "The development of realistic voxel phantoms for electromagnetic field dosimetry," in Proc. International Workshop on Voxel Phantom Development, Chilton, UK, July 1995.
[89] P.J. Dimbylow, "development of the female voxel phantom, NAOMI, and its application to calculations of induced current densities," Physics in Medicine and Biology, 50, pp. 1047-1070, 2005.
[90] P.A. Mason, et al., "Effects of frequency, permittivity, and voxel size on predicted specific absorption rate values in biological tissue during EM field exposure," IEEE Transaction on Microwave Theory and Technology, Vol. 48, No. 11, pp. 2050-2057, 2000.
[91] T. Nagaoka, et al., "Development of realistic high-resolution whole-body voxel models of Japanese adult males and females," Physics in Medicine and Biology, 49, pp. 1-15, 2004.
[92] www.cst.com
[93] https://www.feko.info/product-detail/numerical_methods.
[94] J. B. Kelle r, "Geometrical Theory of Diffraction," *Journal of Optical Society of America*, 52, 1962, pp. 116-130.
[95] J. Zhong, B. Li, and T. Sarkar, "Efficient Ray-Tracing Methods for Propagation prediction for Indoor Wireless Communicaitons," *IEEE Antennas and Propagation Magazine*, Vol. 43, No.2, April 2001.
[96] P. Bernardi, and R. Cicchetti, "A UTD/FDTD Investigation on Procedures to Assess Compliance of Cellular Base-Station Antennas With Human-exposure," *IEEE Transactions on Microwave theory and Techniques*, Vol. 51, No.12, December 2003.
[97] F. Villanese, W. Scanlon, and E. Gambi, "Hybrid image/ray-shooting UHF radio Propagation Predictor for Populated Indoor Environments," *Electronics Letter*, Vol. 35, No. 21, October 1999.
[98] Koutitas, G., "Multiple Human effects in BAN," *IEEE Antennas and Propagation Letters*, Vol.9, 2010.
[99] Alipour, S., F. Donald, " Propagation Characteristics for a 60 GHz WBAN," *Military Communications Conference*, 2010.
[100] Alice, P., A. Brizi, and Y. Hao, "Body-cenric wireless communications at 94 GHz," *ISAP 2012*, Nagoya, Japan, 2012.
[101] Cotton,S.l., W.G. Scanlon, P.S. Hall, "A simulated Study of Co-channel Inter-BAN Interference," *2010 EuWIT*, 2010.
[102] A. Glassner, *An Introduction to Ray Tracing*, San Francisco: Morgan Kaufmann, 1989.
[103] https://www.hft.ei.tum.de/en/research/advanced-electromagnetic-ray-tracing-methods/advanced-electromagnetic-ray-tracing-methods/
[104] Wnag.J., M. Komatsu, and O. Fujiwara, "Human Exposure assessment using a hybrid tech based on RT and FDTd methods," *Proceedings of the Radio Science Conference*, 2004.

[105] Chen, W.T., and H.R. Chuang, "Numerical Computation of human interaction with arbitrarily oriented superquadric loop antenanns in PAN," IEEE Transactions on Antennas and Propagation, Vol. 46, No.6, 1998.
[106] Chen, W.T., and H.R. Chuang, "Numerical Computation of EM Coupling between a circular loop antenna and a full-scale human body model," IEEE Transactions on Microwave Theory and Techniques, Vol. 46, No. 10, 1998.
[107] Meyer, F. and M.A. Stuchly,"human exposure assessment in the near field of GSM bse-station antennas using FEM/Mom," IEEE Transactions on Biomedical Engineering, Vol. 50, No.2, 2003.
[108] Ross. C.T., *Advanced Applied FEM, Horwood publishing, 1999.*
[109] P.S. Hall, Y.Hao, *Antenna propagation for body centric communication*., Artech House, 2014.
[110] Renhart, W., and R. Stollberger, "Modelling and calculation of influences of RF-fields on the human body using FEM," IEEE transactions on Magnetics, vol. 30,no. 5, September 1994.
[111] Kane Yee (1966). "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media". *IEEE Transactions on Antennas and Propagation*, 1966.
[112] Chen, J., and O.P. Gandhi, "Currents induced in an anatomically based model of a human," IEEE Transaction on Mincowave Theory and Techniques, Vol.39, Issue, 1, Jan 1991.
[113] Lazzi, G, and O.P. Gandhi, "A mixed FDTD-integral equation approach for on-site safety assessment in complex EM environments," IEEE Transactions on APS, Vo. 48, Issue. 12, December 2000.
[114] Furse, C.M., and O.P. Gandhi, "The use of the Frequency dependent FDTD method for induced current and SAR calculation," IEEE Trans. EMC, Vol. 36, No .2, May 994.
[115] Dimbylow, P.J., and S.M. Mann, "SAR Cal in an anatomically realistic model of the head for mobile comm trans at 900MHz and 1.8 GHz," Physics Medical Biology, Vol. 39, No.10, 1994.
[116] Ackerman M.J., "Accessing the Visible Human Project D-Lib," 1995.
[117] Xu, X.G., and A. Bozkurt, "VIP-man: an image based whole body male model," Health Phys. 78, 2000.
[118] Lee. A., W.Y.Choi, and J.I. Choi, " Development of Korean Male Body model," ETRI J, Vol. 28, 2006.
[119] Miry,C.R., and R. Gillard, " AN efficient bilateral dual-grid FDTD approach applied to on-body transmission analsysis," IEEE Trans. On Microwave theory and techniques, vol.58, issue 9, 2010.
[120] Xu.L., and Y.Chan, "Radiation charac of ingestible wireless devices in human intestine following RF exposure," IEEE trans on APS, Vol. 57, No. 8, August 2009.
[121] Jingzhen L., Z. Nie, Y. Liu, and Y. Hao, "Characterization of In-body Radio Channels for Wireless Implants," *IEEE Sensors Journal*, Vol. 17, Issue. 5, 2017.
[122] https://www.merriam-webster.com/dictionary/antenna
[123] IEEE Standard for Definitions for Terms of Antenna, IEEE Antennas and Propagation Society, IEEE Std 145-2013.
[124] Lilja, J., and P. Salonen, "Textile Material Characterization for Softwear Antennas," MILCOM:09, Boston, October, 2009.

[125] Salonen, P., et al., "A small planar inverted-F antenna for wearable applications," The third International Symposium on Wearable Computers, 1999.
[126] Salonen, P. and J. Rantanen,"A dual band and wide-band antenna on Flexible substrate for smart clothing," 27th Annual Conference of the IEEE, Vo. 1, 2001.
[127] Matthew, J., et al., "Body Wearable Antennas for UHF/VHF", Antennas and Propagation Conference, 2008.
[128] Kellomaki, T. , et al., "wearable antennas for FM reception," EuCAP 2006.
[129] Soh, P., J., et al., "wearable dual-band sierpinski fractal PIFA using conductive fabric," Electronics letters, vol. 47, 2011.
[130] Tronquo, A., et al., "Robust planar textile antenna for WBAN opering in ISM band," Electronics letters, vo. 42, 2006.
[131] Sankaralingam, S., et al., "Annular Ring MS antenna for body-worn applications," INDICON, 2010 Annual IEEE, 2010.
[132] Salonen, P. , et al., "Dual band wearable textile anenna," Antenna and propagation society inter. Symposium, 2004.
[133] Klemm, M., et al., "A novel circularly pol textile antenna," 34th European Microwave Conference. 2004.
[134] Klemm, M., et al., "A novel circularly pol textile antenna," 7th European Conference on Wireless Tech, 2004.
[135] Kavianto, E., et al., "wearable circularly polarized anenna for personal satellite communication," IEEE trans. On Antennas and Propagation, vol. PP, 2011.
[136] Sanz-Izquierdo, B., et al., "Textile integrated waveguide slot anenna," APSURSI, 2010.
[137] Salonen, P., et al., "Wearable EBG antenna," APSURSI, 2005.
[138] Shaozhen, Z., and R. Langley, "Personal Antennas for Mobile networks," iWAT 2007.
[139] Ahmed,M., Das,D.K., Rahman, A., "Study of Conformal UWB Antenna Designed on Various Nonplanar Surfaces", *Loughborough Antennas & Propagation Conference*, 2012, Loughborough, UK.
[140] Das,D.K., Ahmed,M., Rahman, A., , "Conformal Self-Complimentary UWB Antenna with nonplanar surfaces", *International Workshop On Antenna Technology*, 2013, Karlsruhe, Germany.
[141] Zhang, J., and S. Yan, "A miniature feeding network for aperture-coupled wearable antennas," IEEE transactions on antennas and propagation, 2017 (accepted)
[142] http://www.esa.int/Our_Activities/Space_Engineering_Technology/TTP2/Textile_antenna_promises_futuristic_communications
[143] Pontoppidan, k. and H. Viskum, "Electrical properties of trixially woven fabrics for reflector antennas," Antennas and prop. society inter. Symposium, 2003.
[144] Senbokuya, Y and H. Tsunoda, "Study on radiation characteristics of a flexible patch antenna," APS international symposium, 2003.
[145] Lilja, J., et al., "body-worn antennas making a splash: lifejacket-integrated antennas for global search and rescue," IEEE transaction on APS, vo. 55. Issue. 2, 2013.
[146] Salvado, R., et al., "Textile materials for the design of wearable antennas: A survey," Sensors, 2012, vol 12, 2012.
[147] Ivsic, B., and J. Bartolic, "Considerations on Embroidered Textile Antennas for Wearable Applications," IEEE antennas and wireless propagation, vol. 12, 2014.

[148] Xiaomu, H, S. Yan, “wearable button antenna for dual-band WLAN applications with combined on and off body radiation patterns,” IEEE transactions on APS, vo. 65, No. 3, March 2017.
[149] Yahya Rahmat-Samii, “Wearable and implabntable antennas in Body-centric communications,”.
[150] B. Sanz-Izquierdo, J. C Batchelor, M.I. Sobhy, "Button antenna on textiles for wireless local area network on body applications," *IET Microwaves, Antennas & Propagation,* vol. 4, p. 1980-1987, 2010.
[151] Hertleer, H. Rogier, and L. Langenhove, “A Textile Antenna for Off-body Communication Integrated into Protective Clothing for Firefighters,” *IEEE Transaction on Advance Packaging*, Vol. 57, p. 919-925, 2009.
[152] Salonen, P., et al., “Wearable Antenna performance: a case study of WLAN antennas,” In proceedings of IEEE APS International Symposium, Monterey, CA, USA, 2004.
[153] Locher, I., et al, “Design and characterization of purely textile patch antennas,” IEEE Transactions on Advance Packaging, Iss. 29, 2006.
[154] Ouyang, Y., Chappell, W.J., “ High Frequency Properties of Electrotextiles for wearable antenna applications,” IEEE Transactions on Antenna Propagation, Vol. 58, 2006.
[155] Bai, Q., and R.J. Langley, “Effect of bending and crumpling on textile antennas,” IET Seminar on Antennas and Propagation for Body-Centric Wireless Communications, 2009.
[156] IEEE rRecommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR), IEEE Std 1528-2013.
[157] http://www.icnirp.org/en/frequencies/high-frequency/index.html
[158] “DASY 4 System handbook,” Schmid & Partner Engineering AG, DASY4 Manual V4.5, March, 2005.
[159] Jiang, J.H., and D.L. Wu, “Ice and water permittivities for millimeter and submillimeter remote sensing applications,” Atmospheric Science Letters, Vol. 5, November 2004.
[160] G., Conway, and W., Scanlon, “Antennas for Over-Body-Surface Communication at 2.45 GHz,” *IEEE Transactions on Antennas And Propagation*, Vol. 57.,no. 4, April 2009.
[161] B., Sanz-Izquierdo, J.C., Batchelor, and M. I. Sobhy, “Button antenna on textiles for wireless local area network on body applications,” *IET Microwave, Antennas and Propagation,* Vol. 4, Iss. 11, pp. 1980-1987, 2010.
[162] N. Haga, K. Saito, and K. Ito, “Characteristics of Cavity Slot Antenna for Body-Area Networks,” *IEEE Transactions on Antennas and Propagation,* Vol. 57, no. 5, April 2009.
[163] S. Chen, T. Kaufman, and C. Fumeaux, “A modular Textile Antenna design Using Snap-on Buttons for Wearable Applications,” *IEEE Transactions on Antennas and Propagation,* Vol. 64, no. 3, March 2016.
[164] S. Zhu, and R. Langley, “Dual-band Wearable Textile Antenna on an EBG Substrate,” *IEEE Transactions on Antennas and Propagation,* Vol. 57, no. 4, April 2009.
[165] S. Zhu, and R. Langley, “Dual-band Wearable Antenna on an EBG Substrate,” *Electronics Letters,* Vol. 43, no. 3, February 2007.
[166] R. Salvado, C. Loss, R. Goncalves and P. Pinho, “Textile Materials for the Design of Wearable Antennas: A Survey,” *Sensors 2012*, Issue 12, p. 15841-15857.
[167] D. Fernandez, Y. Mulev, and J.M.H Sengers, “A Database for the static dielectric constant of water and steam,” *Thermophysics Division, National Institute of Standards and Technology,* March 1995.

APPENDIX A: EM Properties and Modeling of Human Body Phantom

Table I shows the findings of the authors as they directly associates to this study because of the frequency.

Table I: EM Properties of Human Body Tissue at 2.5 GHz [70]

| Tissue Name | Conductivity (S/m) | Relative Permittivity | Loss Tangent | Penetration Depth (m) |
|---|---|---|---|---|
| Aorta | 1.467 | 42.47 | 0.24837 | 0.023761 |
| Bladder | 0.69 | 17.97 | 0.27927 | 0.032545 |
| Blood | 2.587 | 58.181 | 0.31981 | 0.015842 |
| Bone, cancellous | 0.8228 | 18.491 | 0.31996 | 0.028087 |
| Bone, cortical | 0.40411 | 11.352 | 0.25597 | 0.044616 |
| Brain, grey matter | 1.843 | 48.83 | 0.27137 | 0.02031 |
| Breast fat | 0.14067 | 5.137 | 0.1969 | 0.085942 |
| Cartilage | 1.7949 | 38.663 | 0.33378 | 0.018638 |
| Cerebrospinal fluid | 3.5041 | 66.168 | 0.38078 | 0.012537 |
| Cornea | 2.3325 | 51.533 | 0.32544 | 0.016548 |
| Eye, sclera | 2.0702 | 52.558 | 0.28321 | 0.018773 |
| Fat | 0.10672 | 5.2749 | 0.14547 | 0.11455 |
| Gall bladder | 2.8447 | 68.305 | 0.29945 | 0.015592 |
| Kidney | 2.4694 | 52.63 | 0.33736 | 0.015811 |
| Liver | 1.7198 | 42.952 | 0.2879 | 0.020434 |
| Lung, inflated | 0.81828 | 20.444 | 0.28779 | 0.02963 |
| Muscle | 1.773 | 52.668 | 0.24205 | 0.021886 |

| | | | | |
|---|---|---|---|---|
| Skin, dry | 1.4876 | 37.952 | 0.28184 | 0.022198 |
| Skin, wet | 23.984 | 20.369 | 0.84665 | 0.0010736 |
| Small intestine | 3.2132 | 54.324 | 0.42529 | 0.012438 |
| Stomach | 2.2546 | 62.078 | 0.26114 | 0.018707 |
| Testis | 2.2084 | 57.472 | 0.27628 | 0.018394 |
| Tongue | 1.8396 | 52.558 | 0.25167 | 0.021083 |

The authors in [70] also showed the significant change in relative permittivity and conductivity over a wide range of frequency. The relation between the frequency and change of electric properties can be found in Fig 1a. The change in penetration depth is also very much noteworthy. The figure showing the change found in [70] is presented below in fig 3.2b.

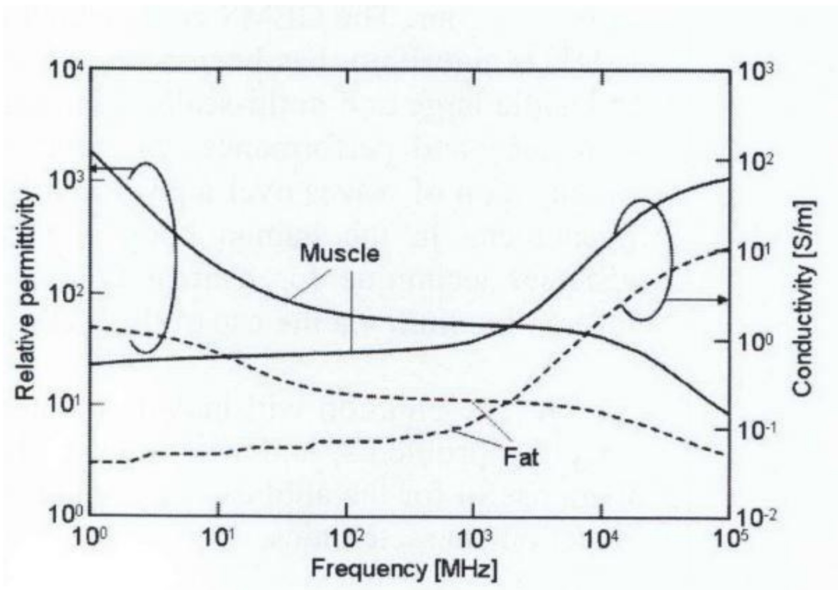



Fig 1a. Electric Properties of Human Tissue [22]

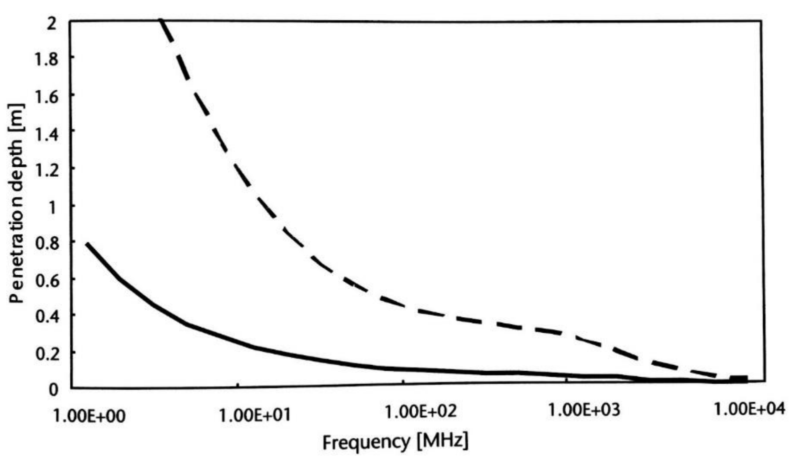



Fig. 1b Changes in penetration depth for fat and muscle [70]

This characteristic of tissue is used in penetration of body tissue to communicate with implanted devices.

## Liquid Phantoms

The oldest type of all the phantoms is liquid phantoms. Liquid phantom is a container filled with some type of liquid that has similar electrical properties as the human body tissue. Tissues with high water content can be mimicked using a mixture of liquid that will exhibit almost similar permittivity and other electrical properties. Various liquid phantoms have been proposed in [78-79]. The main advantage of liquid phantom is its easy preparation of mixing the liquids. In [80], authors have discussed several way of preparing the liquids for liquid phantoms. However, easily prepared liquid phantom comes with some inherent disadvantages too. Tendency of dehydration in the material makes it very difficult to maintain consistency while putting in the mixture together, which results drastic change in the relative permittivity and conductivity of the materials.

Although, detail distribution of fields inside the phantom can be measured using this type but SAR measurement is not possible near the human body. In addition to that, the structure of the liquid phantoms are not accurate to what is supposed to be as a replication of human body. It is also very limited for the materials for having steady permittivity and conductivity with the change of frequency. The container carrying the liquid creates another issue because of its own electrical properties. However, having all those issues, the liquid phantoms still have their usability being very easy to fabricate.

## Gel Phantoms

Gel or semi-liquid material are certainly more solid than the type we already discussed but not strong enough to hold a shape without any support of a container. The reason it has advantages over liquid phantoms is its ability to sustain homogeneity over a longer period. The fabrication process is also simple like the liquid phantoms. In [81], a flow diagram of the fabrication process has been described. Other than solving the issues discussed earlier, rest of the issues described for liquid phantoms remains for gel phantoms too. Besides, this type of gel material may take as long as a whole day for setting up [81].

## Semi-solid (Jelly) Phantoms

This type solves the shaping problem. Using a solidifying agent in the mixture makes the material as thick as jelly that can form a structure without being bolstered. Different recipes use "super stuff" (TX-151) [82] or agar [83] as the solidifying agent. The feature of having its own independent shape makes it suitable for emulation of soft tissues. The electrical properties are stable in this kind of phantoms, which leads to process of building in multi-layered fashion that can realistically resembles the anatomical structure of the human body. However, the fabrication process becomes a bit more lengthy and difficult. A generalized process of fabricating semi-solid phantom has been described in [84].

However, they also have some limitations. Experiments involving invasive measurements such as SAR measurements, implantable devices etc. become complicated with this type of phantom as they get deformations in the material layers with the frequent change of position for the measurement. In addition to that, semi-solid materials are neither reusable nor dielectrically adjustable. They also have the tendency of getting dehydrated which makes it very hard to preserve the material for a long period of time. [84]. Nevertheless, with their low cost and ability of mimicking human tissue over a wide band of frequency, semi-solid phantoms are still very suitable for medical imaging purpose.

## Solid (Dry) Phantoms

Solid phantom is a good fit for those measurements where internal structure of the body needs to be preserved inside the phantom, or the specific absorption rate (SAR) needs to be measured on the surface of the human body. Since the materials used in building solid phantoms are not water-based, they can overcome the issues of hydration and keep their shape for a time period. The materials used in building solid phantoms are called dry ATE (artificial tissue emulating) material [83]. They are mostly molded from ceramic powders, which have wide verities of different permittivity [83]. The ceramic materials are low loss, which results an obstacle in building lossy materials to emulate the actual conductivity of human tissue. However, it is possible to use various conductivity enhancing material with ceramic powders to have the flexibility of controlling the permittivity and conductivity separately [85]. Recipes for solid phantom using silicone rubber mixed with carbon fiber [86], and conductive plastic containing carbon black [86] also can be found in the literature.

Very steady mechanical and dielectric properties of these phantoms make them very suitable for not only SAR measurements, also for the studies of propagation around and inside the body, since they can accurately create a mimicked structure of inhomogeneous human body. However, having almost everything perfect, the solid phantom has the biggest disadvantage in the fabrication process. The fabrication of a solid phantom needs very expensive equipment and special procedure in building the composite structure, such as temperature as high as $260^{o}$ C and very high pressure. However, the temperature dependency of the dielectric properties make it a suitable fit for some applications, like hyperthermia.

# APPENDIX B: NUMERICAL TECHNIQUES

## The Uniform Geometrical Theory of Diffraction (UTD)

Geometrical optics (GO) has been the most widely used theory of light propagation, yet could not address a significant phenomenon called diffraction. It took almost over 150 years when Joseph Keller introduced the revolutionary systematic ray theory of diffraction [94]. The profound contribution that is referred as the geometrical theory of diffraction (GTD) played a significant role in computational electromagnetics (CEM). Like geometrical optics, considering the path of light wave propagation as straight or curved lines called rays, this theory also introduces diffracted rays. Some of the diffracted rays are expected to enter the shadow regions and account for the light there while others go into the illuminated region. Basic geometrical optics describes the incident ray, reflected and refracted rays. However, it fails to account for the incident rays, which hit edges, corners, or vertices of boundary surface. Keller called them diffracted rays and addressed the issue regarding the rays generated from geometrical and/or electrical discontinuity of a radiating object.

The uniform geometrical theory of diffraction (UTD) is the later uniform asymptotic version of GTD where it was developed to solve practical EM problem by patching the regions where the singular behavior at ray-shadow boundaries and caustics are observed. All waves are considered as local plane wave in order to use "ray tracing" in UTD. It also requires the object under study to be electrically large. This criterion can be easily met in the case of human body characterization. Two basic phenomenon associated with the interaction of EM wave and environment, reflection and transmission coefficients can be easily calculated by classic formulation depending upon the polarization of incident wave. Diffractions are considered as a form of scattering by objects with size of same order of magnitude as the wavelength. It is very important to include various diffraction in UTD to make sure the stability in field strength, which may change due to the repositioning of the receiver from line-of-sight (LOS) to non-line-of-sight (NLOS).

Several ray-tracing techniques were combined with UTD in [95] for efficient prediction of propagation in UHF band in indoor environment. In [96], The authors analyzed the human exposure in realistic urban environment for the Global System for Mobile communication (GSM) and Universal Mobile Telecommunication System (UMTS) frequency bands. They drew a conclusion that under certain conditions, the average exposure field levels and specific absorption rate (SAR) can be higher compared to free space environment. On the other hand, in [97], a practical deterministic propagation prediction model was introduced to investigate the effect due to human body scattering at 2.45 GHz frequency band.

Apart from these attempt, in recent years efforts in applying UTD in characterizing channel variations for on-body communication can be observed [98]. In [99], authors applied XGTD in studying propagation conditions for 60 GHz frequency band. In another study, UTD and RT (Ray Tracing) were used in combination to evaluate the on-body measurements at 94 GHz [100].

## Ray-tracing techniques

Ray tracing (RT) techniques are methods of choice for predicting wave propagation for electrically large and complex environments. They are mostly used in cellular phone services, personal communication system (PCS), and wireless local area networks (WLAN). This technique is developed based on high frequency approximation method Geometrical optics (GO) and fulfill the Fermat's principle assuming EM energy is propagated through straight line. RT also provides time delay and angle of arrival (AoA) information for the situation associated with multipath reception. RT can be used in determining signal strength and power delay profile for mobile networks, indoor radio wave propagation, vehicular communication, automotive radar, and radar cross section (RCS) computations.

There are two types of RT models, one is image method and other is ray launching (also known as SBR – shooting and bouncing rays) [101]. These two approaches can be described as following [102]:

**Image Method/ Deterministic ray tracing**

- Image theory is used to compute all the rays between transmitter and receiver.
- Complexity of the process exponentially increases with the number of intersections.
- Requires preprocessing.

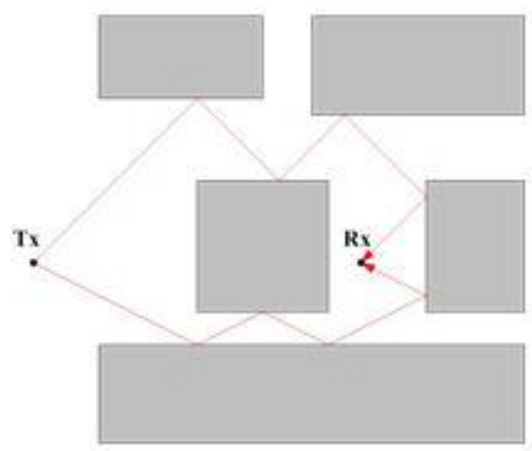



Fig. 2 (a) Image Method [103]

**Ray Launching (SBR)**

- All ray directions are considered as arbitrary.
- Complexity of the process increases linearly with the number of intersections.
- No preprocessing required.

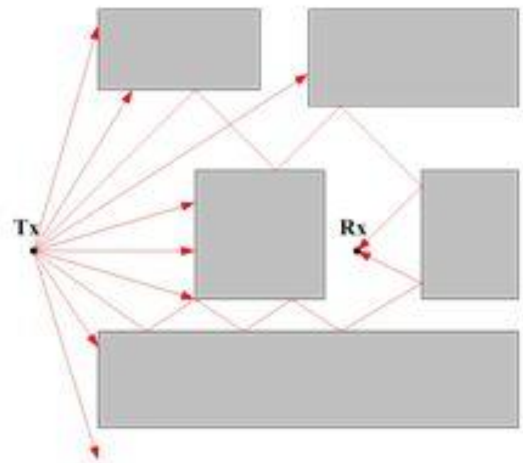



Fig. 2 (b) Ray launching [103]

However, propagation model for several applications using ray-tracing method can be found in literature. In [99], authors have used dual image and ray-shooting approach to present a novel model for indoor wireless communication. At 2.45 GHz frequency, the model is capable of predicting site-specific indoor propagation considering multiple human body moving within the environment. A method for SAR calculation for non-uniform exposure of human body to EM field generated from indoor cellular-base station antennas was presented in [101] using a combination of RT and FDTD methods. RT technique is also found in association with other high frequency methods.

VITA

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