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TAMPERE UNIVERSITY OF TECHNOLOGY

**MD MONIRUZZAMAN TANIM**

# COMPARISON OF PERFORMANCE AND STABILITY OF DIFFERENT WEARABLE PASSIVE UHF RFID TAGS IN BODY - WORN CONFIGURATION.

Master of Science Thesis

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## ABSTRACT

**MD MONIRUZZAMAN TANIM**: Comparison of Performance and Stability of Different Wearable Passive UHF RFID Tags in Body- worn Configuration.
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RFID or Radio frequency identification is an unsymmetrical radio communication protocol, where uplink (from tag to reader) communication is carried out with backscattering modulation. The foundation of Schottky diodes to CMOS processes provided the means of passive RFID, i.e. transponder or tags without a battery, at ultra-high frequencies with justifiable low cost and read range.

The thesis studies the different types of tags on human body and see the performances and their stability. Performance is the measurement of read range of the different tags and stability shows how stable the tags behave on human body. The human body is different in size and shapes. So, it was interesting to see how tag behaves on different types of people.

They solution for this thesis was designed in three ways. i) anechoic chamber measurements ii) human body with the tags in anechoic chamber measurements iii) analysis of tags behaviour in MATLAB. In order to finish the first step, three types of RFID tags were developed in the lab and measured their theoretical read range. Tested tags were a) dipole RFID tags b) slotted patch RFID tags and c) square slotted RFID tags. For second task, tags putted on different human body and measured their response as read range. The human being are different in sizes so responses were different in them. Lastly, all the result was analysed by MATLAB.

Analysis was carried out in three conditions. They are i) line of sight measurements ii) 45-degree right shift measurements and iii) 45-degree left shift measurements. For deep analysis of the thesis work, investigation was emphasized on the vertical and horizontal polarization. All the mentioned steps were analysed in the vertical and as well as in the horizontal plane. The LOS condition is straight forward such as measure the human body containing tags and in the line of sight with the reader antenna. The other two were somewhat tricky because of different angle separation such as '45' degree right or a left shift. Thanks to geometry which has ease this problem.

It has seen that in case of close proximity with human body the RF wave tends to lose its energy so the tags could not operate in regular efficiency. It has also observed that when tag placed on air medium the average read range is around 5m for dipole RFID tags and for the slotted patch it is around 4m. But when tags were attached to the human body upper back side the read range was 3.5m for dipole RFID tag and 3m for slotted patch RFID tags. This change of read range between air medium and human body-worn configuration is due to the human body. Human body is a lossy medium. 70% of human body weight is water and presence of water RF waves decreases its performance. The high dielectric constant and loss tangent is due to human body effects. Because of this problem wearable tags lose its received power from the reader in to the human body. It has also noted that centre frequency has shifted in body-worn configuration. It has also observed that in different angle RFID still working. There was noticeable amount of change in centre frequency due to human body interaction. This is because of human body is not symmetrical.

# PREFACE

The research explained in this thesis was carried out at Wireless Identification and Sensing Systems (WISE) research group at Tampere University of Technology, Department of Electronics and Communications Engineering, between April to November 2017.

Thanks to Professor Leena Ukkonen, who accepted me as a thesis student in her research group and helped me to start. Later the supervision task was handed over to my two supervisors, Toni Björninen and Johanna Virkki. They were always there to help me with practical problems and give valuable comments to my thesis manuscript. Thank you Toni Björninen and Johanna Virkki, for helping me to finish this thesis.

My test subjects (my friends) deserve to be specially acknowledged. Musfequr Rahman, Jahangir Khan, Taoufikul Islam, Bijon Jobair, Remens Rahman and few members of WISE research group especially Shubin Ma patiently stood in awkward positions and held their breath for the sake of my thesis. Also thanks to Muhammad Azizuddin Ph.D who encourage me to complete this thesis.

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Tampere
19/11/2017

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# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| TUT | Tampere University of Technology |
| RFID | Radio Frequency Identification |
| RF | Radio Frequency |
| IoT | Internet of Things |
| VHF | Very High Frequency |
| UHF | Ultrahigh Frequency |
| EIRP | Equivalent Isotropic Radiated Power |
| EU | European Union |
| WBAN | Wireless Body Area Network |
| PMR | Professional Mobile Radio |
| TEM | Transverse electric magnetic field |
| AR | Axial Ratio |
| AC | Alternating Current |
| ASK | Amilitude-shift Keying |
| BLF | Backscatter Link Frequency |
| FCC | Federal Communication Commission |
| ISM | Industrial, Scientific and Medical |
| ETSI | European Telecommunication Standards Institute |
| LOS | Line of Sight |
| EM | Electromagnetic |
| Gen2 | Class 1 Generation 2 RFID standard |
| IC | Integrated Circuit |

| | |
|---|---|
| $\boldsymbol{H}$ | Magnetic Field |
| $\boldsymbol{E}$ | Electric Field |
| $\boldsymbol{U}$ | Radiation Intensity |
| $\boldsymbol{m}$ | Meter |
| $L_{iso}$ | Power Loss Factor |

# 1. INTRODUCTION

Radio frequency (RF) tags are electrical device designed to receive a specific signal and simultaneously transmits a certain reply. Hence it is a two-way communication system with a tag and another device usually known as a reader or an interrogator. Tag communicates with a reader using far field electromagnetic radiation. Sensors and RFID (Radio Frequency Identification) are the two widely use case for RF tags [1]. Use of RFID in different purposes such as services and maintenance information, monitoring and control of production, production identification, payment applications, tracking and tracing and identification and access control are common [2]. In a more simplistic way where contact less services and identifications are needed that can be served via RF Tags. In below given some examples of companies using RFID solutions nowadays: -

i. ABB drives manufacturing plant in *Pitäjänmäki* using RFID solutions since 2004 related to the tracking of transport plywood boxes used in ABB's raw material supply chain. Another Finland based fashion manufacturer and retailer company *Naisten Pukutehdas* (NP) using RFID since 2007 in their batch manufacturing plants for time saving and distributions center processes [2]. *Wal-Mart* using RFID in their supply chain and on their shipments in order to reduce out-of-stocks and bullwhip effects, administration costs and manual order time and to improve customer services [3].
ii. Public transport using RFID solutions for customers in Finland (e.g. HSL). They are providing one smart ''city card'' for paying the bills in different transports and in different area [2]. Also in the United States Department of Defence using passive RFID solutions in supply chain for inventory management [4].

The tag performance depends on the tag antenna. Antenna performance can be affected by several issues such as mismatch in polarizations, antenna deformation and electromagnetic dimensions of the tagged object [5]. This thesis paper will enlighten three different types of antenna and their fabrication then testing them on different people. In addition, the read range will also be measured.

## 1.1 Wearable RFID Trends

In recent times, most of the world's biggest industries utilizing wearable devices for different purposes. Wearable technologies are becoming most essential like smartphones

nowadays. IoT, Data Engineering, Big Data Analytics and Cloud Services are using wearable devices and provide good impact on these services.
The ‘‘smart wearable’’ devices are contributing to several sectors of our life. For instances, wearable technology is being used in healthcare, fitness and wellness activities, logistics, manufacturing and industry warehouses, military or security agencies, personalized tracking and fashion and entertainment sectors. Our day to day life becoming simpler due to the use of smart wearable devices.

It is necessary to mention the types of wearable devices are available in the market in recent times. They are smart watches, smart bands, smart gloves, smart glasses, smart activity trackers, smart health devices and smart footwear [6].

## 1.2 Wearable antennas and wearable wireless communications

For a wearable antenna, it is important to select a material both for the nonconductive and conductive parts. This thesis paper puts emphases on body-worn RFID antennas for very high frequency (VHF) and ultra-high frequency (UHF) bands. VHF/UHF wearable antennas are largely utilized in professional mobile radio (PMR) communication. The customer group of PMR communication are military organizations, law enforcement personnel and emergency operators. FM broadcast utilizes VHF antenna for reception at around 150MHz while the UHF lower band (LB) used for PMR communications at 400MHz. UHF upper band wearable antennas operating frequency is 868MHz and have been use for remote health monitoring system and radio-frequency (RF) energy harvesting systems. For tracking persons and remote wireless identification, both printed and textile wearable antennas are used in 840-960MHz. In VHF/UHF, wearable antennas the free space wavelength is larger than or most comparable with the size of human body sections. Usually, those antennas are attached to the torso, back, legs, arms, shoulder and head. The design of antennas of such kind is challenging due to the antenna performance and wearer’s comfort.

## 1.3 WBAN

Recent technological developments in sensors, wireless communication and low-power integrated circuits have permitted the design of light-weight, a low-cost miniature, intelligent physiological sensor platforms that can be attached to the body area network for health care in the hospitals or home. Wireless body area networks (WBANs) provide unobtrusive ambulatory health monitoring for the patients. It is a system of real time updates about patient’s health condition through internet. Different physiological sensors such as motion sensors, electrocardiographs (ECGs), electroencephalographs (EEGs) and electromyographs (EMGs). The sensors usually attached to the body as a small electrical patch, attached to the clothing or implanted below the muscles or skin. Achieving proper health status is necessary for different medical studies. Although interfacing all these sensors are very challenging. Sensors are located in the different places of the body such as ankle, arm, waist and the thigh. A WBAN can be utilized in many applications, for instances, remote health monitoring, computer-supervised rehabilitation, emergency medical care etc.

## 1.4 Wearable Electronics, Materials and Manufacturing

For the better performance of wearable electronics and wearable antennas, the design criteria, materials selection and manufacturing are very crucial. The human body itself located in a reactive near-field region of the antenna and affects the antenna performance. Human body effects are considered when designing the wearable antennas. Body effects of the antenna operating at microwave or millimeter-wave frequencies are minimized by fine tuning. For instance, body effects in the VHF bands wearable antennas are fairly large due to body is in close proximity of a reactive near field region. In addition, antenna performance does not affect by the large wavelength. Traditional VHF antennas are large and different miniaturization techniques have been employed to fit the antenna inside of the garments and life jackets. It is necessary to keep in the mind that VHF bands antenna does not require the large ground plane which decouples the antenna from the body. Miniaturization of the antenna reduces its performances. Antenna weight and cost increases by magnetic materials. The VHF bands antenna usually made of a copper tape. In order to increase the antenna efficiency, the size of the radiation terminal has to be increased. So, flexible antenna such as the dipole antennas are developed. In case of UHF antenna, a ground plane is designed for the antenna and body separation. The antennas can be more flexible and thinner without a metallic reflector. Changing of the operating frequency change the human body effects. Antenna radiation pattern and input impedance affected due to on-body antenna location, movements and postures of the antenna wearer. Person-to-person variation is lower than the movement, posture of the wearer and the distance between the antenna and body surface. In case of putting in the wearable antennas into garments or clothes textile fabrics are used. For stable VHF/UHF antenna characteristics, the special care should be given on the antenna supporting structure with the body. Proper supporting structure fights against stress, crumpling and compression [7].

## 1.5 Structure of the thesis

This thesis analyses the performance and stability of different wearable passive UHF RFID especially in body-worn configuration. Furthermore, chapter 1 introduces the wearable trends, wireless body area networks, wearable antennas and RFID and its used cases. Also, it covers the short description related to wearable electronics and its manufacturing. Chapter 2 is a literature review of antenna and its parameters and RFID systems. It also provides details review of RFID and backscattering working principles.

It also links the thesis with necessary mathematical equations that is useful for following chapters. In chapter 3, different types of wearable RFID were discussed and it also enlightens how they were fabricated in the lab. Necessary images of prototype antenna were depicted in this chapter. Chapter 4 explains the free space measurements of the all the RFID tags used in this thesis. It also contains a literature review of calibration method. In this chapter, theoretical aspects of this thesis were shown. It has also studied the different anechoic chamber devices used in the thesis. Chapter 5 contains the actual measurements result obtained from body-worn configuration. This chapter also carries the analysis of the thesis. How person-to-person variation effects the read range also discussed. Chapter 6 concludes the thesis and shows future aspects of RFID.

# 2. INTRODUCTION TO ANTENNAS AND RFID

An antenna can receive and radiate EM (Electromagnetic) waves. In other words, an antenna work as a transformer that converts energy from the EM radiation to voltage and currents at its terminals and vice versa. Working principle usually run by Maxwell's equation. Antenna size varies according to market demand and they vary with small size, multi-bands and multi-functions. With the immense development in VLSI (very large-scale integration), it is required to miniaturize the size of antenna. So, there are many researches going on to bring smallest antenna for different devices. Nowadays almost all antennas for wearable or portable devices can be mounted or embedded within the devices. The small size of antenna can be achieved via several ways such as changing in electrical size, physical size and function. As antenna developments are application oriented so they can be miniaturized by many different ways. In this chapter, basic antenna theory and antenna performance parameter will be thoroughly discussed [1-2] [8-9].

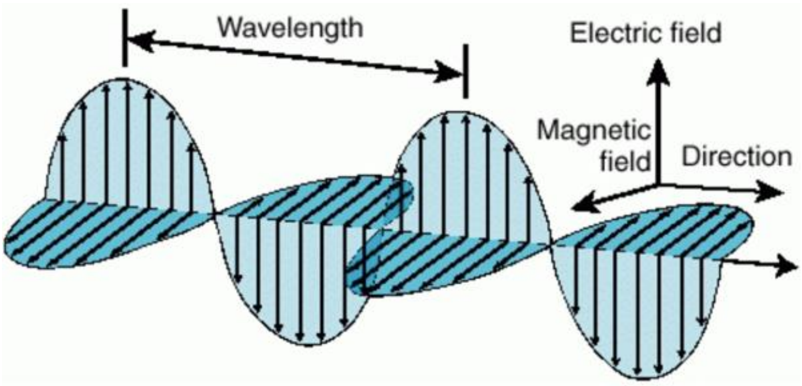


***Figure 1.*** *EM Waves of an Antenna [2]*

## 2.1 Antenna

The type of antenna used for tag communication depends on the antenna field or radiation pattern. There are few general rules for producing fields (magnetic and electric) using current filament given below [3-4] [5-11],

$$\tilde{H} = \frac{I\nabla z}{4\pi}\left[\frac{j\beta}{r} + \frac{1}{r^2}\right] e^{-j\beta r} \sin(\theta)\ \hat{\phi} \qquad (1)$$

$$\tilde{E} = \frac{I\nabla z}{4\pi}\left[\frac{j\omega\mu}{r} + \sqrt{\frac{\mu}{\varepsilon}}\frac{1}{r^2} + \frac{1}{j\omega\epsilon r^3}\right] e^{-j\beta r} \sin(\theta)\,\hat{\theta} + \frac{I\nabla z}{2\pi}\left[\sqrt{\frac{\mu}{\varepsilon}}\frac{1}{r^2} + \frac{1}{j\omega\epsilon r^3}\right] e^{-j\beta r}\cos(\theta)\,\hat{r}$$

(2)

Here, the amplitude of the current pointed in the positive $z$ direction, $\Delta z$ is the length of the current filaments, $\beta = \frac{2\pi}{\lambda}$, phase constant, $r$ is the radius distance from current carrying filament, and $\omega$, $\mu$, $\varepsilon$ represents radian frequency, permeability and permittivity of the medium respectively. There are two main categories of the antenna systems. They are near-field system and far-field system. Near-field system uses an inductive coupling of the tag to the reactive energy circulating inside reader antenna. In far-field, energy is transported far away from the source through EM wave propagation and captured by a distant receiver. LF and HF bands RFID uses near-field coupling system and UHF bands, microwave RFID uses far-field coupling due to achieve long read range. In below *Figure 2,* describes there are three regions of a radiating element. The regions in are *a,b* and *c* and known as (a) reactive near filed region (b) near field or Fresnel region and (c) Far field or Fraunhofer region.

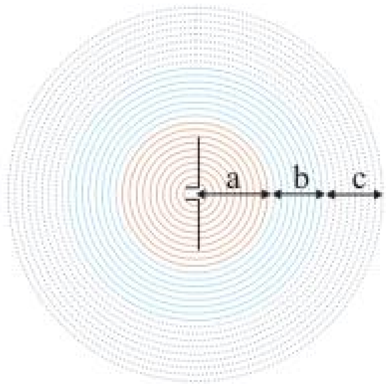


***Figure 2.*** *Different field areas of a radiating element [3]*

According to IEEE, radiation parameters are related to antenna's radiation properties in the far-field. States that the observation points at least $\frac{2d^2}{\lambda}$ away from the antenna, where d, is maximum dimension of the antenna. From equation (1) and (2), these fields decay at a rate of $\frac{1}{r}$ and contain traveling waves that carry power away from the antenna. The area $\sqrt{0.62(d^3/3)}$ away from or near to the antenna is said as a reactive near field. Reactive near field hold standing waves and they do not radiate power but store energy near the antenna. From (1) and (2), these fields decay at a rate of $\frac{1}{r^3}$ . The region contains both standing waves and travelling waves generally called Fresnel region or near field. These fields decays at a rate of $\frac{1}{r^2}$ from equation (1) and (2). In contrast, from Figure 2, (a) reactive near field region < $\sqrt{0.62(d^3/3)}$ , (b) $\sqrt{0.62(d^3/3)}$ < Near field or Fresnel Region < $\frac{2d^2}{\lambda}$ and (c) $\frac{2d^2}{\lambda}$ < Far Field or Fraunhofer Region.

It is important to mention that the fields are continuous with respect to the distance, they do not change so abruptly. In far-field region means far away from the antenna so its shape and size are no more necessary and it act as a point source. Here the electric and magnetic fields are in phase and normal to each other and normal to the direction of propagation [3-4] [7] [5] [12].

## 2.2 Antenna Performance Parameter

In this thesis paper dipole, slot and patch antenna have been used so details of these including antenna performance matrices are discussed in the following section [5-9] [11-15].

### 2.2.1 Radiation Pattern

Antenna radiation pattern is a mathematical function of radiation properties of the antenna as a function of space coordinates. In simple words, radiation pattern describes the sensitivity of the antenna in the different direction. Antenna radiation pattern is determined by the far field region. At far away distance, larger than the wavelength and size of the antenna, the EM fields and waves attenuates and phase is continuously changes with distance. Radiation intensity is defined as the radiation of the power per unit solid angle of the antenna. It can be written as,

$$U=r^2 W_{rad} \qquad (3)$$

Where U is the radiation intensity (W/unit solid angle) and $W_{rad}$ is the radiation density.

### 2.2.2 Antenna Gain and Directivity

Directivity of the antenna can be defined as the ability of focusing radiated energy. In other words, it is the ratio of the radiation intensity (U) in a certain direction from the antenna to the average radiation intensity ($U_0$) over all directions. It can be expressed mathematically,

$$D = \frac{U}{Uo} = \frac{4\pi U}{P_{rad}} \qquad (4)$$

However, gain of the antenna normally tells that efficient transformation of the available power of the antenna terminals into radiated power. Gain of the antenna can be defined as the ratio of the intensity (generally isotropic radiated power) to the total accepted input power. It can be written mathematically as,

$$G = \frac{4\pi U_m}{P_{in}} \quad (5)$$

### 2.2.3 Antenna Impedance

The antenna is a combination of wave phenomenon and hardware circuit. The hardware circuit needs input impedance at the antenna terminals in order to work. So, the antenna impedance or input impedance is the impedance remain present at the antenna terminals. The mathematical expression of the antenna impedance consists of real and imaginary components.

$$Z_A = R_A + JX_A \quad (6)$$

Where $Z_A$, $R_A$ and $X_A$ is the antenna impedance, antenna resistance and antenna reactance of the terminals respectively. The input reactance $X_A$ represent power stored in the near-field of the antenna.

The input resistance $R_A$ represent dissipation.

$$R_A = R_r + R_{ohomic} \quad (7)$$

Where $R_r$ and $R_{ohomic}$ is the radiation resistance and ohomic heat loss resistance respectively.

### 2.2.4 Realised Gain

According to IEEE, the realised gain can be defined as " the gain of an antenna reduced by the losses due to the mismatch of the antenna input impedance to a specific impedance [5] [16]", which can be expressed as

$$G_{real} = \tau G \quad (8)$$

Where $\tau$ and $G$ is the power transmission coefficient and gain of the antenna respectively.

$$\tau = \frac{4R_{chip}R_A}{|Z_{chip}+Z_A|^2} \leq 1 \quad (9)$$

where $Z_{chip} = R_{chip} + JX_{chip}$ is the RFID IC impedance and $Z_a$ is the RFID tag antenna impedance [32] [37].

### 2.2.5 Friis Transmission Equation

Power transmission in the communication link between transmitting and the receiving antenna can be easily found by Friis formula. The simple form of Friis formula given below:

$$P_r = P_t \frac{G_t\, G_r\, \lambda^2}{(4\pi R)^2} \qquad (10)$$

Where $P_r$ is the received power by the receiving antenna, $P_t$ is the transmitting power by the transmitting antenna, $G_t$ is the transmitting antenna gain and $G_r$ is the receiving antenna gain, $\lambda$ is the transmission wavelength and R is the distance between the receiving and transmitting antenna.

Equation (10) can be modified using the impedance mismatch loss at the antenna terminals and polarization mismatch due to misalignment with receiving and the transmitting antenna. So, equation (10) can be written according to the realized gain values and polarization efficiency.

$$P_r = \left(\frac{\lambda}{4\pi R}\right)^2 .\ G_{rT} \cdot G_{rR} \cdot \eta_P \cdot\ P_t \qquad (11)$$

Where $G_{rT}$ is the realized gain of transmitting antenna, $G_{rR}$ is the realized gain of the receiving antenna and $\eta_P$ is the polarization efficiency.

### 2.2.6 Read Range

The read range of RFID is limited by two factors. They are i) maximum transmitted power of the RFID reader ii) the minimum power of the RFID chip to harvest enough energy. There is regulation for maximum power that an RFID can transmit and it is known as maximum EIRP. For the EU region, the maximum allowed EIRP is limited to 3.28W and for North America it is 4W [11].

We can write, $EIRP = P_t \cdot G_t$ (12)

From equation (11) and (12), we can rewrite the read range of the RFID,

$$R_{range} = \left(\frac{\lambda}{4\pi}\right)\sqrt{\frac{G_{rTg} \cdot EIRP}{P_{chip}}} \qquad (13)$$

where $G_{rTg}$ is the realized gain of the tag.

Using calibrated measurement setup, the theoretical read range is calculated. Path loss is involved in the setup during calibration of the setup. So, read range can be written as,

$$R_{range} = \left(\frac{\lambda}{4\pi}\right)\sqrt{\frac{EIRP}{P_{th}.L_{path}}} \qquad (14)$$

Where $L_{path}$ is the calibrated path loss and $P_{th}$ is the threshold power required to activate the tag.

$$P_{th} = \frac{P_{chip}}{(\frac{\lambda}{4\pi})^2 \cdot G_{rTg} \cdot G_{Rdr} \cdot \eta_P} \qquad (15)$$

where $P_{chip}$ is the chip turn on power, $G_{rTg}$ is the realized gain of the tag, $G_{Rdr}$ is the gain of the reader and $\eta_P$ is the polarization efficiency.

## 2.3 Polarization

The spatial orientation of the electrical field (*E*) components is known as polarization of the EM wave. The type of the polarization is defined by the wave propagation. The mark of the electrical field component draws while wave propagating characterises the polarization. Different types of polarization include linear polarization, elliptical polarization, left or right circular polarization [14].

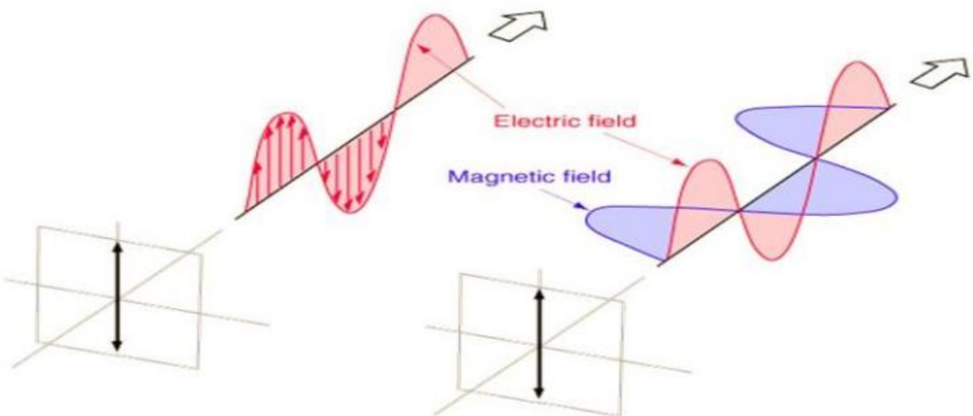


***Figure 3.*** *Linearly polarized waves [25]*

In *Figure 3*, shows the linearly polarized waves. When electric or magnetic field components of EM waves vary only in one given plane known as linear polarization. It is defined by the polarization direction of electric field. In other hand, circularly polarized wave defined as, when electric field of EM waves oscillates only in x-y plane, means EM waves keep their same shape but rotate or circle around the axis. When EM wave is propagating and their electric field is rotating in clockwise direction, this phenomenon known as left circular polarization. When the electric field rotating anticlockwise polarization is known as right circular polarization. *Figure 4*, shows circular polarization. In elliptical polarization, the electric field varies in two planes with change in amplitude. In this case, electric field vector is in the form of eclipse in one plane and propagating perpendicular to the direction of the waves [9]. *Figure 5*, attributes the elliptical polarization.

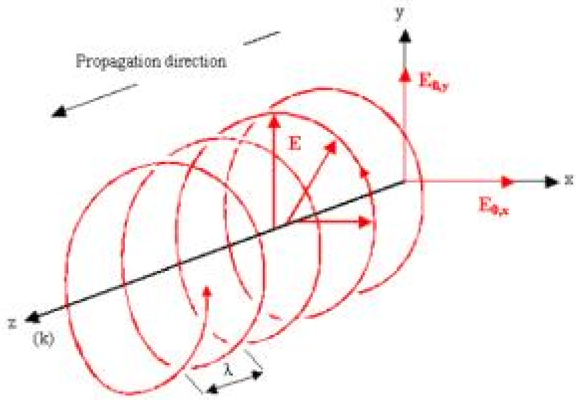


***Figure 4.*** *Circular polarization [25]*

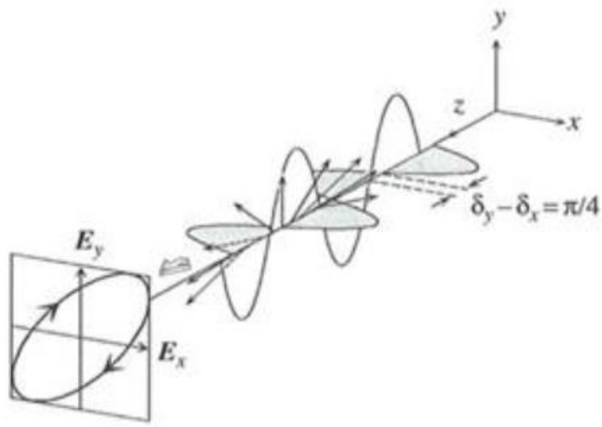


***Figure 5.*** *Elliptical polarization [25]*

Antenna polarisation is defined by the polarisation of its far field radiation. In the far field region, the radiated field is a plane wave. When the electric field is in the same direction, the same value and same phase in the plane normal to the direction of propagation. The same definition is applicable to H fields as well. In propagation wave the E and H field are perpendicular to each other [12].

## 2.4 Wearable Antenna Body-Worn Efficiency

The advancement of wearable technology, the wearable antenna or body worn antenna is new topic to be fully characterised. So, new parameters are needed in order to classify this modern technique. Body-induced gain and body-worn efficiency are the two figures of merit according to Scanlon and Evans [12].

The body-induced gain is the ratio (in dB) of gains between the body-worn antenna and the antenna in free space. In theory, its range varies from $-\infty$ dB to 6 dB for dipoles or other omnidirectional antennas.

In the other hand, body-worn efficiency is the ratio of total body-worn radiated power to the total radiated power in free-space isolation and it represents the overall power loss in the human body. The changes in the impedance does not take care by body-worn efficiency. There is a generalize expression given below for the body-worn efficiency [13],

$$\eta_{bwe} = \frac{\eta_{rad}^{body-worn}}{\eta_{rad}^{free\,space}} \qquad (16)$$

Human body is containing 65-70 % water. Antenna efficiency decreases due to higher dielectric constant of the water. In higher frequencies, high dielectric of water absorbs power and hence efficiency reduced [13].

## 2.5 The RF Tag System and Components

RFID system varies with their design and use. RFID achieved much wider acceptance in the world due to its necessary use and simplistic design. In this thesis, the materials used for fabricating and design RFID tag antenna are very common and less expensive. The later parts of this chapter will reveal the main components of a general RFID system. The key benefits of RFID over tradition identification technologies such as bar-codes and human readable formats are listed below [33]:

- Multiple tag reads at the same time
- RFID tags can be programmable and re-programmable
- Faster read rates than bar codes
- Non-line of sight (LOS) reading
- Improved security functionality

### 2.5.1 The Interrogator or Reader

It is often known as reader and can perform read or write functionality to the RFID tag device according to the necessity. The reader is the primary medium to communicate with the tag and bring tag information in the reader device in visible format. In such manner, the information can be read or write in a more convenient way. This information can be a long code or single bit. The readers contain the component such as an antenna for communicating with the tag, a radio frequency transmitter and receiver module and a control unit. Some modern readers can further transmit data to an auxiliary system such as a robot control system or PC. The reader is a microcontroller based device that contains detector, hardware and a loop of coils. [1] [5] [ 6-7].

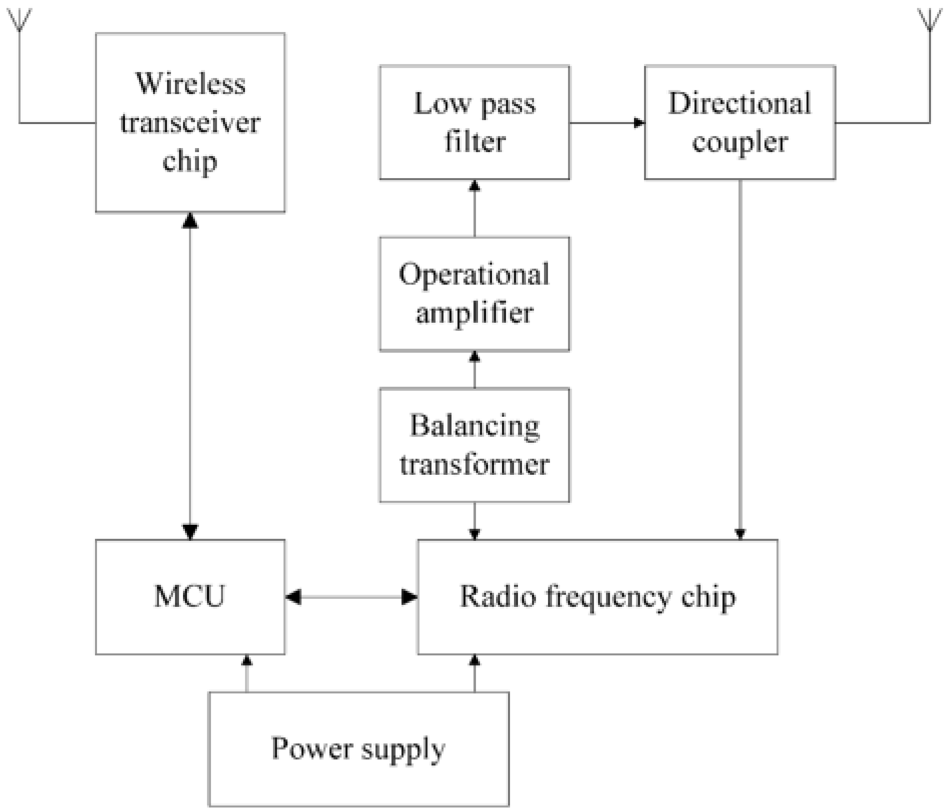


***Figure 6.*** *Schematic diagram of RFID reader [36]*

### 2.5.2 The RF Tags

There are different types of RF tag in the market for different RFID use cases. They can be classified as a 1-bit tag and multiple bit tags. 1-bit tags are simple tell the reader that it is inside the read range. Inductive coupling being used for 1 bit passive tags that operates in a near field region. In an inductive coupling reader detects rapid fluctuations in its coil impedance due to the resonant circuit or material non-linearites. Whereas in multiple-bit tags are capable of transmitting multiple-bit code to the reader. The multiple-bit tags contain antenna, power supply and modulation circuitry. Usually, tag contains silicon memory chip, rectifier bridge circuit and other RF front end devices, tuning capacitor, input or output coil [1] [5] [ 6-7].

The RFID IC consists of three major blocks:

- Analog interface
- Digital control
- EEPROM

In this thesis, NXP UCODE G2iL was used as a RFID IC. Given below a block diagram of G2iL IC

The analog interface provides necessary supply voltage and demodulates the data received from the reader and send to the digital part. Moreover, data transmission happens from tag to reader using the modulation transistor. Memory storage components of RF tags store the multiple-bit or codes that is use for communicating to the reader. The digital block carries the state machines, processes the protocol and handles the communication with the EEPROM, which contains the user data and EPC [34]. Non-writeable tags use read only memories (ROM) to save or transmit the information. Whereas rewriteable tags use electrically erasable and programmable read-only memory known as EEPROM. In an active state, backscatter tags generally use SRAM to store digital codes [5] [23].

Another important block of RFID is power supply. Active and passive tag are the two-main classification of RF tags. Active tags use its own power source (e.g. battery) for circuitry operation and modulation. Active tags usually have good read range while comparing with the passive tags. Passive tags do not have its own power source on board. However, they operate or respond from the power gained from the reader. In simple words, passive components are energy acceptor while active components are the energy donor. Passive tags are cheap and durable compare with active tags [8] [15]. As the received power form reader is very small a rectification circuits are used by most of the tags for power supplies. There are tags that do not use rectification stage but use direct AC voltage appeared in the antenna ports of the tags. [5] [23]

*Figure 7,* showing the typical functional blocks of RFID chip.

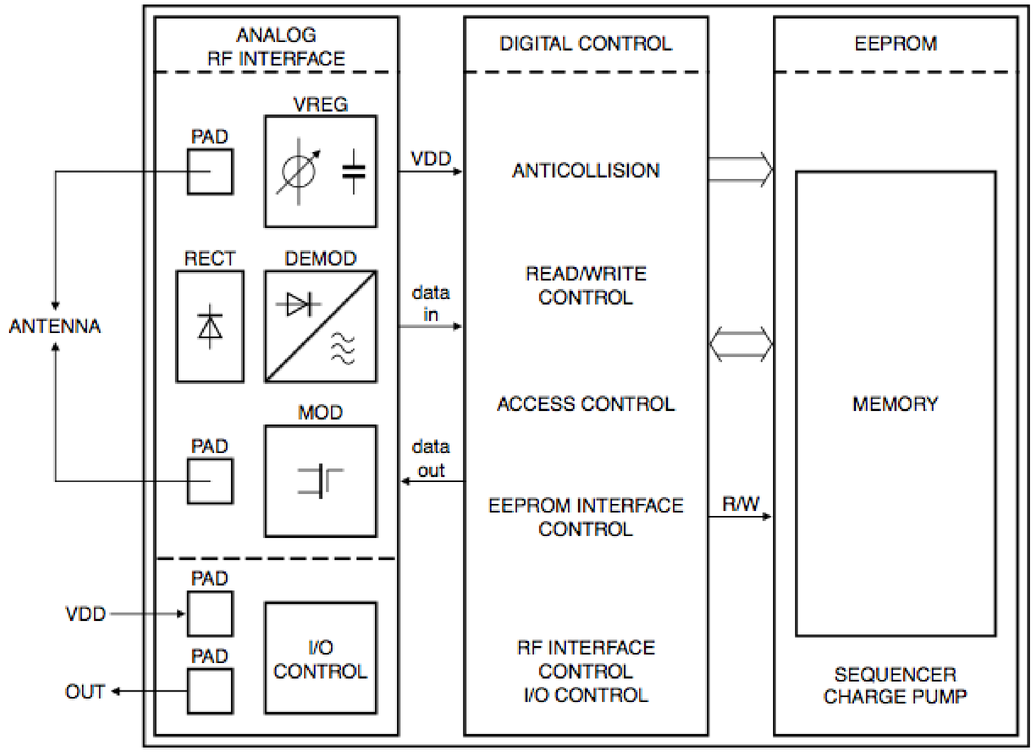


***Figure 7.*** *Block diagram of RFID IC [34]*

In *Figure 8,* describing two different types of communication modes: the RFID tag microchip or tag IC and tag antenna. The antenna is receiving energy coming from the reader as continuous wave form. When there is enough voltage appears in the antenna terminals, its activates the on-chip semiconductor based rectifier circuits hence whole circuit receive necessary power to activate. Tag does not respond simultaneously while IC is fully activated and receiving reader commands. The tag sends its response using backscatter modulation as tags are not transmitter but reflectors and thus allow them to operate at very low power levels [35].

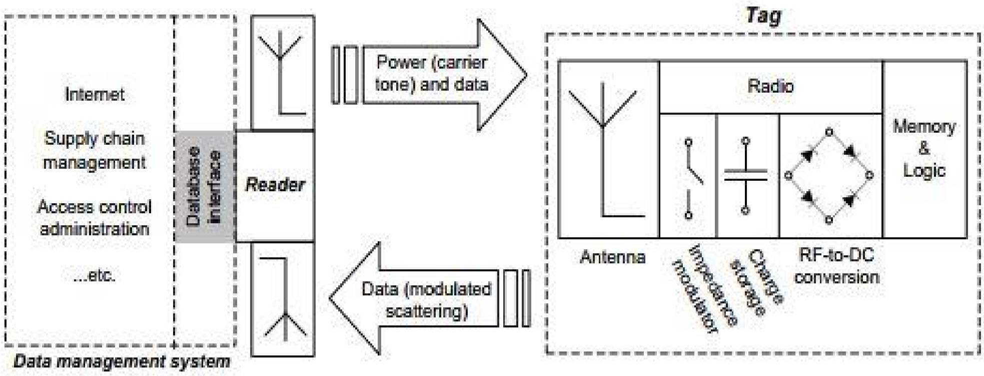


***Figure 8.*** *Working principle of passive RFID system [35]*

## 2.6 Principle of Backscattering Communication

The principle of backscattering communication in RFID is discussed in this point with necessary mathematical expressions.

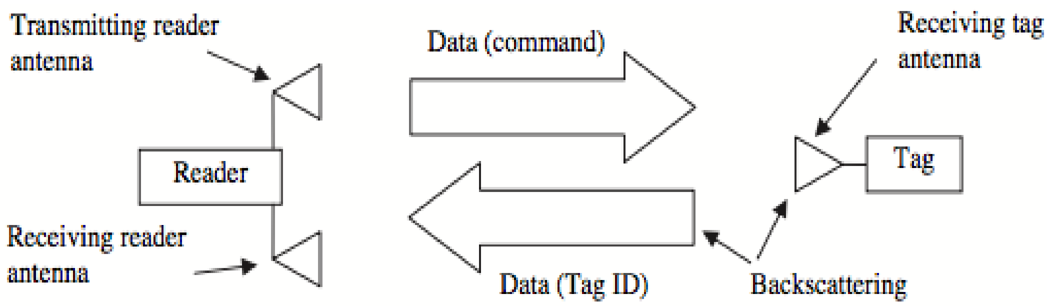


***Figure 9.*** *Passive RFID system [26]*

Passive UHF RFID system works on backscattering principle [26]. That is, in *Figure 7*, reader sends energy, data and commands to tag which then responds its identification data by backscattering to the reader. At first, we define the power transmitted to the tags from reader as $P_{transmitted}$. At distance *R,* the power density *S,* can be define as,

$$S = \frac{G_{reader}P_{transmitted}}{4\pi R^2} \qquad (17)$$

where $G_{reader}$ is the reader antenna gain. Then, the tags received power ($P_{received}$) from the field can be written as,

$$P_{received} = SA_{eff\_tag} \qquad (18)$$

where $A_{eff\_tag}$ is the effective area of the tag antenna. The effective area of the tag antenna is,

$$A_{eff} = \frac{G\lambda^2}{4\pi} \qquad (19)$$

where $G$ is the antenna gain and $\lambda$ is the wavelength of the frequency used. Now putting the value of equation (17) and (19) into equation (18), we get:

$$P_{received} = \left(\frac{\lambda}{4\pi R}\right)^2 G_{reader}G_{tag}P_{transmited} \quad (20)$$

where $G_{tag}$ is the antenna gain. The tag will reflect (backscatter) the wave to the reader. The backscatter field demnsity *S*2 at the reader location is defined as,

$$S_2 = \frac{G_{tag}P_{received}}{4\pi R^2} \qquad (21)$$

The reader received a power $P_{back}$ from the field,

$$P_{back} = S_2A_{eff\_reader} \qquad (22)$$

where $A_{eff\_reader}$ is the effective area of the reader antenna. Substituting equation (19) into equation (22), we get:

$$P_{back} = \frac{\lambda^2}{4\pi}G_{reader}S_2 \qquad (23)$$

Finally, substituting equation (20) into equation (21) and this further to equation (23), we get the reader receive backscatter power:

$$P_{back} = \left(\frac{\lambda}{4\pi R}\right)^4 G^2{}_{reader}\, G^2{}_{tag}\, P_{transmitted} \qquad (24)$$

### 2.6.1 Modulation Circuitry

Data modulation in RFID can be divided by two modulation schemes. One scheme is for *Forward Link* or reader-to-tag and another scheme is *Reverse Link* or tag-to-reader mode. For forward link operation, according to Gen-2 protocol, Amplitude-shift keying (ASK) is employed. In ASK, the amplitude of the signal varies according to the sequence of the bits. In simple words, it works as an on/off state. The two data symbols, Data "0" and Data "1" usually refers off state and on state respectively. Usually off state length is the same all the time whereas on state length varies. These symbol data are trace using lengths or an interval between two off state pulses generally known as *pulse-interval encoding*.

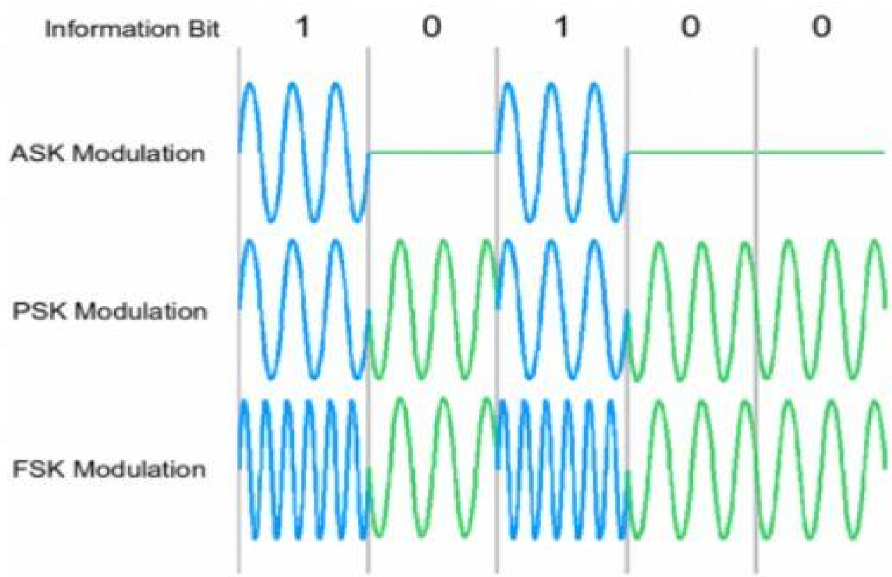


***Figure 10.*** *Different types of modulation techniques used in RFID system [24]*

In *Reverse link* operation, tag sends data to the reader using backscatter modulation or backscatter power. As passive RFID tag does not hold radio by their own so it changes antenna impedance for sending information to the reader. Moreover in between backscattering period tags encodes its data. According to Gen2-communication, the pulse width of the shortest reverse link is known as *Backscatter Link Frequency (BLF)* which is a clock signal. There are four ways to reverse link data encoding such as FM0 baseband, and three different kinds of Miller modulation of BLF subcarrier. FM0 is simple coding, use a square wave at BLF for representing data 0 and for data 1 it uses a square wave at BLF/2. Miller modulation is complex than FM0 encoding. In this modulation, it is easier to decode interference due to its long state transitions [22].

According to the work by Rao *et al.* (2005), impedance matching is important for RFID system. The antenna impedance and the chip impedance are frequency dependent. A small voltage emerges on the tag antenna from the electromagnetic field of the reader antenna. The impedance of chip varies with the power obtained by the chip. The power absorbed by the chip depends on the maximum available power from the antenna and power transmission coefficient. When chip impedance is equal to the antenna impedance then maximum available power achieved. The impedance match between tag chip and antenna can be described by the transmission coefficient. When the value of transmission coefficient is 1, then the perfect complex conjugates impedance match occurred between an antenna and chip. Moreover, for chip to activate, an antenna is matched to minimum threshold power ($P_{th}$) [29].

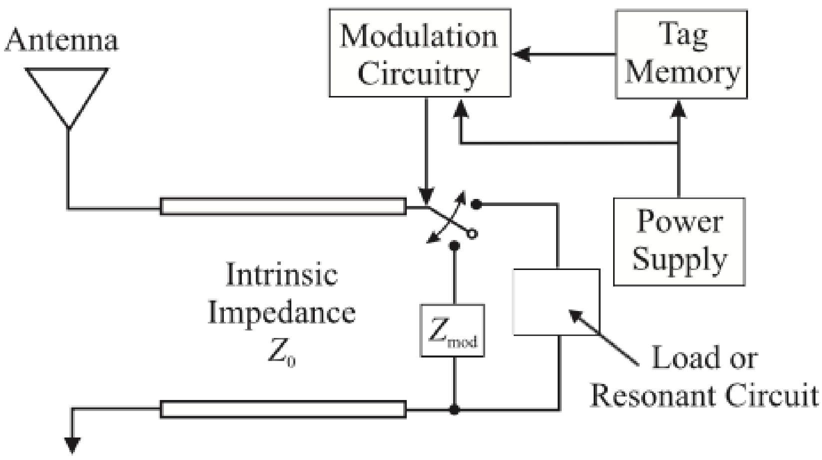


***Figure 11.*** *multiple-bit tag operating blocks [5]*

In *Figure 11*, multiple-bit tag's main operating blocks are representing. Amplitude or phase modulation can be achieved by switching in or out of $Z_{mod}$ (resistive or reactive load). In a near field of the reader, resonant circuit tune and de-tune using $Z_{mod}$. In far field operation tag switches $Z_{mod}$ in and out of the circuit to repeal pulses back to the reader [5].

## 2.6.2 Tags Frequency Ranges

The governing body such as Federal Communications Commission (FCC), industrial, scientific, and medical (ISM) and European Telecommunications Standards Institute (ETSI) has clear instruction over RFID tag frequency ranges in order to avoid interference with the other radio system. Tags frequency bands are unlicensed. *Table 1* is showing the tags operating frequencies in different frequency [23].

***Table 1.*** *Tags frequency ranges in different frequencies*

| Low Frequency | High Frequency | Ultra-High Frequency | Super High Frequency |
|---|---|---|---|
| 125kHz–134.2kHz | 13.56MHz | 860MHz – 960MHz | 2.45GHz |

In this thesis paper UHF Passive RFID tag has been used.

# 3. PROTOTYPING DIFFERENT RFID ANTENNAS

In this thesis paper three different types of RFID Tag Antenna were examined thoroughly. In this chapter, we will show you how these tag antennas were designed, their basic dimensions and Anechoic chamber test result. The three basic types of antennas covered in this thesis paper are given below sequentially:

i) Wearable Dipole Tag Antenna
ii) Wearable Slotted Patch Antenna
iii) Wearable Square Slot Antenna

Materials Required for prototyping these tag antennas are given below: -

i) copper clad laminates
ii) EPDM rubber
iii) conductive epoxy
iv) RFID IC (NXP UCODE G2iL)

The basic manufacturing of the antenna was challenging due to the smallest size and shapes of different antennas. For instance, *Dipole tag antenna* was easiest among all of them. At first the copper cladded paper was cut in the shape and then the RFID IC were placed on the strap pads with conductive silver epoxy. *Slotted patch antenna* was also difficult to fabricate in the lab due to its ground plane. At first copper strap was cut down according to the size and then RFID IC tag attached to this strap pads using silver epoxy. And lastly the same procedure was maintained when *Square slot antenna* were fabricated.

The basic dimensions of these above-mentioned Tag Antenna are given below: -

## 3.1 Dipole RFID Tag Antenna

The dipole antenna fabricated in the lab. The dimensions are given below in the *Table 2*. In addition, *Figure 12*, shows the antenna schematic used in the lab. And finally *Figure 13*, depicted the dipole antenna fabricated in the lab.

***Table 2.*** *Dipole Antenna*

| *t* | *g* | *L* | *W* | *u* | *v* |
|---|---|---|---|---|---|
| 2 mm | 2 mm | 120 mm | 20 mm | 27 mm | 16 mm |

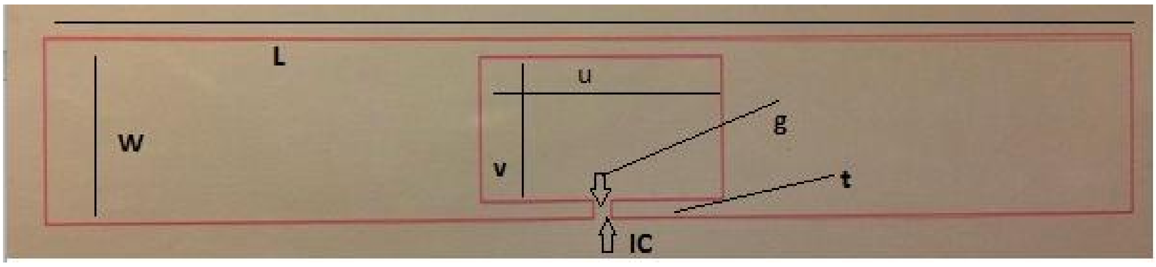


*Figure 12.* Dipole Antenna

*Figure 13.* Dipole Antenna (Lab Prototype)

## 3.2 Slotted Patch RFID Tag Antenna

One of the challenging antenna used in this thesis is slotted patch antenna due to its complex geometrical shapes. Table 3 shows the basic dimension of slotted patch antenna. Moreover, *Figure 14* and *Figure 15* are representing the antenna schematics and lab prototype respectively.

***Table 3.*** *Slotted Patch Antenna*

| *b* | *c* | *d* | *a* | *L2* | *L1* | *v* |
|---|---|---|---|---|---|---|
| 5 mm | 8 mm | 27 mm | 2 mm | 10 mm | 63.7 mm | 29.8 mm |

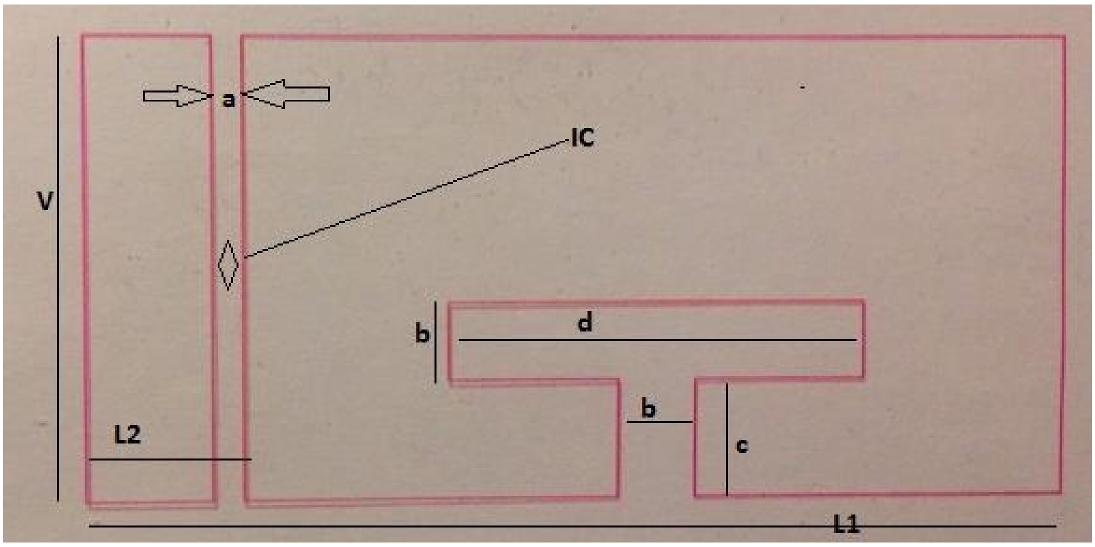


*Figure 14.* Slotted Patch Antenna

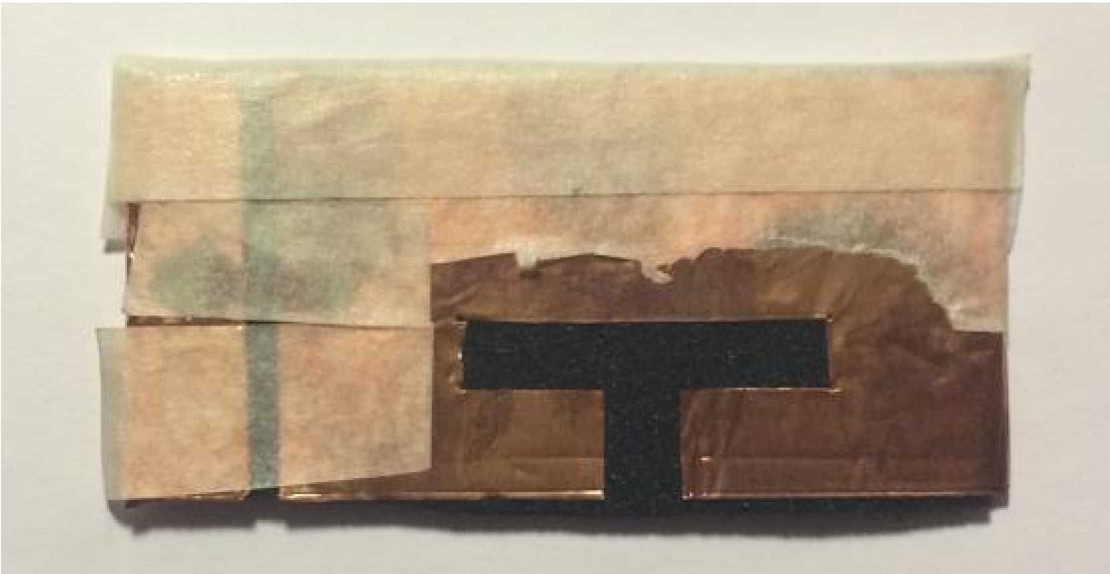

*Figure 15.* Slotted Patch Antenna (Lab Prototype)

## 3.3 Square slot RFID Tag Antenna

Another complex shape antenna used in this thesis was square slot antenna. Table 4 resembles its basic dimensions. *Figure 16* and *Figure 17* shows the schematics and lab prototype square slot antenna respectively.

***Table 4.*** *Square Slot Antenna*

| *Walls* | *a* | *b* | *c* | *d* |
|---|---|---|---|---|
| 4 cm | 2.5 mm | 3 mm | 6 mm | 2 mm |

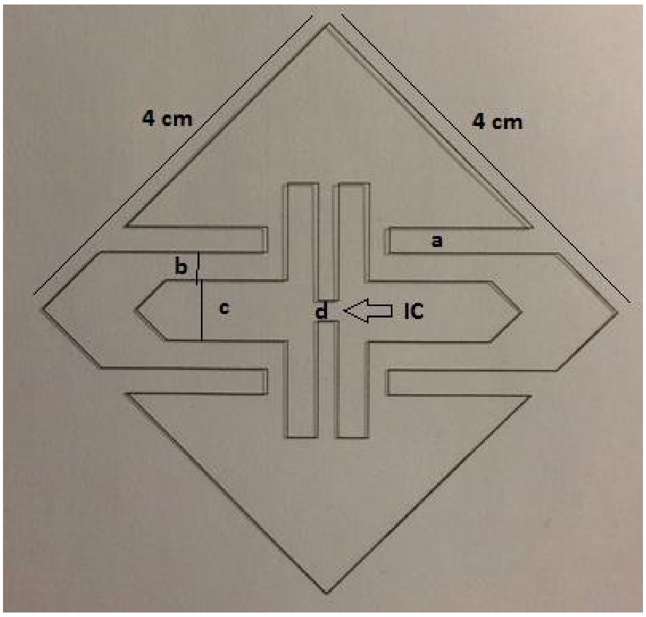


***Figure 16.*** *Square Slotted Antenna*

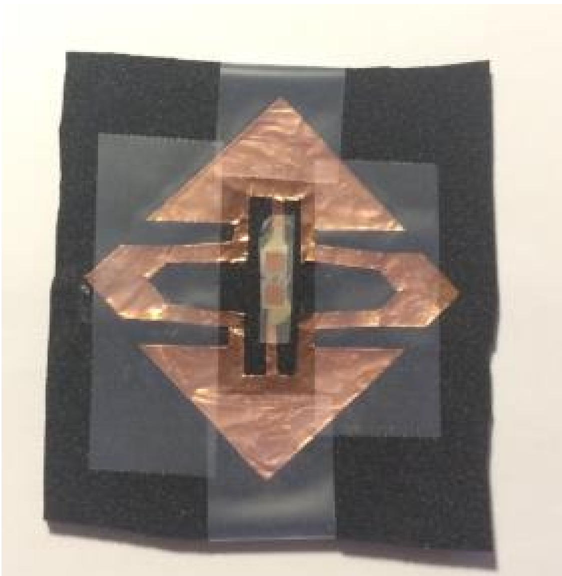

***Figure 17.*** *Square slot antenna (Lab Prototype)*

# 4. FREE SPACE MEASUREMENTS

In this chapter, it will be shown how the free space measurement were carried out in the lab. This chapter is divided in to two sections. First section will cover up the equipment needed for test and last chapter will show the results. For the free space measurement, we need few setup and devices they are given below:

i) Anechoic chamber
ii) Voyantic Tagformance hardware and software

Basic description of above mentioned points is given below.

i) Anechoic chamber is essential for testing the RFID antennas. Generally anechoic chamber absorbs all the electromagnetic waves. They are specially designed for these purposes. These rooms usually consist of small pyramids like rubberized insulating foam. Generally longer pyramids are used for low frequency waves whereas shorter for high frequency waves. Given below of the picture of the small anechoic room for testing designed RFID tag antennas. This room is specially designed by voyantic RFID company for testing different parameters.


*Figure 18.* *Anechoic Chamber*

ii) Voyantic Tagformance hardware and software

The anechoic chamber also equipped with voyantic Tagformance hardware (reader antenna) and software. Voyantic software has so many different parameters for testing e.g. transmitted power (dBm), backscattered power (dBm), theoretical read range forward (m/ft) e.t.c. This thesis paper is based on theoretical read range forward (m/ft) results. In this anechoic chamber measurement results were kept inside 800Mhz to 1000Mhz because UHF RFID tags in this range. Here is the picture of these devices.

***Figure 19.*** *Voyantic Tagformance RFID measurement device*

## 4.1 Calibration

The important properties of a passive UHF RFID tags are the threshold power and theoretical read range. Frequency range was 800-1000MHz. So, threshold power is the minimum amount of output power of the reader for activating the tag. Theoretical read range states the maximum distance between the tag and reader antenna in free space keeping the environment ideal, that is, environment without reflections, diffractions and external disturbances; hence the term named as theoretical read range.

At first, power loss factor ($L_{iso}$) was measured. Power loss factor ($L_{iso}$) can be characterized the wireless measurement channel. It is calculated from the generator's output port to the input port of an equivalent polarization-matched isotropic antenna placed at a reference location.

Power loss factor $L_{iso}$ can be computed as

$$L_{iso} = \frac{\wedge}{P_{th*}} \qquad (13)$$

where $\wedge$ is the sensitivity of the reference tag at each frequency which is supplied by manufacturer. And $P_{th*}$ is the measured threshold power of the reference tag in polarization-matched configuration. Now power density at reference location with an arbitrary output power ($P_{tx}$) of the reader,

$$S_{inc} = \frac{4\pi\wedge}{\lambda^2 P_{th*}} P_{tx} \quad (14)$$

where λ is the wavelength of the transmitted frequency. Threshold power density corresponds to $P_{tx} = P_{th}$ . $P_{th}$ includes all the possible polarization mismatch power loss. In free space conditions, at the critical transmit-antenna-tag separation $d$=$d_{tag}$. Moreover wake-up power of the chip is equal to the power delivered to the tag. So, the threshold power density is equals to the incident power density.

$$\frac{EIRP}{4\pi {d_{tag}}^2} = \frac{4\pi\wedge}{\lambda^2 P_{th*}} P_{tx} = S_{inc,th} \quad (15)$$

where EIRP is regionally regulated equivalent isotropically radiated power. In Europe, EIRP = 3.28W. So, it can be written as,

$$d_{tag}\ (P_{th}, P_{th*}) = \sqrt{\frac{EIRP}{4\pi S_{inc,th}}} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\wedge}\frac{P_{th*}}{P_{th}}} \quad (16)$$

which is fully measurement based estimation of the read range of the theoretical tag[31]. The below section 4.1.1 is the more practical insights of the calibration.

### 4.1.1 Free Space Measurements Result

For calibration (stated in section 4.1.1), we need to warm up the setup and it usually takes around 20 minutes. Calibration was carried out with a calibration tag came from voyantic. The picture of calibration is showing below,

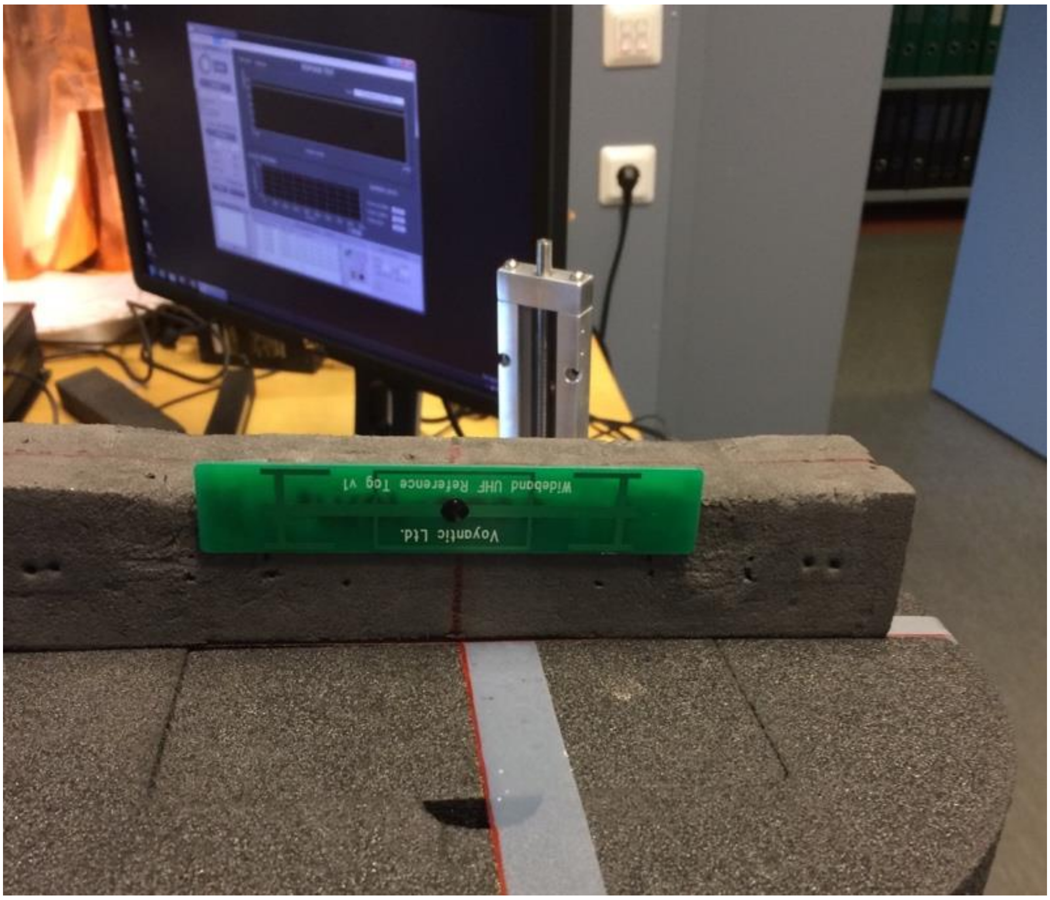


***Figure 20.*** *Voyantic Tagformance calibration tag*

### 4.1.2 Free Space Measurement of Dipole Tags

The dipole RFID designed in section 4.1, showing theoretical read range as liner line fluctuating between 800 to 1000MHz. It has shown that on average 5 meter read range will be achieved. Although dipole has some peak read range after 940 to 1000MHz but mostly UHF RFID tags works in 860 to 960 MHz.

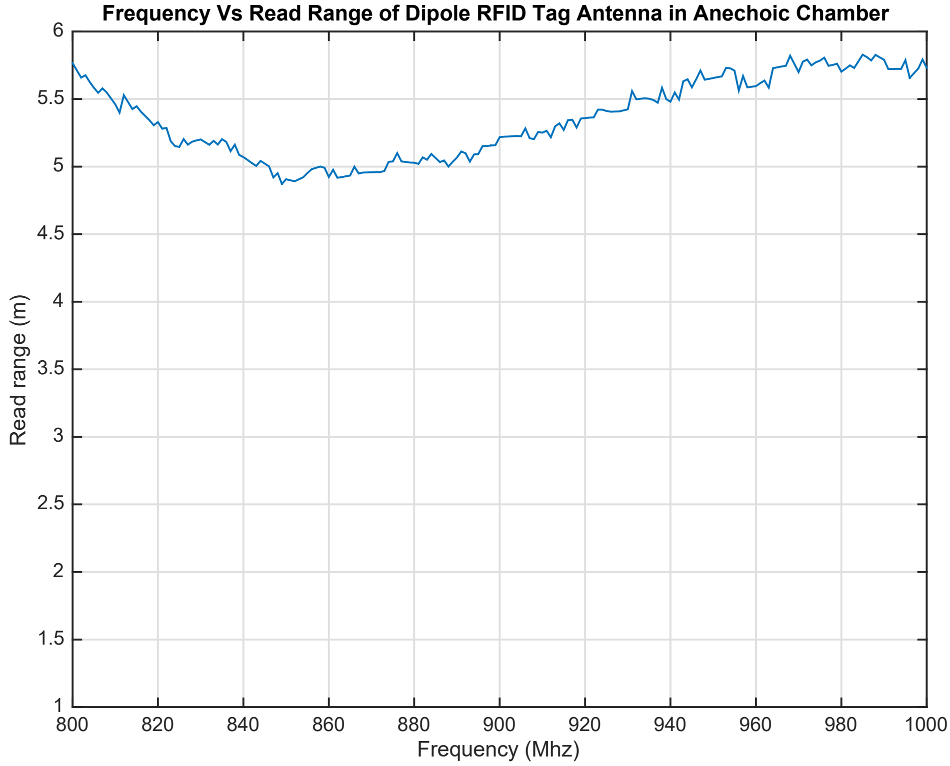


***Figure 21.*** *Dipole RFID Tag Antenna Theoretical Read Range in Anechoic chamber*

### 4.1.3 Free Space Measurements of Slotted Patch Tags

For the slotted patch antenna (section 4.2), provided results like this quadratic curves. It can be seen that maximum read range is 4.9 meter at 905 MHz. Although it has started responding from 855MHz and gradually increases its read range until 905Mhz and then drops back to 1 meter in 960MHz.

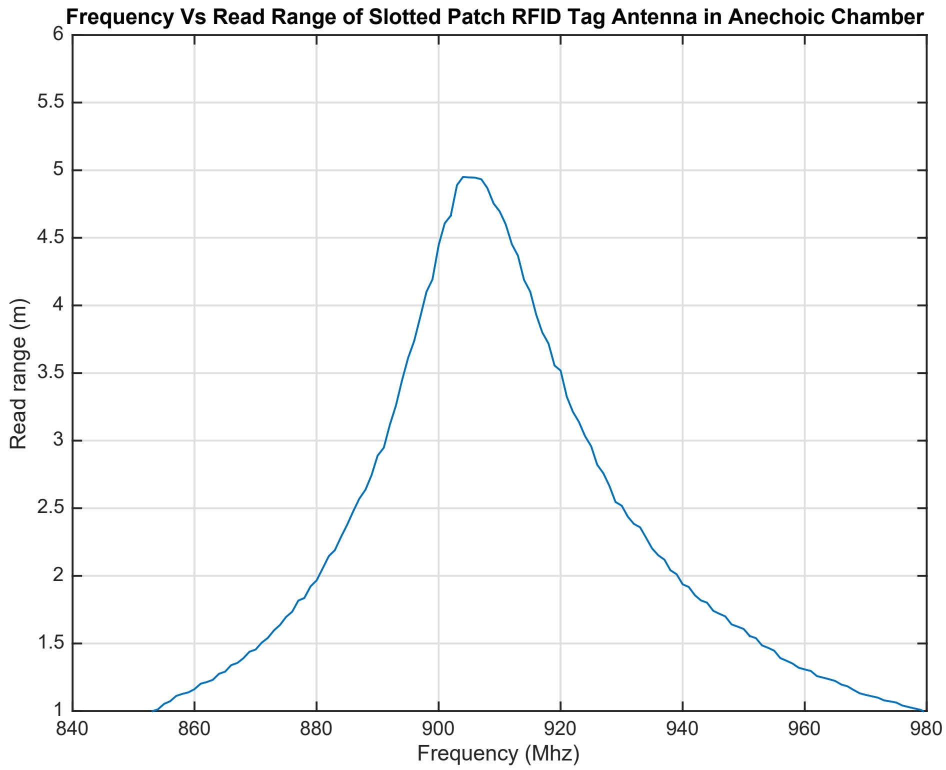


***Figure 22.*** *Slotted Patch RFID Tag Antenna Theoretical Read Range in Anechoic chamber*

### 4.1.4 Free Space Measurements of Square Slot Tags

The response achieved from anechoic chamber for square slot RFID antenna is shown below. It was most difficult to manufacture because of geometrical shape. It has shown that its read range is increasing with frequency increases. On average the read range is around 2.5 meter.

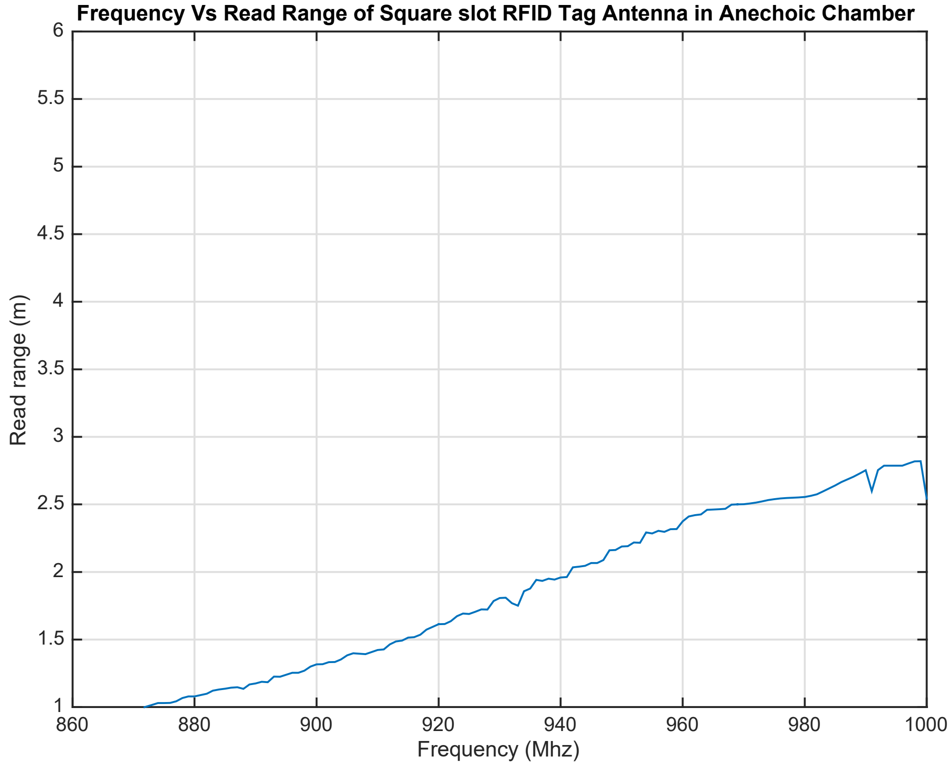


***Figure 23.*** *Square slot RFID Tag Antenna Theoretical Read Range in Anechoic chamber*

# 5. BODY-WORN PERFORMANCE ANALYSIS

In this chapter, the real case scenarios of body worn configuration will be studied. At first, human body properties will be reviewed and then eventually how tag antenna performs on body worn configuration will be discussed.

## 5.1 The Human Body from the Electromagnetic Context

Human body is a complex heterogeneous object. The two thirds of the human body contain water. As the water molecules are polar in nature so the dielectric constant of water is high enough. Antenna properties has changed when water molecules become polarized due to the presence of the external electric field. It has known as dielectric loading. Ohmic losses are present when impurities are present in the water. Another RF losses due to the friction between molecules when they work at a gigahertz frequency. Impure water molecules absorb power and as a result antenna efficiency decreases.

The characterization of the human body can be done in two points. They are i) dielectric constant, ii) loss tangent, these properties are frequency dependent and varies with different tissue. Different types of tissues are compared below.

***Table 5.*** *Comparison of different types of tissues [13]*

| | | |
|---|---|---|
| Fat tissues | Low water substance | Low dielectric constant and less losses |
| Bone | Low water substance | Low dielectric constant and less losses |
| Soft tissues | Muscles, internal organs and skin | High dielectric constant and high losses |
| Blood | Highest water substance | High dielectric constant and high losses |

The below *Table 6* will provide an example of dry skin dielectric properties and loss tangent. The data is taken from *Dielectric properties of body tissues,* a source that permits the computation of the different body tissues within 10Hz to 100Ghz range [30].

***Table 6.*** *Dielectric properties of dry skin*

| **Frequency (Hz)** | **Dielectric Permittivity, (F/m)** | **Loss Tangent** |
|---|---|---|
| 1.00E+08 | 7.29E+01 | 1.21E+00 |
| 1.59E+08 | 6.03E+01 | 1.04E+00 |
| 2.51E+08 | 5.21E+01 | 8.44E-01 |
| 3.98E+08 | 4.68E+01 | 6.63E-01 |
| 6.31E+08 | 4.33E+01 | 5.11E-01 |
| 1.00E+09 | 4.09E+01 | 3.95E-01 |

## 5.2 Measurements set up for on-body testing

The whole body-worn measurements were carried out in the anechoic chamber located in *TUT Sähkötalo* building. At first the reader transceiver antenna was calibrated with the reference tag. The distance between reader and tag antenna were around 92cm.

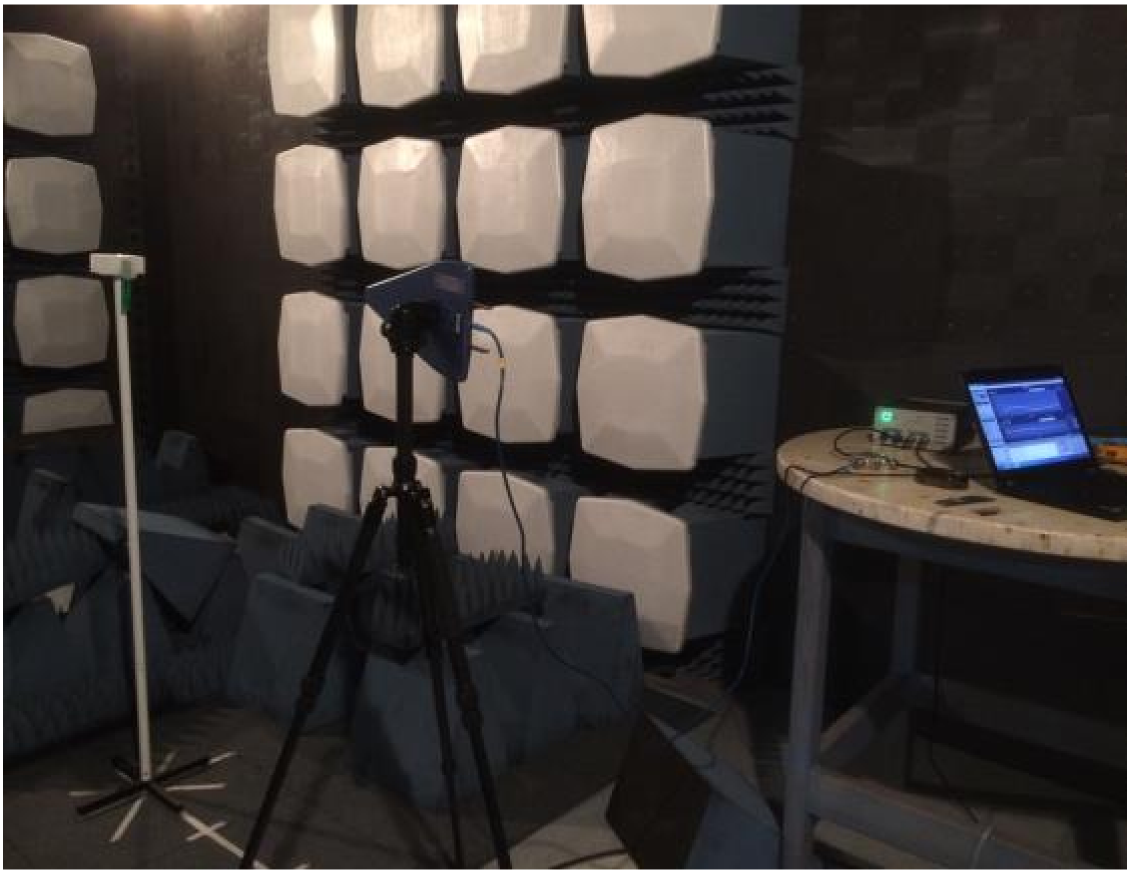

***Figure 24.*** *Anechoic chamber measurements set up*

Measurement was carried out in two ways, they are horizontal polarization and vertical polarization. In each polarization three different analysis parameter were taken into consideration. They are i) line of sight (LOS) measurements ii) 45-degree right shift measurements and iii) 45-degree left shift measurements. The LOS condition is straight forward such as measure the human body containing tags and in the line of sight with the reader antenna. The other two were somewhat tricky. Different angle was drawn on the floor and we advised test subjects (human) to stand on particular angle in order to get 45-degree right or left shift.

In *Figure 25* shows the way tag attached to the human body. Normal scotch tape was used to attach tag with the human body. All the participants were advised to wear t-shirt in order to maintain same scenarios for all test case.

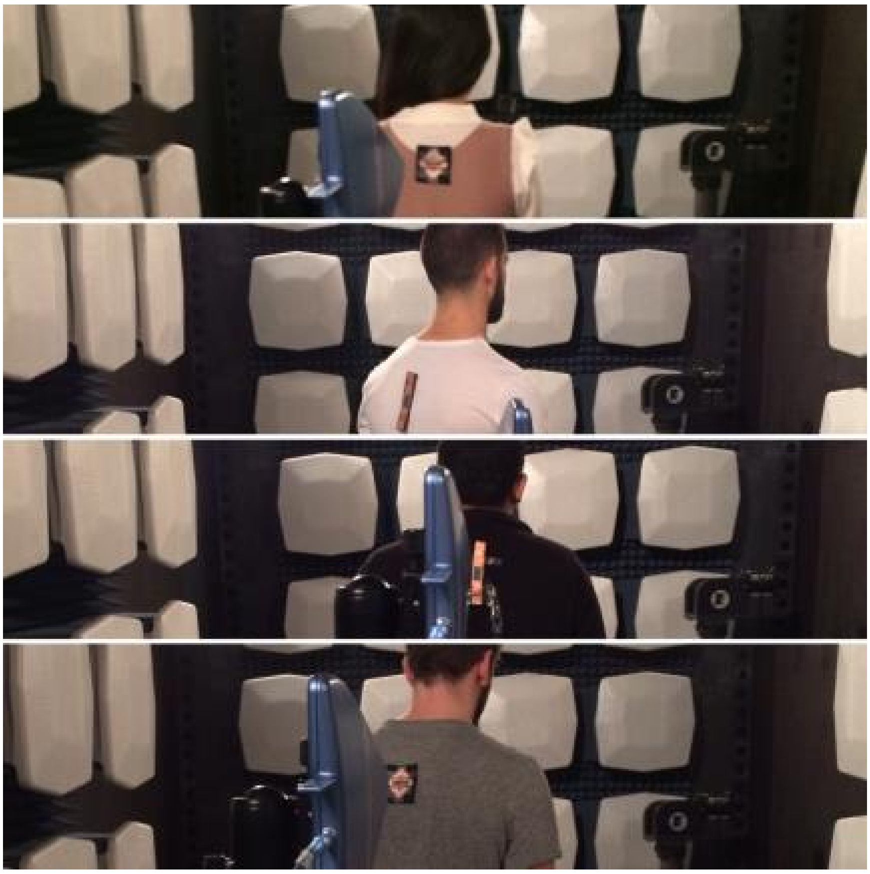

*Figure 25.* Tag attached to the human body

## 5.3 On-Body Measurements of Dipole Tag

The on-body measurements of dipole antenna are divided in two steps as mentioned 6.2. At first the horizontal polarization will be analysed followed by a vertical polarization scenarios.

**Horizontal Polarization**

### 5.3.1 Line of Sight Condition

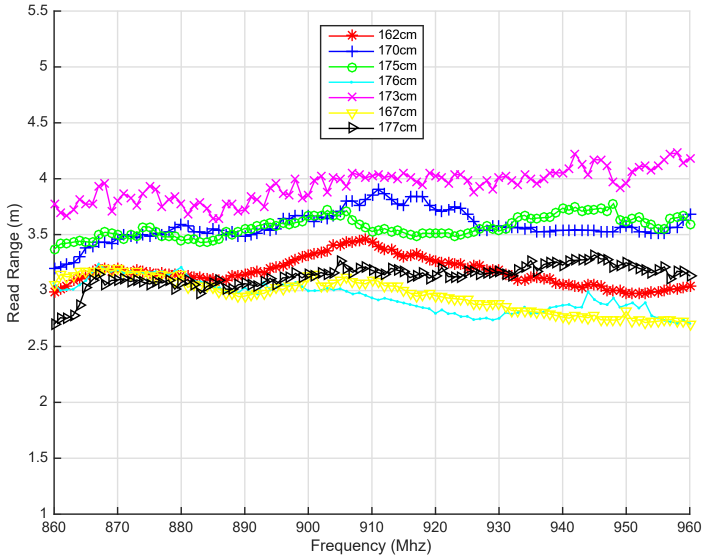


***Figure 26.*** *Frequency vs read range for horizontally polarized dipole RFID antenna*

The highest read range here is 4m for person who is 173cm tall and lowest read range is around 3m for 176cm. The average read range is 3.5m for different person-to-person.

### 5.3.2 45 Degree Right Shift Condition

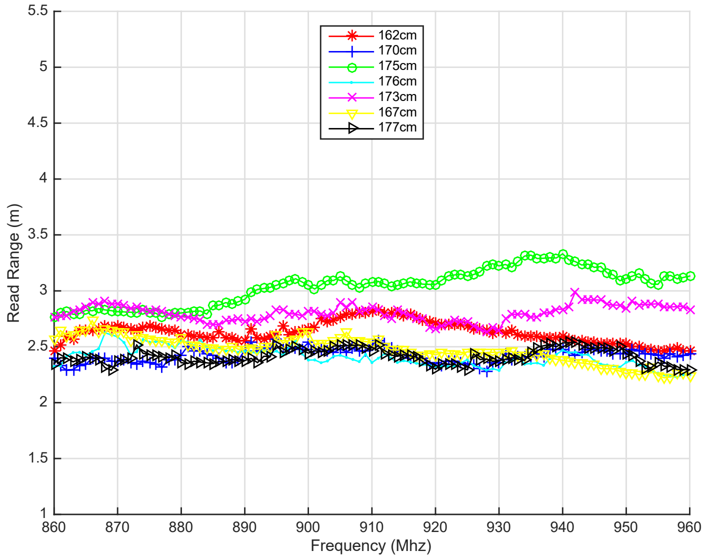


***Figure 27.*** *Frequency vs read range for horizontally polarized dipole RFID antenna in 45-degree right shift*

In this case the read range is decreased due to the change in the angle. The maximum read range in this case is 3m and lowest read range is around 2.3m for three different persons.

### 5.3.3 45-Degree Left Shift Condition

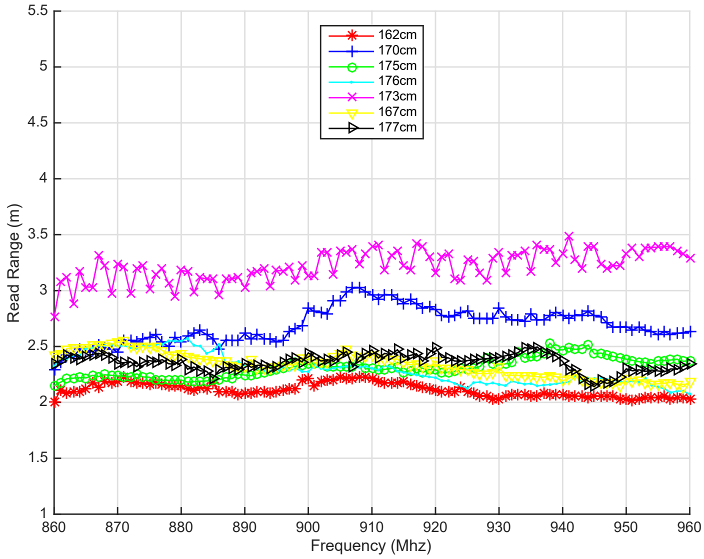


***Figure 28.*** *Frequency vs read range for horizontally polarized dipole RFID antenna in 45-degree left shift*

Here, the read ranges are bit decreased further due to left shift condition of the tag antenna. Such as the highest read range is 3m and lowest read range is 2.1m. The average read range is varied from 2.3m to 2.5m for different people.

**<u>Vertical Polarization</u>**

### 5.3.4 Line of Sight Condition

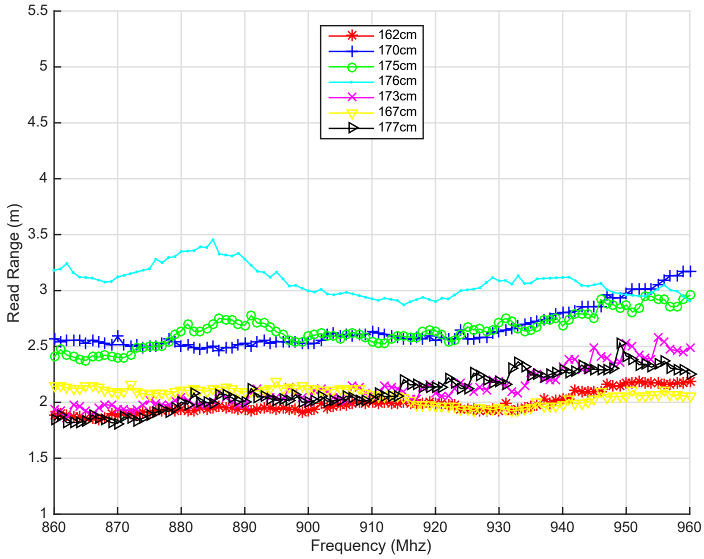


*Figure 29. Frequency vs read range for vertically polarized dipole RFID antenna in LOS condition*

The range varies with the polarization. Here in vertical polarization the highest read range is 3m and lowest read range is around 2m for. The average red range is 2m for different people.

### 5.3.5 45 Degree Right Shift Condition

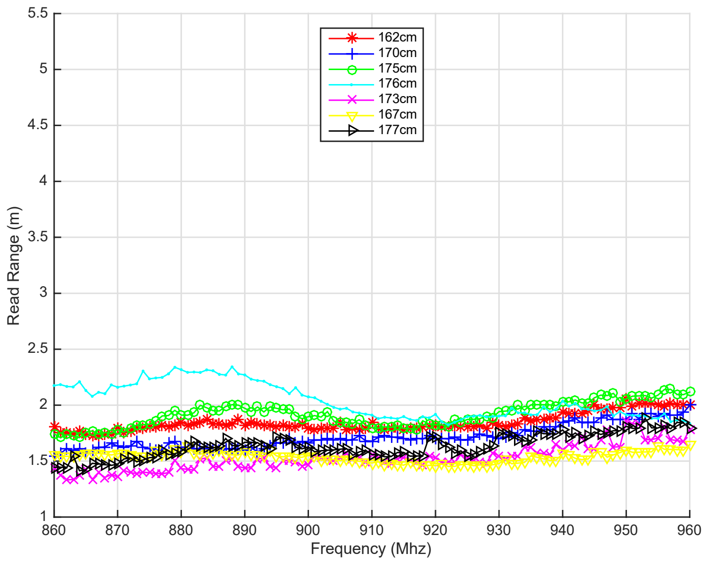


*Figure 30. Frequency vs read range for vertically polarized dipole RFID antenna in 45-degree right shift condition*

The read range drastically reduced in right shift condition. In this case a person moves 45-degree right with respect to the reader transceiver antenna and thus highest read range is 1.8m and lowest read range is 1.3m. The average read range is around 1.5m in other cases.

### 5.3.6 45 Degree Left Shift Condition

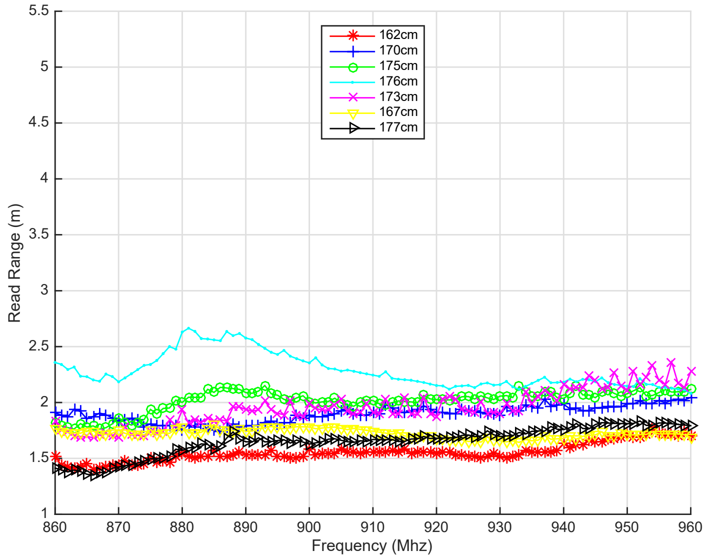


***Figure 31.*** *Frequency vs read range for vertically polarized dipole RFID antenna in 45-degree left shift condition*

Here the scenarios are somewhat same with 45-degree right shift condition. Highest read range is 2m and lowest read range achieved is around 1.5m. In addition, the average read range is 1.7m in different people.

## 5.4 On Body Measurements of Slotted Patch Tag

The slotted patch antenna seen to be more stable in read range. The slotted patch RFID antenna is divided in horizontal and vertical polarization for analysis.

<u>**Horizontal Polarization**</u>

### 5.4.1 Line of Sight Condition

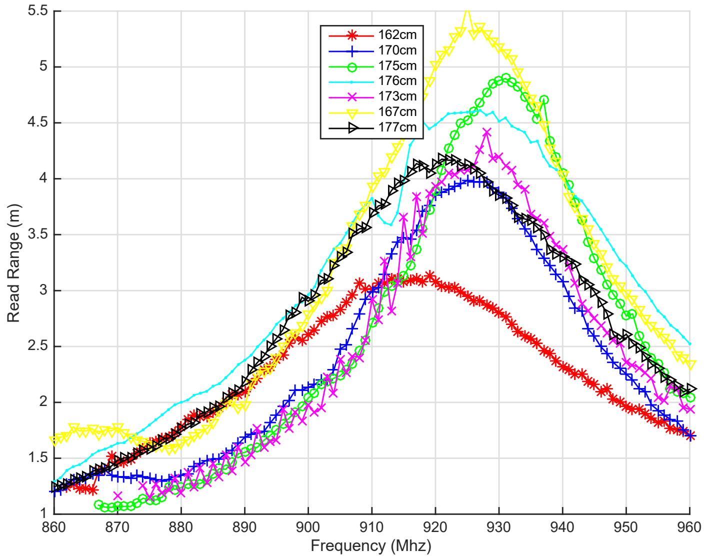


***Figure 32.*** *Frequency vs read range for horizontally polarized slotted patch RFID antenna in line of sight (LOS) condition*

Slotted patch RFID antenna reported the stable and reliable antenna among the tested RFID antenna used in this thesis paper. The maximum read range achieved here is 5.4m and in the other hand the minimum read range is 3m. The average of all the read range reading is about 4m.

### 5.4.2 45 Degree Right Shift Condition

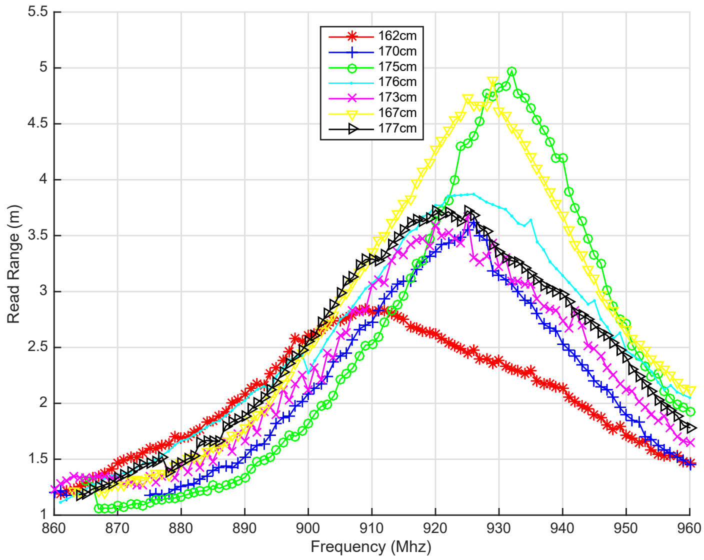


*Figure 33.* *Frequency vs read range for horizontally polarized slotted patch RFID antenna in 45-degree right shift condition*

The average read range for 45-degree right is around 3.5m in different cases. The maximum read range is 4.8m. Also, the minimum read range is around 2.8m.

### 5.4.3 45 Degree Left Shift Condition

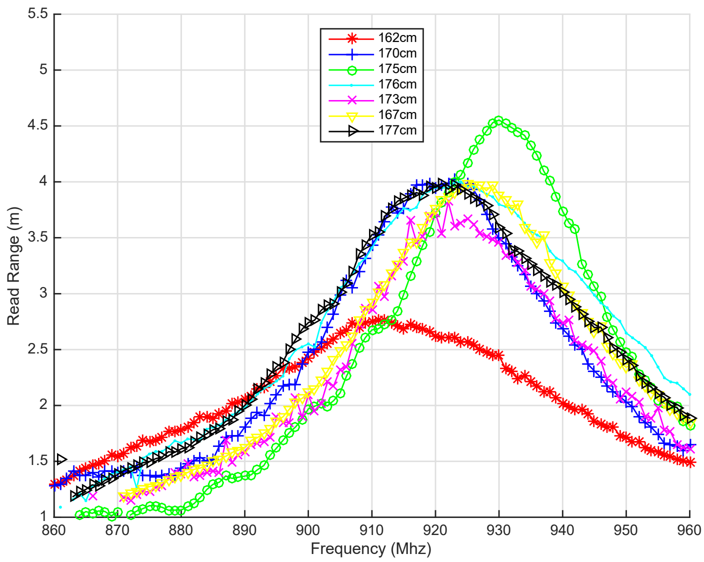


*Figure 34.* *Frequency vs read range for horizontally polarized slotted patch RFID antenna in 45-degree left shift condition*

In 45-degree left shift condition the scenarios is quite same. The maximum read range here is 4.5m and minimum is 2.8m. The average read range is 3.5m for all the cases.

**Vertical Polarization**

### 5.4.4 45 Line of Sight Right Shift Condition

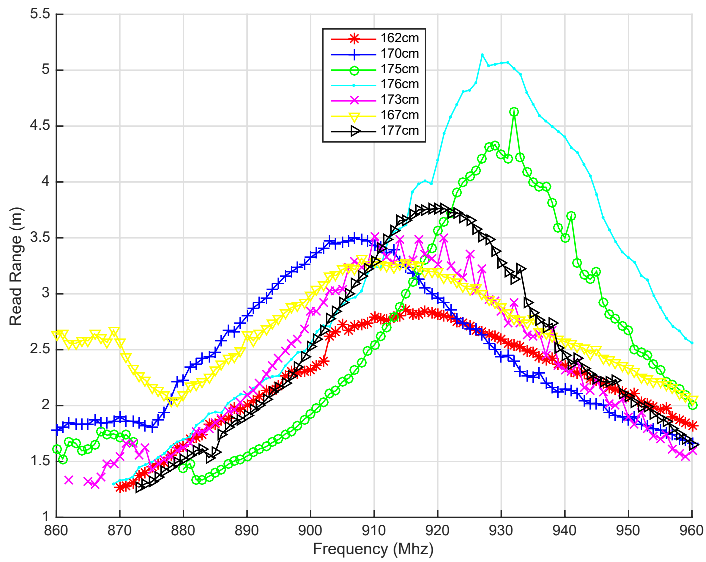


***Figure 35.*** *Frequency vs read range for vertically polarized slotted patch RFID antenna in line of sight (LOS) condition*

In vertical polarization, the maximum read range is 5m and another peak read range is 4.6m. The minimum read range is 2.8m. The average read range in this case is 3.2m.

### 5.4.5 45 Degree Right Shift Condition

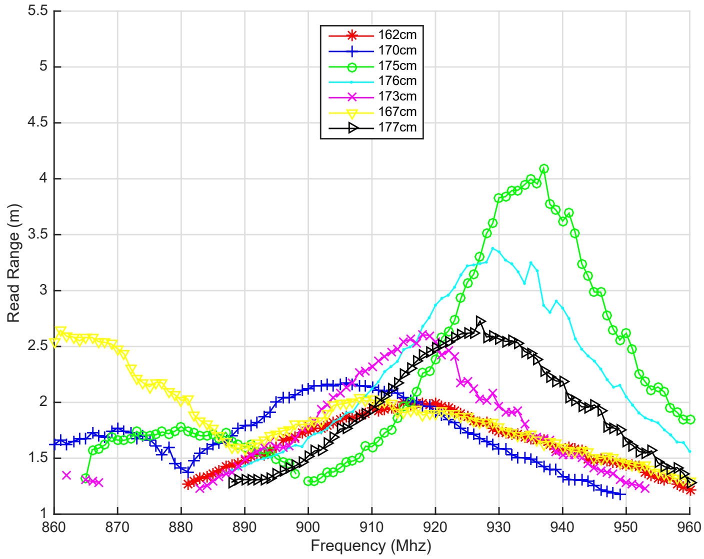


***Figure 36.*** *Frequency vs read range for vertically polarized slotted patch RFID antenna in 45-degree right shift condition*

The achieved result was further decreased to lower read range values in shifted condition. In this case the maximum read range is 3.75m and minimum read range is around 2m for. The average read range is limited to 2m in all the cases.

### 5.4.6 45 Degree Left Shift Condition

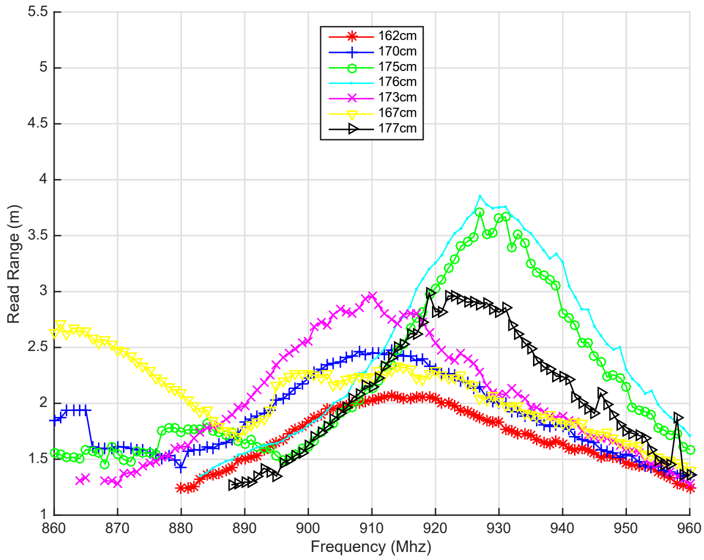


***Figure 37.*** *Frequency vs read range for vertically polarized slotted patch RFID antenna in 45-degree left shift condition*

The maximum read range in this case is 3.75m and minimum read range is 2m. The average read range is around 2.5m in all the samples.

## 5.5 On Body Measurements of Square Slot Tag

The on-body measurements for square slot RFID antenna was very challenging due to its symmetric shape and orientation to the EM waves. It was more time consuming in order to see the responses and very weak responses were reported in several cases. In this thesis book the average result will be shown for square slot RFID tag antenna due its non-stable and non-reliable response.

### 5.5.1 Line of Sight (LOS) Condition

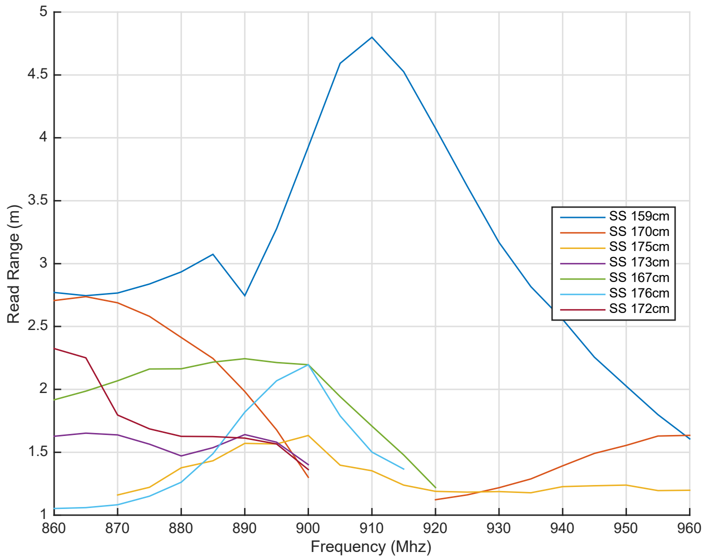


***Figure 38.*** *Frequency vs read range for vertically polarized square slot RFID antenna in line of sight condition (LOS) condition*

Square slot RFID antenna is much unpredictable in terms of responses in body-worn configuration. For instance, from the above figure responses from different peoples were discontinued after 900MHz but in other cases there were some responses. Also, it should be noted that the responses were not reliable as in person-to-person responses showing different characteristics. The response in free space and body-worn configuration is totally different (see chapter 4). The maximum read range in this case is around 4.5m and minimum read range is around 1.3m. The average results were not achieved due to random nature of the responses.

### 5.5.2 45 Degree Right Shift Condition

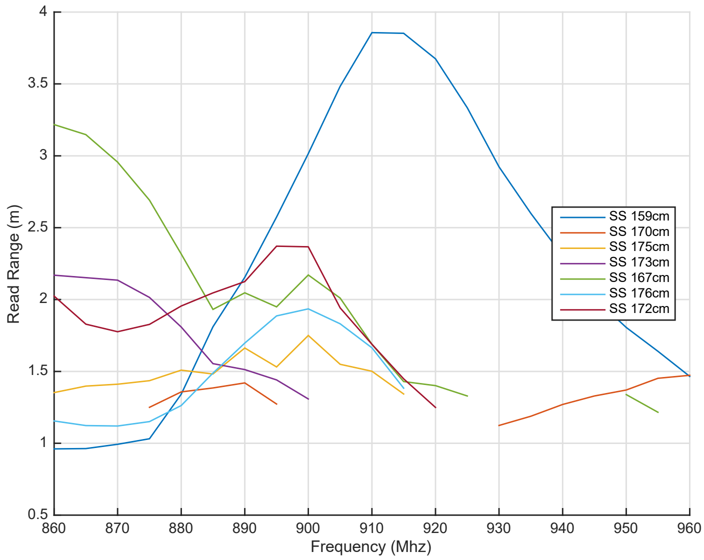


***Figure 39.*** *Frequency vs read range for vertically polarized square slot RFID antenna in 45-degree right shift condition*

It is again seen that in different angle condition square slot RFID tag antenna is less reliable. Here in this scenario after 910MHz all most all of the samples lost their signals and hence discontinuity appears. The maximum read range is 3.75m and rest of other samples were discontinued.

### 5.5.3 45 Degree Left Shift Condition

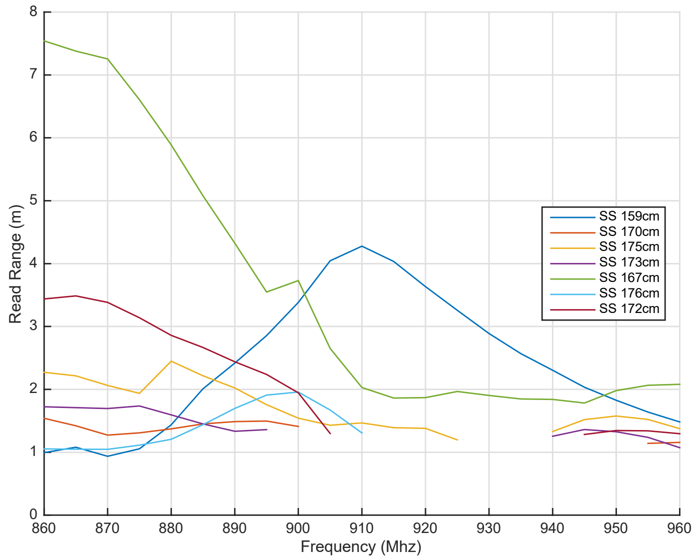


***Figure 40.*** *Frequency vs read range for vertically polarized square slot RFID antenna in 45 degree left shift condition*

Square slot RFID antenna have limitations after 900Mhz in body worn configuration. It is again lost its signal after 900MHz. The maximum read range is 4m. All the other samples have lost their continuity after 890MHz – 910MHz.

## 5.6 Comparison of the performance of different tags

It has been seen that read range are varies due to polarization and person-to-person variability. Dipole RFID antenna is symmetric in size so the emitted EM waves critically affected by person body. The dielectric constant and loss tangent of human body is one reason for variable read range. In most of the cases, the dipole antenna behaviour is stable and provides similar result for body worn configuration with respect to the free space measurements. The slotted patch RFID antenna is the most stable and performing one. It has provided maximum and minimum read range according to the expectation. Results were similar to the free space measurements. But in case of square slot RFID antenna it is very difficult to get the continuous results due to its fairly complex shape and orientation. When human body is in close proximity of the far –field of the antenna, it alters the field distribution and absorbs the power from field. The magnitude of the effects is less in person-to-person. But when antenna-body separation changes the magnitude of the effects also changes. The comparison of these three tags showing below in a table.

*Table 7. Comparison of the performance of different tags.*

| Context | Dipole | Slotted Patch | Square Slot |
|---|---|---|---|
| Size | Symmetric | Asymmetric | Symmetric |
| Ground Plane | No ground plane | Ground Plane | No Ground plane |
| Multipath effects | Multipath (Reflection, scattering and diffraction) effect | Multipath effect | Severe multipath effect observed |
| Orientation | Symmetrical | Not symmetrical | Symmetrical |
| Read Range (Free-space) | 5m | 5m | 2m |
| Read Range (Body-worn) | 3.5m to 4m | 3.75m to 4m | 1.5m to 2m |

# 6. CONCLUSION

In this thesis paper, the three different types of wearable RFID antennas and their behaviour on the human bodies were studied. This thesis has also set out to investigate the vertical and horizontal polarization of wearable RFID tag antenna in body-worn configuration at 860-960MHz frequency range. The result was achieved after several successful body-worn configurations. Most challenging part of this thesis work was to fabricate the RFID tags in the lab with the proper size and shapes. It was given highest priority. Couple of redundant pieces were made of each RFID tag antenna for cross checking the uniform operations.

At first the tags were tested for theoretical read range inside an anechoic chamber. After successful collections of the theoretical read range, the tags were placed on human body (upper back) for further investigations. In body-worn configuration three different test conditions were selected and they are line of sight (LOS), 45 degrees right and 45 degree left shift. In every condition, the read range and human body effects on wearable RFID tags were investigated.

Different types of devices and software helped were used in this work. The whole work was executed inside an anechoic chamber with *Voyantic Tagformance* hardware and software. Number of samples or people were chosen randomly regardless the size, height and weight. Noticeable male and female were participated in the test. The solo objective was to study RFID tags behaviour on the human body and to study the core concept of wearable antenna and wearable antenna - human body interactions.

Inside the anechoic chamber and human body RFID tags testing we were very careful with the posture and movements of the peoples. All the test subjects were given a fixed point to stand and proper instructions were delivered for the smooth scientific procedure. But sometimes it was difficult to control the whole experiment setup due to hardware and software technical failure and people’s busy schedules. We were very careful about the homogenous experiment setup, although it was seen that all the test results were in close proximity of each other.

Post-processing of the results was simulated in the *MATLAB* for further analysis. At first the theoretical read range were analysed with *MATLAB* and then eventually we studied the test results obtained from the human body of different people.

It is noticeable that the performance of the slotted patch antenna in the body-worn configuration provided a better result compared with the dipole and square slot antenna.

The ground plane of the slotted patch antenna reduces the body effect on the antenna. Dipole is also a good example of the wearable RFID antenna for body-worn configuration due to its dipole nature. But it is seen that the range is quite smaller than the slotted patch antenna. Mostly because of the dipole antenna is symmetrical in both ends and no ground plane was designed. It is also seen that the performance of the square slotted antenna is very poor in the body-worn configuration. This is because of the human body effects is much more on this antenna. The square slot antenna is not strong enough to reduce these effects. Lastly, this thesis work was an eye opener for what limits the wearable- human body interactions. We have studied key limiting factors, challenges and possible solutions. At the beginning, RFID was emerging for business and manufacturing companies for private and governmental industries. But in this era of technological evolution, RFID is becoming an important solution for almost all the major industries in the world. Robusta and secure networks of RFID opens the door for RFID-enabled start-ups. Different smart technological solutions are offered by these new companies. 5g and future cellular network also going to use RFID based positioning and location solution. Indoor positioning is not anymore dream for the companies. Also, IoT or IoE internet of thigs and internet of everything is also researching on smart RFID based solutions. Possibly in the future studies we can develop novel RFID solution for human body and wear-able electronics. Also, nowadays wireless body centric communication achieved momentum due to its wide applicability in biomedical and electromagnetics in health technologies fields.

Finally, the biggest advantages of using RFID system is that it is inexpensive, maintenance free, portable, simple and flexible. Based on these benefits it is easily can assume that RFID technology is here to stay.

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