TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

ANITA VINCENT

PERFORMANCE ANALYSIS OF PASSIVE UHF RFID SENSOR TAGS ON VARIOUS MATERIALS

Master of Science thesis

Examiner: Prof. Leena Ukkonen
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ABSTRACT

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RFID (Radio Frequency Identification Technology), came into existence during the Second World War, when the military used this technology for IFF (Identification of Friend or Foe) purposes. In recent years RFID is used extensively. Wal-Mart the multinational retail enterprise have invested millions of dollars to replace their bar code system with RFID technology.

The main advantage of using an RFID system is that it is simple, inexpensive, maintenance free, flexible and portable. The entire system consists of a reader, tag, IC, antennas and a controller. There can be numerous readers present in a particular area, and these readers network via a controller.

However, it is vital to test the RFID system to ensure it performs optimally. The tags can be placed virtually on any material, but it is necessary to analyze how the tag will perform on the different materials under various environmental conditions. It should be possible for the tag to provide accurate results with changing environmental conditions, for instance, in the presence of moisture. Sensor tags provide a solution to this problem. Sensor tag is a type of RFID tag which can sense moisture, temperature or pressure levels and adjust the readings accordingly. Sensor code and RSSI code values are important factors determining the performance of the sensor tag.

This thesis mainly focuses on the analysis of the performance of a sensor tag known as sensor dogbone tag on different materials under different environmental conditions using a reader (NordicID), which is specifically used to read sensor tags. A comparative study is made on the above conditions to determine the most suited position for the tag to be placed, in order to obtain results. The tag is placed on reference materials at constant read range and measurements are taken using a NordicID reader under various instances like, sunny outdoors, presence of moisture, embedded inside materials, enclosed inside a cardboard box etc. This thesis also offers an introduction to the RFID technology, its components and the communication of the RFID network.

PREFACE

This master thesis, “Performance Analysis of Passive UHF RFID Sensor Tags on Various Materials” was done in partial fulfilment of the requirement for the Master of Science degree in Communication Systems and Networks major, in the Department of Electronics and Communication Engineering at the Tampere University of Technology. All research and investigations have been done under the supervision of Prof. Leena Ukkonen.

I would like to express my sincere gratitude to my thesis examiner and supervisor Prof. Leena Ukkonen for her immense guidance, influence and encouragement, which has helped increase my interest towards RFID technology. I am also very thankful to Jussi-Pekka Turunen and Muhammad Rizwan of the WISE team, for all the help and information provided to me during my thesis writing.

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Tampere, October 2015

Anita Vincent

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LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating Current
ADC	Analog to Digital Converter
AR	Axial Ratio
ASIC	Application Specified Integrated Circuit
ASK	Amplitude Shift Keying
CDMA	Code Division Multiple Access
CRC	Cyclic Redundancy Check
CW	Continuous Wave
EIRP	Effective Isotropic Radiated Power
EPC	Electronic Product Code
FDMA	Frequency Division Multiple Access
FDX	Full Duplex
FR4	Flame Retardant
GHz	Gigahertz
HDX	Half Duplex
HF	High Frequency
IC	Integrated Circuit
IFF	Identification Friend or Foe
ISM	Industrial Scientific and Medical
ITU	International Telecommunication Union
K	Kelvin
KHz	Kilohertz
LF	Low Frequency
LOS	Line Of Sight
LRC	Longitudinal Redundancy Check
MHz	Megahertz
NFC	Near Field Communication
PC	Personal Computer
PIE	Pulse Interval Encoding
POM	Polyoxymethylene
POM-C	Polyoxymethylene Copolymer
PR-ASK	Phase Reverse Amplitude Shift Keying
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl chloride
RF	Radio Frequency
RFID	Radio Frequency Identification
RO	Read Only
RSSI	Received Signal Strength Indication
RW	Read Write
SAW	Surface Acoustic Wave
SBR	Styrene Butadiene Rubber
SDMA	Space Division Multiple Access
SEQ	Sequential systems
SRD	Short Range Device
TDMA	Time Division Multiple Access
TE	Transverse Electric
TEM	Transverse Electro-Magnetic

TM	Transverse Mode
TUT	Tampere University of Technology
TX	Transmission
UHF	Ultra High Frequency
UPC	Universal Product Code
VT	Ventec USA
WORM	Write Once Read Many
XOR	Logical Exclusive OR
Γ	Transmission co-efficient
σ	Material Conductivity
θ	Beam width
α	Attenuation Constant
γ	Complex Propagation Constant
π	Pi
ε	Dielectric Constant
λ	Wavelength
Ω	Resistance (Ohm)
cm	centimeter
f	Frequency
c	Speed of light in vacuum
G	Gain
P	Power
Q	Electric Charge
R	Resistance
m	Meter
X	Reactance
Z	Impedance

1. INTRODUCTION

1.1 Overview

Radio Frequency Identification (RFID) came into existence in the 1930s, when the technology was first used in IFF by military aircrafts. Transponders installed in airplanes used this technique to help identify the plane in case of lack of visibility, due to fog, rain etc. This technology is also used widely to aid in the identification and tracking of countable articles like gadgets, consumer products, artifacts and various other objects. It is now embedded in the human body and animals for identification, tracking and monitoring purposes [1].

In recent years RFID is used tremendously in manufacturing, servicing, government, industrial and business environments as tags can be attached to virtually anything. Wal-Mart, the American multinational retail corporation has invested millions of dollars to replace the omnipresent bar code labels with RFID tags. These tags can store much more information than a simple bar code, and is also used to share information with an accuracy rate of up to 98%. This technique gained popularity because it facilitates retailers in tracking the buying patterns, demand rate, number of items, updating of items, production rate, manufacturing date, manufacturing place, expiry date, inventory situation, and distributor's information of products sold by them. Simplicity is another major aspect of RFID technique. Therefore RFID technology is considered to be one of the fastest growing sector in the radio technology besides mobile phones and cordless phones.[2]

Moreover tags makes tracking specific objects ergonomic for humans as it is not necessary to scan the tags manually, the reader can do the job using a technique similar to NFC. The products containing the RFID tags is passed through a portal containing a tag reader and all the information present in the tag is gathered and stored in a database for future reference. This is a very time saving process compared to the bar code system. The tag information can also be updated in the database if a particular product is either purchased or replenished. RFID systems are also used in toll booths where a car passing through the booth gets automatically registered and money is paid directly from the bank without manual intervention. These are just a few examples portraying the convenience of using RFID.[3][4]

Although RFID proves to be a very efficient system, the main reason of adopting this technique is that the components of RFID are cheap and simple to implement. The reduced price of electronics after the invention of transistors and chips makes installation of an RFID system quite easy. Moreover passive tags do not require a battery to operate. [4][5][1][3]

Nowadays, passive UHF RFID tags are installed with sensing function so that the tags can sense various environmental changes like, change in temperature, moisture level, pressure etc. Passive sensor tags have been embedded with various sensing prototypes for sensing changes in the surroundings. Temperature and pressure sensor tags are being implemented. Sensor dogbone tag which comprises of RFMicron's Magnus S sensor, is a sensor tag which is specifically designed to detect moisture levels. The tag is passive and can tune itself in the presence of moisture. Furthermore, the sensor chip installed in sensor dogbone tag can operate at temperatures from -40 °C to +85 °C. [6]

1.2 Objective of the Thesis

Since RFID technique is gaining importance in many fields, the tags must be tested for flexibility and accuracy for every given situation. Heat and other chemicals present in the environment are major factors affecting the accuracy of the data readings. Moreover extreme temperature, types of material the tag is embedded in, density of the environment, distance between the tag and reader are other aspects that are possible to disturb the readings.

It is vital to note that the performance of the tag varies according to the material it is placed in and also the environment. RFID tags must be able to sense moisture to a certain extent so that the moisture present in the environment does not tamper the readings. Moreover, sensor tags have the ability to sense moisture levels in the environment. Therefore, a sensor function is integrated into RFID tags to detect the level of moisture present.

In addition, HF tags can penetrate through water than UHF or microwave signals, therefore HF is considered a better choice for tagging in damp conditions. Sensor dogbone tag is one such tag which has the ability to sense moisture thus making the tag work efficiently in humid conditions. But it is also important to check its ability to perform in various other conditions like warm weather conditions, below zero temperatures, acidic environment, on different materials etc.

This thesis performs the measurement analysis of sensor dogbone tag on various environmental conditions for given reference materials and a comparative study is made, to estimate the degree of performance of the tag. The values are compared and a graph is produced for the same. It is noticed that the graph tallies with the analytical concept. Moreover, the optimum environmental condition can be determined for the tag to provide better performance results.

1.3 Structure of the Thesis

This thesis analyzes the performance of a sensor dogbone tag on materials the RFID technique is applied in. Furthermore, Chapter 1 introduces the RFID system and explains the importance of RFID and the reason for its growing popularity. Chapter 2 deals with the basics of RFID, the components that comprise an RFID system and the communication between each component. It also provides details on what criteria the tags can be classified, the different modes of operation of the RFID system and the frequencies through which the whole structure communicates.

In addition, Chapter 3 enlightens the theoretical concepts of antenna, impedance and impedance matching are described and how the above factors influence an RFID system are studied. Chapter 4 explains the RFID reader and the tag used for the measurement analysis of this thesis. The reader is Nordic ID and the tag used is a sensor tag known as sensor dogbone tag. The concepts of sensor code and RSSI value is explained in this section, and also the materials used for the measurement analysis and its chemical properties which makes it unique is also described. Chapter 5 consists of the actual measurement analysis of the tag on different materials under various environmental conditions. A comparative study of the tag's performance is illustrated with the help of a graph. Finally, Chapter 6 concludes the thesis and provides further measurement ideas that can be performed on the sensor dogbone tag.

2. RFID THEORY

2.1 Basics of RFID

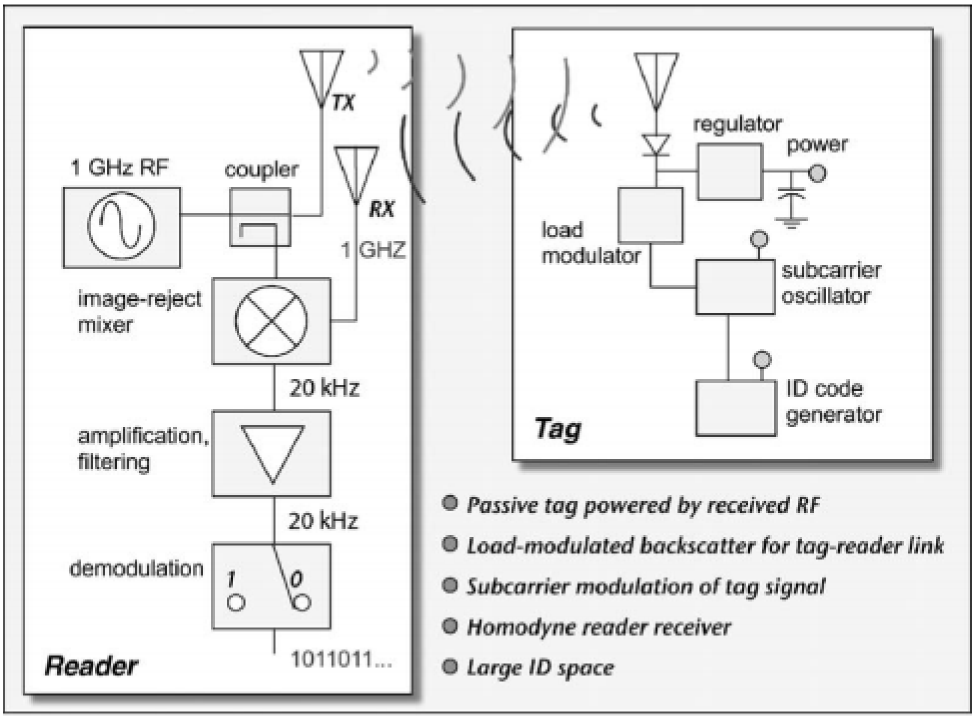

Figure 2.1: *Working Principle of UHF RFID System* [1]

The RFID system mainly comprises of a tag reader, tag, IC also known as silicon chip, controller and antennas. The antennas and the IC is embedded on the tag. Tags also referred to as 'smart labels' transmit and receive data, to and from the reader. The reader also known as the interrogator, can communicate with more than 1 tag at a single instance. Anti-collision algorithm is implemented in the reader so that the data present in one tag read by the reader does not interfere with the data of other tags. The reader gets information of the specific object from the tag placed on the object. There can be many readers present in a warehouse and they can all be connected to a single controller. The controller is considered to be brains of the RFID system. [1][6]

Moreover, the controller can be a PC or workstation which have the required applications running that connect the readers together to form a network. This network aids in communication. The readers and controller are connected together, they interrogate the tags to process information. In addition, the chip consists of a memory slot where all the data of the particular tag is stored. Batteries and transistors are not included in the chip, this makes the passive tag simple and maintenance free. Printing the antenna onto a plastic substrate and installing the IC is one of the common methods adopted to create the tags. Figure 2.2 shows a printer that is used for printing RFID tags that uses conductive ink like gold, silver, copper etc. [2]

Figure 2.2: *Zebra R110Xi4 RFID printer used for printing RFID tags* [7]

Reader reads the data from tags, processes it and sends it to the controller. The reader supplies power to the passive tag and also writes information into the tag. The tag and the reader communicate via radio waves. The digital transmission of data from tag to reader and vice versa is in binary fashion. The reader consists of the three components, antennas, an RF electronics module and controller electronics module. Unlike bar-code system, in RFID the reader does not require the tag to be in LOS with it to obtain the reading. RFID is not NFC, but both have a lot of similar characteristics. [8]

2.2 Classification of RFID Tags

Tags can be classified based on power source and memory type as follows:

2.2.1 Power Source

The power consumed by the tag is quite an important criteria. Tags are manufactured such that they can be either dependent, independent or partially dependent on in-built power. Tags can be classified according to power consumption as follows:

Active Tags - The Active tag facilitates information to be stored directly into the tag as they have an in-built power source, such as, a battery. Active tags are able connect with less powerful readers, they can also transmit data over longer distances. The memory capacity of these tags are up to 128Kbytes. [3] This way information can be obtained directly without the need of looking into a database. This form of tags is very useful during overseas shipments. Unfortunately, active tags are much expensive compared to passive tags and they also require maintenance as the batteries need to be replaced.

Passive Tags - Passive tags do not have a power source attached to it. They directly derive power from the reader. Therefore these tags are much cheaper and easier to maintain. The effective range of these tags are shorter compared to active tags.

Semi-passive Tags - These tags are also known as battery-assisted passive tags, since they have a battery installed, but do not use the available battery for signal transmission. They mainly use the battery for on-board electronics. An example of usage of semi-passive tag is, a food producing firm can use semi-passive tags equipped with temperature sensors to monitor the temperature of the food during transportation and storage. If the temperature rises above a threshold level then this occurrence must be marked in the database of the tag. Such tags require battery during the transportation and storage process [3].

2.2.2 Memory Types

Memory of the tag can be defined as the amount of data a particular tag can store without the aid of any external data-base. Tags can be classified according to memory type as follows:

Read-only - These tags can be programmed only once by the product manufacturer and the contents of the tag cannot be altered in any condition.

Read-write - Also known as smart tags can be flexible with data. The stored data can be modified according to the needs of the user. Large amounts of data can be stored and altered. RW tags are more expensive than RO tags.

Write Once Read Many - WORM tags are similar to RO tags, they are mainly used in assembly line to enter the manufacturing details like serial number of the tag, before shipment.

In addition to the above classification, tags come in various shapes and sizes according to the needs of the consumer and the environment the tag is to be placed in. Tags can also be manufactured using different materials using different printing techniques.[1][4][2]

2.3 Modes of Operation

RFID systems can operate in FDX or HDX, and SEQ modes. In full-duplex and half duplex systems, when the reader is in the RF field, its response is broadcasted to all tags present in the vicinity, since the tag's antenna is too weak to obtain the signal. The signal is transmitted via load modulation technique using a subcarrier. Load impedance transmits the information. This method is quite slow but easy to implement. Channels carrying information from the reader to tag are downlink or forward link and those carrying information from tag to reader are uplink which is also referred to as reverse link.

Whereas, in sequential procedure, the interrogator is periodically switched off for brief intervals. These gaps are recognized by the tags and they use it to transmit data. The FDX/HDX mode is much more efficient than SEQ as there is continuous power supply. [2]

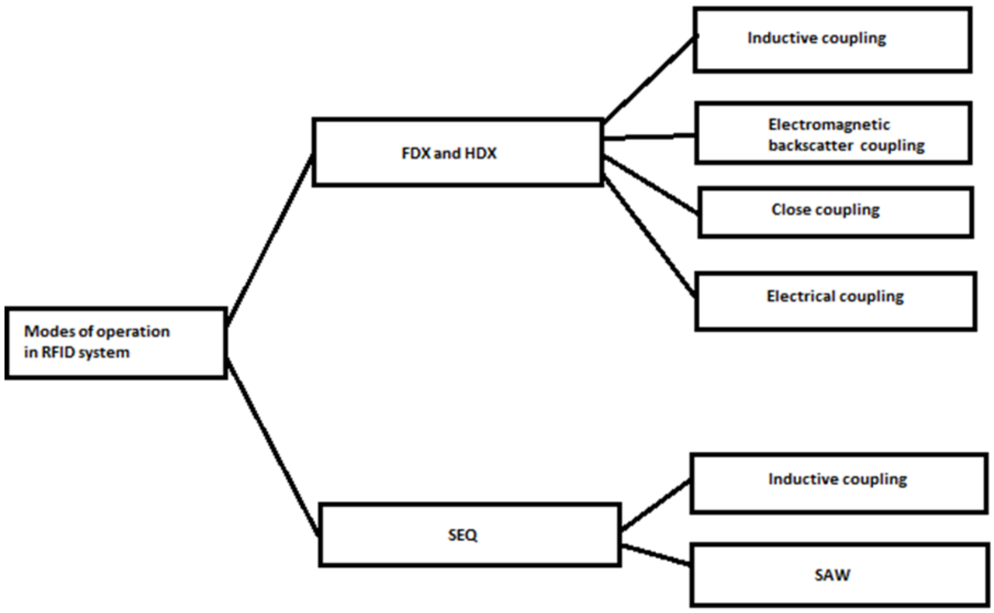

Figure 2.3: *Different operating principles in RFID system*

2.4 FDX/HDX Procedures

2.4.1 Inductive Coupling

Inductive coupling is the main method used to supply power for passive tags. This tag comprises of a microchip, coil, and a conductor loop which function as an antenna. Since inductively coupled tags are mostly operated passively, they have an antenna which generates a high frequency electromagnetic field. The reader's antenna functions in frequency band less than 135 KHz. As the frequency increases, the number of turns in the coil of the antenna reduces. Majority of the RFID tags operate according to inductive coupling principle.

2.4.2 Electromagnetic Backscatter Coupling

Long range systems have their readers and tags more than 1 m apart, therefore they operate in the UHF frequency range of 868 MHz. Moreover, the measurements analysis for this thesis work operates in the similar frequency range. For the tag to access the available energy, free space path loss is calculated:

$$a_F = -147.6 + 20\log(r) + 20\log(f) - 10\log(G_T) - 10\log(G_R) \qquad (2.1)$$

In the above equation GT and GR is the gain of the tag and reader respectively separated by a distance r and operating at frequency f, free space path loss obtains the relation between the RF power of the tag and reader. Substituting the values of distance r in the above given equation for a constant frequency band of 868MHz the free space path loss is obtained.

Distance *r*(m)	***a_F*** **(dB)** ***for*** **868 MHz**
0.3	18.6
1	29.0
3	38.6
10	49.0

Table 2.1: *Free space path loss for different distance r in dB* (modified from [2])

In order to retain the battery life, the chips installed in RFID system have ‘standby’ mode. If the reader moves away from the tag, the chip automatically turns to ‘standby’ mode. Communication between the reader and tag is solely based on the electromagnetic field emitted by the reader.

2.4.3 Close Coupling

In this system the reader and the tag are placed in ranges between 0.1 cm and 1 cm. This technique is similar to NFC. The tag is generally inserted into the reader, this way it is precisely positioned into the reader and facilitates reading in an efficient way. The voltage is proportional to the frequency the tag works in. High frequency must be selected for ideal working of the system and for losses to be low. Close coupling is perfect for high power consumption microprocessors.

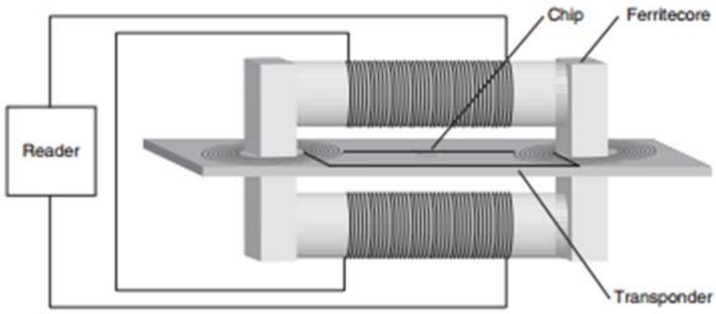

Figure 2.4: *Close coupling tag inserted into a reader with magnetic coupling coils* [2]

2.4.4 Electrical Coupling

In electrical coupling the system generates a high frequency electrical field. The antenna of the reader has a large conductive area like a metal foil or a metal plate. The system operates in a voltage range of a few hundred volts to a few thousand volts. The resonant frequency of the circuit corresponds to the transmission frequency of the reader. The current that flows between the electrodes of an electrically coupled system is very small. Electrical coupling is another source of power supply to passive transponders.[2]

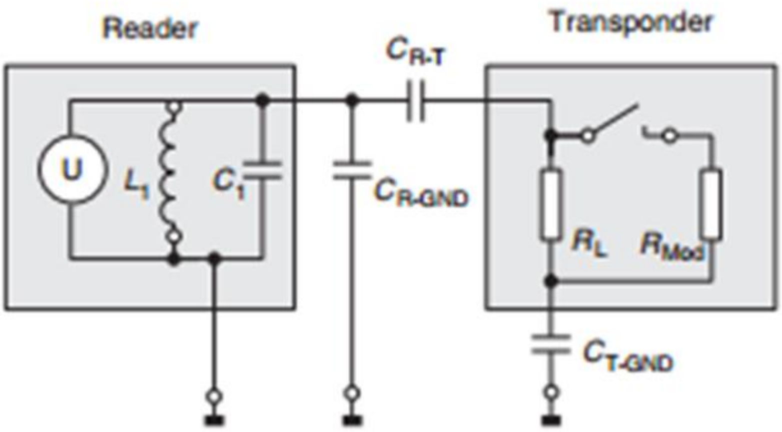

Figure 2.5: *Electrically coupled RFID system* [2]

2.5 Sequential Procedures

2.5.1 Inductive Coupling

SEQ mode of operation uses inductive coupling for frequencies below 135 KHz. Alternating field from the reader induces the voltage generated in the tag which can be used as a power supply. The tag goes into standby mode when not in use or when charging, this way almost all the received energy is used effectively. Minimum capacitance of the capacitor can be obtained from the equation below:

$$C = \frac{Q}{U} = \frac{It}{(V_{max} - V_{min})} \quad (2.2)$$

The parameters Vmax and Vmin are the voltage limit, I is the power consumption and t is the time required for the transmission of data.[6]

2.5.2 SAW Transponder

Surface Acoustic Wave devices are mainly based on an effect known as the piezoelectric effect. This effect is generated due to the dispersion on the surface of electric waves at low speed. SAW is operated usually on microwave frequencies of the range 2.4 GHz. A high frequency pulse is generated by the reader from the dipole antenna of the transponder into a transducer, and is converted into an acoustic wave. The frequency of surface acoustic wave corresponds to the carrier frequency of the sampling pulse. Part of the wave is distributed and the rest travel throughout and reach the end of the substrate and is absorbed. [2][4]

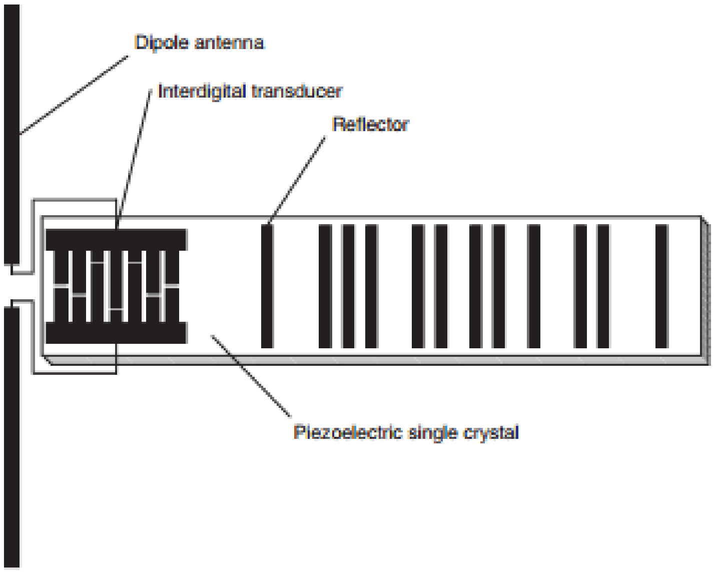

Figure 2.6: *SAW Tag. Interdigital transducers and reflectors on piezoelectric crystal* [2]

2.6 Frequency of Operation

2.6.1 Frequency Range used by RFID

A major factor contributing to communication of the reader and tags is the frequency. It is particularly essential to make sure the RFID frequency range do not interfere with the range of television, mobile phones or radio. ISM frequencies are reserved for devices using high frequency range. In addition, ISM frequencies are used for radio transmissions as long as the transmission is designed such that there is no interference. The two main ISM frequencies used by RFID system is 13.56 MHz and 2.45 GHz.

In fact, the RFID system uses different frequency bands for communication. The frequency can range from less than 100 KHz to 5 GHz. Frequency is a factor that avoids interference of signals from different tags. Each tag operates using a different frequency. Some of the frequency bands are 125/134 KHz (low frequency), 13.56 MHz (high frequency), 860-960 MHz (UHF), 2.4 GHz and above (microwave readers). The UHF range is mainly used for SRDs. Moreover the wave propagation of UHF frequency band is quasi-optical, where the diffraction becomes significant and huge obstacles cause reflection of the incident wave. [1][4]

The read range of a passive tag is 30cm or less in LF range [9], since the antenna gain is quite low. Antenna gain is directly proportional to the wavelength and wavelength is inversely proportional to the frequency band the tag operates in. The wavelength of an RFID tag ranges from 12cm to 2km. The mathematical relation of frequency and wavelength is as follows:

$$\lambda = \frac{c}{f} \tag{2.3}$$

Passive tags operate in LF, HF and UHF whereas active tags use UHF and microwaves. UHF and microwave have been assigned power limits due to health reasons, since high frequency radio waves can be hazardous to health. LF tags have low data rates. HF tags are gaining importance nowadays as it is smaller and less expensive to produce compared to LF tags. Data rates of the system increases with the frequency. However, size of the antenna should be increased in order to produce LF and HF signals compared to UHF waves and microwaves. In UHF RFID systems, the tag antenna is smaller than the wavelength and therefore, inductive coupling is adopted. At higher frequencies capacitive coupling is adopted. [1][2]

2.6.2 Preferred Frequencies for Different Applications

Frequencies less than 135 KHz is considered for much longer range compared to HF, and are low cost tags. In this frequency range high level of power supply is available for the tag and power consumption of the tag is also quite low. There is also high penetration rate. Whereas, 6.78 MHz frequency is the global ISM frequency according to ITU, and this range can be used for low cost and medium speed tags, the available power is slightly more than the NFC range, which is 13.56 MHz.

Similarly, 13.56 MHz is also a globally available ISM frequency which can be used for high speed and high end applications. It can also be used for medium speed, low end applications. This frequency is mostly used for fast transmissions and has a high clock frequency as the speed is directly proportional to the frequency used by the RFID system, but the frequency is inversely proportional to the distance of communication. The frequency 27.125 MHz is used only for special applications and is not a worldwide ISM frequency. It has really fast transmission rate because of the large bandwidth. The frequency 27.125 MHz is suitable for small ranges and has a high clock frequency facilitating cryptological functions. [2][4][9][5]

2.7 Data Authentication and Precision in RFID Communication

Data authentication, encryption and decryption is adopted by the reader for security reasons. It is necessary to take appropriate measures for the transmitted data to be accurate. Hence, the following methods are adopted for data precision:

2.7.1 Parity Checking

Parity checking is a simple and popular checksum procedure for checking transmission errors and initiating correcting methods. A parity bit is inserted into every byte so a byte has 9 bits instead of 8. Before sending the data, it must be checked whether the transmitted data has even parity or odd parity. Odd parity has odd number of the value 1 and even parity bit has even number of 1s. The parity is checked using the XOR operation.

2.7.2 LRC Technique

This process is quick and easy. The checksum is XOR is generated by gating the XOR recursively in a data byte. For instance byte 1 is XOR gated with byte 2 and the result is XOR gated with the next byte that is byte 3 and so on. The obtained result must always be zero, if not there is presence of error in the transmitted data. The algorithm used for this procedure is very simple and quick. Unfortunately, LRC technique is not very reliable as it results in quite a lot of errors and mismatching of obtained data.[9][8]

2.7.3 CRC Procedure

This is a highly reliable error detection mechanism. The CRC algorithm is quite complex, therefore checksums of large data quantities can be generated using this process. This method can detect burst errors. CRC is more powerful than parity checking and LRC in detecting errors. Unfortunately, this technique does not support error correction. The calculation of CRC is a cyclic procedure. The given string to be detected is divided by a divisor and if the resulting remainder is zero, then there is no error. Figure 2.7 shows the step by step procedure on how to calculate a CRC check sum:[4][2][10]

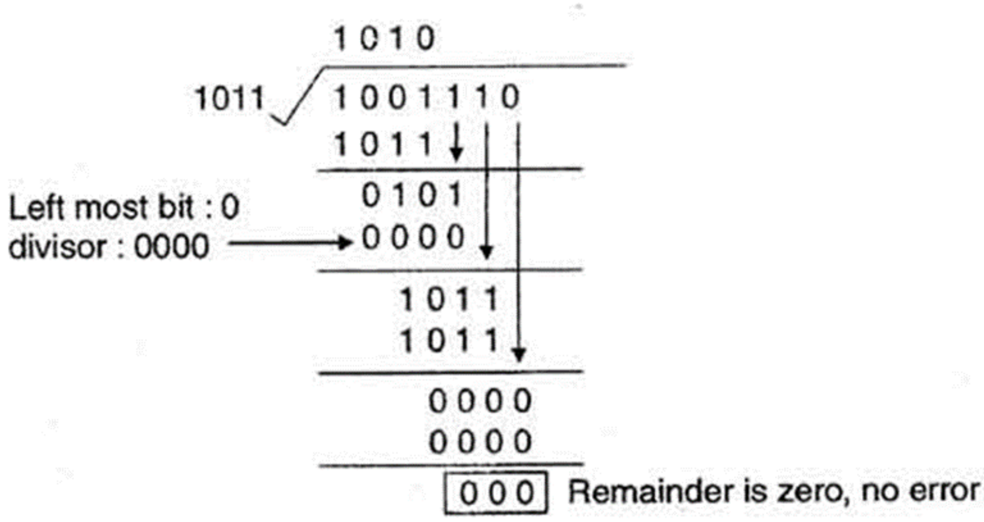

Figure 2.7: *Step by Step calculation of CRC checksum*[10]

3. RADIO ESSENTIALS OF RFID

3.1 Communication Theory

RFID operates in the magnetic and electromagnetic fields of the electromagnetic spectrum. Electromagnetic waves radiate charges. It is important for a radiating device to transmit charges that do not cancel out for a long distance. As mentioned earlier, inductive coupling can be adopted to avoid cancelling of charges.

3.1.1 Modulation

A CW does not carry any information, hence the signal must be modulated in order to carry information. Modulation is the process of introducing the baseband information and carrier frequency into the continuous signal. The carrier wave, an unmodulated electromagnetic wave alters the signal parameters. Moreover, modulation depends on three factors which are, power, frequency and phase position. If a wave is modulated it must be demodulated back to reconstruct the original signal in the baseband to recognize and rectify any transmission errors. Therefore, the normal configuration of an RFID system consists of a modem (modulator-demodulator). RFID technology uses digital modulation procedures like ASK, FSK and PSK. However, PIE is adopted in order to avoid power problems. [1][6]

3.1.2 Multiplexing

In order to read the signal from a particular tag without any interference from the other tags multiplexing technique is adopted. This process involves multiple signals propagating through a single medium. The anti-collision techniques are FDMA, TDMA, SDMA and CDMA also known as spread spectrum. FDMA is a commonly used multiplexing technique in RFID. TDMA is also used. For frequency multiplexing to take place the signal must be modulated.

FDMA - In this technique, an individual user is allocated a specific pair of frequencies, one for downlink and one for uplink. If the channel is not used it is considered idle, this way there is resource wastage. After the allocation of frequency the transmission of data from the tag to the reader is continuous and simultaneous. FDMA operates in narrow bandwidth generally. FDMA systems are less complex compared to TDMA systems.

TDMA - In FDMA the frequency band remains idle and thus results in resource wastage. To avoid this problem TDMA is used. In TDMA systems, the entire bandwidth is available to a single user for a fixed period of time. It is important to note that TDMA requires time synchronization in order to avoid collision. Since several tags use a single carrier frequency the allocation of time slots depends on available bandwidth. Data transmission in this multi access technique is not continuous which results in low power consumption as the power is switched off when channel is not in use.

SDMA - In SDMA the distance between the transmitter and receiver is the main factor that is taken into consideration. The same frequency is used in channels that are separated by some distance. This facilitates frequency re-use. This approach increases the capacity of the system due to frequency re-use.

CDMA - It is one of the spread spectrum techniques used in multiplexing. This technique is used to transmit narrowband signals without interference from the tags to reader and vice versa. In this method the entire channel is allocated to all the tags at all times. The tags are differentiated by a unique code. However, CDMA experiences near far problem. [11][12]

3.2 Basics of RFID Tag Antenna

An antenna is a device that radiates charges which travels long distances without getting cancelled. Antenna must also be able to send out a continuous wave. In order to make the wave continuous, the wave sent by the antenna must be a periodic function of time. Inductive coupling, radiative coupling or capacitive coupling can be used to avoid cancellation of charges. Tags use induced antenna coil voltage for operation. In RFID, at lower frequencies inductive antennas are opted, but for higher frequencies dipole antenna is used. [13]

Moreover, antenna gain, impedance, frequency and bandwidth have a deep impact on the design of the antenna. As mentioned earlier antenna gain is directly proportional to antenna size, but higher the antenna gain, more expensive the device. A simple dipole antenna consists of a copper wire of definite length. A half-wave dipole antenna contains the line copper wire of length $l = \lambda/2$. Moreover, a well-designed antenna system is required for the RFID system to communicate efficiently. [14]

In the RFID system, the reader antenna sends an RF signal to the tag and the tag antenna receives the signal which in turn powers up the IC component of the tag. In addition, the tag acknowledges the signal to the reader thus modulating the backscattered signal. For this purpose the impedance of the reader antenna and the tag antenna must be matched. If the antenna of the tag is matched with the operating frequency of the tag, then the signal can be radiated successfully. [14][15][13]

The read range of the tag antenna can be determined by the maximum distance in which the reader can detect the backscattered signal from the tag. Moreover, the reader is more sensitive than the tag itself. Read range which is the maximum distance the signal can travel, depends on factors such as, the material in which the tag is placed in, environment the tag is placed in, orientation of the tag, presence of moisture in the tag, temperature of the environment etc.[15]

3.2.1 Performance of Tag Antenna

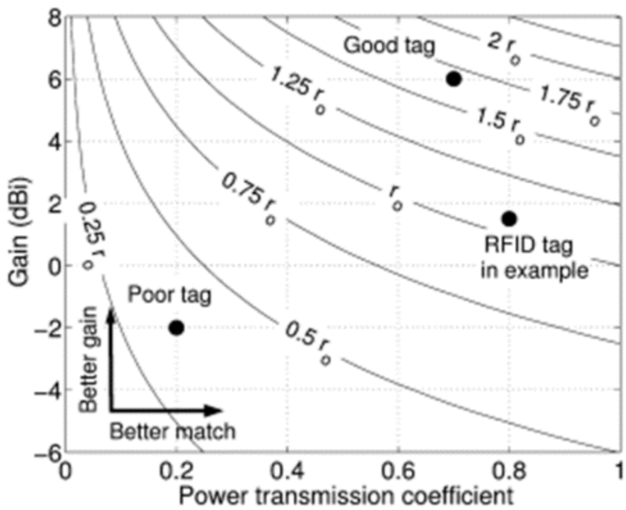

Figure 3.1: *Performance of the Tag Antenna [15]*

In Figure 3.1 the contours of constant range that is normalized is shown as gain-transmission co-efficient where the multiplier of the range (r_o) is given by:

$$r_o = \left(\lambda/_{4\pi}\right)\sqrt{P_t\,G_t/_{P_{th}}} \tag{3.1}$$

3.3 Antenna Design Parameters

The antenna of the tag is influenced by many factors:

3.3.1 Frequency Range

Different countries are allocated a particular frequency range to operate on. Depending on the regulations of the country, the frequency of operation of the tag will be determined.

Size of the Antenna - The type and make of object the tag should be placed also defines the antenna design. The tag can be designed to be attached to various materials such as books, bags, buildings, bottles etc. Therefore, the antenna design changes accordingly.

Read Range - The read range of the tag is further determined by factors such as, EIRP specific to the country, object the tag is placed in, orientation of the tag, coverage of the tag etc.

Type of Application - Depending on the whether the application is mobile or not, the design of the tag antenna can be modified. Moreover, in this type of design, the Doppler Shift should be taken into consideration due to the mobility of the tag.

Cost - It is one of the main factor that determines the design parameters. Even though tags are low cost devices, the antenna of the tag and the substrate the tag is made of affect the cost of the tag. As mentioned before, the conductive ink used for tag antenna design is copper, silver or aluminum.

Reliability - It is important to access the antenna based on the reliability of the tag, since it is placed in conditions which vary due to change in temperature, humidity, pressure etc. [1][2][4]

3.4 Antenna Design Process

Initially, the tag to be placed on the application is selected. The design parameters is checked and confirmed. The materials for the construction of the antenna is determined. The RF impedance of the packaged ASIC is evaluated. The type of antenna is identified (whether it is mobile or not). The parameters for the antenna is chosen too. Next step is the parametric study and optimization. If the parameters are met and optimized, the design requirements are satisfied, after which the design process can be carried out to construct the tag antenna. The entire process is illustrated by a flowchart given below:

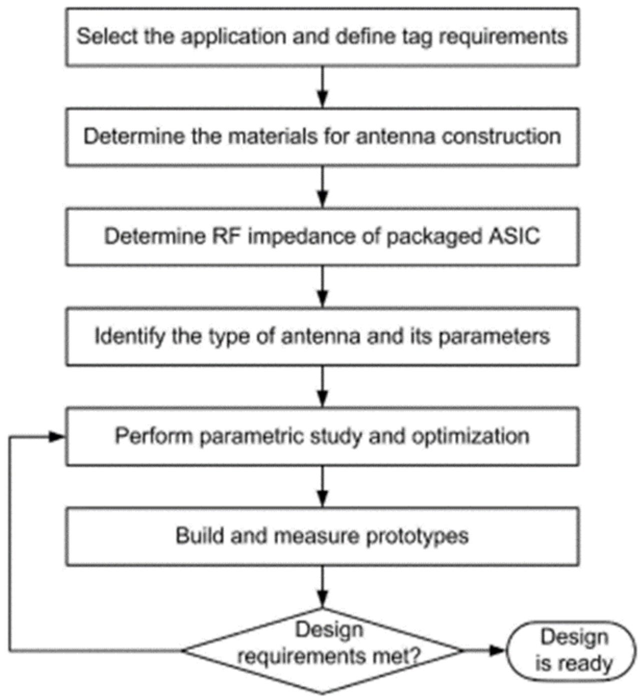

Figure 3.2: *RFID Tag Antenna Design Process* [14]

3.5 Cross Dipole Antenna

The reader (Nordic ID Medea) used for the measurement purpose of this thesis work consists of a cross dipole antenna. A cross dipole antenna is typically used for UHF band of wireless communication, such as satellite communication, WLAN, RFID etc. due to its low cost, easy fabrication and simple implementation property. In SAW devices high frequency waves are radiated by the dipole antenna. Moreover Nordic ID reader uses cross dipole antenna since this antenna offers the possibility of an enhanced impedance and AR bandwidth for achieving a circularly polarized wave. Also by choosing an optimum radius of the delay, the impedance can be improved even more.

RFID communication prefers the cross dipole antennas to have an omnidirectional antenna pattern. A dipole antenna functions by radiating signals from transmitter to receiver. The signal strength of this antenna is uniform at most of the points, but at some points the signal strength will be zero creating invisible spots called “nulls”. Null spots can occur even when the tag is placed in the vicinity of moisture and metals, or even if two tags are placed in close proximity of each other. Fortunately, this shortcoming can be overcome by implementing frequency hopping technique in the antenna. [16][4]

A cross dipole antenna is operated by a single coaxial cable and is compact. The first dipole arm pair is longer that the second pair of arms, so that an automatic phase shift of 45, 135, 225, 315 degrees is achieved without the aid of an external phase shifter. [17]

3.6 Impedance

Impedance is the measure of extent to which a particular circuit opposes the flow of electricity. It is a 2-Dimensional quantity comprising of two scalar quantities, resistance and reactance. Impedance is measured using a multimeter. Materials loose energy in the form of heat due to the presence of resistance that is offered by the material. This in turn reduces the flow of current in the circuit which is made using the material. Thus, lower the resistance, lower is the impedance. In AC the impedance of the material is influenced by inductance and capacitance, whereas in DC, the impedance is equal to resistance. Inductance and capacitance together is known as reactance. The reactance of a material depends on the frequency and components of the material. Reactance is present in AC but not in DC. [18]

Electric conductors like copper, gold, silver etc. have low impedance. Dielectrics have very high impedance. Dielectrics include glass, water, mica, polythene etc. Semiconductors like silicon, gallium etc. have intermediate levels of impedance.

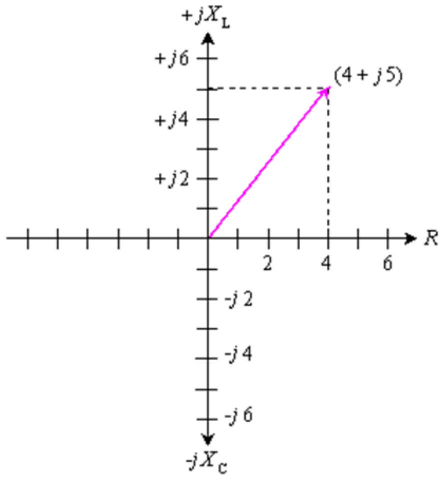

Figure 3.3: *Co-ordinate system Representing Impedance* [19]

Figure 3.3 illustrates a complex-number impedance. Horizontal axis is resistance, the left side of the horizontal axis is not numbered since negative resistance is not used in practice. Inductive reactance is denoted on the positive side of the y-axis. Capacitive reactance is represented on the negative side of y-axis. In the above graph 4 ohms of resistance and +j5 ohms of inductive capacitance gives a vector impedance marked as a linear curve. Both the reader and tag of the RFID system have complex input impedances. [18][19][20][21]

Impedance is extensively used for the analysis of AC circuits. Gradually it was applied to transmission lines which served for communication purposes. Moreover, it is an important link between electromagnetic theory and circuit theory. Impedance which is a crucial factor for RFID communication can be classified as:

3.6.1 Intrinsic Impedance

This particular impedance is mainly dependent on the material parameters of the medium. For plane waves, intrinsic impedance is equal to wave impedance. Intrinsic impedance (η) is related to material co-efficient as follows:

$$\eta = \sqrt{\frac{\mu}{\varepsilon}} \tag{3.2}$$

3.6.2 Wave Impedance

Wave impedance is the characteristic of a particular wave. It varies from wave to wave. TEM, TM and TE waves have the respective impedance, ZTEM, ZTM, ZTE. The impedance of the above mentioned waves depend on the wave guide, material and operating frequency. The wave impedance (ZW) is given as:

$$Z_W = \frac{1}{Y_W} = \frac{E_t}{H_t} \tag{3.3}$$

3.6.3 Characteristic Impedance

It is the ratio between voltage and current for a wave travelling on a particular transmission line. For TEM, the characteristic impedance is unique due to the fact that the voltage and current are uniquely defined for TEM waves. However, for TM and TE waves the impedance is not uniquely defined. The characteristic impedance is given as:

$$Z_o = \frac{1}{Y_o} = \frac{V^+}{I^+} \tag{3.4}$$

3.7 Impedance Matching

Impedance matching can be simply defined as the technique of making one impedance look like another. In the case of RFID system, it is essential to match the load impedance of reader to the impedance of the sensor tag. A trusted tool to measure impedance matching is the Smith chart, which is a graphical impedance chart. [20][22][23]

Impedance matching affects the power consumption, read range, frequency utilization etc. of the tags. The impedance can be affected by the frequency and power of the received signal. Read range, which is the maximum distance from which the tag can be detected, is an important characteristic that affects the RFID system. It is crucial to have a good read range for the impedance to match. Improvement in read range can help match the impedance better to obtain good power consumption. In order to design an antenna that could maximize the read range, Friis equation is adopted. [24]

$$r = \frac{\lambda}{4\pi}\sqrt{\left(\frac{P_t G_t\ (\theta,\phi)\ G_r(\theta',\phi')p\ \left|T_{tag}\right|^2}{P_{th}}\right)} \tag{3.5}$$

In the above given equation λ is the wavelength, Pt is the transmitted power (reader), Gr (θ, ϕ) is the gain of the transmitting antenna (reader) facing the tag. The product P_t G_t is the EIRP of the transmitter (reader). Gr (θ', ϕ') is the receiving antenna (tag) gain facing the reader antenna. P_{th} is the minimum power required to turn the chip on. Ttag is the power transmission coefficient of the receiver (tag), p is the polarization efficiency.[24]

The above equation shows that there are not many parameters to be changed to improve the performance of the system. As mentioned above the RFID tag consists of a dipole antenna printed onto a substrate, the gain of the antenna is estimated to be 2 dBi which is quite impossible to improve without compensating for the omni-directional property of the tag.

Consider the circuit of the RFID tag as shown below:

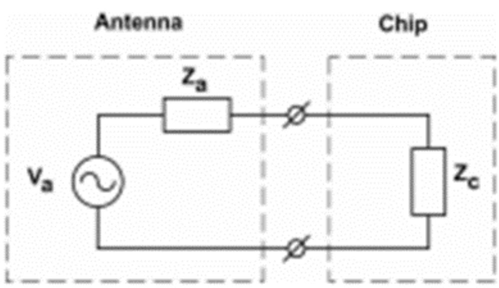

Figure 3.4: *Circuit equivalent to that of an RFID tag* [21]

The above given circuit represents an RFID tag in receiving mode where, Zc is the chip impedance and Za is the antenna impedance. Both Za and Zc are dependent on frequency. Moreover, the impedance of the reader and tag must be matched for the passive tag to receive minimum threshold power from the reader in order to respond to the reader. This threshold power is dependent on the transmission co-efficient. Therefore, the performance of the tag greatly depends on the transmission co-efficient Γ. The antenna matching and chip matching is vital for the implementation of a well-designed tag. The antenna and chip impedance can be normalized if both the impedances are matched. The reflection co-efficient is given as:

$$\Gamma_{tag} = \frac{Z_c - Z_a}{Z_c + Z_a} \tag{3.6}$$

However the calculated power reflection co-efficient curve is not quite accurate for proper designing of the antenna. Therefore, it is necessary to also take into consideration the impedance of the chip during the designing process which is in turn characterized by the transmission co-efficient. [21][23][13]

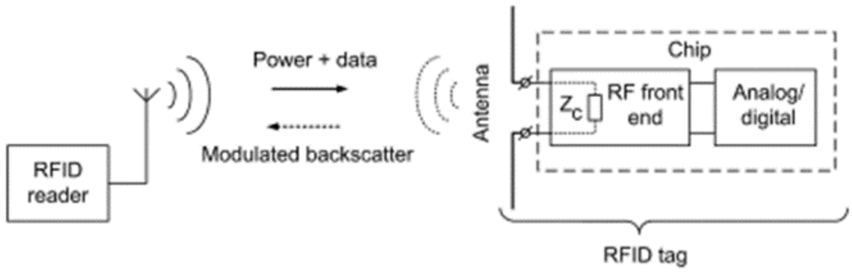

Figure 3.5: *Backscattered signal modulated by Chip Impedance (Z_c) change* [14]

4. RFID COMPONENTS USED FOR MEASUREMENTS

4.1 Sensor Tag

The wireless passive sensor tag is enabled by Chameleon Technology which is a trademark of RF Micron. The tag itself consists of an antenna and a Magnus-S die as shown below:

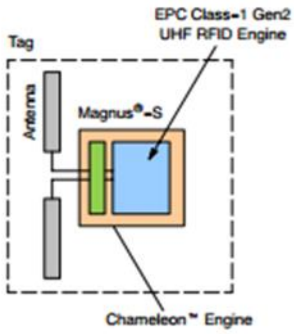

Figure 4.1: *Passive Sensor Tag consisting of Magnus-S die and Antenna* [25]

The die itself consists of tuning capacitors, antenna ports and EPC Class-1 Gen2 RFID engine. The engine dynamically adjusts to the input impedance by altering the capacitors. By doing so the power to the RFID engine is maximized. In the Magnus-S die the capacitors has 32 states and a 5-bit sensor code. If the antenna's impedance changes, the sensor code also changes respectively. The tag is designed to respond to change in the environment by changing its antenna readings and in turn the impedance.

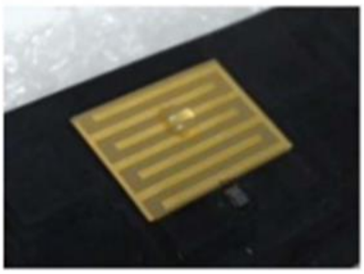

Figure 4.2: *A Water Drop on the Sensor Capacitor of Sensor Tag* [25]

Figure 4.2 shows a passive tag with a drop of water on its capacitor. This drop of water has an effect on the antenna as well as the impedance of the tag. The tag will adjust itself by changing the sensor code values to adopt to the changes in the environment.

Figure 4.3 depicts the difference in sensor code values due to the presence of a water droplet.

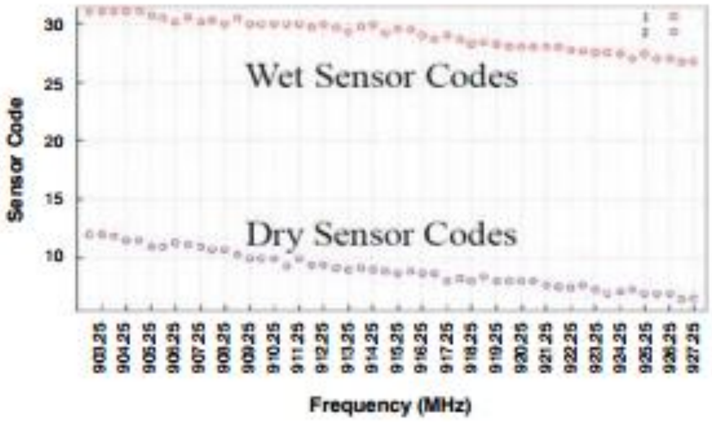

Figure 4.3: *Sensor Code Change Indicating the Presence of Moisture* [25]

Cost efficiency is one of the main reasons behind adopting the Magnus-S die. The sensor tag consists of a single IC on an antenna. No other components are required for the tag to function. Moreover, since the tag is passive, the need of batteries is omitted. The installation cost of these tags are negligible. The antenna of a sensor tag behaves like a resistor, inductor and a capacitor tuned circuit. Any of the mentioned factors or its combination, affect the antenna readings. The antenna must be designed in such a way the impedance level is sensitive to the environmental changes. Figure 4.3 above shows that the tag is wet due to the presence of water. The dielectric constant of water is very high, hence the capacitor experiences a large change in capacitance. The dipole antenna experiences a change in impedance, the Chameleon engine will convert the impedance into sensor code that way obtaining the amount of water present in the tag. [25]

4.1.1 Sensor Tag Properties

The inductance and capacitance of the tag are the main properties which can be altered using materials with different properties. Inductance and capacitance do not affect the read range of the RFID system. The Chameleon engine is an ADC. It converts impedance to a 5-bit number. Sensors with Chameleon engine have noise conversion approximated to white noise. Noise amplitude moves the sampled impedance by at least 1 code and the impedance value takes values between 2 codes. ADC in the device uses oversampling and averaging to increase the resolution in order to obtain more accurate results by increasing the number of bits in the resolution.

$$Z_{OS} = 4NZ_S \tag{4.1}$$

In the above given equation N is the number of bits of resolution, ZOS is the number of oversampled channels and ZS is the number of sampled channels before oversampling takes place. Usually ZS is considered to be 1. [25]

4.1.2 Sensor Tag Applications

The applications of sensor tags are unlimited. A sensor can detect change in capacitance, resistance or inductance devices placed in such situations can employ a sensor. Due to sampling at multiple frequencies the resolution can be as high as 7.8 bits.

Sensor tags can be placed to read measurements in moisture laden environments. For sensing, the wetness in a desired dry environment, detecting leaks, identifying water vapors etc. these tags are used. Sensor tags can also respond to gaseous circumstances to detect imbalance of gases in industries. The tags can also be embedded inside buildings to detect the change in moisture levels. The movement of buildings can be recognized by pressure sensitive sensor tags.

4.2 Sensor Code and RSSI value of Sensor Tags

The measurement analysis for the thesis uses sensor dogbone tag as the tag and NordicID Medea as the reader which comprises the main components of the RFID system. As mentioned above, impedance matching is an important aspect for obtaining the maximum amount of information from the tag, by the reader. Two important factors for impedance matching in dogbone tag is on chip RSSI and sensor code. Sensor code indicates the impedance of the RF input, and on chip RSSI measures the power received by the tag from the reader. The values of the above mentioned factors fluctuate accordingly to match the impedances. Tags placed on different materials have different sensor code and different RSSI values. [26][4]

RSSI value is not only used in measuring the power received by the tag from the reader, but it is also used to estimate the distance between the reader and tag. Higher the RSSI value closer is the tag to the reader, thus making it possible for a more accurate reading. Moreover, RSSI value is also used for identifying the direction of movement of the tag, that is whether tag is coming closer or moving farther away from the reader, but RSSI value does not estimate where the particular tag is headed. These values are used for analyzing the optimum conditions for the tag to work efficiently and also for locating the local host system.

RSSI value is affected by various factors like metals and reflecting elements the tag is placed on, other materials attached to the tag, objects that come in LOS of the tag and reader, moisture present in the tag, height difference of the reader and tag etc. [26]

4.3 Sensor Dogbone Tag

Sensor dogbone tag used for measurements in this thesis work, is a moisture sensing, self-tuning passive UHF sensor tag. Operating in the frequency range 860-960 MHz (UHF), it comprises of EPC Gen 2 standardization. (EPC is used to represent individual number associated with the RFID tag or chip. EPC was developed in 2000 at MIT's Auto-ID center. EPC is the modern day replacement for the UPC [6].) The dogbone tag is made with a Magnus S Sensor chip supplied by RFMicron which can operate in temperatures ranging from -40 °C to +85 °C and it consists of a sensor code and on-chip RSSI code. The sensor code is a 5-9 bit value and the RSSI code is a 5 bit value [27][25]. Larger the above mentioned values, higher is the power the tag is receiving and operating in. The sensor code fluctuates according to the changing RSSI values, that way the tag matches the impedance according to the changing conditions. An application is installed into the reader, which is supplied by RFMicron to read the dogbone tag. Sensitivity of the tag depends on the type of user the tag is designed for. Moreover, shorter the read range, more accurate will be the reading.

The sensor tag can be designed by the manufacturer according to the needs of the user. For example, in health care environment, customization of tags is quite essential. If the dogbone tag is placed in an environment, the reader can detect the presence or absence of moisture in that particular environment, due to the change in impedance value experienced by the antenna. These tags are also used for storing drug information in pharmaceutical companies where presence of moisture is unavoidable. [28]

Sensor dogbone tags are also a brilliant way to detect the amount of moisture present in soil, cement, glass, plastic, cardboard etc. Presently, these tags are also being modified to detect the presence of moisture and humidity in the surrounding environment.

Since the tag is passive and requires a reader to capture the readings, it is not possible to store data in tags. However it is possible for the reader to automatically forward the readings for different environments periodically to a cloud based server. Although the main advantage of a passive tag is that it can be embedded inside construction material, without the need to worry about replacing batteries. [29]

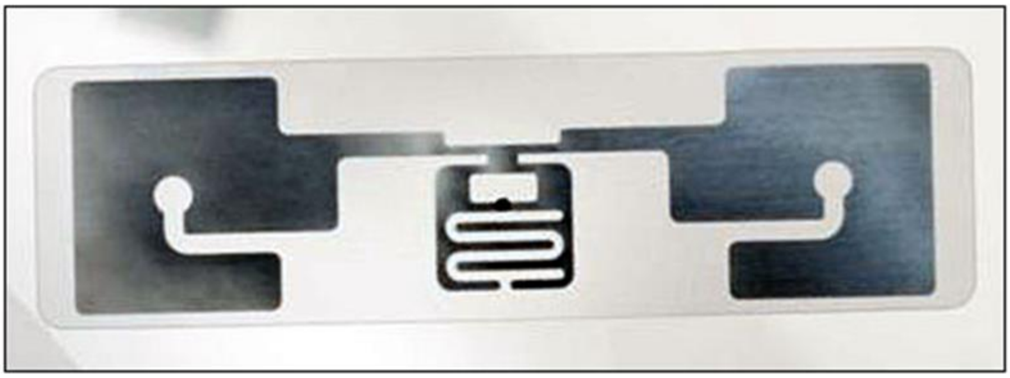

Figure 4.4: *Dogbone tag made with RFMicron's Magnus S Sensor* [29]

4.4 Nordic ID Tag Reader

Nordic ID is a hand held mobile tool for reading RFID tags. It has touch screen facility and a cross dipole antenna. RFMicron application is installed in the Nordic ID reader to read the tags and display the values of the fields. When the reader is in the vicinity of many tags, it displays details of all the tags present. This can be very misleading as reading required for the particular tag cannot be obtained, hence for that reason every tag has a unique tag model number, which makes it easier to obtain the desired details of the required tag. In a normal scenario, items with tags ranging up to 2000 or more will be placed next to each other or bundled on top of each other. The reader will have to read all the tags and provide the details of all the tags in a readable fashion. Therefore the reader has to consider all types of tag arrangement and provide accurate information.[27] [30]

4.4.1 Factors Affecting the Readings of the Nordic ID reader

Numerous factors affect the reading of the RFID tag by the Nordic ID reader. The efficiency of the reader is directly proportional to the transmission power. It is essential to have the power up to maximum since the tags are placed really close to each other, hence more the RF power, more response from the tags. TX modulation is another factor, the settings for this particular reader is ASK and PR-ASK .In ASK the wave's amplitude is altered, and in PR-ASK the phase of the wave with altered amplitude can shift suddenly. The main advantage of adopting PR-ASK to ASK is that the former is slightly easier to read. Unfortunately, not all tags support PR-ASK. [30]

Session is another affecting factor. Session is a tool for managing inventory of the reader easier to manage. There are 4 types of sessions specified in ISO 18000-6c RFID spec, session 0 to 3. The allocation of session to tags makes it much easier to read a lot of tags that are placed close to each other. When a tag is placed into inventory it is silent, thus making the reader to discover more tags in the vicinity. If the tag is inventoried then a session number is assigned to it. Session 0 does not stay inventoried at all, session 1 stays inventoried for 0.5-5 seconds. Session 2 stays inventoried for at least 2 seconds, session 3 also stays inventoried for at least 2 seconds. In the above situations the tag is out of RF field and not receiving power. When the tag is receiving power, session 0, 2 and 3 stays inventoried for indefinite time. Round value is another factor, it evaluates the number of inventory rounds done before the results are returned to the host application. When the round is set to 1, then the RFID module has only one inventory round.

Figure 4.5: *Nordic ID reader used for the measurement analysis* [29]

The Nordic ID reader should be configured so that it can read tags which are placed really closed to each other or placed on top each other in a disorganized way. The evaluation can be based on speed and accuracy. The two factors influence each other, if the speed is high, then the accuracy is compromised and vice versa. Distance is also influential. Shorter the distance, better is the speed and/or accuracy. A good scanning pattern can read up to 90% of the tags in 50% of the given time. When the number of tags to be read exceeds a particular limit, that scanning becomes impossible before session 2 or 3, then the tag reverts back to its original position, thus altering the results. It is recommended to partition the tags in 30 second batches so that it is possible to read all the tags taking into account the session. [30][31]

Figure 4.6: *Nordic ID mobile reader used to read RFID tags in a textile factory* [29]

5. MEASUREMENT ANALYSIS

5.1 On-Chip RSSI and Sensor code

Measurements analysis have been taken when the tag is placed in the following environmental circumstances, LOS of reader, sunny outdoors, in the presence of moisture, inside a cardboard box, sandwiched between two slabs of the same material and acidic conditions. The sensor code and RSSI code values for the given reference materials under the above conditions is measured and noted, the different values are analyzed and a final graph is produced to compare the performance of the tag in various situations. All measurements on the above materials were conducted in Tampere University of Technology (TUT) and the frequency used for the measurement purpose is 865-868 MHz which is the UHF band.

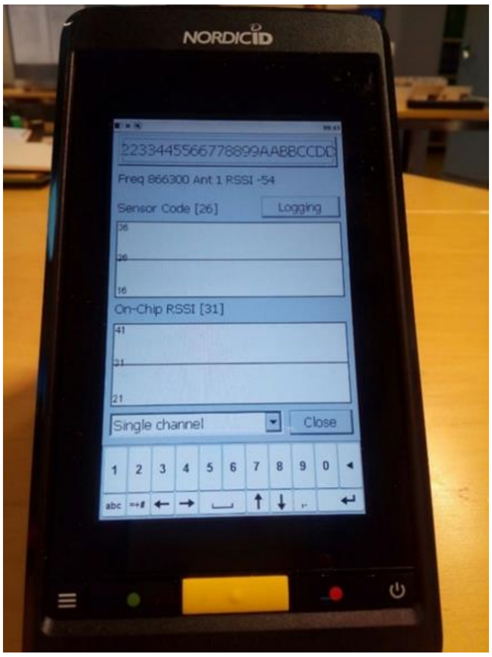

Figure 5.1: *Nordic ID Reader depicting the Sensor Code and RSSI Code*

Figure 5.1 clearly shows the sensor code and RSSI code graph. This measurement is obtained after the tag was placed in LOS with NordicID reader antenna. NordicID readers are exclusively designed to read sensor tags. It is touch screen based, and has a software produced by RF Micron. The installed software helps identify the sensor tags and aids to take readings. The reader can even be connected with the PC via the port provided in the reader.

In Figure 5.1 given above, the tag is placed 10 cm away from the reader on a material substrate. After the tag is placed on the material slab, the reader is not disturbed. The measurements are obtained when the reader antenna is kept still. This particular graph has both the sensor code and the on-chip RSSI value constant. The sensor code value shows 26 and the RSSI value remains a constant 31 without any fluctuations. The value 2233445566778899AABBCCDD on the topmost section of the reader is the unique number given to the sensor dogbone tag which helps differentiate it from the other tags. The frequency band used for the measurement is shown on the top left corner of the reader which is 866300 KHz. The antenna chosen for this measurement is antenna 1, antenna 0 is also selected for measurement purposes.

5.2 Materials used for Measurement Analysis

Various materials were used for measurements and analysis. The sensor tag is placed on the given reference materials and readings are obtained via Nordic ID reader. The rubber material is waterproof and a good insulator. It is also elastic and resistant to tearing. After vulcanization rubber can retain back its original shape after stretching. The rubber sheet used for this particular measurement has dimensions 130×130×4mm, 1.55g/cm3, SBR standard.

Polytetrafluoro-ethylene (PTFE) is a thermoplastic polymer which has a melting point of 600K. PTFE has one of the lowest coefficients of friction. It is mainly used as a non-stick coating for cookware, as it is non-reactive to most of the substances. PTFE with dimensions 130×130×4mm, 2.18g/cm3, Guarniflon PTFE G400 is used for the comparisons. Polyvinyl Chloride (PVC) is a widely used synthetic plastic polymer, which has both rigid and flexible forms. Rigid form used in construction of pipes, manufacturing bottles, packaging. Flexible form mainly used to plumbing and electrical cable insulation [32] . The measurements of PVC are, dimensions 130×130×4mm, 1.4g/cm3, Etradur.

The next material used was cardboard with dimensions and density 130×130×2mm, 1500g/m2. Cardboard is known for its insulating properties. It is recyclable, puncture resistant and also does not tear very easily. Main use of cardboard is packaging, including food materials. POM with dimensions 130×130×4mm, 1.41g/cm3, Ertacetal C, is a highly stiff thermoplastic material, with low friction, high heat resistance, low moisture absorption, high strength and rigidity.

Fiber glass used has dimensions 130×130×4mm and 73% sand (silicon dioxide), 15% soda (sodium carbonate), 10% limestone (calcium carbonate) and 2% various additives. Fiber glass is highly resistant to chemical and heat erosion. It is strong, light weight, does not conduct electricity, non-magnetic [33][34] . FR-4 is a flame resistant material composed of woven fiberglass cloth. It is mainly used for electrical insulation. FR4 is known to retain its mechanical properties and electrical insulation in both dry and humid conditions. Dimensions of FR-4 used for the measurements are 130×130×3.2mm, 1.850 kg/m3 Ventec VT-481. [6][26][35]

5.2.1 Dogbone Tag is in LOS of the Reader

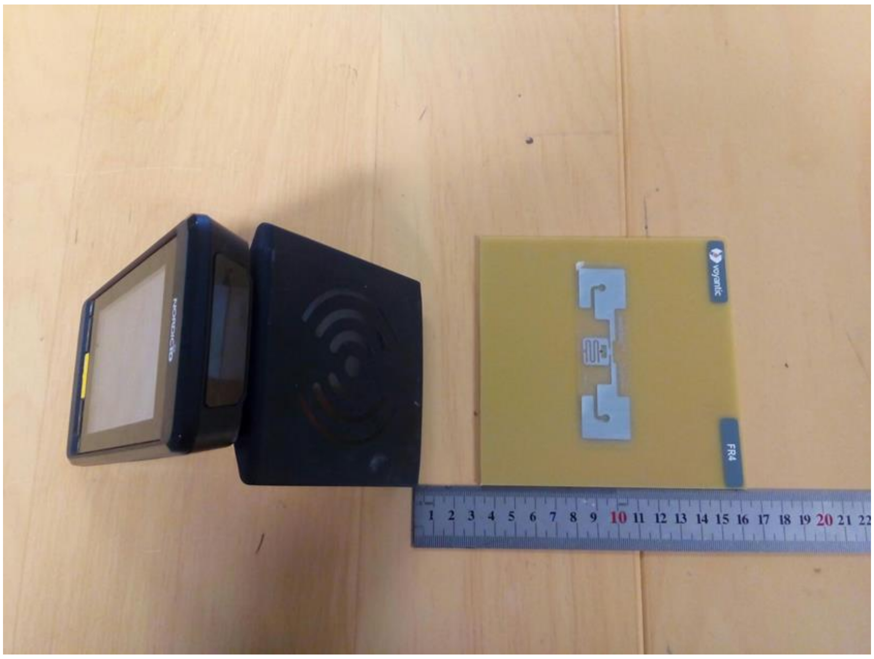

Figure 5.2: *Tag placed 10 cm apart from reader antenna*

Figure 5.2 shows that the tag is placed 10 cm from the reader antenna and measurements were performed inside the lab, having the tag in LOS with the reader, at a temperature of 22°C on different materials using Nordic ID tag reader to determine the RSSI code and sensor code on dogbone tag. The materials used have a specific density and make. In order to test for impedance matching, the tags are placed in different environments and the difference in sensor code and RSSI code values are compared and evaluated.

Material	Frequency [KHz]	Antenna	RSSI [dBm]	Sensor code	On-Chip RSSI	Channel
Rubber	866300	Antenna 0	-60	14	30	Single
PTFE	866300	Antenna 1	-52	13,14,15	31	Single
PVC	866300	Antenna 1	-52	13,14	31	Single
Cardboard	866300	Antenna 1	-52	13,14	31	Single
POM	866300	Antenna 1	-52	15,16	18,31	Single
Glass	866300	Antenna 1	-52	12,14,20	31,24	Single
FR4	866300	Antenna 1	-52	15,16,17,28	31,15	Single
Foam wrap	866300	Antenna 1	-52	13,14,31	31	Single

Table 5.1: *Measurement readings for the mentioned materials inside the lab*

As seen in Table 5.1, the frequency for all the materials is the same that is 866.300 MHz, which is well within the range of 860-960 MHz [36], and also channel used is single channel in this form of communication. There were two antennas present in the measurement, antenna 1 and antenna 0. The antennas keep fluctuating when the reader is placed in various positions. The two values that are different for different materials in the measurements are sensor code and on-chip RSSI value, this fluctuation aids in impedance matching

Initially the tag is placed in a rubber sheet. The RSSI values is -60 which is quite different from the RSSI value of other materials. The sensor code is 14 and the on-chip RSSI is 30, which is quite unchanged. Antenna reading was taken from antenna 0 which is also different from rest of the materials antenna, which is antenna 1. When the tag was placed in a PTFE slab, the RSSI values is -52 which is quite similar from the RSSI value of other materials. The sensor code alters between values 13, 14, 15 and the on-chip RSSI remains 31, which is quite constant.

Moreover, the sensor code for PVC is shifting between 13, 14 and the on-chip RSSI is 31 which remains constant throughout the measurement process. The cardboard piece has fluctuating sensor code of 13, 14 and on-chip RSSI of 31. POM has a changing sensor code of 15, 16 and on-chip RSSI which is 31 but has peaks of 18 at various intervals. Fiber glass (Float Glass) has a sensor code which varies between values 12, 14, 20 and on-chip RSSI of 31, with periodic peaks of 24. FR4 has a sensor code of fluctuating values 15, 16, 17, 28 and on-chip RSSI of 31, and random peaks at value 15. Finally foam wrap which is folded 4 times has unstable sensor code of 13, 14, 31 and on-chip RSSI of 31.

5.2.2 Tag is placed outdoors

Table 5.2 below shows the measurement readings outdoors for the same materials. The weather is cool and sunny with a temperature reading of 11 °C and a humidity of 61%. The dew point is 3.0 °C. Measurements were taken in the morning at 11:00am Finnish time. The tag in placed on top of the respective material which is then positioned directly in front of the antenna of the NordicID Medea. The reader is placed 10 cm away from the IC chip of the tag. The particular tag is free from moisture and placed on a dry environment. The antenna is not disturbed when the following readings are taken:

Material	Frequency [KHz]	Antenna	RSSI [dBm]	Sensor code	On-Chip RSSI	Channel
Rubber	866300	Antenna 0	-64	20	26,31	Single
PTFE	866300	Antenna 0	-64	30	27	Single
PVC	866300	Antenna 0	-60	27	31	Single
Cardboard	866300	Antenna 0	-64	29,30	24,25	Single
POM	866300	Antenna 1	-52	15,16,17	31	Single
Glass	866300	Antenna 1	-54	3	31	Single
FR4	866300	Antenna 1	-52	13,14,15	31	Single
Foam wrap	866300	Antenna 1	-52	18,20	31	Single

Table 5.2: *Measurement readings for the mentioned materials in sunny outdoors*

Table 5.2 depicts that the frequency for all the materials is the same that is 866.300 MHz, the channel used is single channel in this form of data transmission. There two antennas present in the measurement are, antenna 1 and antenna 0 which fluctuates when the reader is moved. The sensor code and on-chip RSSI value keeps fluctuating in this particular condition to match the impedance, this fluctuation aids in impedance matching which helps in the maximum utilization of power by the tag.

The tag placed in rubber sheet had RSSI value of -64. The sensor code is 20 and the on-chip RSSI is 31, but has a dip at 26 when the reader is disturbed. When the Nordic ID reader is untouched then sensor code and on chip RSSI values do not change. Antenna reading was taken from antenna 0. When the tag was placed in a PTFE slab, the RSSI value is -64 too, which is quite similar to the RSSI value of rubber. The sensor code remains unchanged at 30 and the on-chip RSSI remains 27, which is quite constant.

On the other hand, the sensor code for PVC is 27 and the on-chip RSSI is 31. The two values remain constant throughout the entire measurement process. The RSSI value is -60 for PVC. The cardboard piece has RSSI value of -64, and fluctuating sensor code of 29, 30 and on-chip RSSI is 24, 25. POM has a changing sensor code of 15, 16, 17 and on-chip RSSI which is constant at 31. Fiber glass has a sensor code value which is unchanged at 3 and on-chip RSSI of 31. FR4 has a sensor code of unstable values 13, 14, 15 and on-chip RSSI of 31. Lastly foam wrap which is folded has sensor code of 18, 20 and on-chip RSSI of 31. The RSSI value for POM, FR-4 and foam wrap is -52. Glass has RSSI value of -54.

5.2.3 Tag has a Dab of Tap Water

Table 5.3 demonstrates the readings inside the laboratory at a temperature of 21 °C. Tap water is swabbed onto the IC of the sensor dogbone tag using a paper towel. The tag is placed in LOS of the reader with a distance of 10 cm separating the tag and the reader.

Material	Frequency [KHz]	Antenna	RSSI [dBm]	Sensor code	On-Chip RSSI	Channel
Rubber	866300	Antenna 1	-52	16,17	31	Single
PTFE	866300	Antenna 1	-52	13,14,16	19,31	Single
PVC	866300	Antenna 1	-52	23,24,26	31	Single
Cardboard	866300	Antenna 1	-52	19,21	24,31	Single
POM	866300	Antenna 1	-52	18,19	18,31	Single
Glass	866300	Antenna 1	-52	16,17	31	Single
FR4	866300	Antenna 1	-52	23,24	31	Single
Foam wrap	866300	Antenna 1	-52	18	31	Single

Table 5.3: *Measurement readings for the materials in presence of moisture*

Table 5.3 above shows that the frequency remains the same that is 866.300 MHz, the channel used is single channel in this form of data transmission. The antenna used is Antenna 1 for all the reading instances. The sensor code and on-chip RSSI value keeps fluctuating in this particular condition to match the impedance.

Initially the tag was placed in rubber sheet, the sensor code showed 16, 17 and the on-chip RSSI is 31. Antenna reading was taken from antenna 1. When the tag was placed in a PTFE slab, the RSSI value is also -52 dBm. The RSSI remains -52 dBm for all the materials. The sensor code switches between 13, 14 and 16 and the on-chip RSSI is 19 and 31. The sensor code for PVC fluctuates between 23, 24 and 26, and the on-chip RSSI is 31. The material made of cardboard has a varying sensor code of 19 and 21. The on-chip RSSI is 24, 31. POM has a changing sensor code of 18, 19 and on-chip RSSI of 18, 31. Fiber glass has a sensor code of 16, 17 and on-chip RSSI of 31. FR4 has a sensor code of values 23, 24 and on-chip RSSI of 31. Lastly foam wrap which is fold-ed, has sensor code of 18 and on-chip RSSI of 31.

5.2.4 Tag is placed inside a Cardboard Box

Measurements were taken inside the lab, at a temperature of around 21°C on the above mentioned reference materials using Nordic ID tag reader. The given materials were placed inside a thick box of cardboard material and the box was placed 5 cm away from the reader in the absence of moisture, then the RSSI value and sensor code on the sensor dogbone tag was determined. The following readings were obtained:

Material	Frequency [KHz]	Antenna	RSSI [dBm]	Sensor code	On-Chip RSSI	Channel
Rubber	866300	Antenna 1	-54	9	31	Single
PTFE	866300	Antenna 1	-52	20,21	31	Single
PVC	866300	Antenna 1	-52	19,20	31	Single
Cardboard	866300	Antenna 1	-52	20,21	31	Single
POM	866300	Antenna 1	-52	17,19	31	Single
Glass	866300	Antenna 1	-52	8	31	Single
FR4	866300	Antenna 1	-52	14	31	Single
Foam wrap	866300	Antenna 1	-52	20	31	Single

Table 5.4: *Measurement readings of the materials when tag is placed inside a cardboard box*

Table 5.4 indicates that the frequency for all the materials remains the same that is 866.300 MHz, the channel used is single channel in this form of data transmission. The sensor code and on-chip RSSI value keeps fluctuating to facilitate impedance matching.

When the tag was placed in rubber sheet, it had an RSSI value of -54. The sensor code was only 9 and the on-chip RSSI is 31. When the tag was placed in a PTFE slab, the RSSI value is -52. The sensor code fluctuates between 20 and 21, and the on-chip RSSI remains the same that is 31. The RSSI value remains -52dBm for all the reference materials except rubber, which is -54dBm. The sensor code for PVC is 19 and 20, and the on-chip RSSI is 31.

The RSSI value is -52dBm for PVC. The cardboard piece has RSSI value of -52, and fluctuating sensor code of 20, 21. The on-chip RSSI of cardboard is 31. POM has a changing sensor code of 17 and 19 and on-chip RSSI which is constant at 31. Fiber glass has a sensor code value which is stagnant at 8 and on-chip RSSI of 31. FR4 has a sensor code of 14 and on-chip RSSI remains the same, 31. Finally foam wrap which is folded has a constant sensor code of 20 and on-chip RSSI of 31. It is noticed that the RSSI value remains constant for the reading of all the materials.

5.2.5 Tag is sandwiched between Two Slabs of Same Material

Measurements were performed indoors, inside the lab, at a constant temperature of 22°C on the given reference materials using Nordic ID tag reader. The materials were sandwiched between two slabs of the same material with similar dimensions. The reader was placed 10 cm away from the tag and it is made sure that no moisture is present in the tag. The RSSI value and sensor code on the sensor dogbone tag was determined. The following readings were obtained:

Material	Frequency [KHz]	Antenna	RSSI [dBm]	Sensor code	On-Chip RSSI	Channel
Rubber	866300	Antenna 1	-52	9	31	Single
PTFE	866300	Antenna 1	-52	18,19,20	31	Single
PVC	866300	Antenna 1	-52	15	31	Single
Cardboard	866300	Antenna 1	-52	18,19	31	Single
POM	866300	Antenna 1	-54	15,16	31	Single
Glass	866300	Antenna 1	-54	0	31	Single
FR4	866300	Antenna 1	-54	5	31	Single
Foam wrap	866300	Antenna 1	-52	16,17	31	Single

Table 5.5: *Measurement readings when the tag is placed between two slabs of same material*

The frequency for all the materials remains 866.300 MHz, the channel is single channel. Antenna 1 is the antenna used by the reader for sensing the tag. The sensor code value keeps fluctuating to facilitate impedance matching. Whereas the on-chip RSSI is constant at 31.

When the tag was placed in rubber sheet, it had an RSSI value of -52. The sensor code was only 9 and the on-chip RSSI is 31. When the tag was placed in a PTFE slab, the RSSI value is -52. The sensor code fluctuates between 18, 19 and 20, and the on-chip RSSI remains the same, which is 31. The sensor code for PVC is 15, and the on-chip RSSI is 31. The RSSI value is -52dBm for PVC. The cardboard piece has RSSI value of -52, and fluctuating sensor code of 18 and 19.

Moreover, the on-chip RSSI of cardboard is a constant value of 31. POM has a sensor code of 15 and 16, and on-chip RSSI which is constant at 31. Fiber glass has a sensor code value which is stagnant at 0, no amount of displacement changes the result. The on chip RSSI value of POM is 31. FR4 has a sensor code of 14 and on chip RSSI value remains the same, 31. POM, glass and FR4 has an RSSI of -54dBm. Folded foam wrap has a varying sensor code of 16 and 17 and on-chip RSSI of 31. The RSSI value is -52dBm for foam wrap.

5.2.6 A Dab of Acetic Acid placed on the Tag

A dab of acetic acid is swabbed on the IC of the sensor dogbone tag. Table 5.6 below shows the measurement readings for the above mentioned scenario. The readings were taken inside the lab, with the temperature maintained at 21.0 °C. The tag in placed on the material which is then placed 10 cm from the reader antenna. The reader is placed 10 cm away from the IC chip of the tag. Table 5.6 shows the measurement readings taken for the mentioned scenario.

Material	Frequency [KHz]	Antenna	RSSI [dBm]	Sensor code	On-Chip RSSI	Channel
Rubber	866300	Antenna 1	-52	4	31	Single
PTFE	866300	Antenna 1	-52	16	31	Single
PVC	866300	Antenna 1	-52	13,14,16	31	Single
Cardboard	866300	Antenna 1	-52	13,14	31	Single
POM	866300	Antenna 1	-52	13,14	31	Single
Glass	866300	Antenna 1	-54	19,20	31	Single
FR4	866300	Antenna 1	-52	7	31	Single
Foam wrap	866300	Antenna 1	-52	13,14	31	Single

Table 5.6: *A dab of Acetic Acid placed on the tag*

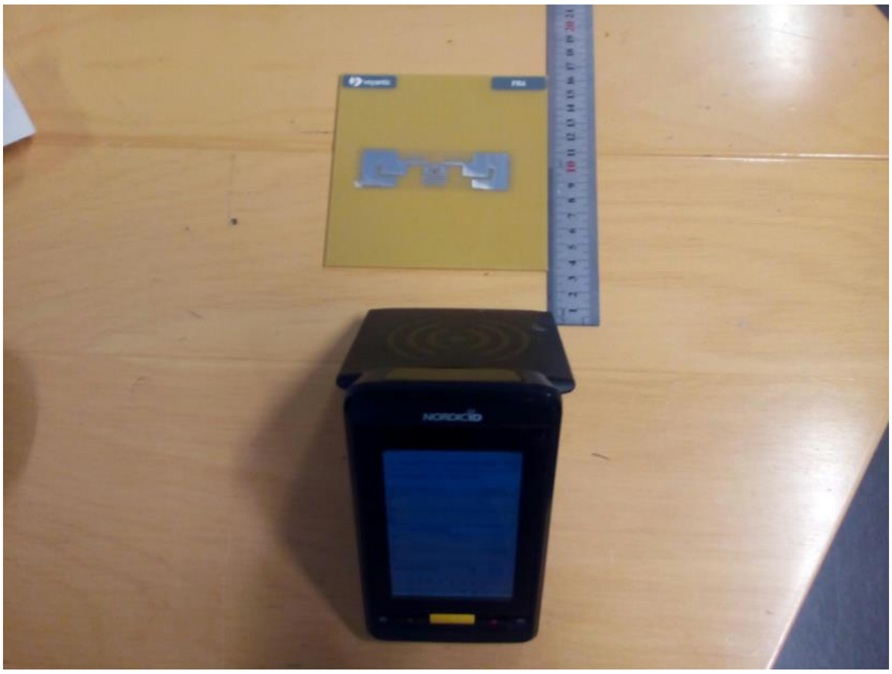

Figure 5.3: *Readings taken when a dab of Acetic acid is placed on the tag that is 10 cm away from the Reader Antenna*

When the tag was placed in rubber sheet, it had an RSSI value of -52. The sensor code was 4 and the on-chip RSSI is 31. When the tag was placed in a PTFE slab, the RSSI value is -52. The sensor code remains constant at 16 and the on-chip RSSI is the same that is 31. The RSSI value remains -52dBm for all the reference materials except glass, which is -54dBm. The sensor code varies between 13, 14 and 16, the on-chip RSSI is 31. The RSSI value is -52dBm for PVC. The cardboard piece has RSSI value of -52, and fluctuating sensor code of 13, 14. The on-chip RSSI of cardboard is 31. POM has a changing sensor code of 13, 14 and on-chip RSSI which is constant at 31. Fiber glass has a sensor code value of 19, 20 and on-chip RSSI of 31. FR4 has quite a low sensor code of 7 but the on-chip RSSI remains the same, 31. Finally foam wrap which is folded has a sensor code of 13, 14 and on-chip RSSI of 31.

It is noticed that the RSSI value remains constant for the reading of all the materials. Table 5.6 represented above also indicates that the frequency for all the materials remains the same that is 866.300 MHz, the channel used is single channel in this form of data transmission. Even when displaced, the reader uses only antenna 1 to detect the tag in this particular set of readings.

5.3 Comparison of the Sensor Code values under Different Conditions

Taking into consideration the optimum value of the fluctuating sensor code, a table is created for the different measurements taken. From the obtained table, a graph is plotted for the given material substrates and the varying conditions. The sensor dogbone tag has different levels of performance under different environmental conditions. A graph can easily portray the performance of the tag. This way the performance of the tag can be analyzed and compared for different conditions easily.

Material	Inside lab	Sunny outdoors	Dab of Water	Embedded in box	Sandwiched b/w slabs	Dab of Acetic Acid
Rubber	14	20	16	9	9	4
PTFE	13	30	14	21	19	16
PVC	14	27	24	20	15	14
Cardboard	14	29	21	21	19	14
POM	15	16	19	19	16	13
Glass	14	3	17	8	0	19
FR4	17	14	24	14	5	7
Foam wrap	14	20	18	20	17	14

Table 5.7: *Comparison of Sensor tags under different conditions*

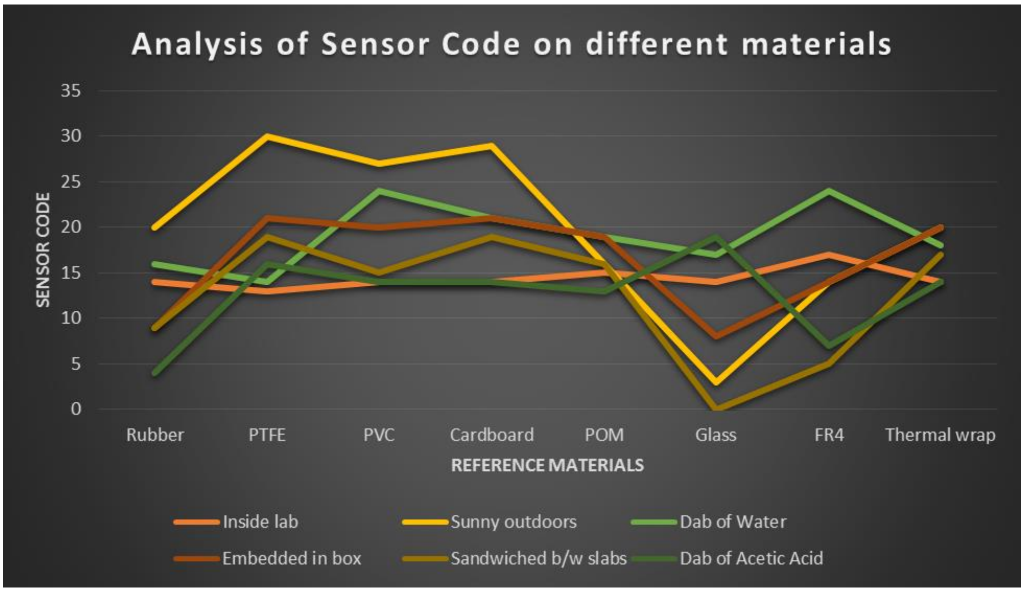

Figure 5.4: *Analysis of Sensor Code on different materials*

The above graph is plotted using the optimum value of the sensor code under different circumstances. Six curves are obtained for six different measurement analysis performed. The plotted values prove that the performance of the dogbone tag is different for different material substrates and under different conditions. The graph shows that in sunny outdoors the sensor code is the highest so highest power consumption by the tag will take place in this situation. As sensor code decreases the power consumption also decreases, hence the performance of the tag will also be reduced. The graph also illustrates that the type of material the tag is placed in also affects the readings. In case of fiber glass the sensor code has a dip in all circumstances except inside the lab when acetic acid is present on the tag, this in fact proves that glass is not an ideal material to place the tag on, in order to obtain the desired results.

Inside the lab, the values are almost constant for all materials, this may be due to the reason that the temperature is maintained inside the lab and also the tag is in LOS with the materials giving it a less probable chance for variation. Materials made of PTFE, PVC, cardboard and POM have almost similar sensor code values for most of the situations. FR4 material has a slightly higher sensor code value making the tag performance high in FR4 substrate.

It is also noticed that tap water and acetic acid have different effect on the sensor code as the sensor code values have noticeable difference for both liquids. But, the tag is able to perform well even in the presence of moisture with high sensor code values since the sensor tags do respond to the moisture present in the environment. When tag is placed inside a cardboard box, the sensor code readings are comparatively high even though the tag is not in LOS with the reader antenna. Also when the tag is sandwiched between two slabs of similar material, the sensor code values seems to be high, which makes the dogbone tag suitable to be embedded inside building walls and placed inside cartons, boxes etc. Moreover, the presence of moisture inside the buildings will not affect the readings to a very high extent and this way desired results can be obtained in such circumstances.

6. CONCLUSIONS

6.1 Conclusion

In this master thesis, a sensor tag known as the sensor dogbone tag is used as the transponder and NordicID reader is used to take the measurements from the sensor dogbone tag. The chosen tag is placed on the given reference materials with varying chemical properties. This is done in order to compare the performance of the sensor tag on different materials which has different make and varying density, chemical properties and level of flexibility. The readings are taken from the tag on the above mentioned materials under different circumstances. The circumstances include the tag being placed, inside the lab in LOS with the reader, sunny outdoors, the materials slab placed inside a cardboard box along with the tag, inside the lab with the tag having a dab of moisture on its IC etc. The tag is placed at a constant distance of 10 cm from the reader antenna. Therefore distance is not a factor that is taken into consideration in this master thesis. Moreover, the reader is not moved while the measurements are taken.

However, the readings taken when the tag is placed on the given reference materials in different conditions show a lot of variations. Impedance should be matched in order to obtain maximum power hence the fluctuations seen in the sensor code. It is noticed from the measurements that is sensor code value is the main factor that is fluctuating, the RSSI code value has negligible impact on the change in material or circumstance. RSSI value is mostly constant. Environmental changes like temperature change, presence of moisture etc. also affect the sensor code. Situational changes like, when the tag is embedded inside buildings or present inside boxes also affect the sensor code readings to a high extent. These changes are illustrated in the measurement analysis and the various results obtained are presented in a graph for easy comparison under different circumstances.

Sensor dogbone tag is a passive sensor tag that can operate without the aid of inbuilt power supply. Therefore, the tag is activated by the power received from the reader. The NordicID Medea reader is mainly used to measure the sensor code and RSSI code. The reader depicts the mentioned factors in the form of a graph for improved accuracy. There is fluctuations present in the sensor code values and the RSSI values in order to provide reliable readings. The frequency band used by the sensor tag for measurement analysis is UHF between the ranges 860-960 MHz.

In order to maintain compatibility, the RFID system follows a particular standardization. The Nordic ID reader makes use of cross dipole antenna. The dogbone tags generally use dipole antenna. A dipole antenna improves the impedance matching of the system thus improving the power received by the tags eventually providing better results. Obtaining readings from the sensor dogbone tag using Nordic ID reader is very easy and does not consume much time.

It is vital to continuously monitor the tags performance under different conditions to modify the tags such that they can provide improved and more reliable results. These measurements analysis provide a means to choose the optimum material and condition where the tag is placed to obtain the maximum sensor code value which in turn helps aid maximum power consumption by the sensor dogbone tag from the NordicID reader.

Future analysis can be carried out focusing on the read range of the tag antenna. Moreover, the initial measurements taking into consideration the read range with the reader and tag antennas in LOS is provided further in Appendix A.

7. REFERENCES

[1] D. M. Dobkin, *The RF in RFID: Passive UHF RFID in Practice*. Newnes, 2007.

[2] T. by D. M. Finkenzeller, Klaus, “RFID Handbook,” *John Wiley & Sons, Ltd*, 2010. .

[3] M. P. V. Daniel Hunt, Albert Puglia, “RFID: A Guide to Radio Frequency Identification,” *A John Wiley & Sons, Inc., Publication*, 2007. .

[4] Bill Glover ; Himanshu Bhatt, “RFID Essentials,” *O’Reilly Media*, 2006. .

[5] K. P. Fishkin, M. Philipose, and A. Rea, “Hands-On RFID: Wireless Wearables for Detecting Use of Objects,” in *Ninth IEEE International Symposium on Wearable Computers (ISWC’05)*, 2005.

[6] P. J. S. II, “RFID For Dummies,” *Wiley Publishing, Inc.*, 2005. .

[7] “Zebra R110Xi4 RFID Printer.” [Online]. Available: http://www.barcodesinc.com/zebra/r110xi4.htm. [Accessed: 05-Aug-2015].

[8] T. Deyle, H. Nguyen, M. Reynolds, and C. C. Kemp, “RFID Receive Signal Strength Indicator (RSSI) Images for Sensor Fusion and Mobile Manipulation.”

[9] “RFID Tag Maximum Read Distance.” [Online]. Available: http://skyrfid.com/RFID_Tag_Read_Ranges.php. [Accessed: 29-Sep-2015].

[10] “Cyclic Redundancy Check (CRC).” [Online]. Available: http://ecomputernotes.com/computernetworkingnotes/communication-networks/cyclic-redundancy-check. [Accessed: 28-Aug-2015].

[11] T. S. Rappaport, *Wireless Communications: Principles and Practice*, Second. Singapore: Pearson Education, Inc., 2002.

[12] K. Feher, *Wireless digital communications : modulation and spread spectrum applications*. Upper Saddle River N.J.: Prentice-Hall PTR, 1995.

[13] F. Leipold, V. Furtula, M. Salewski, H. Bindslev, S. B. Korsholm, F. Meo, P. K. Michelsen, D. Moseev, S. K. Nielsen, and M. Stejner, “Antenna design for fast ion collective Thomson scattering diagnostic for the international thermonuclear experimental reactor,” *Rev. Sci. Instrum.*, vol. 80, no. 9, pp. 359–370, 2009.

[14] K. V. S. Rao, P. V. Nikitin, and S. F. Lam, “Antenna design for UHF RFID tags: a review and a practical application,” *IEEE Trans. Antennas Propag.*, vol. 53, no. 12, 2005.

[15] D. M. Pozar, “Microwave Engineering,” *John Wiley & Sons, Inc.*, 2012. .

[16] Y. He, W. He, and H. Wong, “A Wideband Circularly Polarized Cross-Dipole Antenna,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 13, pp. 67–70, 2014.

[17] W. Ernest Payne, “Cross-dipole antenna configurations,” Dec. 2012.

[18] “What is Impedance?” [Online]. Available: http://www.wisegeek.org/what-is-impedance.htm. [Accessed: 02-Sep-2015].

[19] M. Rouse, “Impedance,” 2005.

[20] R. public of K. K. Yang-Hann (Korea Advanced Instit ute of Science and Technol ogy (KAIST), “Sound Propagation: An Impedance Based Approach,” *John Wiley & Sons (Asia) Pte L td, 2 Clementi Loop, # 02-01*, 2010. .

[21] K. V. S. Rao, P. V. Nikitin, and S. F. Lam, “Impedance matching concepts in RFID transponder design,” *Proc. - Fourth IEEE Work. Autom. Identif. Adv. Technol. AUTO ID 2005*, vol. 2005, no. 1, pp. 39–42, 2005.

[22] L. Frenzel, “Back to basics: impedance matching,” 2011. [Online]. Available: http://electronicdesign.com/communications/back-basics-impedance-matching-part-1. [Accessed: 16-Jun-2015].

[23] P. V. Nikitin, K. V. S. Rao, S. F. Lam, V. Pillai, R. Martinez, and H. Heinrich, “Power reflection coefficient analysis for complex impedances in RFID tag design,” *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 9, pp. 2721–2725, 2005.

[24] C. Loo, K. Elmahgoub, F. Yang, A. Elsherbeni, D. Kajfez, T. Elsherbeni, L. Ukkonen, L. Sydänheimo, and M. Kivikoski, “Impedance Matching for RFID Tag Antennas,” *24th Annu. Rev. Prog. Appl. Comput. Electromagn.*, pp. 749–753, 2008.

[25] A. Note, “AND9209 / D Chameleon t Technology Enables Low - Cost Smart,” pp. 1–4, 2015.

[26] “Applying RSSI filters for optimal RFID performance - RFID Arena.” [Online]. Available: http://rfidarena.com/2013/8/28/applying-rssi-filters-for-optimal-rfid-performance.aspx. [Accessed: 11-Jun-2015].

[27] RF Micron, “RFMicron Application Note AN002,” pp. 1–3, 2014.

[28] L. Catarinucci, R. Colella, M. De Blasi, L. Patrono, and L. Tarricone, “Enhanced UHF RFID tags for drug tracing.,” *J. Med. Syst.*, vol. 36, no. 6, pp. 3451–62, Dec. 2012.

[29] “Smartrac’s New Passive Sensor DogBone Transmits Moisture Levels - RFID Journal.” [Online]. Available: http://www.rfidjournal.com/articles/view?12723. [Accessed: 10-Jun-2015].

[30] “Nordic ID Medea.” [Online]. Available: https://www.flickr.com/photos/mobile-rfid/sets/72157647490735878/. [Accessed: 16-Jun-2015].

[31] “RFID card, Proximity Card of Huayuan RFID, The RFID manufacturer.” [Online]. Available: http://www.rfidhy.com/. [Accessed: 16-Jun-2015].

[32] “poly(vinyl chloride) (CHEBI:53243).” [Online]. Available: http://www.ebi.ac.uk/chebi/searchId.do?chebiId=53243. [Accessed: 12-Jun-2015].

[33] F. Sarvar, N. J. Poole, and P. A. Witting, “PCB glass-fibre laminates: Thermal conductivity measurements and their effect on simulation,” *J. Electron. Mater.*, vol. 19, no. 12, pp. 1345–1350, Dec. 1990.

[34] “» Eurograte® Fiberglass Components FRP Products GRP Properties.” [Online]. Available: http://www.eurograte.co.uk/fibreglass/. [Accessed: 12-Jun-2015].

[35] K. Azar and J. E. Graebner, “Experimental determination of thermal conductivity of printed wiring boards,” in *Twelfth Annual IEEE Semiconductor Thermal Measurement and Management Symposium. Proceedings*, 1996, pp. 169–182.

[36] “The Different Types of RFID Systems | Impinj.” [Online]. Available: http://www.impinj.com/resources/about-rfid/the-different-types-of-rfid-systems/. [Accessed: 11-Jun-2015].

8. APPENDIX A: FUTURE ANALYSIS

8.1 Tag placed 10 cm from the Reader Antenna

Read range is considered to be an important aspect determining the impedance matching factor of the RFID tag. It is important to analyze the sensor code of the sensor tag considering the read range as an important factor. Taking into consideration an instance from the previous measurement analysis performed inside the lab. The tag being placed 10 cm in LOS with the reader antenna. The following readings are obtained:

Material	Frequency [KHz]	Antenna	RSSI [dBm]	Sensor code	On-Chip RSSI	Chan-nel
Rubber	866300	Antenna 0	-60	14	30	Single
PTFE	866300	Antenna 1	-52	13,14,15	31	Single
PVC	866300	Antenna 1	-52	13,14	31	Single
Cardboard	866300	Antenna 1	-52	13,14	31	Single
POM	866300	Antenna 1	-52	15,16	18,31	Single
Glass	866300	Antenna 1	-52	12,14,20	31,24	Single
FR4	866300	Antenna 1	-52	15,16,17,28	31,15	Single
Foam wrap	866300	Antenna 1	-52	13,14,31	31	Single

Table 8.1: *Measurement readings for materials when tag is in 10 cm LOS with the Reader Antenna*

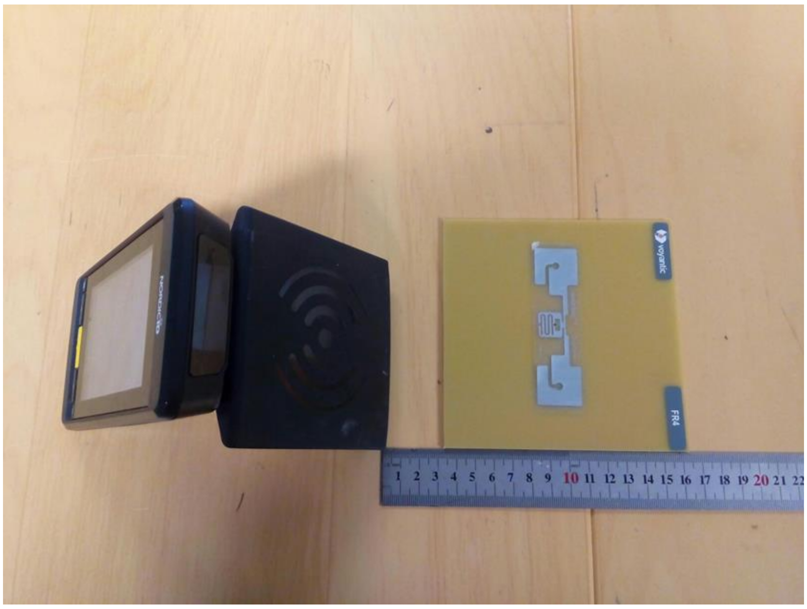

Figure 8.1: *Tag placed 10 cm from the Reader Antenna*

8.2 Tag placed 40 cm from the Reader Antenna

To compare the read range with the previous range of 10 cm. The next set of measurements were taken inside the lab where the distance between the tag and the reader antenna is 40 cm.

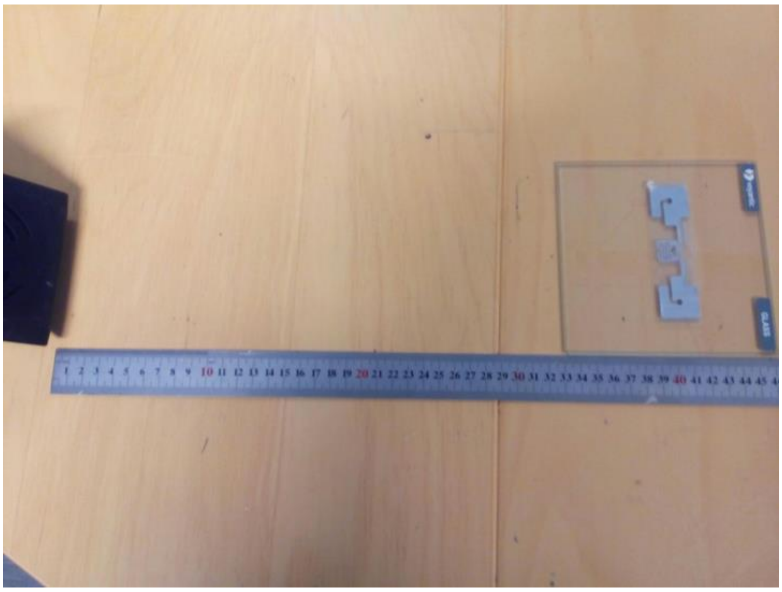

Figure 8.2: *Tag placed 40 cm from the Reader Antenna*

The followings readings were obtained for the measurement analysis where the tag and reader antenna is separated by a distance of 40 cm:

Material	Frequency [KHz]	Antenna	RSSI [dBm]	Sensor code	On-Chip RSSI	Channel
Rubber	866300	Antenna 1	-58	19,20	31	Single
PTFE	866300	Antenna 1	-54	26	31	Single
PVC	866300	Antenna 1	-56	26,28	31	Single
Cardboard	866300	Antenna 1	-54	26	31	Single
POM	866300	Antenna 1	-56	26	31	Single
Glass	866300	Antenna 1	-60	23,25	24,31	Single
FR4	866300	Antenna 1	-58	22	31	Single
Foam wrap	866300	Antenna 1	-56	24	31	Single

Table 8.2: *Measurement readings for materials when tag is in 40 cm LOS with the Reader Antenna*

8.3 Comparison of Sensor Code LOS from 10 cm and 40 cm

The optimum values were taken from the reading

Material	LOS 10 cm	LOS 40 cm
Rubber	14	19
PTFE	13	26
PVC	14	26
Cardboard	14	26
POM	15	26
Glass	14	23
FR4	17	22
Foam wrap	14	24

Table 8.3: *Comparison of Sensor tags w.r.t distance of 10 cm and 40 cm*

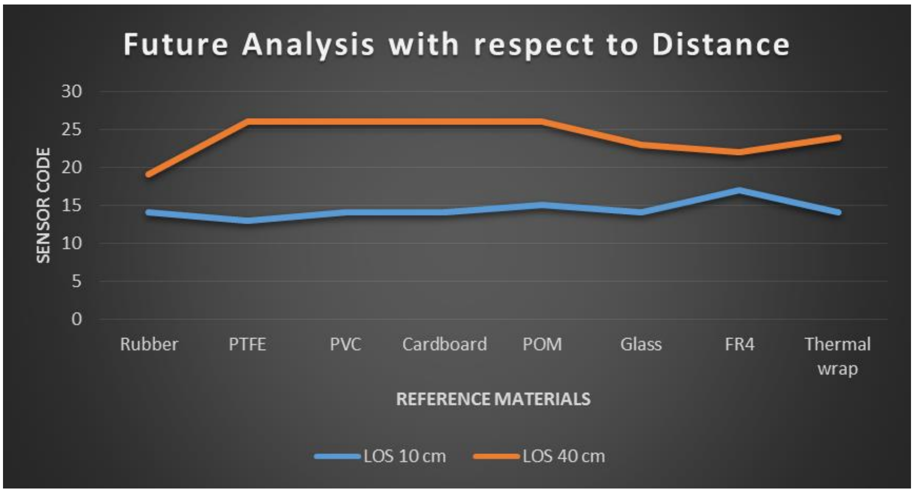

Figure 8.3: *Analysis of Sensor Code w.r.t Distance*

It is evident from the above graph that distance has an impact on the sensor code value of the dogbone sensor tag. But, the graph contradicts the above mentioned theory that the sensor code value increases as the distance from the tag and the reader decreases. One of the reason for this kind of behavior can be the increase in path loss with the increase in distance. As mentioned in chapter 2, the equation for path loss is:

$$a_F = -147.6 + 20\log(r) + 20\log(f) - 10\log(G_T) - 10\log(G_R) \qquad (8.1)$$

Substituting the UHF frequency range in the above given equation we get the following distance which is also mentioned in chapter 2. As shown in the table below, the free space path loss increases as the distance increases.

Distance *r*(m)	***a_F* (dB) *for* 868 MHz**
0.3	18.6
1	29.0
3	38.6
10	49.0

Table 8.4: *Comparison of Free Space Path loss at different distance [2]*

Moreover, the power received by the antenna also varies as the antenna distance changes. Since the power has an effect on the IC, the capacitors experience impedance change. The sensor code reflects the antenna environment of the tag. The antenna environment has a larger effect on the tag when the distance increases between the tag and reader. Therefore, this particular behavior of the sensor code value needs to be studied further on different materials to make concrete analysis.