Tampere University

S M Musfequr Rahman

DEVELOPMENT OF PASSIVE MOISTURE SENSOR

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ABSTRACT

S M Musfequr Rahman: Development of Passive Moisture Sensor
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A sensor acts as a connecting medium between the physical world and electrical devices. Based on the power source, there are two types of sensors: active and passive. The passive sensor does not require any direct power source, and it is a less expensive device. Radio Frequency Identification (RFID) is a low-cost, reliable, and fast technology that uses radiofrequency to track down objects and their position. Passive ultra-high frequency (UHF) RFID tags are fast in object tracking, which can operate from several meters distance. To activate the passive tags it required the radio frequency from the RFID reader. Passive UHF RFID tags are extensively used in supply chain management, object tracking, etc. Due to low power data transmission capability, it is used in wireless sensing technology.

Electronic waste is one of the leading causes of environmental pollution. In this thesis, the main goal was to implement and test a low-cost, environment-friendly moisture sensor. We manufactured passive UHF RFID tag on low-cost materials, i.e., commercially available dishwashing cloths as substrates. Three different substrate materials were used for moisture sensor fabrication. By using conductive thread and embroidery techniques, the moisture sensors were fabricated. In cases where hand stitching methods were complicated, the embroidery machine was used to fabricate the moisture sensors. For moisture testing, two methods were applied: submerging in water and spraying water. The soluble thread was used to give a circular shape to the moisture sensor tags to observe the bending effect and the substrate's shape-changing tendency after the moisture test on the sensor tags.

In this thesis, mainly, three tests were performed to observe the moisture sensor tags' performance in different conditions. Firstly, all the sensors' tags were tested for observing the bending effect on the substrate materials. It was observed that all the materials had similar bending effects, and their read range decreased due to the increase of bending on the sensor tags. Secondly, moisture sensor tags of all the three materials were tested during initial dry, wet, and redried conditions without bending the moisture sensor tags. When redried from the wet condition, the moisture sensor tags' read ranges were improved but could not reach the level of initial dry condition. Compared to all the three substrate materials of moisture sensor tags, Material-2 showed better performance after the moisture testing on the tags. Finally, the moisture sensor tags were tested in a combination of bending and wet conditions. All the tags were tested in two different positions like sidewise bending and hanging from the top in bending condition. In both cases, Material-2 demonstrated better performance when compared to the other two materials.

To conclude, though all the moisture sensor tags showed sensing properties within the UHF RFID band, for moisture sensor tag development, “Mikrokuituinen lisi sieniliina” (Material-2) was better of the three materials, whereas “Talousliina 3m” (Material-3) is the least preferred.

Keywords: RFID, UHF, Passive tags, Dishwashing cloth, Moisture sensor.

The originality of this thesis has been checked using the Turnitin OriginalityCheck service.

PREFACE

The master thesis, “Development of Passive Moisture Sensor,” was done in partial fulfilment of the requirement for the Masters of Science degree in Electronics Engineering major in the Department of Electronics and Communication Engineering at Tampere University. The thesis and experiments were supervised and examined by Postdoctoral Research Fellow Xiaochen Chen and Academy Research Fellow Johanna Virkki. I would like to thank my thesis supervisors for their continuous support and guidance in helping me to complete my thesis.

I would also like to thank Zahangir Khan, Shabaz Ahmed, and Adnan Mehmood for guidance and support during my thesis. Incredibly thankful to my parents and family members for their support throughout my life while I was in an inconvenient situation. Finally, I am thankful to my friend Nazmul Anam Rafi and all other friends who encouraged me to pursue my dream by giving moral support.

Tampere, 17 December 2020

S M Musfequr Rahman

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LIST OF SYMBOLS AND ABBREVIATIONS

RFID	Radio Frequency Identification
UHF	Ultra High Frequency
3D	3 Dimension
2D	2 Dimension
IEEE	Institute of Electrical and Electronics Engineers
dB	Decibel
dBi	Decibel isotropic
E plane	Electric Field
H plane	Magnetizing Field
Ph1	Phi 1
Z	Z plane
ω	Angular Frequency of the Wave
U	Radiation intensity
r	Radius of the antenna
Wrad	Radiation density
D	Directivity
Uo	Radiation intensity of an isotropic source
Prad	Total radiated power
$U(\theta, \varphi)$	Radiation intensity in a given direction to E filed
Pin	Toral input(accepted) power
FNBW	First null beamwidth
HPBW	Half-power beamwidth
Pr	Power of receiving antenna
Pt	Power of transmitting antenna
Gr	Gain of antenna R
Gt	Gain of antenna T
r	Distance between two antennas
λ	Wavelength of the frequency
D	Maximum antenna length
R1	The area of reactive near field
R2	The radiating near field
L	Length
d	Dimension
Zt	Input impedance
Zo	Characteristics impedance of the transmission line
L	Length of the folded dipole antenna
c	Speed of light
f	frequency
RF	Radio Frequency
IFF	Identification Friend or Foe
FET	Field-effect transistor
IC	Integrated Circuit
ID	Identification
PSK	Phase-shift keying
FSK	Frequency-shift keying
QAM	Quadrature amplitude modulation
CDMA	Code division multiple access
GHz	Giga Hertz
CMOS	Complementary Metal Oxide Semiconductor
EPC	Electronic Product Code
AISC	Application-specific integrated circuit
DC	Direct current

dBm	Decibel milliwatts
cm	Centimetre
SNR	Signal to noise
µF	Microfarad
WSN	Wireless sensor network
A/D	Analog to Digital
EIRP	Enterprise resource planning system
MRP	Manufacturing resource planning
WMS	Warehouse management system
DRER	Dynamic relationship ER model
RDBMS	Relational Database Management System
ESP	Extensible sensor stream processing
Mm	Millimetre
CM	Centimetre
KM	Kilometre
TID	Tag Identifier
Gen2	Generation two
°C	Degree Celsius
EEPROM	Electrically erasable programmable read-only memory
dtag	Measured read range
EIRP	Equivalent Isotropically Radiated Power
Λ	Sensitivity constant
Pth	Threshold power
P_{th}*	The measured threshold power of the system reference tag
NFC	Near Field Communication
Ω/m	Linear Resistance Ohm per Metre
F	Fahrenheit
kHz	Kilo Hartz
W	Watt
%	Percentage

1. INTRODUCTION

Radio Frequency Identification is known as RFID [1]. This RFID technology uses electromagnetic waves for the identification of any object or people. There are three parts in RFID technology : host computer, RFID reader, and RFID tag [2]. This identification technology is not dependent on the line of sight. For maintaining communication between the reader and the tag, a unique code from the tag is used for identification. This tag identification code (electronic product code) is identified in the RFID reader and then it is matched with the database. After that, it establishes the communication channel between the RFID reader and the RFID tag and then it extracts the information from the RFID tag. RFID technology is commonly used all over the world for different applications. Nowadays, RFID technology is used in magnetic strip card and in the smart card for identification. There are three types of RFID tags: passive, semi-passive, and active [2][3]. In this thesis, a passive UHF (Ultra High Frequency) RFID tag is used for the development of the moisture sensor. UHF RFID operating frequency range is 860 MHz to 960 MHz [1]. A passive RFID tag is a low-cost technology because it does not require any battery for operation. RFID technology is also used for object detection, parking management, toll collection, patient management, sensing temperature, moisture, etc. [2].

A sensor is a device that converts the physical property into an electrical property. Nowadays, sensors are widely used in everyday life. Factory automation, seismometer, hydrogen sensor, airflow meter, altimeter, accelerometer, photodiode, thermocouple, thermometer, moisture sensor, etc. are examples of sensors' application. Active and passive sensors are the main two types of sensors. A passive sensor does not require an external power source for its operation [3]. A sensor is an expensive device. One moisture sensor from VH400 Soil Moisture Sensor Probes is $ 39.95 [4]. Environment pollution is one of the major concerns nowadays. Electronic waste can cause health and environmental hazards. Globally the electronic waste is nearly 5 percent of the municipal solid waste. For improving this situation, every industry is moving towards a sustainable and renewable solution [5].

The aim of this thesis is to develop a passive moisture sensor. We have taken passive UHF RFID technology into consideration, which is low cost and easy to construct for this development. As the installation substrate for moisture sensor, we used dishwashing cloth, which is environment friendly. Also, we aimed to develop a cost-effective moisture sensor. Flow chart diagram of the development of the thesis, as shown in Figure 1.

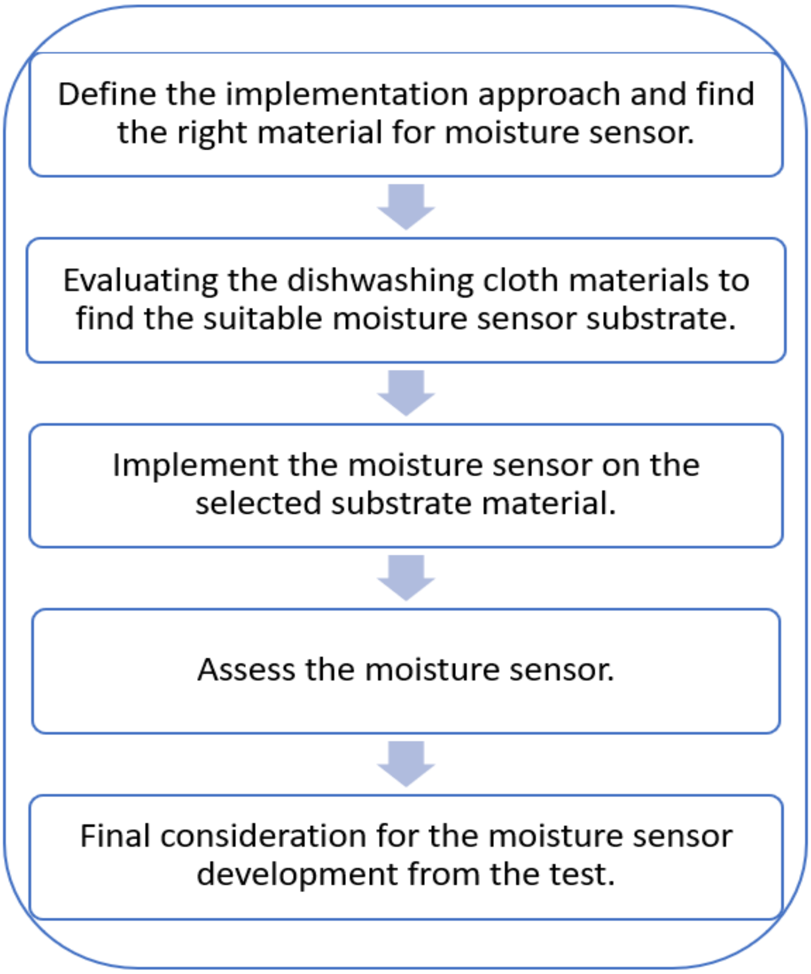


Figure 1. *Flow diagram of the development of the thesis.*

Here, chapter 2 includes the antenna essential and antenna characteristics. Chapter 3 gives a general idea about the RFID systems. Chapter 4 reviews the sensor basics and RFID sensors. Chapter 5 discusses the materials for moisture sensor developments. Chapter 6 describes the fabrication process of the moisture sensor and the measurement setup. Chapter 7 includes the measurement test results of the developed moisture sensors and the thesis's challenges. Chapter 8 is the conclusion and the summary of the thesis work and the scopes of future development of passive UHF RFID moisture sensor is also discussed in this section.

2. ANTENNA BASIC

An antenna is a crucial device for the wireless communication system. It can convert one type of energy to another like electrical energy to a radio wave or vice versa. The antenna can work in two modes in the radio communication system, as transmitter and receiver. The antenna has a close relation with electricity and magnetism. In 1819, the magnetic field was detected by the Johannis Orsted from the compass needle effect due to the flow of electric current. Magnetic field strength depends on the flow of electric current. When the electric current value reaches to maximum, then the magnetic field becomes more vigorous. At Princeton University, in 1842, the first radiation experiment was done by Joshep Henry [11]. The first existence of electromagnetic waves was predicted by James Clerk Maxwell in 1873 [9][10]. In 1888, Hertz established the capacitor plate dipole antenna and loop antenna [8][10]. In 1888, to make the radiation more directive, Hertz constructed the parabolic cylinder reflector antenna by using a zinc sheet [11]. Antenna technology is used in the RFID communication setup, which functions as a support of the principal link between the RFID reader and the RFID tag. To understand this RFID technology, understanding the essential antenna characteristics and antenna basic is crucial, and this chapter will discuss some of the basics about antenna and antenna characteristics.

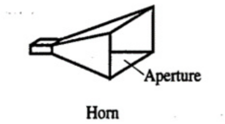
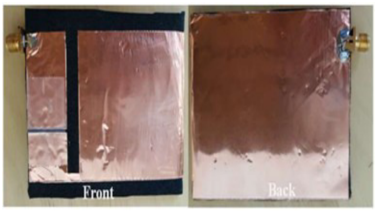
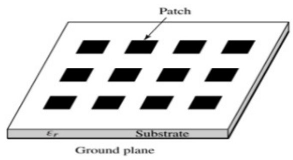
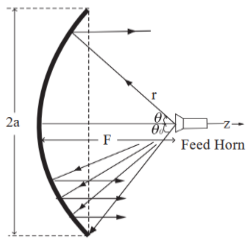
2.1 Antenna definition

According to Webster's Dictionary, an antenna is defined as "a usually metallic device (as a rod or wire) for radiating or receiving radio waves" [6]. According to the IEEE (Institute of Electrical and Electronics Engineers) standard definition, an antenna is, "That part of a transmitting or receiving system that is designed to radiate or to receive electromagnetic waves" [7]. An antenna is a device used to transform a radio frequency signal, traveling within a conductor, into an electromagnetic wave in free space. This signal carries information and this information remains intact, regardless of transmitting or receiving signals even though it faces any obstacle.

2.2 Antenna types

Types of antenna vary according to its application, operating frequency, constitution, material, etc. Table 1 shows the different types of antenna.

Table 1. Different types of antenna.

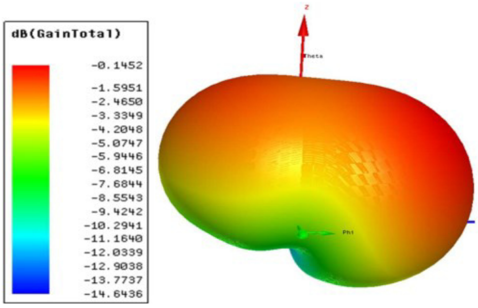
Antenna type	Description	Example
Wire Type	Wire type antenna is the most common type in the surroundings. Dipole, loop, helix, etc. are the examples of a wire antenna [8][9][11][12].	 Dipole antenna.
Aperture type	Aperture type antenna is mostly used for specific sophisticated applications with higher frequency like a horn antenna, rectangular waveguide, reflectors, etc. [8][9][11][12].	 Horn antenna [11].
Microstrip type	Microstrip type antenna is mostly used in government and commercial applications. It became popular in the 1970s. It is a low-cost antenna, which easy to fabricate and analysis. It is versatile for the resonant frequency, impedance, polarization etc. [8][9][13][15].	 Fabricated slotted patch antenna [16].
Array antenna	Array antenna is a set of several antennas which work together as a single antenna to receive or transmit radio waves. This combination arrangement can be electrical and geometrical [8]-[10][13].	 Microstrip patch array antenna [9].
Reflector type	Reflector type antenna is used in long-distance transmission and reception, where the signal travels millions of miles. For this type of antenna, the antenna dimension has to be sizable to achieve higher gain to support long-distance signal transmitting and receiving operation [8]-[11][13].	 Typical reflector antenna configurations [8].

2.3 Antenna characteristics

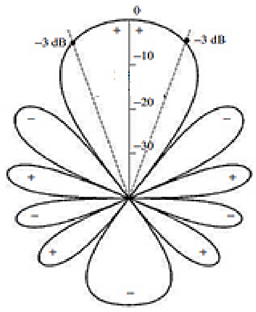
Antenna maintains the same characteristics in case of transmitting or receiving conditions. It can transform radio frequency to electromagnetic waves in a definite direction. For this operation, some of the antenna characteristics affect antenna performance. Some of the characteristics are discussed in this section.

2.3.1 Radiation pattern

The radiation pattern is one of the essential characteristics of an antenna. It stands for the antenna parameter by graphical or mathematical function in free space. It also represents the electromagnetic power distribution of the antenna. According to the IEEE antenna definition, radiation pattern is, "The spatial distribution of a quantity that characterizes the electromagnetic field generated by an antenna" [7]. In far field region the radiation pattern is verified by directional coordinates. Power flux, field strength, polarization, density, etc. are the properties of the radiation pattern [8][9][11][18].



(a)



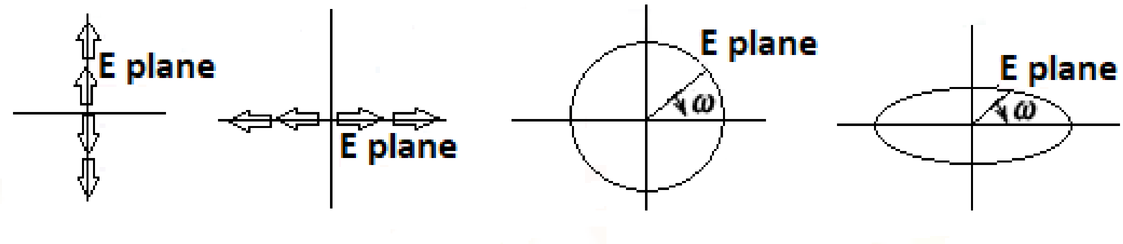
(b)

Figure 2. *(a) 3D circular radiation pattern of UHF RFID reader slotted patch antenna [16], (b) 2D radiation normalized power pattern in dB of 10-element linear array with spacing of d = 0.25 λ [9].*

The radiation pattern can be two dimensional and three dimensional. Figure 2 shows the 3D (Three-Dimension) and 2D (Two-Dimension) radiation patterns. There are two types of radiation patterns: field pattern and power pattern. The most common unit of power pattern is the decibel (dB) [9]. The magnitude of electric or magnetic plot in angular space in linear scale represents the field pattern, and the magnitude of electric or magnetic plot in angular space in the decibel scale represents the power pattern. The electric field is known as E-plane and the magnetic field is known as H-plane [8][9][13][18].

2.3.2 Antenna polarization

Electromagnetic waves are characterized by its polarization, frequency, magnitude, and phase concerning from the point of observation. This electromagnetic wave which varies simultaneously with time. In each direction, the radiated power of a transmitting antenna is an antenna polarization [11]. For, over a period of time, the sum of electric field projected orientation on an imaginary plane concerning the direction of the propagating path of a radio wave is known as polarization. Elliptical polarization is the most common type of polarization. Linear polarization orientation is dependent on the electric field vector along with the plane course of propagation [9]. There are two types of linear polarization: vertical and horizontal. Antenna polarization is also dependent on the vertical and horizontal placement. For example, a straight wire simple antenna has different polarization when it is placed vertically than it is placed horizontally. From the antenna construction, the antenna polarization can be predicted. Reflection influences antenna polarization. Figure 3 shows the several types of polarization [8][9][11][18].



(a) (b) (c) (d)

Figure 3. *Several types of polarization, (a) Vertical line of polarization, (b) Horizontal line of polarization, (c) Circular polarization, (d) Elliptical polarization [11].*

Circular type polarization can be classified by using the direction of thumb rule of propagation. The helical antenna can produce circular type polarization. The linearly polarized antenna can also produce circular type polarization by feeding the same magnitude power into two different points at a 90-degree phase different from each other. Antenna polarization matching between transmitting and receiving antenna is essential for receiving maximum signal strength between the networks [8][9][11][13].

2.3.3 Directivity

According to the IEEE standard definition, the directivity of an antenna in a given direction is “The ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions” [7]. In the case of partial directivity, the radiation intensity is dependent on the polarization and average overall directivity of radiation intensity [8][9][11][18]. It is a dimensionless quantity that can be expressed by dBi (Decibel isotropic). The general Equation (1) [9] of directivity of a given direction is,

$$D = \frac{U}{Uo} = \frac{4\pi U}{Prad}, \tag{1}$$

Where,

D = Directivity

U = Radiation intensity

U_o = Radiation intensity of an isotropic source

P_{rad} = Total radiated power

2.3.4 Gain

Antenna gain is an essential parameter for antenna efficiency performance. Gain is a dimensionless parameter. IEEE standard definition defines the gain of a given direction as "The ratio of the radiation intensity in a given direction to the radiation the intensity that would be produced if the power accepted by the antenna were isotopically radiated" [7]. The general Equation (2) [9] of the gain is

$$Gain = 4\pi \frac{\text{radiation intensity}}{\text{total input (accepted) power}} = \frac{4\pi\, U(\theta,\varphi)}{Pin}\,, \tag{2}$$

Where,

U (θ, φ) = Radiation intensity in a given direction to E-filed

P_{in} = Toral input(accepted) power

An antenna's gain is not dependent on the impedance, polarization, or any type of mismatch of the connected antenna. Antenna gain can be equal to the directivity if it is free from dissipative loss of the antenna. The maximum radiation intensity is considered when the direction of the antenna is not specified. Realized gain has a relationship with the mismatch of the antenna impedance [8][9][11][13].

2.3.5 Beamwidth

Beamwidth stands for the antenna's radiation shape and it defines the operating frequency range of the antenna. Beamwidth varies with different types of antenna. Half power beamwidth is the most used term for beamwidth. According to the IEEE standard definition, half-power beamwidth (HPBW) is, "In a radiation-pattern cut containing the direction of the maximum of a lobe, the angle between the two directions in which the radiation intensity is one-half the maximum value" [7]. Half power beamwidth is also known as -3 dB beamwidth and it is half of the first null beamwidth (FNBW). Figure 4 illustrates the half-power beamwidth and first null beamwidth [8][9][11][13].

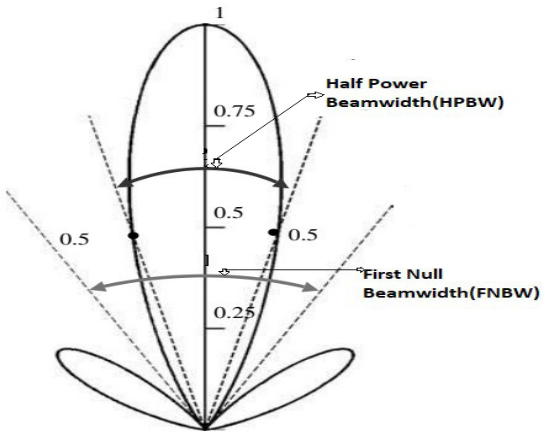


Figure 4. *Two-dimensional representation of half power and first null beamwidth [9].*

2.3.6 Bandwidth

Bandwidth is an operating frequency range of the antenna concerning the antenna characteristics or specific standard [9][11]. It is considered in both sides from the antenna's centre frequency where all the antenna parameters like beamwidth, impedance, gain, radiation pattern, directivity, etc. are in the acceptable range. In the case of a broadband antenna, the lower frequency is ten times lesser than the upper frequency, which is observed from the antenna bandwidth [9]. In Europe, the standard RFID tag antenna frequency bandwidth is 860 MHz to 960 MHz [1]. The bandwidth of a narrowband antenna is stated in percentage, which defines the acceptable operating range. The relationship of the bandwidth with antenna characteristics varies from case to case of the antenna parameters and there is no standard of qualities for bandwidth determination [9]. However, bandwidth can be distinctive as pattern bandwidth and impedance bandwidth. Pattern bandwidth depends on the characteristics of the antenna-like gain, polarization, directivity and beamwidth. Moreover, impedance bandwidth depends on antenna impedance and efficiency of the antenna radiation [8][9][11][13][21].

2.4 Friis transmission equation

The Friis transmission equation shows the relationship between the transmitted and the received power of two antennas as in Figure (5) [20]. These two antennas are placed in the far-field region in ‘r’ distance in such orientation that both the antennas have the maximum gain with matched polarization [8][9][19][20]. Then the general equation (3) [20] for the Friis transmission equation is,

$$\frac{Pr}{Pt} = Gr\ Gt(\frac{\lambda}{4\pi r})^2, \quad (3)$$

Where,

P_r = Power of receiving antenna

P_t = Power of transmitting antenna

G_r = Gain of antenna R

G_t = Gain of antenna T

r = Distance between two antennas.

λ = Wavelength of the frequency.

$\mathrm{AeR} = \mathrm{Gr}\,\lambda^2 / (4\pi)$ is the equation of effective area of receiving antenna.

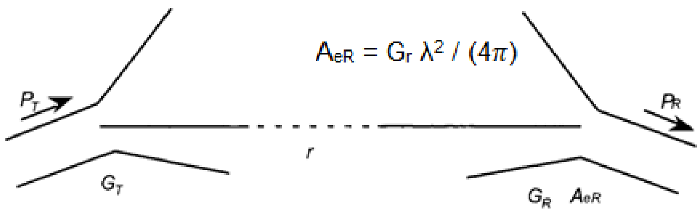


Figure 5. *Friis transmission equation between two antennas [20].*

2.5 Near Field and Far Field area

The antenna is surrounded by two field areas: near field and far-field. Near field is of two types: reactive near field and radiating near field. Figure 6 shows the antenna's field region boundaries, and it is not unique for all the antennas. The radiating energy patterns usually radiate towards and away from the antenna and field energy patterns change very rapidly concerning the distance from the antenna. Field energy is higher when it is closer to the antenna [8][9][11][13].

Antenna’s far-field area is distance independent in case of angular field distribution from a specific point of the antenna. For example, if the maximum antenna length is D and λ is the wavelength, then the antenna’s far-field's existence is on more than the two times of D^2 / λ distance from the specific point of that antenna [9]. Antenna far-field is dependant on the propagation constant of the medium where D is larger than π / $|\gamma|$ [9]. The radiation pattern in the far-field area is known as far-field radiation pattern. From Figure 6, R1 is the area of reactive near field, and R2 is the radiating near field [8]-[11][13][19].

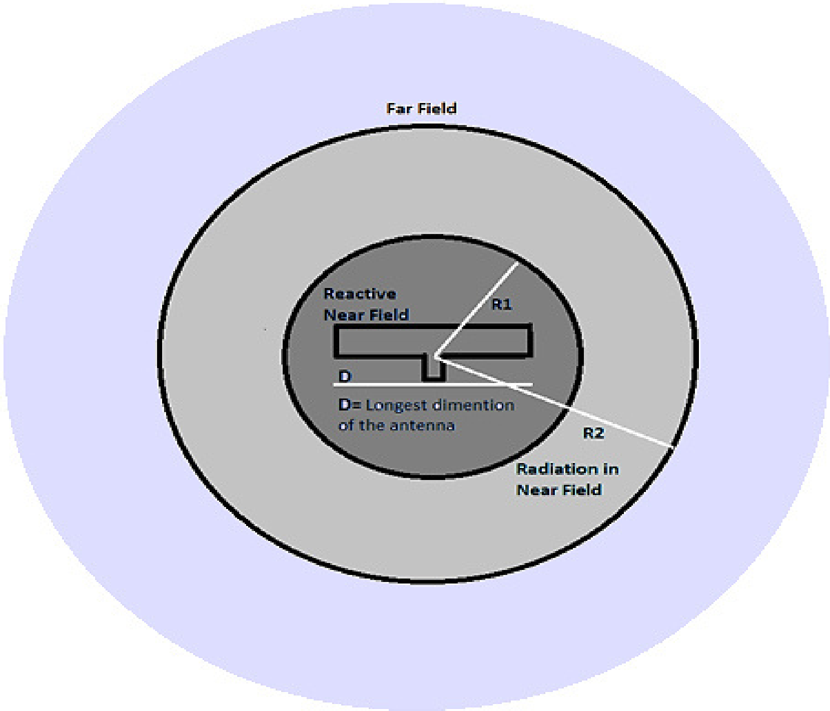


Figure 6. *Antenna field region of near and far-field (Not in scale) [10].*

Near field is the region between far filed and antenna. Any radiation pattern near the antenna is known as fresnel pattern. The reactive near field is the closest surrounding area of the antenna. In a short dipole or equivalent radiator, the reactive field area from the antenna surface is $\lambda / 2\pi$, where λ = wavelength [8][9]. Radiating near field is the area between reactive near field and far-field. For angular field distribution, the radiating near field area is dependent on the distance from the antenna. If the wavelength (λ) is larger than the maximum antenna dimension D, then the radiating near field will not exist [8]-[11][13][18].

2.6 Dipole antenna

In this thesis we used a dipole antenna to develop the moisture sensor so in this section dipole antenna is described in brief. The dipole antenna is the most common and primary wire type antenna. Figure 7 shows the basic structure of a dipole antenna. The dipole antenna operating range is from low frequency to the ultra-high frequency spectrum. A dipole antenna consists of two conductive poles or items on its basic structure. Electromagnetic radiation occurs due to the current and voltage flow through the antenna's conductive path and it radiates outwards of the antenna structure. On the basic dipole antenna structure, the feeder point is in the middle of the antenna. Typically, the two conductive parts of the dipole antenna work as transmitter and receiver of the antenna, and it is placed on the same plane. The intermediate feeder is connected with the dipole antenna receiver or transmitter for power transfer between different points. The length of the dipole antenna affects the parameters like centre frequency, antenna resonance, antenna impedance, etc. which affect the antenna performance [8][9][11][13].

Figure 7. *The basic structure of a dipole Antenna [11].*

There are different types of a dipole antenna, like ideal dipole antenna, small dipole antenna, half-wave dipole antenna, multiple half waves dipole antenna, folded dipole antenna, short dipole antenna, non-resonant dipole antenna, sleeve dipole antenna, cylindrical dipole antenna, etc. Ideal dipole and short dipole antenna have a half-power beamwidth of 90 degrees and directivity of 1.5 dBi or 1.76 dBi. The current distribution for the ideal dipole and the short dipole antenna is uniform and triangle, respectively. For both the ideal and short dipole antennas, the length is much shorter than the frequency wavelength [8][9][11][13].

Half-wave dipole antenna (Length, L = λ (wavelength) / 2) is electrically half wavelength of the antenna conductive parts. At the end of the antenna conductor, the current becomes zero, but voltage becomes maximum. However, at the centre of the antenna, the current becomes maximum, where the electrical wavelength is one fourth from the endpoint of the antenna. The feeder is connected to the midpoint of the half dipole antenna. The half-wave dipole's radiation resistance is 73 ohms, which is close to resonance resistance. It has an omnidirectional H plane radiation pattern required by the mobile communication sector. The half-wave dipole antenna's directivity is 1.64 dBi or 2.15 dBi [10][11][13], which is in between short dipole and full wavelength dipole antenna. The half-power beamwidth is 78 degrees [19]. The current distribution for the half-wave dipole antenna is sinusoidal [8][9][11][13][19]. The folded dipole antenna is the most used wire type antenna. In the structure, the two parallel dipoles become narrow and make it like a loop, as Figure 8.

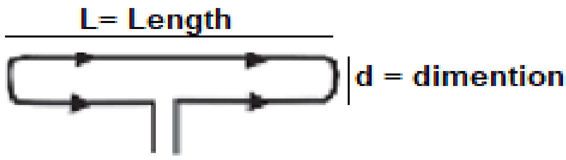


Figure 8. *The Folded dipole antenna structure [11].*

The feed point is in the centre of the antenna. There are two modes for analysing the folded dipole antenna: antenna mode and transmission line mode. In the far-field region, the transmission line mode becomes null due to the small dimension (d) of the antenna structure [8][9][11][13]. From Equation (4) [11], the input impedance can be calculated by the transmission line of the folded dipole antenna.

$$z_t = jz_o tan\beta \frac{L}{2}, \quad (4)$$

Where,

Z_t = Input impedance

Z_o = Characteristics impedance of the transmission line

L = Length of the folded dipole antenna

For a folded dipole antenna, the feeder impedance becomes high, i.e. like 73 ohms to 300 ohms in free space. It has wider bandwidth due to a flatter frequency response. The folded dipole antenna is used as a feeder antenna for the Yagi antenna [8][9][11][12].

3. BASIC OF RFID AND RFID SYSTEM

RFID is one of the most effective and robust technology for detecting objects since World War II. There are three main parts of RFID technology. This section will discuss about the RFID development history, RFID application, working frequency range and different RFID parts, which are used in the RFID technology.

3.1 History of RFID

Radio Frequency Identification (RFID) is a system that uses radiofrequency to detect and identify any products, places, objects, or living things. This technology was first introduced during World War II in 1941 to detect friends and foe aeroplanes. German air force applied this RFID technology in their aeroplanes to detect their allies planes. During World War II, the German radar operator used the backscattered signal from allied aeroplanes to identify the allied target [2][3][21][39] as Figure 9.

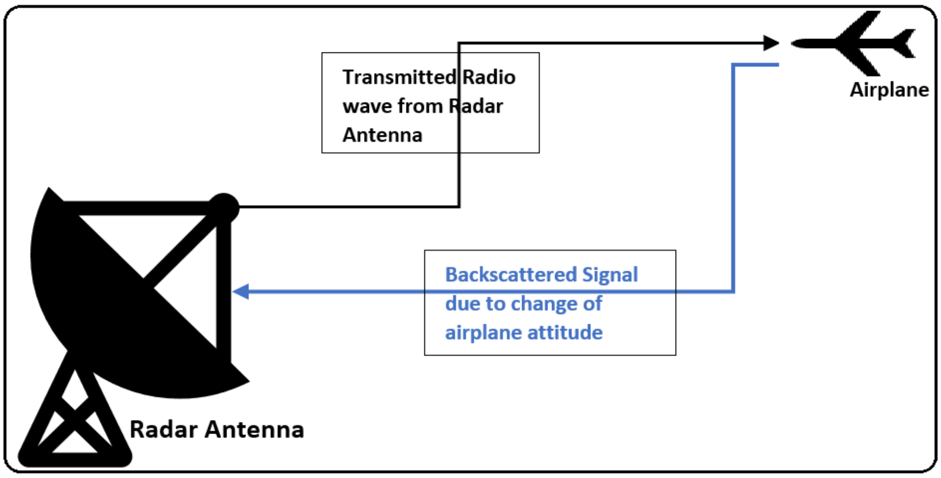


Figure 9. *Communication channel maintaining between radar and aeroplanes by using backscattered power from the aeroplanes [2].*

In 1937/1938, a simple IFF (Identification Friend or Foe) system was tested using active beacon by the USA and Britain [2]. However, later, this technology was limited due to the cost and size of the transponder. In the mid-1950, radar transponder used six-digit identification codes, which was known as Mark III. A mode C transponder received aircraft altimeter and altitude information. Moreover, the S mode transponder could receive the message and display it to the pilot [2][17]-[19].

In 1948, Harry Stockman investigated secure communication by using backscattered radiation. In that investigation, he applied a conventional microphone and speaker coil to modulate the received antenna signal for positioning it using received sound in the microphone [2]. Additionally, this case gives the example of a backscattered radio link that consists of enough information from the transmitter [2][3][22][28].

Modern transponder uses the substantially delay signal from the target to estimate the object's distance using the relativity of the transmitted pulse because it reflects at the speed of light about which is 1 km to 3 in micro second. At 1030 MHz, the transponder is interrogated with a pair of pulse in the ultra-high frequency (UHF) and replies with 12 pulses at 1090 MHz containing information of 1 bit [2]. The RFID system was expensive when it used the transponder system. After the invention of the transistor and integration of logic circuits by scaling down, according to Gordon Moore’s law in the 1960s, the price of RFID starts decreasing which helps cost-effective identification of an object [2][3][23][29].

3.2 Application of RFID

The invention of RFID and the commercialization of this technology has a significant impact on the day to day life. There are many uses of RFID in the present world. RFID technology has reduced the use of barcode. It is a low-cost technology. Passive RFID does not require a line of sight and it also does not require any internal power source such as a battery. It accurately tracks down products, animals, humans, etc. RFID communication can be used for multiple tags [2]. Some of its applications are listed below:

3.2.1 Supply chain and retail business

Passive RFID is used in supply chain management and the retail business sector. It helps to track down the product throughout from production to supply to the retail shop. This technology can be used in any supply chain management system and retail business such as the apparel industry, grocery product, medical sector, cargo handling etc. In the RFID-based supply chain management system, the product has the RFID tag since the manufacturing period [2]. This tag holds the required information about the product throughout the production process, storing in the warehouse and supply to the retail shop. By using an RFID reader, the product information is entered into the control centre in the warehouse. In the host computer, the quantity of the products is recorded showing which products are inside and which are going out of the warehouse. In the end, the final information is stored in the product tag, which is used to find the product in the distribution centre [2][3][32].

3.2.2 Mail department

The RFID tag is used for tracking the mail, parcel etc. with the help of the logistical system. It can store postal code, address etc. RFID can be used for sorting the parcels automatically. The delivery department uses the RFID tag and reader combination to sort out and deliver it to the customer. For this purpose, the handheld RFID reader is used, which is connected with the logistic maintenance server. The monitoring centre can track real-time while delivering mails and parcels [2].

3.2.3 Other applications

Smart homes can be implemented using passive RFID technology. Temperature, moisture, humidity, light, etc. sensor can be used to monitor the home condition for better living for humans. These sensors are usually installed in walls or floors, sometimes in windows for monitoring. It will help to minimize the energy consumption of the house and make it more environment friendly. Household electronics can be integrated with RFID tags to monitor the usages and maintaining the household supply chain [2]. The agriculture sector can use RFID tags to track down cattle. RFID is usually used for maintaining ownership of the livestock. RFID technology also is vital in the commercialization of livestock management. When the ‘mad cow’ disease spread, this animal tracking helped to recall those products from the market [2][3][24]. RFID technology is used for access control and human tracking nowadays. By using this technology, a company can control the security, entry and exit inside the premises and track down its employee’s movement [2][25][33][34]. RFID technology can be used to track books inside the library for supporting the autonomous library system [2][27]. Transport and tourism industry uses RFID technology for toll collection, tracking the vehicles, maintaining parking areas etc. [2][26]. The uses of RFID has drastically increased in the healthcare sectors. It is used for tracing patients, maintaining patients’ samples data like blood, urine etc., medical devices, monitoring health conditions etc. [2][3][31].

3.3 RFID systems technology

A reader, a tag and an antenna are the primary units of a simple RFID system as shown in Figure 10. A reader is known as an interrogator and a tag is known as a transponder. The reader antenna is connected to the reader unit with a cable and tag antenna is integrated into the tag. Usually, a single silicon chip IC (Integrated Circuit) is used for tag ID (Identification) and a protocol is used as a guidance to communicate with tags and readers. Mostly user interfaces the reader. Sometimes, reader and reader antenna is connected with the host computer or network where the user interfaces to control the reader and store, display and resulting data from tags [2][22][36].

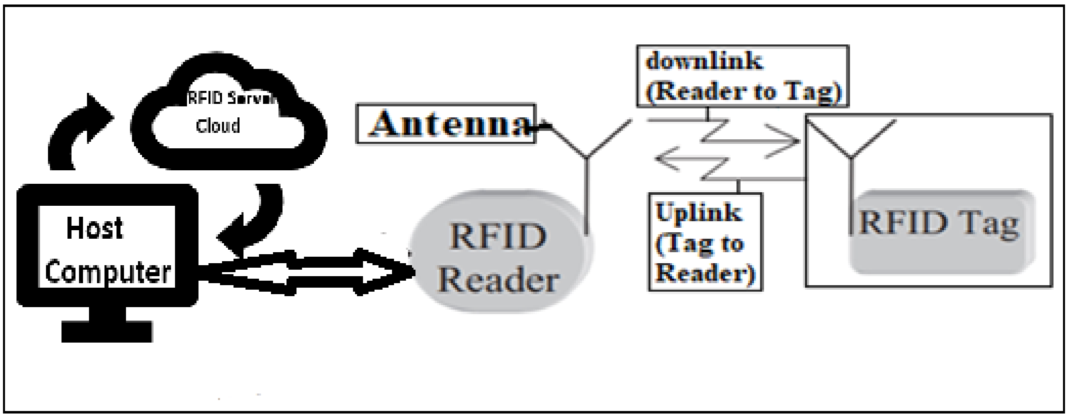


Figure 10. *Overview of RFID System [36].*

The communication channel from the reader to tag is known as forward link or downlink, and tag to the reader is known as uplink or reverse link. Furthermore, this communication channel is used for collecting data in between readers and tags. One reader can communicate with multiple tags within its neighbouring read range in the real-time scenario, and there might be several readers in that neighbourhood at a time [2][3][36][37].

3.4 RFID system frequency band

The RFID frequency band is essential for choosing the operating frequency of the system, protocol and sources of power. It also has an impact on the cost, features, and range of the systems. A user can decide the frequency band according to requirements. Figure 11 shows the frequency band of the RFID. Usually, the RFID frequency range is

100 kHz to 5 GHz. However, with the requirements, it can operate in different narrow-band frequencies. The most used frequency bands' ranges are 125/134 kHz, 13.5 MHz, 860-960 MHz, 2.4-2.56 GHz [2]. Low Frequency (LF) tags and readers work in the operating range of 125/134 kHz. High Frequency (HF) readers' operating frequency is 13.56 MHz. UHF band RFID tags and readers working range is 860 - 960 MHz. At 2.4 GHz frequency, the UHF RFID systems are known as microwave systems [2][14][35][38][40]. RFID operating range wavelength (λ) depends on the ratio of the speed of light (c) and frequency (f), which is shown as Equation 5 [2].

$$\lambda = \frac{c}{f} \quad , \tag{5}$$

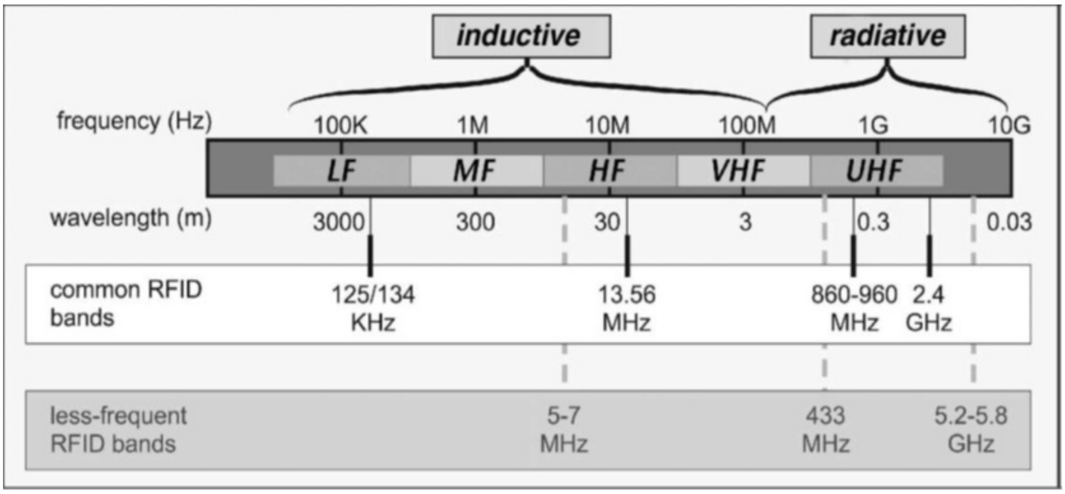


Figure 11. *RFID Frequency Bands [2].*

The RFID system, especially the tag antenna design, affects the operating frequency range. Also, this frequency range can decide the operating communication range between readers and tags [2]. Table 2 shows the worldwide UHF band allocation in 2006.

Table 2. *Worldwide UHF RFID band allocations in 2006 [2].*

Country or Region	Frequency Range
EU, Russia	865-868 MHz or Sub-bands
USA, Canada	902-928 MHz
Mexico	915 MHz, Case by Case
China	917-922 MHz, Required License
Taiwan	922-928 MHz
Australia	918-926 MHz
South Africa	865.6-867.8 MHz, 917-921 MHz

3.5 Types of RFID tags

In real life, three types of tag antennas are used based on the power source: passive, semi-passive, and active tag antenna. In this section, all these three tags are discussed below.

3.5.1 Passive tag

A passive tag is an independent source antenna driven by received rectified radio frequency waves from the reader antenna. When this tag antenna circuitry is turned on, then it sends back the information to the reader antenna. Figure 12 shows a simple diagram of the passive tag communication system [2][27][41][45].

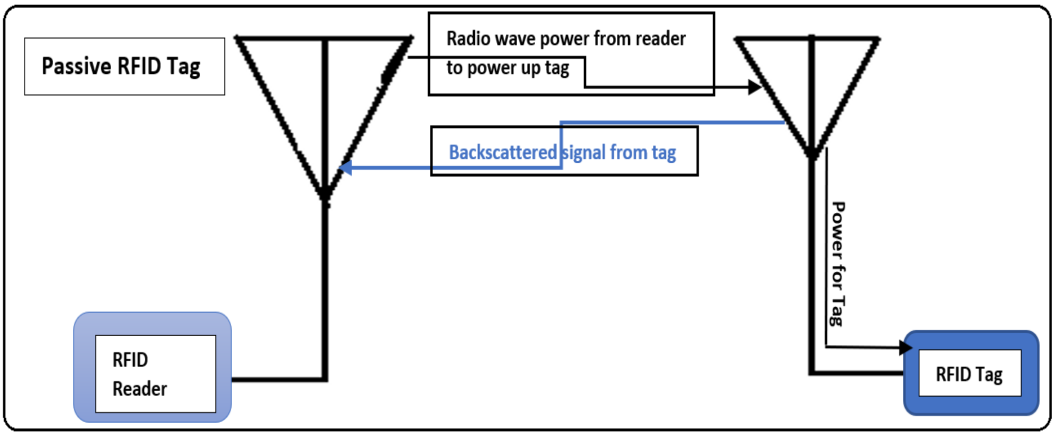


Figure 12. *Passive tag power / transmit configuration [2].*

This passive tag antenna turns on with the help of electromagnetic field waves, which produces high frequency (HF) voltage on the circuitry. In the circuitry, a diode is used for voltage rectification and a storage capacitor is used for smoothing the resulting signal to get constant voltage for operating logic circuitry to access the memory inside the tag antenna. Memory circuitry of the tag antenna is non-volatile during turn off mode. On the reader side, similar circuitry of rectification is used to demodulate the received information. This demodulation technique is known as envelope detection. The tag antenna changes the electrical characteristics and modifies the signal to send the information back to the reader antenna. A field-effect transistor (FET) is used for switching the circuitry. When FET is turned on, then the antenna is grounded [2].

Cost-effectiveness, power source independencies, no crystal frequency reference, no power amplifier requirements, no synthesizer for high-frequency generation, no low noise amplifier requirements, etc. are the benefits of the passive tag structure [2][26]. The main demerit of the passive tag is the low read range [42]. This limitation is acute because of the passive UHF RFID tag. A keen reader signal is required for the passive UHF RFID tag to turn on the circuitry and to send the information back from the tag to the reader [2][44]. In the section of 3.8 passive UHF RFID tag is discribed in further details.

3.5.2 Semi-passive tag

The semi-passive tag antenna is a passive tag that is aided by a local battery source. The local battery helps to turn on the circuitry, but it uses backscatter communication to communicate between the reader and tag for uplink communication as a communication channel. Figure 13 shows a simple diagram of the passive tag communication system.

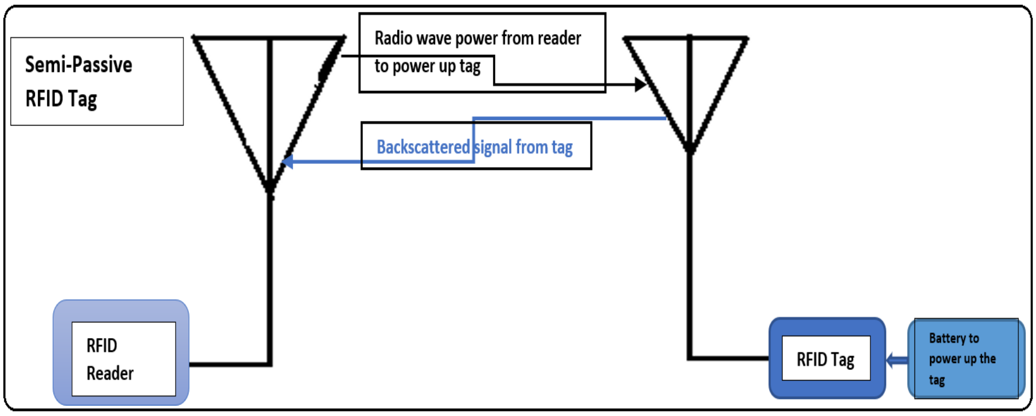


Figure 13. *Semi-Passive tag power / transmit configuration [22].*

In general, the power consumption of the semi-passive tag antenna circuitry is higher than the passive tag antenna for standard commercial integrated circuit (IC). The envelop detection technique is used for a semi-passive tag. Local battery source is used for implementing other RF (Radio Frequency) function and high-frequency amplification. The read range of the semi-passive tag is 1 meter to 100 meters, and it is more dependable compared to the passive tag. In the automobile tolling sector, a semi-passive tag is widely used nowadays [2][43]-[45].

3.5.3 Active tag

Active tag is a bidirectional typical radio system that is powered by both local and traditional transmitted power. An active tag antenna has a battery, receiver, transmitter, filter, mixer, amplifier, control circuitry etc. Figure 14 shows an active tag configuration and schematic diagram of the active tag. Usually, amplitude modulation is used by an active tag. However, it can also use phase-based modulations like phase-shift keying (PSK), frequency-shift keying (FSK), quadrature amplitude modulation (QAM) for specific and sophisticated transmission and demodulation. This phase-based modulation makes it more robust from noise. It uses code division multiple access (CDMA) technique for reusing the same frequency band by multiple tags. The active tag operating read range is 1 meter to a few kilometres, which depends on the environment, frequency band and transmitted power. For having a high read range, it uses significant transmitted power, filter, and amplification. The active tag dose does not depend on environmental obstacles. It can work perfectly with a metal container, even though those containers are near to one another or no line of sight is available from the reader to the tag. However, the active tag is expensive due to the full radio system, size, and maintenance. For finding the active tag antenna location, it uses the signal relative time delay between the tag and the reader [2][26][44]-[46].

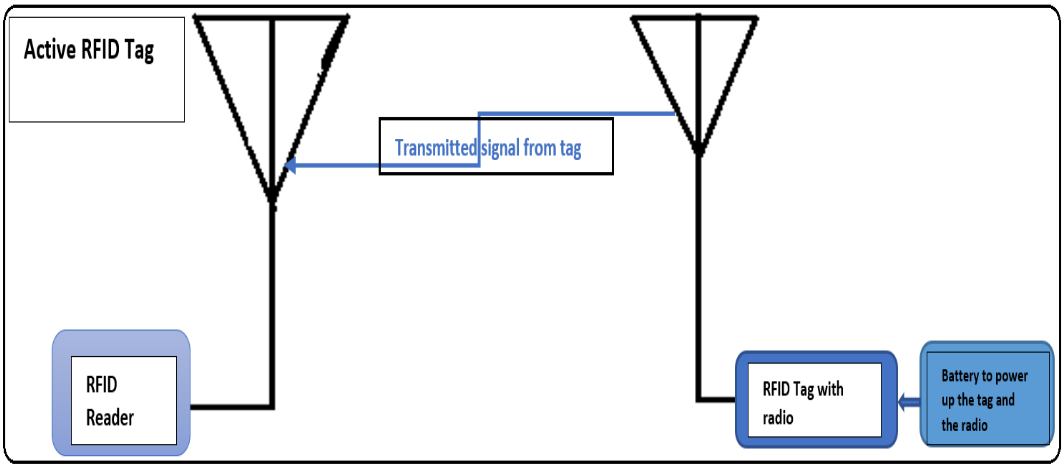


Figure 14. *Active tag power / transmit configuration [22].*

3.6 RFID reader

Modern RFID reader technology has been improved nowadays with smart antenna systems, embedded systems, networking features, digital signal processing units, etc. The RFID reader features help to transfer data with standardized data transfer protocols. For the different RFID applications, the reader needs frequency and coding techniques for full-range operation in low frequency. However, it can create a problem for ultra-high frequency (UHF) tags. To mitigate this problem, the digital signal processing unit of the RFID reader plays a significant role in the data transfer of UHF tags in the standardized protocols [2][36].

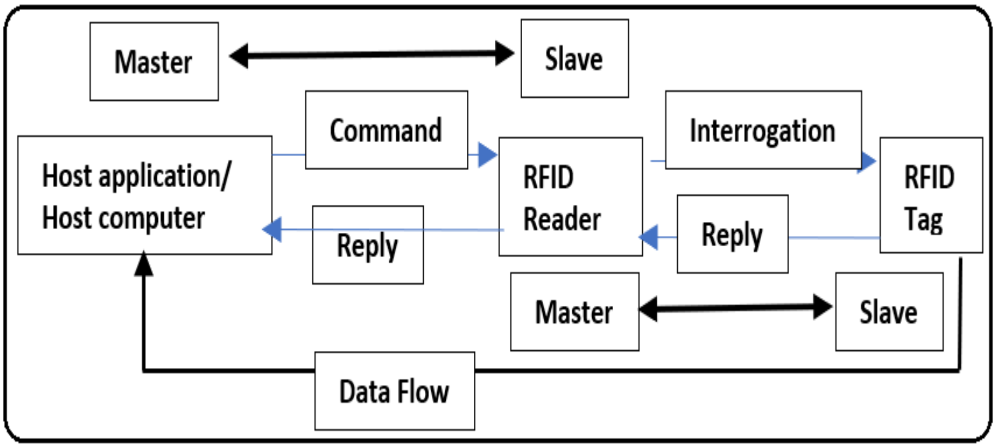


Figure 15. *Block diagram of data architecture of RFID reader [36]*

Figure 15 shows the data structure architecture of the RFID reader. RFID reader functions as a master to RFID tag and host computer acts as a master to the RFID reader. At first host computer sends a command to the RFID reader, then the RFID reader sends an interrogation request to the RFID tag [36]. RFID tags respond to the RFID reader request, and then the RFID reader takes the response data to the host computer. For data extraction from the RFID tag, the RFID reader uses the signal demodulation technique. Passive RFID tag signal responds due to the interrogation request signal from the RFID reader signal [36]. Passive RFID tag operation depends on the RFID reader, but an active RFID tag does not depend on the RFID reader operation. The control section, high-frequency interface and the antenna are components the RFID reader [2][36].

The digital signal processing is done in the control section of the RFID reader by using RFID transponder data. It also performs the modulation and demodulation tasks of the data from the transponder and communicates wirelessly with the transponder [36]. This control section is also responsible for reading and writing data on the RFID tag. The HF interface unit supports the radio wave communication between the RFID reader and RFID tag, and it uses two directional signals for communication. HF interface units consist of the local oscillator, power amplifier, mixer, low noise amplifier and directional coupler for modulation and demodulation of RFID transponder data [36]. Most of the RFID reader of 2.4 GHz uses the binary phase-shift keying and amplitude-shift keying for modulation and demodulation technique [2][36].

The classification of RFID reader varies on several factors, like as power supply, mobility, communication interface, frequency spectrum, data encoding protocols, RFID reader antenna pattern, etc. [2][36]. Figure 16 shows the classification chart of RFID reader.

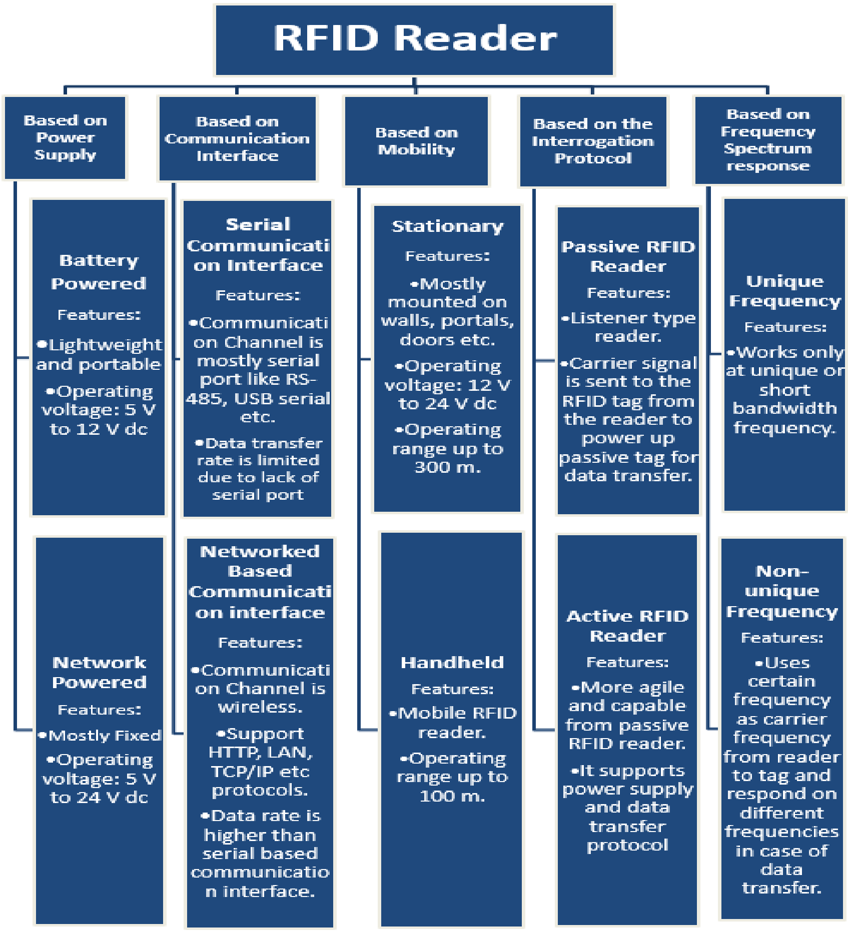


Figure 16. *RFID reader classification [2][23][36][47].*

3.7 RFID coupled antenna types

There are two types of coupled antennas based on wavelengths: inductively coupled antenna and radiatively coupled antenna. The inductively coupled antenna works at a higher wavelength. In this case, the energy is harvested from the reader antenna, and it fades away when the tag is moving out towards the opposite direction of the reader antenna, as shown in Figure 17. The communication between tags and the reader depends on the time fraction of the complete cycle of the RF voltage [2]. The RFID reader and tag system magnetically couple the current flow through the reader and voltage across the tag. For establishing the communication between reader and tag, the radiative coupling is used in the systems when the antenna is comparable to the wavelength in size [2][36].

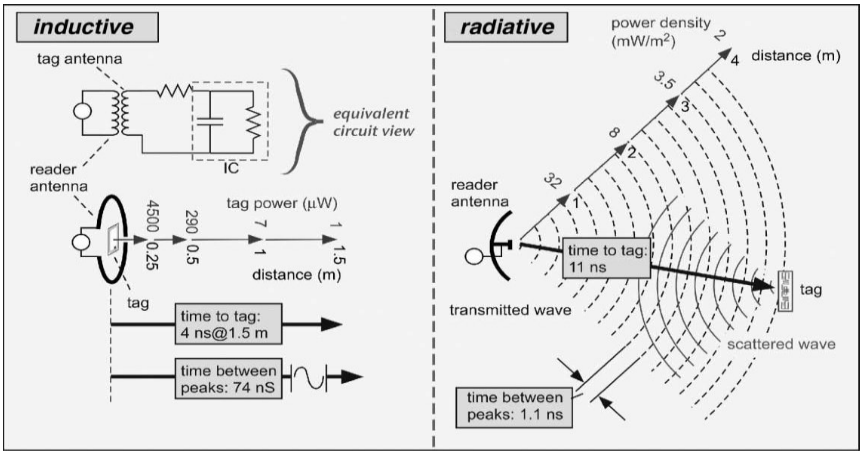


Figure 17. *Inductively and radiatively coupled RFID antenna [2].*

The reader antenna emits electromagnetic wave which reaches to tag antenna. However, the received time is a bit longer than a single Radio Frequency cycle. The performance of the RFID tag depends heavily on the difference between inductive and radiative coupling [2]. The inductive coupling between the reader and tag depends on the distance between them. The communication channel between the reader and the tag fades away quickly as the tag moves away from the reader antenna. If there is some metallic barrier between the reader and tag, then the coupling becomes less stable [2]. Also, the read range of the inductively coupled tag and the reader depends on the size of the reader antenna and direction beam formation [2][36].

For the case of radiative coupling, the power fades away slowly with the increase of distance between the reader and tag. In this coupling, the wavelength is smaller than usual distances between the reader and tag. In this coupling, reflections created by distant obstacles can produce a very complex region of interest and interference with the waves emitted by the reader antenna, which makes the received power dependent on the location of the tag [2]. If a tag antenna is placed inside a rectangular box, then the power received from the walls and the floor is the reflected power. If the distance between the reader and tag is more than 1 m, then the received power of the tag antenna becomes a complex scenario [2]. If the tag is gradually moving away from the reader, then the received power will gradually increase concerning a decrease of half of the wavelength in the case of radiatively coupled RFID reader. Consequently, the radiatively coupled tag may disappear or reappear to the reader antenna several times [2][36].

3.8 Passive UHF RFID tag

In this thesis the passive UHF RFID tag antenna is used for the moisture sensor development. So, in this section passive UHF RFID tag is described elaborately. Passive antenna tag impedance matching is essential for antenna design of both application-specific integrated circuit (ASIC) and the antenna. Nowadays, due to the increasing use of RFID technology, RFID tag optimization is increased. Some individual tags are optimized to use on glass surface, on liquid container surface, on metal surface etc. CMOS technology has minimized the cost of the passive UHF RFID tag [2][22]. Electronic Product Code (EPC) Generation 2 class 1 is the standard protocol for most RFID ASICs. Electronic Product Code (EPC) holds 96 bits, and it supplies information of product manufacture, serial number, protocol version and type. For UHF RFID tags and readers, Generation 2 sets the physical and logical standards for operation [22]. The passive tag receives DC voltage from the RFID reader to energize the transponder circuitry. Minimum power transmission to the tag from the RFID reader is essential for a successful data transfer request-response. For RFID ASIC, the power sensitivity range was – 8 dBm to – 20 dBm for the last fifteen years [2][48]. Designing RFID tag antenna with maximum radiation efficiency is the main requirement. Maximum radiation efficiency can stand for maximum read range. It also depends on the material loss of the tag and the size of the passive tag [22]. Tag antenna performance depends on the radiation pattern and polarization of the RFID reader and the passive RFID tag. A distributed matching element is used for constructing a low-cost tag by supporting a planner geometry. Antenna impedance affects the antenna bandwidth. The worldwide acceptable bandwidth range for passive UHF RFID tag is 860 - 960 MHz [2][22].

The planner dipole antenna, like a half-wavelength dipole, is the most common passive UHF RFID tag. However, the half-wavelength dipole antenna size length can exceed 15 cm to operate in working frequency. Size optimization of the dipole antenna depends on the application and tag materials. The winding technique is used for size optimization, and most of the general-purpose tag size length range is 7 cm to 10 cm. However, size optimization can compromise the tag antenna performance. By capacitive tip loading of the dipole tag antenna with meandering is one of the typical size reduction processes. This process can increase the antenna capacitance, but it may reduce the self-resonating frequency range. Increasing the antenna bandwidth is also a requirement for size optimization. For this dipole antenna width, the increment can reduce the antenna inductance. The antenna quality factor is inversely proportional to the dipole antenna's width for the same size as the thin dipole antenna. However, a thick dipole antenna can increase production cost, which depends on the fabrication process [2][49]-[51]. The read range of the tag represents the passive UHF RFID tag performance. The maximum distance between the RFID reader antenna and the RFID tag is known as the passive UHF RFID tag's read range. The maximum read range depends on tag characteristics, tag orientation, surface influence where the tag is placed, an obstacle between the tag and the reader antenna, nearby tag influence or microwave equipment interference etc. [2][22].

4. BASIC OF SENSOR

Energy consumption has been increased in the modern world, which has caused environmental pollution. Every day, the human consumption of natural resources makes modern human life more comfortable. With the increasing environmental pollution, the risk of health has increased significantly, which has increased pressure on the economy and health system. Also, the modern life system increases humans' life expectancy as well [52][53].

Sensor helps to achieve the significant goals of the comfortable and autonomous livelihood of the humanity of the 21st century. In this modern world, industrial automation, medical therapeutics, home appliances, environment condition monitoring like water, air pollution, transport sector, etc. use sensor systems to make it more autonomous for humans. Smart sensors are integrated with information and communication technology to check the environment [52][53]. This chapter contains a discussion about the basic of sensor and different RFID based sensors.

4.1 Sensor

The device that converts physical phenomenon into an electrical signal is known as sensor [54]. It is an interconnecting medium between the physical world and electrical devices. Sensors and actuators are mostly related to sensor technology. An actuator converts the electrical signal into a physical phenomenon [55][56]. For example, the pressure sensor senses change of pressure and that changes are detected by the voltage change, which is an electrical property that can be the input of the microprocessor for further process of an industry.

4.2 Characteristics of sensor properties

To understand the working principle of a sensor, the study of the characteristics of sensor performance is necessary. A sensor has many characteristics properties. Different domains of the properties of a sensor have different names. Some of the essential properties are discussed in this section.

4.2.1 Range

Range defines the maximum and minimum values of both input and output. Span is known as the full scale of the range. It defines the maximum and minimum values, which can supply the best, accurate operation of that sensor. Moreover, the input voltage of maximum and minimum value stands for the operating voltage of the sensor. If the operating input voltage is not supported, the sensor may be permanently damaged [52][54].

4.2.2 Sensitivity

Sensitivity is the ratio of a minor change of input physical signal and output electrical signal. In the case of liner sensor response, the sensitivity will be constant for an ideal sensor for the sensor's range. Moreover, for the nonlinear sensor, the range of sensitivity varies and it can be derived from the derivatives of the transfer function concerning the physical signal [52][53][63].

4.2.3 Resolution

The minimum detected signal change in the output due to the smallest change in the measurand is known as the sensor's resolution. Resolution should consider the sensor measurand nature. Higher resolution increases the sensor price because it can detect the slightest change in the measurand. The threshold is the incremental change of the measurand from zero to describe the resolution of the sensor [52][53][63].

4.2.4 Bandwidth

The bandwidth of a sensor stands for the cut-off frequency range of upper and lower response times of the sensor due to the change of physical signal in the sensor output. The response time is instantaneous to change in physical signal. However, some sensor has decay time which affects the output response [52][53][63].

4.2.5 Accuracy

Sensor accuracy represents the sensor's ability to provide output value as close as to the actual measurand value. The maximum expected error can be determined from actual and ideal output signals [52][53][63]. It also represents the sensor span. The accuracy of the sensor is determined by using Equation 6 [52].

$$Percentage\ Relative\ Error = \left[\frac{(MeasuredValue - TrueValue)}{TrueValue}\right] x100, \quad (6)$$

4.2.6 Precision

Precision and accuracy have no similarities between them. Precision is the repeatability of the sensor output value for a measurand [52]. Figure 18 shows the difference between accuracy and precision by using a dartboard analogy.

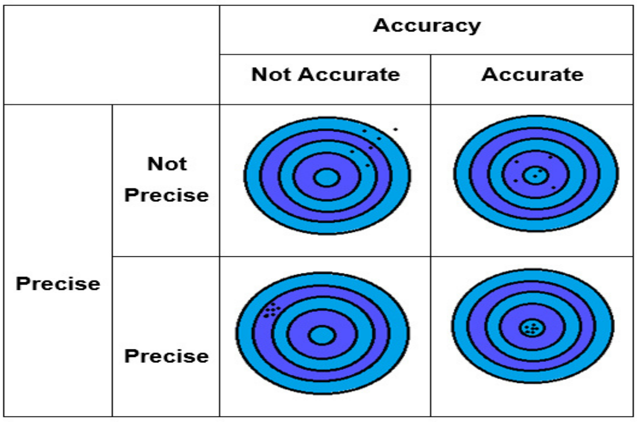


Figure 18. *Difference between precision and accuracy representation [52].*

4.2.7 Error

The difference between reference value or standard value and the measured value is called error. Systematic and random errors are the two forms of error [52]. Systematic error produces inaccuracies. Different compensation methods like feedback, filters, etc. can be introduced in the sensor systems [52] to mitigate systematic errors. Noise is known as random error. Noise signal does not carry information, and it is expressed by signal to noise (SNR) ratio for the case of the signal's quality. If the SNR value is high, then the signal quality is excellent [52][53].

4.3 Types of sensor

Sensor classification depends on different variables. According to the power source, the sensors are two types as active sensors and passive sensors. Active sensors need an additional power source for its operation. This external source is also known as an external signal, which modulates for producing an output signal of the sensor. It is also known as parametric. The modulated signal carries the measured value information of the modulated sensors existing signal. A thermostat is an example of an active sensor, which is a temperature-sensitive resistor. The external electrical current passes through resistance, and it is measured by the variations in voltage or current across the sensor. From known transfer function, this variation can relate to the temperature [62][63].

The passive sensor does not require an external power source for measurement and output. External force produces an electrical signal in the sensor which is converted to an output signal by the passive sensor. The thermocouple, piezoelectric are examples of the passive sensor [53][62][63]. According to the reference selection, sensors are of two types: absolute and relative. The absolute sensor physical scale is independent of the measurand, and it detects the agitation in input compared to the absolute sensor and gives the output signal. The thermistor is an example of an absolute sensor. The relative sensor gives an output signal depending on the particular cases compared to the agitation in the input. The thermocouple is an example of a relative sensor [63].

4.4 Moisture sensor with RFID technology

Environmental comforts for human beings and the animal kingdom depend on the water content in the air. Moreover, it can be determined by relative humidity and ambient temperature. Humidity and moisture are not the same things. Some types of equipment need certainly favourable humidity conditions to work appropriately. In the U.S, moisture is a significant property for gross National products. Moisture expression changes according to the industry or application. In gas, moisture is the amount of water vapour in pounds per million cubic feet of that gas [64]. In general, moisture is the water content of that material, especially for liquids and solid elements. Moisture is the volume of water content in the liquid or solid, which can be extracted as the same water volume from that liquid or solid without any chemical alteration on the material property. Moreover, this moisture water is usually absorbed by that liquid or solid [63].

Moisture sensors can be classified into three types: capacitive, resistive and microwave-based [63]. Capacitor based moisture sensor is cost-effective, reliable and vastly used in the commercial sectors. Ultracapacitor makes the moisture sensor ultrasensitive. Ultracapacitor uses an activated carbon electrode and a porous silicon layer. When moisture increases in the sensor, the capacitance also increases. The capacitance varies from 0 to 17μF for relative humidity changes from 5% to 80% [63]. Here some of the application of developed moisture sensor is discussed below.

The moisture sensor system was developed using passive UHF RFID for the highly moist environment by using the backscattered power of the sensor tag to the reference tag. These sensor tags were constructed by embroidery and three-dimension technique. This sensor system was an example of low-cost battery less moisture sensor system [57].

A flexible PCB (Printed Circuit Board) RFID based sensor was used to detect the wetness of the flexible surface at 13.45 MHz [30]. A UHF RFID based moisture sensor was developed to measure the gravimetric water content in the soil for the smart agricultural monitoring system. By using the reference of the capacitive moisture sensor, this developed moisture sensor can measure the moisture content in the soil [62]. For landslide monitoring, RFID based moisture sensor was used to detect the moisture content in the soil from remotely [58]. By using the backscattered power of passive RFID tag, the moisture content was sensed for sand and soil locations [59]. For monitoring, the moisture condition in the health care sector embroidered passive UHF RFID based moisture sensor could be used for monitoring remotely [60]. A paper-based printed capacitor integrated with a passive RFID tag was used to monitor the moisture content in the soil [61]. For monitoring, the moisture content in the steel-reinforced concrete structure passive RFID based moisture sensor was developed [65]. Printed sensor attached on the simple UHF RFID tag was used for detecting the moisture in the surface [66]. Low-cost moisture sensor was developed by using commercially available kodak photo paper [67]. To measure and detect the moisture content inside the diaper to protect further infection related to the moisture for infant, disable and senior citizen, a passive UHF RFID tag was used as moisture sensor [68].

5. MATERIALS

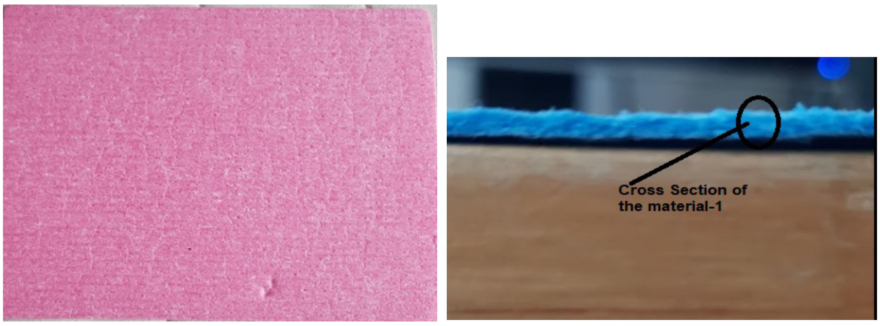
This chapter discusses different substrate materials (dishwashing cloths), which is commercially available in the market, for constructing the moisture sensor tags, the conductive thread, the soluble thread which was used for bending the moisture sensor tags during the moisture test, an RFID IC.

5.1 Substrate material (Dishwashing cloth)

In this thesis, commercially available dishwashing cloths were used as moisture sensor substrates. By conducting moisture testing on the dishwashing materials, the right dishwashing cloth materials were selected. Two criteria were taken into consideration in the dishwashing cloth material selection. Firstly, how much time the material took to be redried and secondly, how the shape of the material changed when was redried. Finally, three dishwashing cloth materials were chosen from six dishwashing cloth materials for this thesis by considering the redried time, material composition, shape changing tendency and durability of the materials.

5.1.1 Sieniliina 10 kpl original

"Sieniliina 10 kpl original" dish washing cloth is commercially available and make by the company named WETTEX. In this thesis "Sieniliina 10 kpl original" dish washing cloth is denoted as Material-1 for representing the test results and discussion that used for this thesis. It is a superabsorbent, 100% biodegradable product that is flexible and soft. This cloth is made of cotton and cellulose. It can absorb 15 times water than its weight. The thickness of the Material-1 is 2 mm. Figure 19 shows the substrate Material-1 [69].



(a) (b)

Figure 19. *(a) Moisture sensor substrate of "Sieniliina 10 kpl original" (Material-1), (b) Cross-sectional view of the dish washing cloth "Sieniliina 10 kpl original" (Material-1).*

5.1.2 Mikrokuituinen iisi sieniliina

"Mikrokuituinen Iisi sieniliina" dish washing cloth is made by the company named IISI. In this thesis "Mikrokuituinen Iisi sieniliina" dish washing cloth is denoted as Material-2 for representing the test results and discussion. "Mikrokuituinen Iisi sieniliina" (Material-2) is a sponge cloth that is made of 80% polyester and 20% polyamide. A sponge cloth is placed in between the outer cloth. It can be washed in the machine at a 60-degree temperature. The thickness of Material-2 is 4 mm. Figure 20 shows the substrate Material-2 [70].

(a) (b) (c)

Figure 20. *(a) "Mikrokuituinen Iisi sieniliina" (Material-2) outer surface image, (b) Inside the structure of the "Mikrokuituinen Iisi sieniliina" (Material-2), a foam layer in between the cloth surface, (c) Cross-sectional view of the dishwashing material "Mikrokuituinen Iisi sieniliina" (Material-2).*

5.1.3 Talousliina 3m

"Talousliina 3m" dish washing cloth is made by the company named SINI. In this thesis "Talousliina 3m" dish washing cloth is denoted as Material-3 for representing the test results and discussion. "Talousliina 3m" is a dishwashing cloth which is composed of cotton and cellulose. It is durable, soft, and water absorbent. The thickness of Material-3 is 1.5 mm. Figure 21 shows the substrate of “Talousliina 3m” as Material-3 [71].

(a) (b)

Figure 21. *(a) Moisture sensor substrate of “Talousliina 3m” (Material-3) (b) Cross-sectional view of the dish washing cloth “Talousliina 3m” (Material-3).*

Table 3 shows several characteristics of the substrate materials.

Table 3. *A short comparison of three substrate materials*

Characteristics	**Material 1**	**Material 2**	**Material 3**
Composition	Cotton and cellulose	80% of polyester and 20% of polyamide	Cotton and cellulose
Thickness	2 mm	4 mm	1.5 mm
Structure	Single structure	A foam layer inside of both cloth outer layer	Single structure

5.2 Conductive thread

Shieldex® 110/34 dtex 2 ply high conductive thread was used in the construction of the moisture sensors. The conductive thread’s linear resistance is < 30 Ω/m; elongation is about 43 %, melting point is 492 F [72]. Figure 22 shows the conductive thread, which was used to fabricate the moisture sensors tags.

Figure 22. *Conductive thread for construct the sensor.*

5.3 Soluble thread

The soluble thread was used to bend the moisture sensor tags to observe how the sensor tags change their shape in redried condition. For this thesis, the 20 degrees 40 s/w soluble yarn was used as Figure 23 [31].

Figure 23. *Soluble thread for evaluating the sensor in bending condition.*

5.4 RFID IC

NXP's UCODE G2iL is the RFID IC in Figure 24, which was used in this thesis to fabricate the moisture sensor tags. Its IC sensitivity is -18 dBm, and during the read and write stage, its sensitivity reaches up to -27 dBm. This IC is a UHF RFID Gen2 chip with 128-bit EPC memory and reads protection facility. The operating frequency range of NXP's UCODE G2iL is 840-960 MHz. Tag IDentifier (TID) is 64 bits with a 32-bit unique factory lock serial number. This data can be stored for 20 years on this IC if it is not physically damaged. The operating temperature range is -40 °C up to +85 °C. The read/write range is high because of its low power design [73][74].

Figure 24. *Used IC of NXP's UCODE G2iL front and back view.*

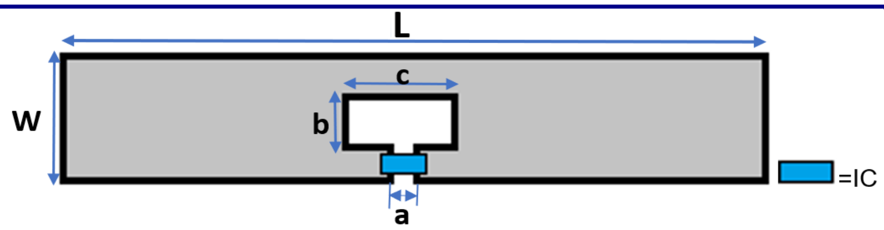
This IC consists of three major blocks of an analogue interface, digital control, and EEPROM. This analogue part supports the power supply, and the digital part controls the data for processing from the reader and sends it back to the reader after modulation using the analogue part. EEPROM controls EPC and user data [73][74]. This IC is connected by a copper pad and a plastic film of 3 x 3 mm2. This IC was connected with the tag antenna using conductive thread by stitching to make the UHF RFID based moisture sensor [73][74].

6. SENSOR FABRICATION AND MEASUREMENT SETUP

This section discusses the sensor fabrication and measurement process. For the fabrication of moisture sensors, embroidery machine and hand stitching techniques were used and for measuring the sensor performance, Tagformance RFID measurement system was used.

6.1 Design of moisture sensor tag

The antenna pattern used for the moisture sensor fabrication in this experiment is as shown in Figure 25 [31]. The antenna was constructed along the edge of the black line of this design.



a	b	c	W	L
2 mm	8.15 mm	14.3 mm	20 mm	100 mm

Figure 25. *Design of a dipole antenna for moisture sensor tag [31].*

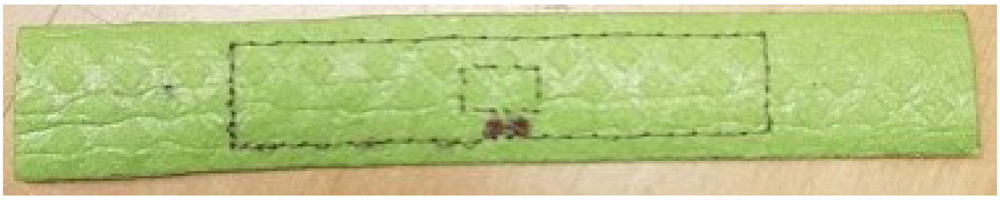
6.2 Fabrication of moisture sensor

Three different materials, as mentioned in Table 3, were used as the substrate for the moisture sensor tags. Twenty-four tags were made by hand stitching methods, eight from each material. However, after hand stitching the moisture sensor tag on Material-2, the sensors were unresponsive. Therefore, the antenna pattern was embroidered on Material-2. In this manner, eight sensors were produced.

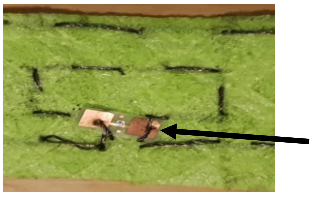
6.2.1 Hand stitching

Initially, the antenna design outline was made with a pen. Then using conductive thread and needle, the moisture sensor tag was constructed on the outline. Initially, one round of the conductive thread was used for the sensor tag construction, as Figure 26. However, the read range was exceptionally low. So, more than one round of conductive thread was added along with the outline. That significantly increased the read range of the sensor tag. The RFID IC was attached to the moisture sensor by stitching as shown in Figure 27 (a). When stitching that IC, the copper portion of the IC part was connected by the conductive thread, as in Figure 27 (b).

Figure 26. *Construction of Passive UHF RFID moisture sensor tag by hand stitching in Material-3.*



(a)



(b)

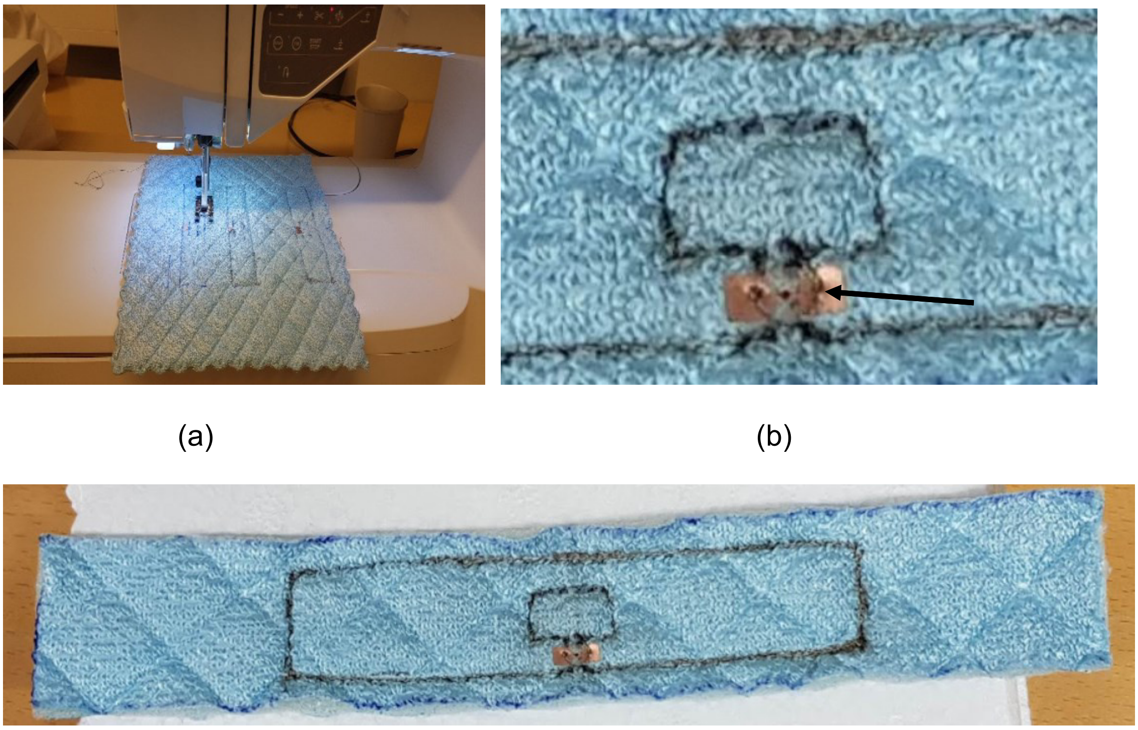
Figure 27. *(a) Final construction of the moisture sensor by hand stitching, (b) IC attachment in the sensor tag by a conductive thread.*

6.2.2 Sewing machine

An embroidery sewing machine was used to construct a moisture sensor for material 2. It was challenging to construct a moisture sensor with Material-2 by hand stitching method. Figure 28 is the sewing machine of the Husqvarna Viking model of DESIGNER-TOPAZ-50 [75].

Figure 28. *Husqvarna Viking embroidery machine.*

Figure 29 shows the process of embroidery. The speed and style of embroidery can be customised according to need in this embroidery machine. In this process, the IC was attached to the substrate by a conductive thread.



(a) (b)

(c)

Figure 29. *(a) Construction of moisture sensor by using a embroidery machine, (b) IC attached on the substrate by a conductive thread, (c) Final constructed sensor tags of Material-2 by using the embroidery machine.*

6.3 Moisture test

For the performance measurement of the moisture sensor, two types of moisture testing were conducted on the sensor tags. The first type of moisture test was done by spraying water on the moisture sensor, and the second type of moisture test was done by submerging the moisture sensors in water. Figure 30 shows the water spray bottle used and water pot where the sensor tags were submerged in water. For the initial substrate selection, fifty sprays of water were applied to them. It was then observed that the substrates took more than twenty-four hours to dry. Therefore, the sprays were reduced to twenty sprays. The moisture sensor tags were submerged in a bowl of water for one minute for moisture test. All the moisture test data were recorded on the host computer by using the Tagfromance RFID measurement system.

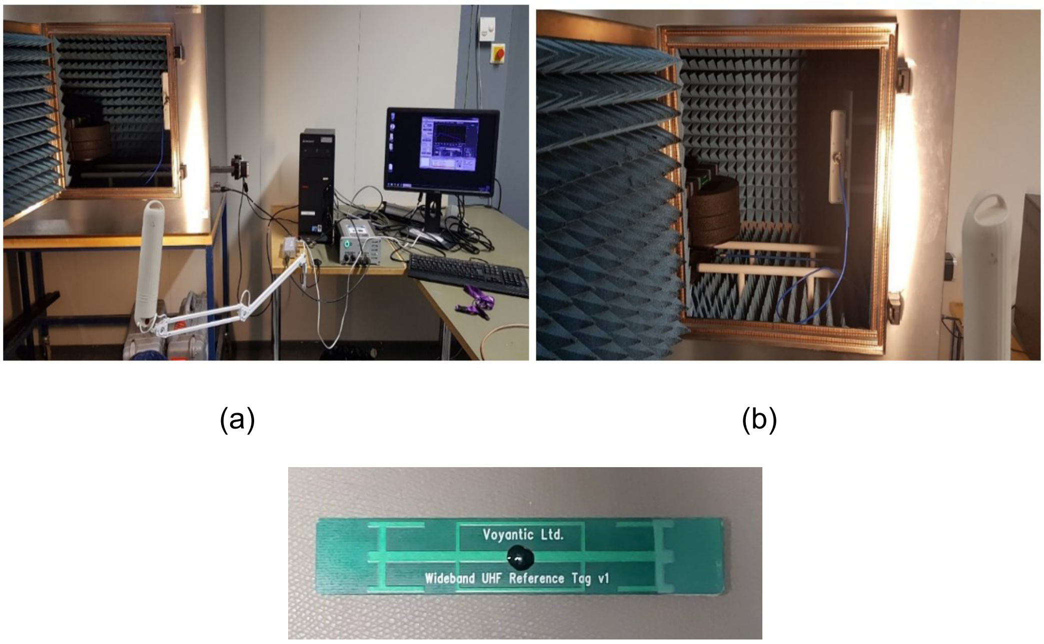
(a)

(b)

Figure 30. *(a) Spray Bottle for a moisture test and, (b) Water submerging test.*

6.4 Voyantic Tagformance

Voyantic Tagformance measurement setup consists of a host computer, a reader antenna, a reference RFID tag, absorbent material inside the anechoic chamber, a Tagformance RFID measurement module and an anechoic chamber. This Tagformance RFID module was connected with the host computer for measurement and measured data storage. Also, Tagformance module was connected to the reader antenna inside the anechoic chamber to read the RFID tag performance. Figure 31 shows the setup and types of equipment used in Tagfromance RFID measurement system. For the measurement, it uses a linearly polarized reader antenna. As communication channel standard between RFID tag and the reader, it uses ISO 18000-6C [31][72].



(a) (b)

(c)

Figure 31. *(a) Tagformance measurement setup, (b) Anechoic chamber, and (c) Reference RFID tag for calibration the setup.*

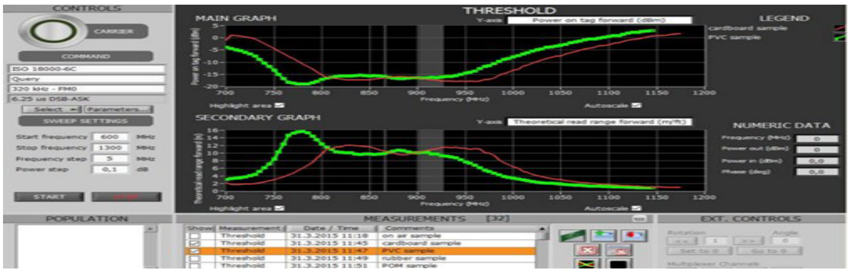


Figure 32. *The software interface of the Tagformance for measurement.*

Using this Tagformance module, usually, we can measure the reader RFID. UHF frequency full range is 800-1000 MHz and resolution 100 kHz. The accuracy of the Tagfromace module is +/-1 dB, and repeatability is 0.1dB. UHF maximum radiated output power is 36 dBm. This Tagformance module can measure both RFID and NFC tags. Tagformance can be used for benchmarking of the tags, and it is a very high-quality professional testing equipment to measure better performance. Figure 32 shows the software interface of Tagformance. It can be measured through the threshold power, backscattered power, threshold read range, link budget, orientational sensitivity, read range, tag emission testing etc. [31][76]. Tagformance uses the Equation (9) [31] for measuring the tag. Here, d_{tag} is the measured read range, λ is the wavelength of the carrier frequency, EIRP is the Equivalent Isotopically Radiated Power, which is equal to 3.28 W, Λ is the sensitivity constant, P_{th} is the threshold power, and P_{th}* is the measured threshold power of the system reference tag [31].

$$dtag = \frac{\lambda}{4\pi r}\sqrt{\frac{EIRP}{\Lambda}\,\frac{Pth*}{Pth}}\ , \qquad (9)$$

7. MEASUREMENT AND RESULT DISCUSSION

In this section, the measurement process and test results of the thesis are discussed.

7.1 Measurement of moisture sensor for different radius bending at dry condition.

At first, the moisture sensors were assessed to understand the effect of bending on the sensor tags by using three different radius surfaces and the measurement setup, as shown in Figure 33.

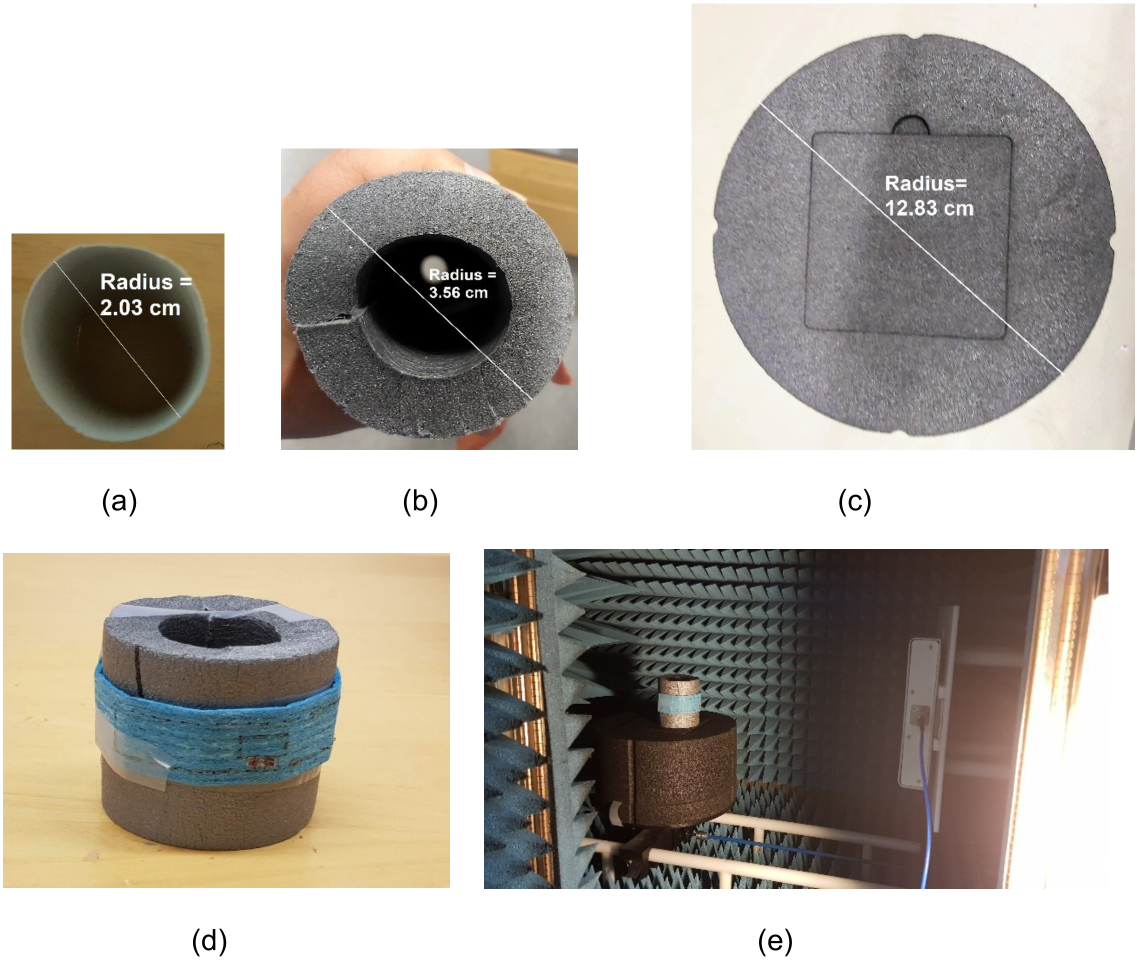


Figure 33. *(a) Bending surface object of the radius of 2.03 cm, (b) Bending surface object of the radius of 3.56 cm, (c) Bending surface object of the radius of 12.83 cm, (d) Attached moisture sensor on the bending surface of 3.56 cm radius, (e) Measurement of the bending effect of the moisture sensor on the radius of 3.56 cm.*

7.1.1 Material-1

Because of the bending effect, the read range of Tag-1 and Tag-2 of Material-1 started decreasing compared to their initial condition read range. So we could say that Tag-1 and Tag-2 showed similar read range pattern. The read range decreased with bending increment because of the changes on the surface of the moisture sensor and tag antenna performance. For instance, in Figure 34 (b), on the initial condition, the read range was 7 meters at 800 MHz frequency, and when the 2.03 cm bending took place, the read range decreased to 4.75 meters. Figure 34 shows the read range pattern of the bending effect of the moisture sensor tag in the testing surface.

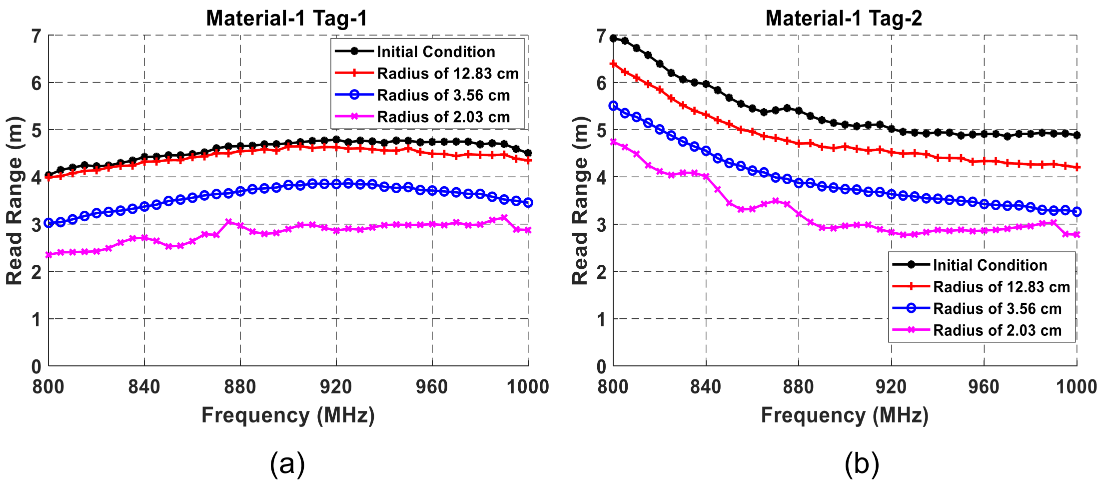
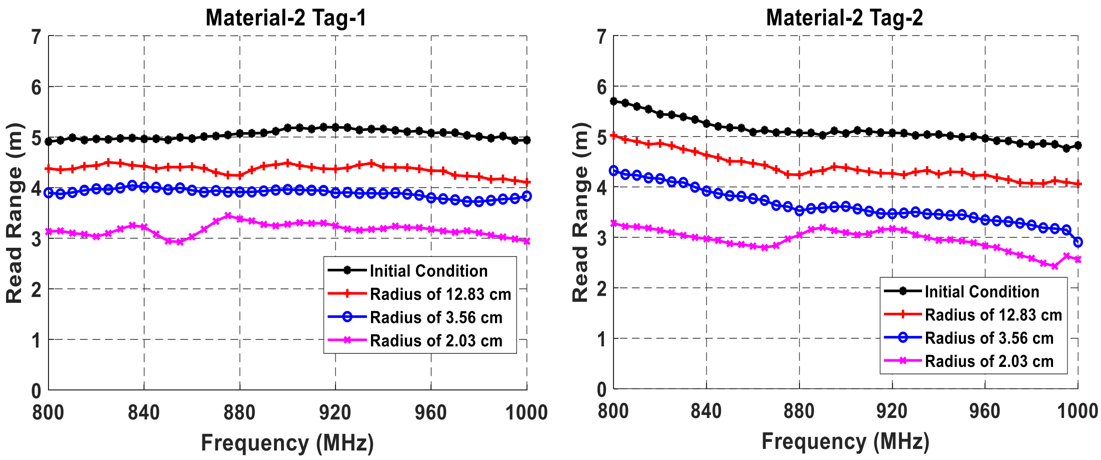


Figure 34. *Read range of Material-1 (a) Tag-1 and (b) Tag-2, in bending condition for different radius.*

7.1.2 Material-2

The read range pattern of Tag-1 and Tag-2 of Material-2 showed a normal initial read range. This read range for both tags were dependent on the bending of the surface. Because of the decrease in radius, the bending of the testing surface increased, which affected the moisture sensor tag's read range. Figure 35 shows the read range responses.

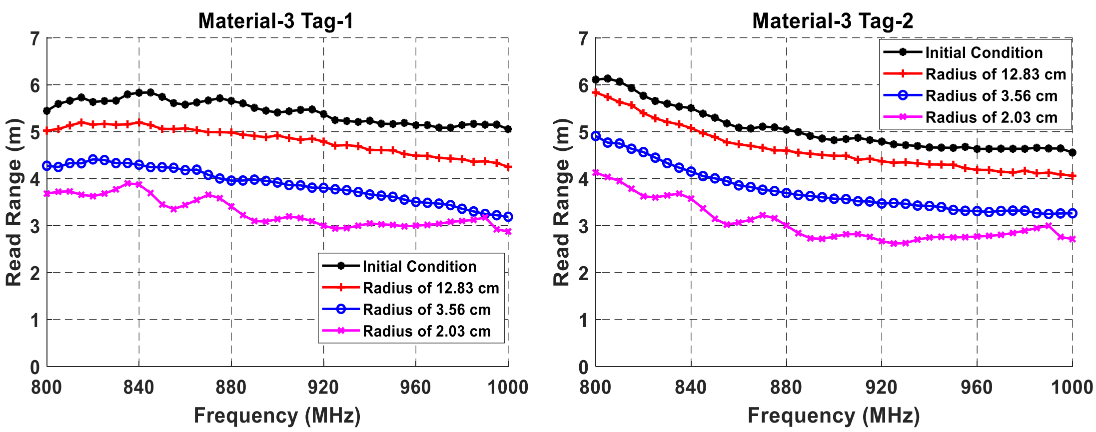


(a) (b)

Figure 35. *Read range of Material-2 (a) Tag-1 and (b) Tag-2, in bending condition for different radius.*

7.1.3 Material-3

There was a similarity in the initial read range of Tag-1 and Tag-2 of Material-3. Read ranges were reduced when bending increased. For example, the initial read range was 6.1 to 5.6 meters for the Material-3 moisture sensor tags. Furthermore, when the bending was on 12.83 cm testing surface, the read range became 5.7 to 4.3 meters for Material-3. When the radius was 2.03 cm, then the read range became 4.2 to 2.2 meters. Figure 36 shows the read range pattern and the test results for different bending conditions of the Material-3 Tag-1 and Tag-2.



(a) (b)

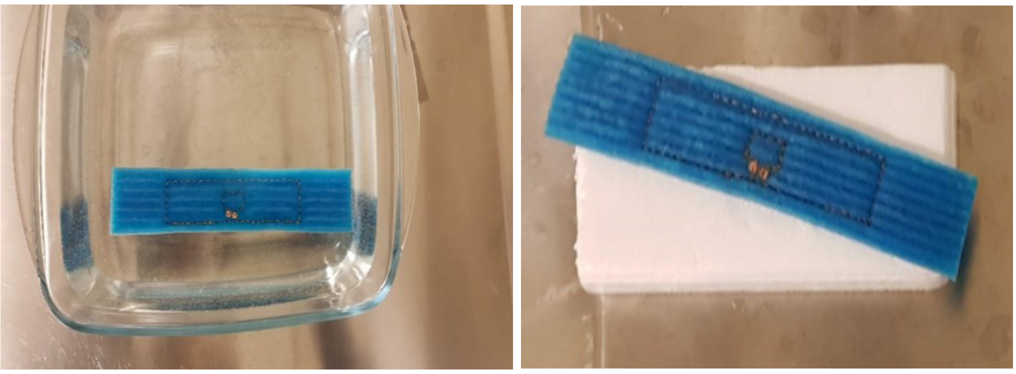
Figure 36. *Read range of Material-3 (a) Tag-1 and (b) Tag-2, in bending condition for different radius.*

7.1.4 Observation of the bending effect

Finally, from the bending test results, it was observed that an increase in bending condition results in the reduction of read ranges of the moisture sensor tags.

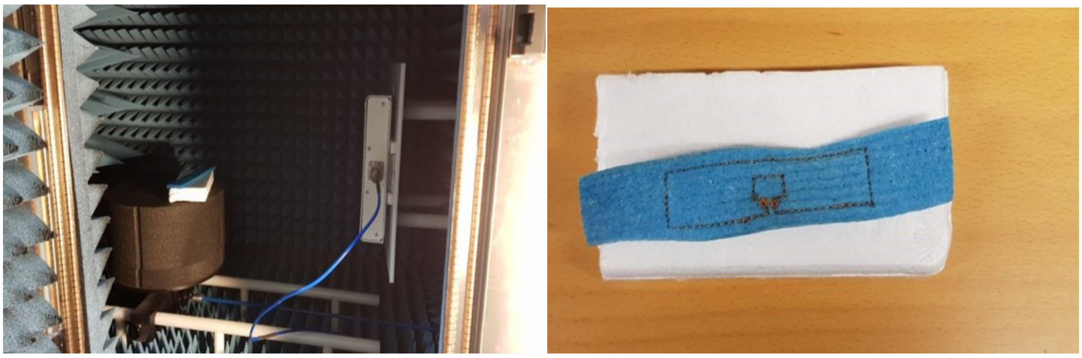
7.2 Measurement of moisture effect on moisture sensor

The moisture affects the read range of the moisture sensor tags. The moisture tags were measured in the initial condition (dry state), and then it was submerged in the water, and after that read range was measured. Then finally, when redried the read range was measured to observe the effect of moisture on the moisture sensor tags. Figure 37 shows the moisture testing on the moisture sensor, and Figure 38 shows the measurement setup and measurement of moisture sensor tag when redried.



(a) (b)

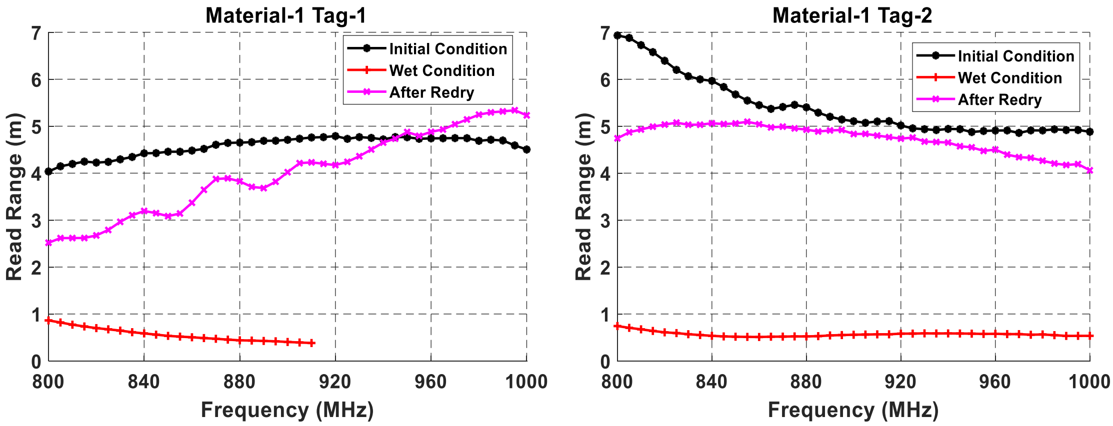
Figure 37. *(a) Testing the moisture sensor by submerging in the water, (b) Moisture sensor after submerging in the water.*



(a) (b)

Figure 38. *(a) Measurement setup for testing the moisture in moisture sensor read range, (b) Fully dry condition of moisture sensor.*

7.2.1 Material-1 moisture effect

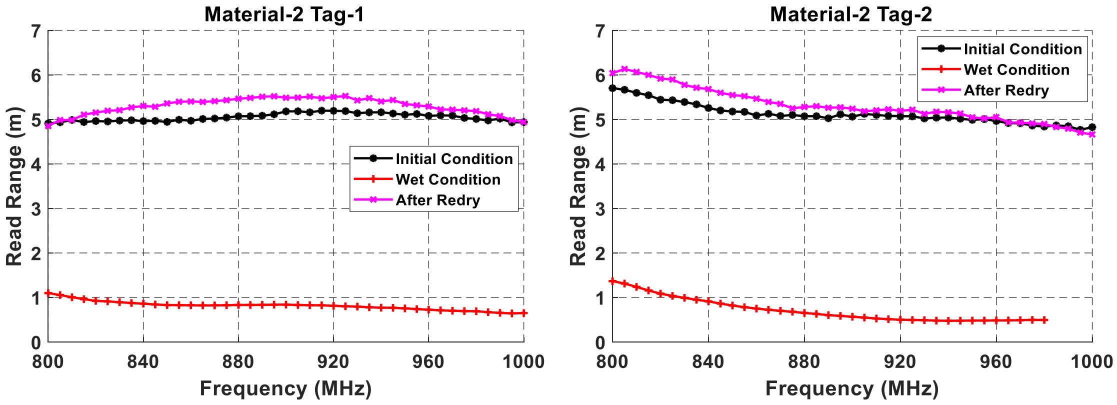


(a) (b)

Figure 39. *Read range of the moisture sensor of Material-1 (a) Tag-1, and (b) Tag-2 in different moisture conditions.*

The performances of the Material-1 Tag-1 and Tag-2 are shown in Figure 39. The results show that when the tag was wet, the tag's maximum read range was reduced by several meters, i.e., from 4.8 meters to 0.9 meters. One possible reason is because of the higher dielectric permittivity of water than that of air. Later, when the tags redried, the read range patterns were expected to return to the original conditions. However, it did not happen due to the deformation in the geometrical shape of the tag antenna. Furthermore, the thread's conductivity for the fabrication of the tags also changed, contributing to the change in the read range values.

7.2.2 Material-2 moisture effect



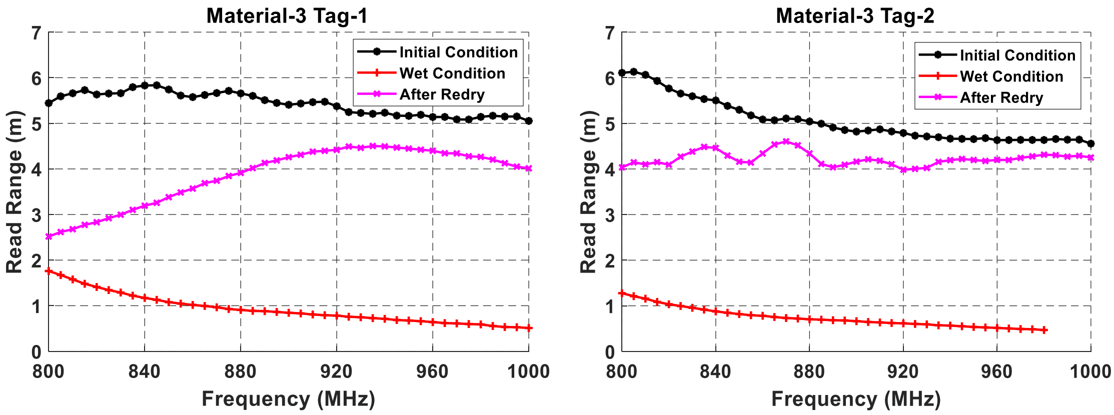
(a) (b)

Figure 40. *Read the range of the moisture sensor of Material-2 (a) Tag-1, and (b) Tag-2 in different moisture conditions.*

Material-2 Tag-1 and Tag-2 showed a familiar initial read range pattern in Figure 40. The read range was significantly decreased when it was in wet condition. Furthermore, when it redried, then the read range became similar to the moisture sensor's initial condition.

7.2.3 Material-3 moisture effect

Material-3 Tag-1 and Tag-2 exhibited a familiar initial read range pattern for both of the tags. Figure 41 showed the moisture sensors' test results for different conditions like dry, wet and redried state. The read range was dependent on the moisture condition. The read range considerably decreased when the tag became entirely wet.



(a) (b)

Figure 41. *Read the range of the moisture sensor of Material-3 (a) Tag-1, and (b) Tag-2 in different moisture conditions.*

7.2.4 Observation of the effect of moisture in the moisture sensor

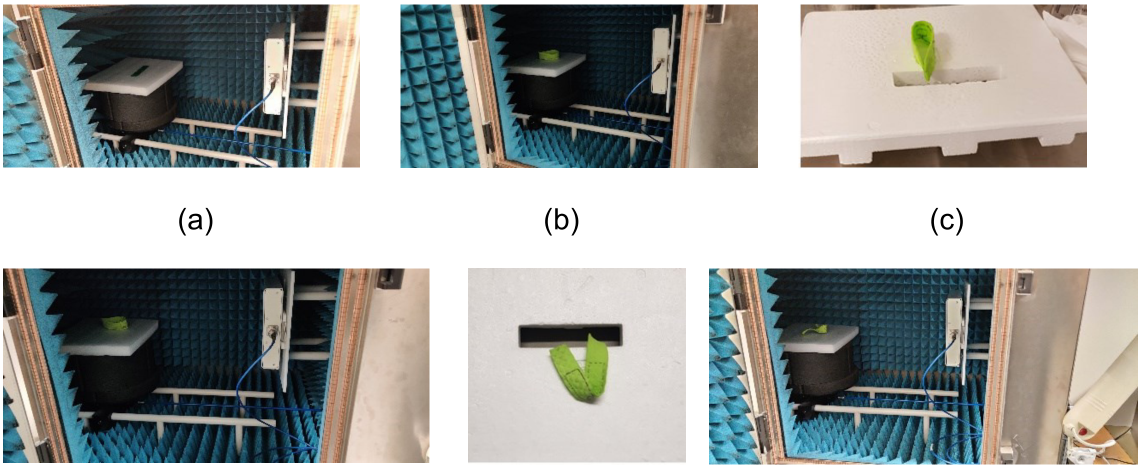
From all the results above, it was observed that the moisture sensor showed a drastically lower read range during the wet condition. In these measurements, the tags were kept on a flat surface to observe the situation without any geometrical shape deformation in the tags. The read ranges of the redried tags were similar to their initial condition. However, that Material-3 showed a reduced read range in the redried condition due to change in the geometrical shape of the moisture sensor tags. In comparison with the other two materials, the performance Material-2 Tag-1 and Material-2 Tag-2 were better.

7.3 Measurement of moisture sensor tags in different condition

The fabrication method of tags was the same for every three substrates (dishwashing cloth) material. The Tagformance measurement setup with an anechoic chamber was used. All the tags were bent using soluble thread, as Figure 42.

Figure 42. *All the tags were freely bent using soluble thread*

Moisture sensor tags were tested in initial condition (dry), wet condition, and redried conditions by bending sidewise, as in Figure 43.

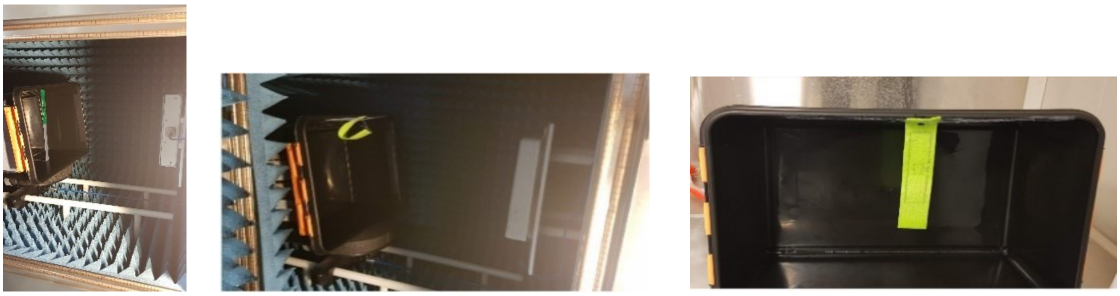


(a) (b) (c)

(d) (e) (f)

Figure 43. *(a) Calibration of the setup using calibration tag, (b) Measure the moisture sensor tag at dry condition, (c) Apply the water on the moisture tag, (d) Measuring the moisture tag in wet condition, (e) Moisture tag after fully dry condition, (f) Measuring the moisture tag after the fully dry condition.*

Moisture sensor tags were tested initial condition (dry), wet and redried conditions by bending in hanging position, as in Figure 44.



(a) (b) (c)

(d) (e) (f)

Figure 44. *(a) Calibration of the setup using calibration tag, (b) Measure the moisture sensor tag at initial condition, (c) Applying moisture on the moisture tag, (d) Measuring the moisture tag on wet condition, (e) Moisture tag after redried condition, (f) Measuring the moisture tag after the redried condition.*

Table 4 shows the different states of moisture sensor when redried in the case of bending sidewise, and Table 5 shows the redried condition of moisture sensor tags in bending by hanging position.

Table 4. *Sidewise bending position of moisture sensor tags at initial, wet and redried state*

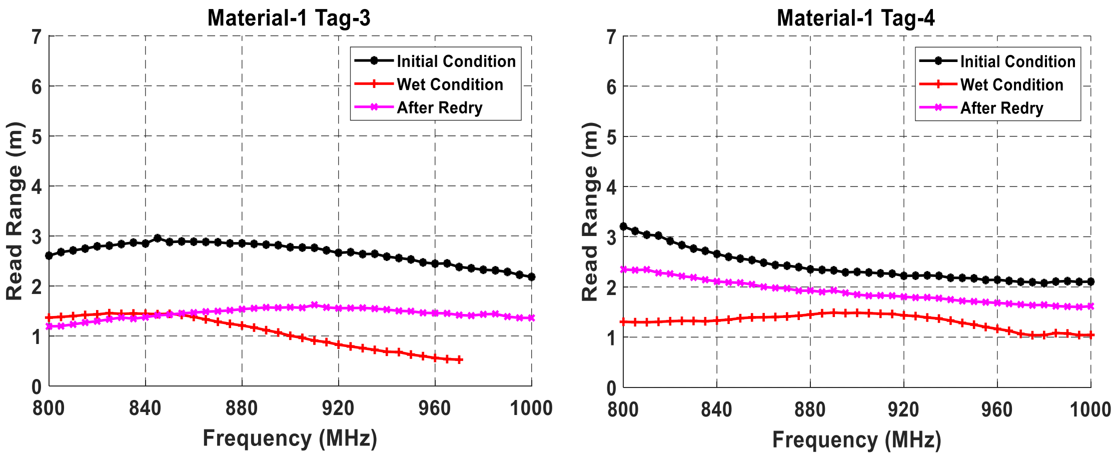
Bending in Sidewise Position	**Initial Condition**	**Wet Condition**	**Redried Condition**
Material-1			
Material-2			
Material-3			

Table 5. *Bending in hanging position of moisture sensor tags at initial, wet and redried states*

Bending in Hanging Position	**Initial Condition**	**Wet Condition**	**Redried Condition**
Material-1			
Material-2			
Material-3			

7.3.1 Measurement of Material-1 moisture sensor tag

Material-1 was observed by bending in both sidewise and hanging position to record the effect of moisture on the design of moisture sensor tags.



(a) (b)

Figure 45. *Read range of moisture sensor tag (a) Tag-3 and (b) Tag-4 of Material-1 in bending sidewise position under initial, wet and redried conditions.*

Tag-3 and Tag-4 of Material-1 were observed in sidewise bending position, and the test results are shown in Figure 45. The read ranges were measured in the anechoic chamber for three different conditions: initial (bending dry), wet and redried. Both of the tags' read range patterns were similar in the initial and redried conditions.

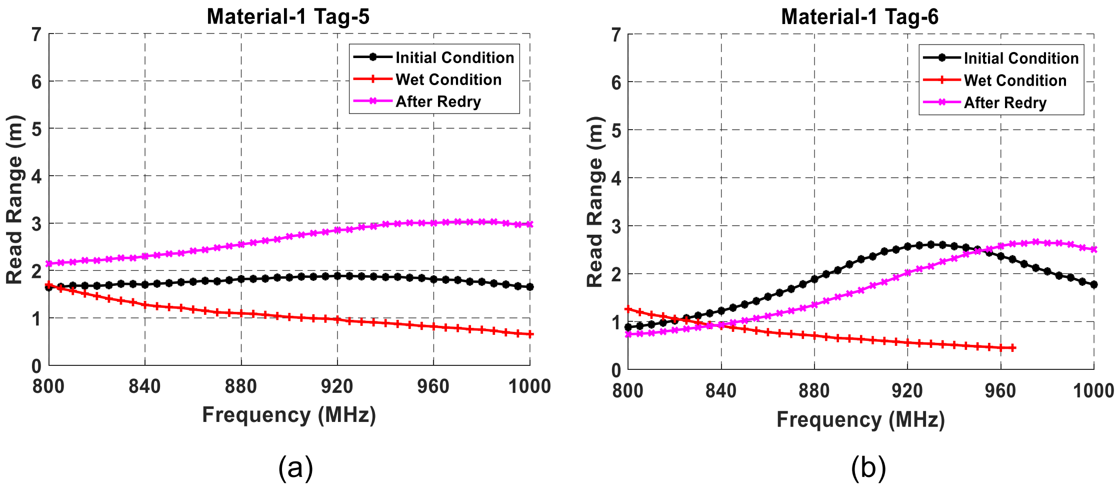


Figure 46. *Read range of moisture sensor tag (a) Tag-5 and (b) Tag-6 of Material-1 in bending in hanging position under the initial, wet and redried conditions.*

The read ranges of Material -1 Tag-5 and Tag-6 were shown in Figure 46. Those had a similar read range pattern in both initial and redried states. Read ranges of the tags were considerably reduced in their bent states. The read ranges of Tag-5 and Tag-6 had decreased by 55 % approximately. In the lower frequency, the read ranges of tags in the wet state were higher than the redried state of the tags.

7.3.2 Observation of Material-1 moisture sensor after testing

From the Table 4 and 5, the tested materials show that in the hanging position the shape of Material-1 returned to its initial shape in the redried state, but in the sidewise position the initial shape could not be reached in redried state. Tag-3 and Tag-6 of Material-1 stopped working in wet condition, but it started working in the redried state. When the tags were redried from their wet condition, they could not reach their initial read rage level.

7.3.3 Measurement of Material-2 moisture sensor tag

The test results of Material-2 moisture sensor tags in different positions are shown in Figure 47.

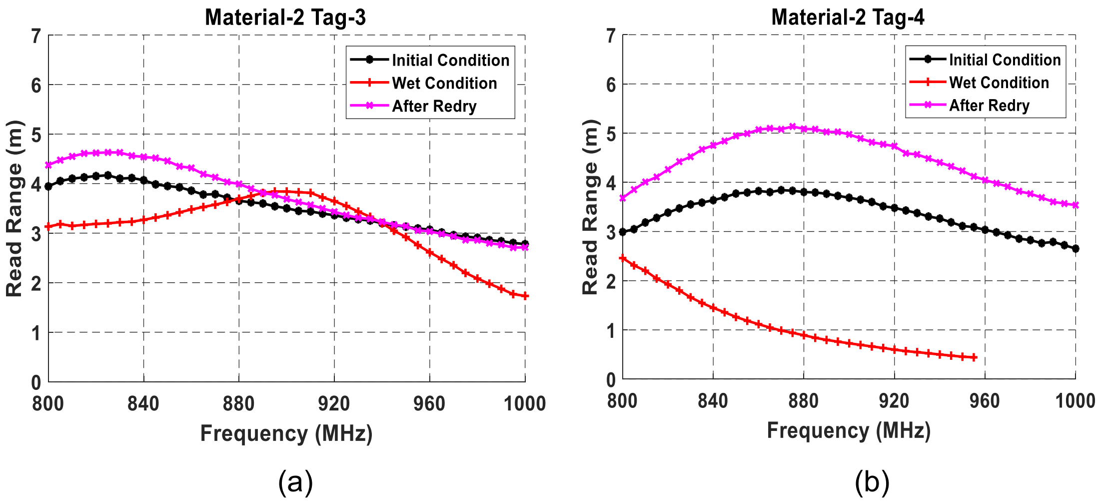


Figure 47. *Read range of moisture sensor tag in bending in sidewise position test result for three conditions of Material-2 (a) Tag-3 and (b) Tag-4.*

Moisture sensor tags of Material-2 were assessed by bending sidewise. Figure 47 shows the read range of Tag-3 and Tag-4 of the different conditions like initial (bending dry), wet, and redried states in the sidewise bending position. For both sensor tags, the read range patterns of the initial and redried condition were similar.

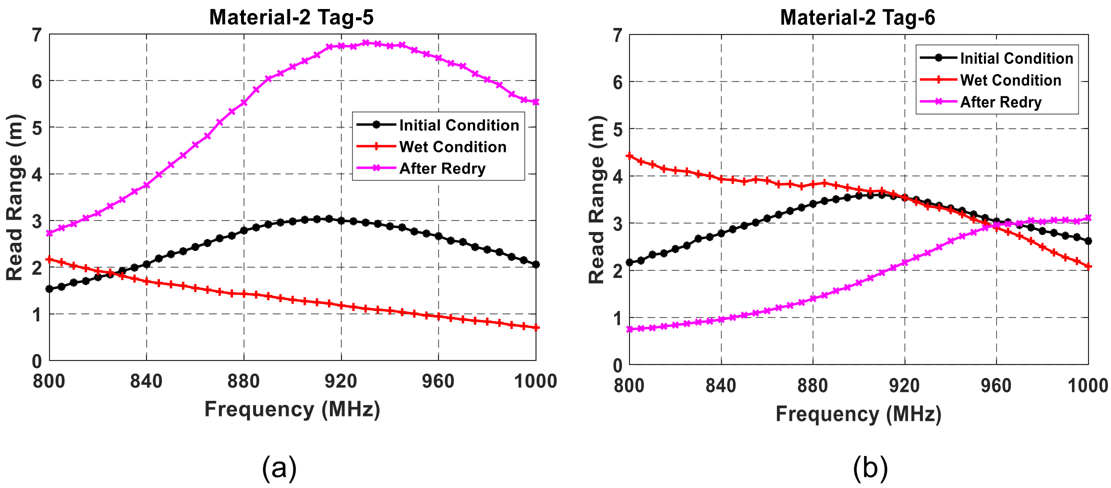


Figure 48. *Read range of moisture sensor tag bending in hanging position test result for three conditions of Material-2 (a) Tag-5 and (b) Tag-6.*

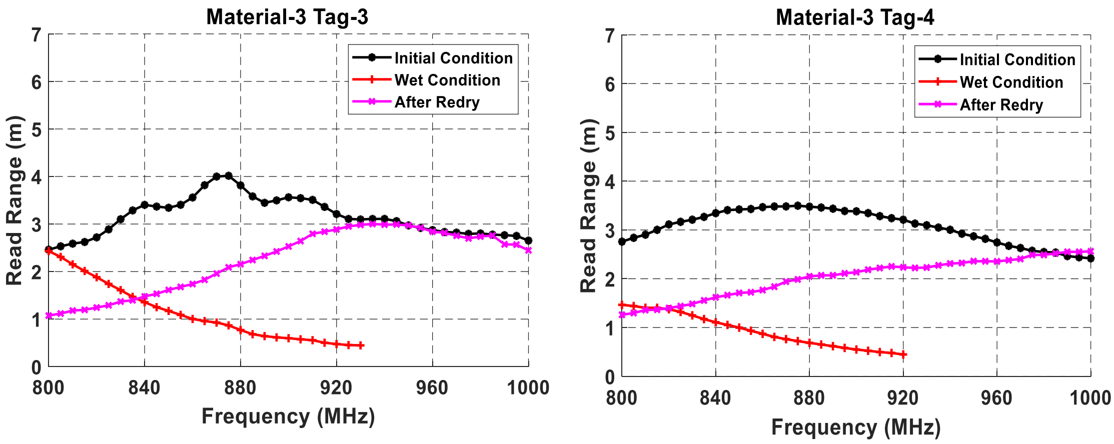
The read ranges of Tag-5 and Tag-6 of Material-2 were shown in Figure 48. Both the tags were tested by bending in the hanging position and reached to their original shape in the redried condition from the wet state. The read range patterns for both tags were similar in their initial and redried conditions.

7.3.4 Observation of Material-2 moisture sensor after testing

Table 5 show that in the hanging position the shape of Material-2 returned to its initial shape in the redried state, but from the Table 4 it observe that in the sidewise position the initial shape could not be reached in redried state. However, when the sensor tags redried, the read range improved but could not reach the initial read range level.

7.3.5 Measurement of Material-3 moisture sensor tag

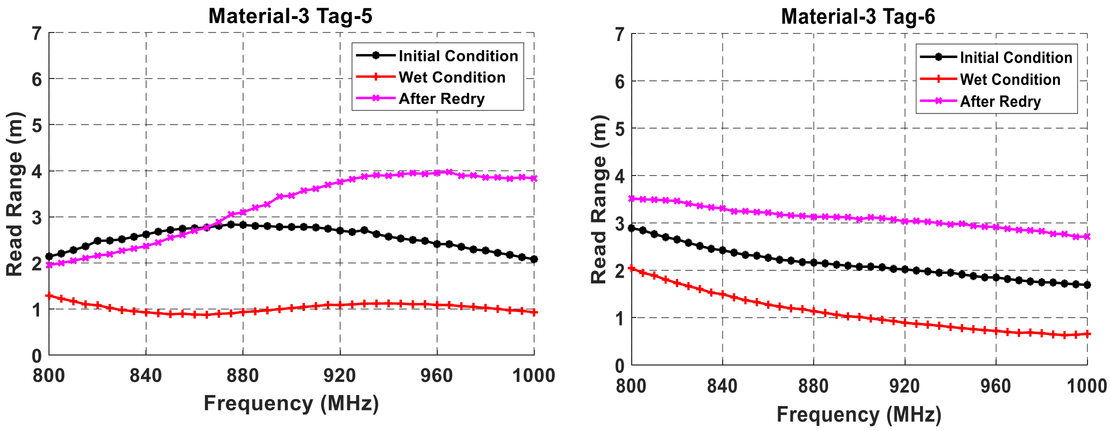
Moisture sensor tags of Material-3 were assessed by bending sidewise and bending in the hanging position. Both moisture sensor tags' initial read range patterns were similar to their redried condition's read range patterns. Figure 49 shows the test results of moisture sensor tags in sidewise bending position. In wet condition, Tag-3 and Tag-4 stopped working in higher frequency.



(a) (b)

Figure 49. *Read range of moisture sensor tag in bending in sidewise position test result for three conditions of Material-3 (a) Tag-3 and (b) Tag-4.*

Tag-5 and Tag-6 of Material-3 were tested by bending in the hanging position. From the test results of Figure 50, it was observed that the read ranges of both tags were higher in redried condition than in the wet state and the read range patterns in the initial sates were similar to redried read range. From Table 5, we observed the moisture sensor tags of Material-3 regained their original shapes when redried.



(a) (b)

Figure 50. *Read range of moisture sensor tag bending in hanging position test result for three conditions of Material-3 (a) Tag-5 and (b) Tag-6.*

7.3.6 Observation of Material-3 moisture sensor after testing

Material-3 moisture sensor tags were tested by bending in two different positions. The shapes of moisture sensor tags of Material-3 regained their original shape in their hanging position, but in the sidewise position the tags could not regain their original shape. However, when the tags dried, the read range improved but could not reach the initial read range.

7.3.7 Discussion of different materials for moisture sensor tags

Moisture sensor tags were made of three different (dishwashing cloth) materials. Several tests were done to find the best possible optimally working moisture sensor from the selected materials. For evaluating the test results, the UHF band of 860 MHz to 960 MHz was considered for discussion.

Initially, two tags from three materials each, a total of six tags were developed to observe the effect of bending on the read range. From the test results, all three tags behaved similarly with the increment of bending on the tags. When the testing surface radius was 12.83 cm, then the difference between initial and bending condition was minimal for all three materials. Read range started decreasing when the radius of the testing surface was reduced. Furthermore, this situation happened for all the tags of three materials. Because of bending surfaces, the reduction of the read ranges of three different materials occurred almost in the same ratio.

Again, six tags, two from every three different materials, were developed to find out the moisture effects on the moisture sensor tags. In this testing phase, the tags were kept on a flat surface to prevent any sort of shape distortion of the materials. Moisture effect in the moisture sensors was observed by submerging them in water. Test results consisted of measurements taken at the initial dry state, then after submerging in water and finally in the redried state. From the test results of six moisture sensor tags, it was observed that Material-2 was better than the other two materials for constructing sensor tags. Moreover, Material-2 regained its original shape when it fully dried from the wet condition. After the moisture test, Material-1 and Material-3 could not recover the initial shape when those got fully dried from their wet condition. That could be one of the reasons that the read range of tags from Material-2 was considerably better than tags from Material-1 and Material-3.

Next twelve moisture sensor tags, four from every three materials, were tested in two different positions: bending sidewise and bending in hanging. Test results were taken in three bending conditions: initial (dry) condition, wet condition, and redried condition. In wet conditions, most of the tags showed a higher read range in the lower frequency range compared to the redried state. Some of the tags stopped working in wet conditions: Tag-3 and Tag-6 of Material-1, Tag-4 of Material-2 and Tag-3 and Tag-4 of Material-3. However, those tags started working in the redried condition. Due to the higher dielectric permittivity of water than that of air, the moisture sensor tags' read ranges reduced considerably in wet conditions in comparison to their initial read ranges. The threads conductivity was affected due to the moisture, which caused a change in the read range of the moisture sensor tags.

When the moisture sensor tags were evaluated by bending sidewise, most of the redried tags could not return to their initial geometrical shape. The read ranges of the redried tags were improved in comparison to their wet conditions. However, the redried tags could not achieve the level of their initial read range. Material-2 could not regain its initial shape in redried condition like the other two materials moisture sensor tags. However, Material-2 exhibited an impressive read range in redried condition compared to the other two materials moisture sensor tags.

In case of hanging position, all the tags from three different materials showed notable improvement of the read range when those redried. Material-2 suffered the least, and Material-3 suffered the most geometrical shape distortion when redried in comparison to the geometrical shape of the initial condition. This changed shape negatively affected the read range of the moisture sensor tags.

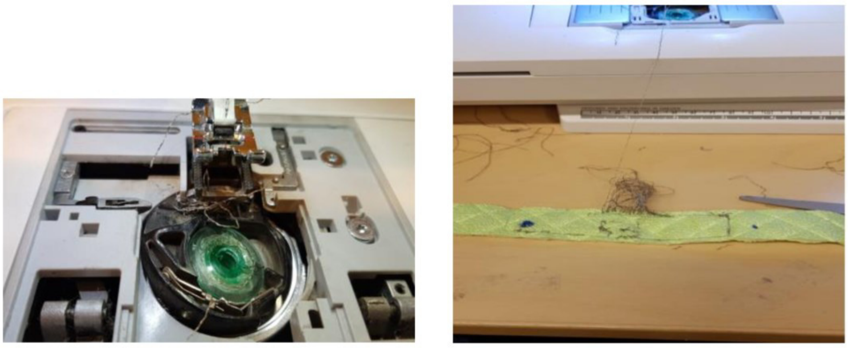
In this thesis soluble thread played a vital role for development of moisture sensor. In the initial (dry) condition, the moisture sensor was measured in circular shape to observe the bending effect by using soluble thread. The soluble thread was helpful in observing the shape changing tendency of the dish washing clothes in redried states when the thread was dissolved in wet condition in both sidewise and hanging positions, which helped to develop the most effective moisture sensor from three different commercially available dish washing clothes in this thesis.

If we consider the UHF RFID band range of 860 MHz to 960 MHz as a standard, then all the tags were functioning within the frequency band range. According to the sensor characteristics the developed moisture sensor sensitivity was good for detecting the moisture and the accuracy of the sensor was good but not precise for all the developed sensors. Based on the above measurement results we can say that Material-2 is the most suitable material for the development of moisture sensor because of the improved read range in its redried state from the wet condition, tendency to regain the initial geometrical shape and a better read range. Material-1 comes second in preference for constructing moisture sensor while Material-3 is the least preferable material.

7.4 Challenges

- Constructing the moisture sensor tags on dishwashing materials were challenging. Especially for Material-2 because of its material composition, since it needed extra force to construct the moisture sensor tags by hand stitching.
- Maintaining the tag antenna structure was a challenge during both hand stitching and sewing with the embroidery machine.
- Attaching RFIC in the tag was a challenge. Initially, it had lost contact with the conductive thread, so it was not giving measurement results. Then it was attached firmly with the dishwashing substrate material by several rounds of conductive thread. Sometimes the IC was torn while stitching on substrate materials.
- Maintaining the precise length of conductive thread was not possible for both hand stitching and sewing techniques. It differed from one tag to another, so there were changes in the read range for the same material tags. Since the moisture sensor tags were handmade, the probability of human error was high during the construction of those tags. Hence it may have affected the recorded read ranges of the tags, since they were often showing different read ranges in the same test even if they were made from the same materials.

- For the case of an embroidery machine tag construction, the conductive thread was torn, and the bobbin thread stuck several times as Figure 51 (a). Moreover, the stitching went on entirely over the drawn antenna structure of the materials on one side, but there was a cluster of threads on the other side of the tag materials as shown in Figure 51 (b) .



(a) (b)

Figure 51. *(a) The conductive thread stacked on the bobbin of the embroidery machine , (b) Cluster of thread on the sensor substrate during the construction of moisture sensor during sewing on the embroidery machine.*

- There were slight differences in the bending of the tag materials, and this difference affected the read ranges of the moisture sensor tags.

8. CONCLUSION

Passive UHF RFID tags and passive sensors are power source independent and low-cost devices. The objective of this thesis was to develop a low-cost, environment-friendly moisture sensor by using a passive UHF RFID tag. For the development of a moisture sensor tag, we used dishwashing cloths as the substrate materials. Initially, six substrate materials were studied, and finally, three dishwashing cloths for moisture sensor tag substrate were chosen for the development of the passive moisture sensor. Twenty-four moisture sensor tags were made by hand-stitching technique, and eight moisture sensor tags were made using the sewing machine. Then all the tags were tested under three different circumstances. Firstly, moisture sensor tags were tested and observed by only bending them. Then the tags were tested to observe the moisture effect on them. Finally, all the moisture sensor tags were tested to find the effectiveness of the tags as the proper moisture sensor by bending them under the moisture effect.

We observed that moisture sensor tags read ranges decreased under bending effect: more bending caused more decrease in the read range. All the tags read ranges decreased in the wet condition when they went through the moisture test. The read ranges of those tags increased in the redried condition. The performance of Material-2 was better in achieving the initial read range level in the redried state than the other two materials. Under the bending effect in the wet condition, the read ranges of the tags decreased, but the read ranges increased in their redried states. Among all the materials, Material-2 attained a read range which was closed to its initial read range and regained its original shape, especially in the hanging position. Since the motive of this thesis is to develop the passive UHF RFID moisture sensor with the consideration of the read range, Material-2 was more effective than the other two materials. In contrast, Material-3 was the least preferable in consideration of read range in the redried state, geometrical shape-changing tendency, and attaining the read range near to its initial level.

As future development, if a newly designed tag antenna is used, which has less effect on the tag materials while bending, it might have the same results for all the tags. If the tag construction was an automatic process and human contribution was lesser, then the effectiveness of the moisture sensor performance might have been better.

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