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EVALUATION OF CONDUCTIVE THREADS FOR OPTIMIZING PERFORMANCE OF EMBROIDERED RFID ANTENNAS

Faculty of Information
Technology and Communication
Sciences
Master of Science Thesis
September 2019

ABSTRACT

MUSTASIN MAHMOOD SAKIF: EVALUATION OF CONDUCTIVE THREADS FOR
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Tampere University

Master of Science Thesis, 55 Pages

September 2019

Master's Degree Program in Electrical Engineering

Examiners: Academy Research Fellow Johanna Virkki and Postdoctoral Research Fellow

Han He

Radio frequency identification (RFID) refers to a technology that utilizes radio signals for identifying objects automatically. This technology consists of a reader that detects the objects and a transponder that gets attached to the object and it is called tag. The tag is an enclosure that houses the antenna and an IC that stores the necessary information on that object.

This thesis focuses tag antennas made for embroidered RFID. Embroidered antennas are made by sewing antenna using conductive thread onto a fabric using a computerized sewing machine. This enables us to extend the field of RFID technologies to textiles. Conventional RFID systems that use metal conductors are easy to model but the same cannot be said for embroidered RFID. The reason being conductive threads and embroidered antennas don't have definite conductivity. The conductivity of an embroidered antenna depends multiple factors like thread conductivity, thread density, stitch density, sewing pattern etc. The target of this thesis is experimenting with conductive threads physically and for their conductivity followed by evaluating them for the use of embroidered RFID antenna fabrication for optimizing the performance.

In this thesis, using same antenna pattern and technique, tags were fabricated from 6 different conductive threads onto the same cotton fabric. The conductive threads were investigated for their conductivity, thread thickness and their strength. The antennas were tested for their read range and the effect of different threads on the antenna were analysed. The threads with the highest conductive nature gave the highest read range of 6.2 meters. The threads were also evaluated for their usability for embroidery. Some threads were too thick, some had exposed structures leading to malfunction in the sewing machine and others were too thin and ripped easily during sewing. The selected thread should not only have great performance, but also it needs to be practical. It is seen that the conductivity of antenna and hence the performance is easily improved with using high conductive thread. After taking all the factors into account, finally a thread was selected that can be used to make high performance embroidered RFID antennas and also highly suitable for embroidery process.

In the future, the same work can be revisited or extended to other more versatile and higher conductivity threads. Also, the advancement in embroidery techniques will allow for more conductive threads to be compatible for embroidery opening more options for optimization.

Keywords: Passive UHF RFID, Embroidered RFID, Embroidered Antenna, Conductive Thread, Conductivity

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

PREFACE

The Master's thesis "Evaluation of conductive threads for optimizing performance of embroidered RFID antennas" is conducted at Tampere University as a requirement for Master of Science in Electrical Engineering with Electronics as a major. The thesis and experiment were supervised and examined by Academy Research Fellow Johanna Virkki and Postdoctoral Research Fellow Han He.

I would like to thank my supervisors Johanna Virkki and Han He for their constant guidance and support during the whole time. I also want to thank Zahangir Khan for and Xiaochen Chen for their help in the process of embroidery.

Special thanks go out to my parents for they have guided and supported me in my studies my whole life. Finally, my appreciation goes out to all the friends and seniors that constantly encouraged me and provided me moral support.

Tampere, 22 September 2019

Mustasin Mahmood Sakif

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LIST OF SYMBOLS AND ABBREVIATIONS

ASK	Amplitude Shift Keying
DC	Direct Current
EM	Electromagnetic
FSK	Frequency Shift Keying
HC	High Conductive
HF	High Frequency
IC	Integrated Circuit
ID	Identification
LF	Low Frequency
NFC	Near Field Communication
OCR	Optical Character Recognition
PA11	Polyamide 11
PVA	Polyvinyl Alcohol
PSK	Phase Shift Keying
RFID	Radio Frequency Identification
SNR	Signal to Noise Ratio
UHF	Ultra High Frequency
<i>B</i>	Anti Tarnish Coating
Ω/m	Linear Resistance Ohm per Metre

1. INTRODUCTION

RFID is short for radio frequency identification. In this technology, one can automatically detect and identify any object using radio waves. This technology accomplishes the same purpose of a conventional identification method called bar-codes that we see in our daily lives. But RFID provides more functions and advantages. Instead of reading a printed pattern, RFID uses radio links to access a unique identification number assigned for each object. Furthermore, it can achieve this from distance while reading many objects at the same time irrespective of their positions [1][2].

RFID has a lot of potential and applications because of its unique features and advantages. Researchers have identified this as an active topic and lot of advancements are taking place in this field. The component which stays with the object for identification purpose is the tag. In passive RFID, the tag works without its own power supply. This makes the tag cheap and low maintenance. This technology is taken to another level by integrating with textiles. This makes the tags wearable and opens up a whole new world of possibilities. One of the methods is embroidering the antenna into textiles to make the tags. However, this technology faces a lot of challenges. The antenna is made from a thread that can conduct electricity and this conductive thread is the basis of embroidered RFID. The challenge is finding the proper thread to use for getting the optimal results. This study is performed to get an understanding of conductive threads and evaluating them for optimizing embroidered RFID antenna [2-6].

RFID technology has several advantages. It is capable of identifying a tag from long distances compared to barcodes. Also, there is no need for line of sight in RFID. This means a tag can be used for applications that a barcode cannot accomplish. A tag holds a small memory in its IC. Hence, it can store data. On the other hand, barcodes read digits that are usually 10-12 characters long. it is possible to replicate barcodes without much difficulty. But the same is not applicable for RFID which makes it more secure. Maintenance cost is low for most RFID systems and requires less human interaction. It takes very short time to read a tag. In fact, the time to read a barcode is much longer compared to reading a tag. In the duration of reading a barcode, about 40 tags can be accessed. A tag is reusable, it can be written with other information for other application. The tags are usually protected by covers made from various thickness of plastic. This

makes them tough which is necessary for many applications. But there are many reasons why RFID is yet to replace other technologies. There are some challenges and limitations it faces. First is the cost. For some applications, the cost of providing a RFID system is too much compared to cheaper alternatives. It has difficulty in reading tags through metal or liquid mediums which again limits some applications. An area which is dense with tags can cause multiple tags to activate. In this situation, tag collision can occur. Although RFID is secure compared to many identification technologies, it is still vulnerable to hacking. A database holds all the necessary information and identification is done using the database. Software is used for this purpose and it raises security concerns [2][52].

RFID technology has applications in many fields of the industry. The most obvious use is in supply chain. Retailers are trying to include new technologies to increase their work capacity and decrease their cost. RFID is adopted by many large corporations such as Wal-Mart allowing them to save up to 600 million dollars. It is also a hot topic in research, and it has seen growth in many RFID firms. Integrating sensors with RFID leads to many possibilities. In medical field, this can be used for patient and medicine monitoring. Warehouse management can be an exhausting task. But with RFID, locating items that are about to expire, replenishing new stock, tracking items necessary for delivery etc. are many times easier. Inclusion of RFID and near field communication (NFC) in smartphones provides new solutions such as micropayments. In automotive industry, RFID provides keyless ignition and smart security system. Possibilities are endless and we are yet to explore all the fields that RFID can make our life easier [53].

In this study, Passive Ultra High Frequency (UHF) tags were fabricated using embroidery. Conductive threads are sewed onto cotton textile where the textile works as the substrate and the threads are sewed in a pattern that works as a RFID antenna. The purpose of this study is evaluating different threads for using in embroidered RFID. Six different threads were used to make individual tags from each of them. The tags were tested for their performance and compared against each other. By evaluating the tags and the threads, the focus was to reach a conclusion that optimizes the antenna performance and to weigh in other factors that determines the usability of the used threads in embroidery. The experiment was conducted by sewing the same antenna pattern on the same substrate with the threads and same IC attached to each antenna. Then the antennas underwent testing to determine their performance and the respective threads were evaluated based on that. Other factors that affect embroidery such as thread strength, conductivity, structure and usability were also considered and finally the optimal conductive thread was selected for the purpose.

This thesis presents the field of embroidered RFID which merges RFID technology with the world of textiles. The chapter 2 discusses RFID and its fundamentals. It contains literature on the structures of RFID system, its components and several other factors related to RFID. Chapter 3 introduces tag manufacturing technologies, embroidered RFID and conductive threads. Embroidery is compared with other technologies, along with conductive thread and its current state.

Chapter 4 presents the embroidery and RFID tools used for making the tags. It also discussed the antenna design and some techniques used for the fabrications and introduces the conductive threads that were used. Finally, it gives a walkthrough of the tag preparation. Chapter 5 introduces RFID tools used for taking measurements and testing procedure. It presents the results and analysis in the end. Finally, Chapter 6 summarizes the thesis and presents the conclusions. The work done is discussed in brief along with discussion. The work has future potential and some suggestions are mentioned for overcoming the challenges and obtaining better results.

2. RFID

This chapter contains literature about RFID, RFID system components and basics of RFID.

2.1 Introduction

If we want to recognize and differentiate between objects, places, people, and just about anything, first we need to identify them. And for the identification we use names, numbers or both. Identification is important in everything we do. What we do with the object, how we interact, what is its value and its purpose, all these questions can be answered through identification of the said object. During World War II in 1941, the catastrophe that happened in Pearl harbour was due to the inability to identify the Japanese Bomber Planes. At that time radar was used to spot planes, but the problem was there was no way of differentiating between enemy aircrafts and returning aircrafts. The Germans discovered that when pilots changed direction of their plane towards base, the reaction radio signal was different. This is considered as the first RFID implementation and application [2][7].

Some applications such as inventory and logistics management require more than human abilities. This results in designing the technology to automatically identify objects. The most common method is barcodes. Barcodes are specific lines printed on the object that needs to be identified. Barcode scanners can read them and identify them. This is an optical method. There are other optical methods such as two-dimensional bar codes, Optical Character Recognition (OCR). Optical methods show various shortcomings. They require sight, distorted barcodes may provide wrong identification, and other outside factors that can hamper this system. To overcome the limitations, RFID is used. RFID is a technology where radio signals are used to establish a link with the object and identify it [2].

Radio frequency identification is vital for our technological stride. We use RFID to increase efficiency and productivity of many applications. For instance, tracking assets, tracking books in libraries, collecting toll, animal processing, identification and tracking, anti-theft, parking systems, material management, electronic passports, luggage tracking, access control systems, public transport fare collection, etc. For object identification, RFID is faster, more robust, flexible and reliable than any other method [7][8].

2.2 Applications

RFID has countless applications in modern world due to its advantages like easy fabrication and design, long read range. It is capable of scanning a large number of items with no contact [40][41]. Few applications are described below,

RFID has a lot of medical uses due to its developed studies and the tag structure provide optimized methods to track equipment and even personnel. This can be done using automatic data entry and it eliminates human error. High frequency tags used for lower range applications like in fluid, blood or tissue sample. On the other hand, for long range applications, UHF tags are being used [40]. The range is crucial to track and locate any medical device. This will tell the staff where to acquire the device and save time in critical situations. Devices can be managed efficiently and automatically and this helps to reduce overhead and offer heads up when critical equipment is running out and needs replacing or replenishing. The accuracy of tracking means there is less possibility of errors occurring from wrong data entry or handling error. The samples can automatically be processed into the database and added to patient record [41].

The most useful feature of RFID is that it can recognize every item. This means there are countless prospects in inventory management and supply chain. RFID provides accurate product location, capacity for tracking and tracing. Another use for RFID tags are the use of self-checkout at supermarkets. This can be used for fashion industry as well, where the tag can serve as item identifier, receipt and it can also be part of the cloth if wearable antennas are used. The same method goes for borrowing and returning books from the library [41].

2.3 The RFID System

RFID works by establishing communication between a specific point and moving object or various movable objects using short range radio technology. Objects requiring identification are attached with tags and transponders. They are small, simple and inexpensive. Readers on the other hand are more complex devices. They are most likely attached to a computer or network [2]. Figure 1 illustrates a basic RFID system.

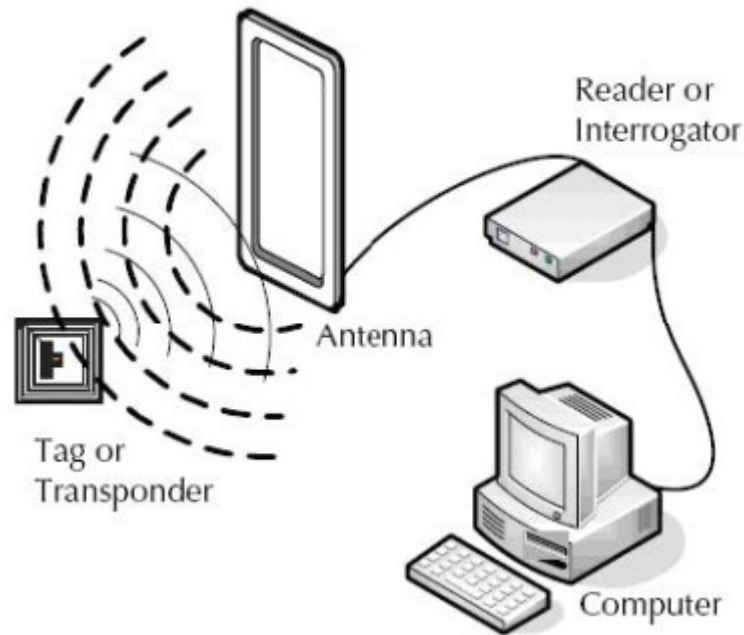


Figure 1. A basic RFID system [2]

After establishing a link between the transponder and tag, the transponder instruction to the tag using radio signal. The tag receives the signal. The signal is modified by the load impedance of the tag and returned to the reader. Then the system collects the information from the reader for processing and storage. When the direction of transmitted signal is towards the tag coming from the reader, this link is the downlink or forward link. The tag sends the backscattered signal back. This is the uplink also otherwise called reverse link [2]. The link is shown in Figure 2.

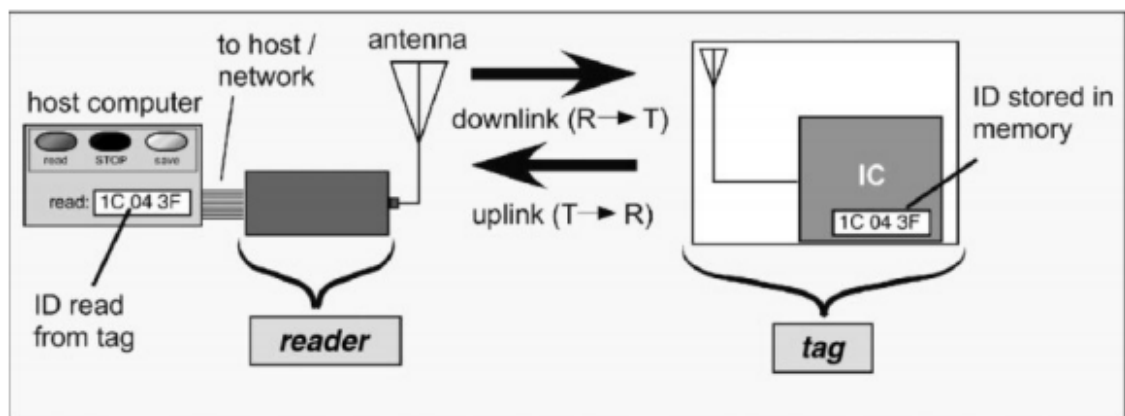


Figure 2. RFID radio link [2]

A RFID system have 2 ends, a transmitter or the reader and transponders or the tags. Tags are connected to the objects that are needed to be identified. The reader which is generally connected with a computer and network and it has an antenna that transmits data, commands and often power to the tags. Tags hold the valuable information; they

are used for identification and tracking. RFID tags are mostly movable and RFID readers can link with them from distance [2].

2.3.1 RFID Tags

Out of the whole RFID system, a component that is tracked by the reader is the RFID tags. A tag features an antenna that receives radio signal from reader and returns the signals to the reader. It also contains an integrated circuit (IC). The IC is attached to antenna [9].

Tags look for signals generated by reader all the time. RFID tag receives the request, then responds and transmits its own ID code. The tags are usually differentiated based on power usage. Antenna design also varies based on the application. No antenna design is ideal for every application. The application decides the antenna specification. Some applications require a specific frequency band while other applications may desire better performance. Antennas are made with many kinds of materials. They can be manufactured with different techniques as well; they are usually stamped, etched, printed or sewed. A single antenna can have an orientation resulting in dead zones. On the other hand, tags with multiple antennas don't have such dead zones and has greater read capability but requires a particular chip [2].

2.3.2 RFID Readers

The devices that communicate with the tags are called readers. They use a method called interrogation. The readers must provide enough energy to the passive tag to receive information. Reader creates an area called interrogation zone and tags in the zone can only be read by the reader. They are normally connected to a host computer. Readers are equipped with transceiver and antenna for sending and receiving radio signals. It also consists of a processor to decode data [10]. Readers are also designed to perform additional functions, such as amplifying weaker signals, generation of high frequency signals, combining various frequencies or mixing, and filtering of unnecessary signals [2].

In a specific application, a reader must fulfil certain criteria for it to be selected. The operational frequency is one of the criteria. It must also be able to read in given protocol. Another criterion is getting allowed by the regulations depending on the region. It may need to be able to work with multiple antennas as well [10]. Readers are classified into three types based on their application. Firstly, there are fixed readers. In a location where

objects move significantly in a specific area, the readers that are used are fixed readers. These types of readers are placed in a location and locate objects that pass by the readers by reading the tags. Then there are handheld readers. These readers are held in hand which gives it a significant advantage where tags are detected in any versatile area. In loading or unloading operations in applications such as inventory and logistics management, these readers are moved to anywhere and used without much hassle. Another type of reader is mobile reader. Where human intervention is not required, mobile readers are used in those places. These have self-tracking instruments that detects the RFID tags. It can be moved which has advantage over fixed readers. It also does not need human intervention hence it has advantage over handheld readers [10].

2.4 Reader Antennas

Antennas are topmost vital component in RFID. They receive important signals as well as transmitting signals. Voltage is generated in the antenna by induction when signals are being transmitted, depending on the operating frequency. Various kinds of antenna are utilized in RFID system which mainly depends on the kind of purpose it is going to serve. Out of all kinds of antennas, the important ones are linear, circular, monostatic and bi static [11].

Linear antennas work in a situation such that we know tag orientation. The antenna also requires a fixed location. Circular-polarized antennas are utilized when we don't know in advance the tag orientation. Bi-static antenna has two ports and one port is used for transmitting the signal and the other port for the received signal. The most common one is the Monostatic having a single port. The signals both travel in and out using single port [2]. Some performance factors must be considered before selecting an antenna. Some of them are:

- Directivity: The ratio of maximum radiation intensity of an antenna in a particular direction to intensity of an isotropic antenna over every direction is called directivity. Directivity for any isotropic antenna will always be unity. That's why directivity of any other antenna will always be higher than unity [13].
- Beam width: It is the model of the region with highest radiation over a path that represents primary lobe in an antenna. Half lobe beam width is the most widely known and it happens in the area with transmitted and received power being half of maximum transmitted or received power [12].
- Radiation pattern: Antenna emits electromagnetic radiation in all directions, which vary in intensity. Isotropic radiators have the radiation pattern where the intensity is

equal in all directions and considered as ideal antennas. The field where the energy is returned is the reactive near-field area of antennas. The angular displacement of the radiated field depends on the antenna distance. The radiating fields dominate in far field region. It is where electric, magnetic field vectors are perpendicular to one another. [12].

- **Polarization:** Two spherical components of electric field with a difference of phase exists in an antenna far-field region. It creates a phenomenon that makes the antenna elliptically polarized. If the phase difference is positive or negative 90 degrees while keeping the same amplitude, it creates circular polarization. In case the phase difference is 0 or 180 degrees, then we get linear polarization [12].
- **Bandwidth:** The spectrum of frequencies at which the antenna operates is called the bandwidth. The characteristics of the antenna depends on the bandwidth. The spectrum of frequencies outside centre frequency at which antenna operates normally is considered as the bandwidth. Outside the central frequency the impedance matching degrades [12][13].

2.5 Classification of RFID Tags

RFID tags usually get classed into 3 categories based on power usage: Passive tags, Active Tags and Semi-Passive Tags.

2.5.1 Passive Tags

Most widely used tags are passive tags and they contain one IC and one antenna. There is zero source of power in tag itself for any processing or communication. It depends on the reader to start the communication process and feeds from the energy of the radio signal that it receives from the reader. This energy powers up the tag circuit. When the tag starts operating, it sends back the information that is stored in the IC. Since there are no power sources in the passive tags, they are quite cheap to manufacture. And this simplified design means the size is kept to minimum, they are more flexible and there is less requirement for maintenance [2][14].

In a RFID tag, the IC processes and stores the information in the storage. The cost of the IC depends on the storage capacity. For radio communication, the tag antenna is used. The components are enclosed, and they are fabricated on a substrate made by plastic glass, rubber. They can be printed on surfaces as well as sewed onto clothes [2]. In our case, the antenna is sewed onto fabric and IC is attached to it.

2.5.2 Active Tags

In an active tag, there is separate power source. The power source is a battery which provides power to the components for transmitting. Since the active tags have their own power, they can communicate with the reader from a greater distance. But the battery source makes the active tags more expensive, less flexible and higher maintenance compared to other type of tags. The active tag does not depend on the reader for initiating the communication like the passive tags. They can transmit their signal up to 100 meters because it is capable of modulation techniques. That's why they are also referred as transmitters. Another type of active tags which does not transmit information all time to save energy. The tag remains in a sleep state until reader provides a request [2].

2.5.3 Semi-passive Tags

The energy of semi-passive tags is provided by a power source and they operate as passive tags. The energy source powers up the circuitry, but it does not make the tag initiate communication with reader. The reader first sends radio signal to communicate and then the tag starts operating. Like the passive tags, this type of tags also uses backscatter technique for uplink. Figure 3 shows the differences between the types of tags. Semi-passive tags are known to reach tens of meters of read range due to the fact of having its own power source and generate faster response than passive tags. But this means the cost increases, it is less flexible, bigger in size and requires higher maintenance compared to passive tags [2].

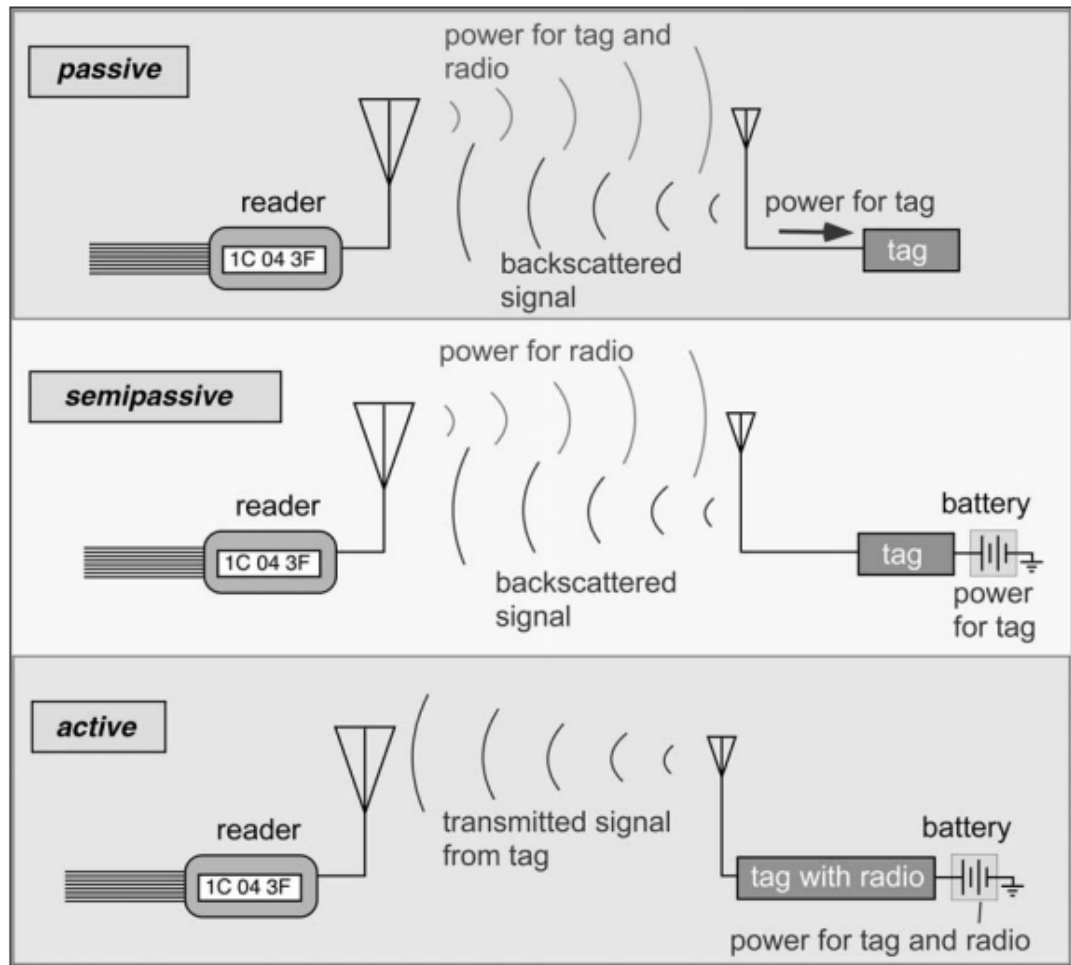


Figure 3. Differences between RFID tags [2]

2.6 Frequency Bands for RFID

The operation of RFID system happens in a broad spectrum of frequencies. The spectrum is typically from 100 kHz to 5 GHz. The most common bands for RFID are 125-134 kHz, 13.56 MHz, 860 to 960 MHz, 2.4 to 2.56 GHz. LF (Low frequency) RFID system works at 125-134 kHz band which is called LF band. 13.56 MHz is called HF (High frequency) band. 860 to 960 MHz and 2.4 to 2.56 GHz bands are called the UHF (Ultra high frequency) band. UHF RFID system operates in these bands. The 2.4 to 2.56 GHz system is also called the Microwave system [2]. For this thesis, UHF or Ultra high frequency RFID system was used.

2.7 Challenges of Wearable RFID

We face many challenges when we want to design a RFID antenna that is passive in nature and has to work on the body of a human. Antenna can be affected by human tissue substantially [28]. RFID performance have diverse results depending on various

body parts [30]. The size is also an issue since it is restricted by body part on which the device is going to be worn [6].

For making a device comfortable to wear, it must be as small as possible. At the same time, it needs to be flexible so that it does not hinder the physical motions of the person wearing it [31-34]. For an antenna to be wearable, it needs to endure multiple number of environments and various treatments. It needs to be flexible and endure most bending and stretching that occur due to the motions for a human while wearing it. A garment requires to be washed and so the antenna requires to be water resistant as well. This is the toughest challenge to make the device durable enough to survive many cycles of washing. For this reason, the IC needs to be extremely secured. A high level of relative humidity can deactivate the IC [37][38]. This means any device that has wearable application must require high quality protection that ensures that the IC is safe from mechanical strains from a laundry machine [39].

3. MANUFACTURING TECHNOLOGIES AND CONDUCTIVE THREAD

This chapter introduces some manufacturing technologies for tags, discusses further into embroidered RFID and brief information on conductive RFID.

3.1 Tag Manufacturing Technologies

Many different technologies are used for manufacturing tags like thermal printing, inkjet printing, 3D dispensing and embroidery. These are discussed briefly below.

Thermal Printing is a technology where printing is done using thermal method. It gets transferred thermally onto substrate. A ribbon having 3 layers is used. The first layer has an acrylic adhesive layer which is sensitive to heat. The middle layer consists of a thin metal layer. Plastic membrane is the last layer. The metal is transferred to the substrate from the using exchange of heat. The adhesive attaches the metal with the substrate surface. The thermal printhead performs this method to obtain the desired shape of the antenna [54]. Figure 4 shows a thermal printing process of transferring ink onto substrate.

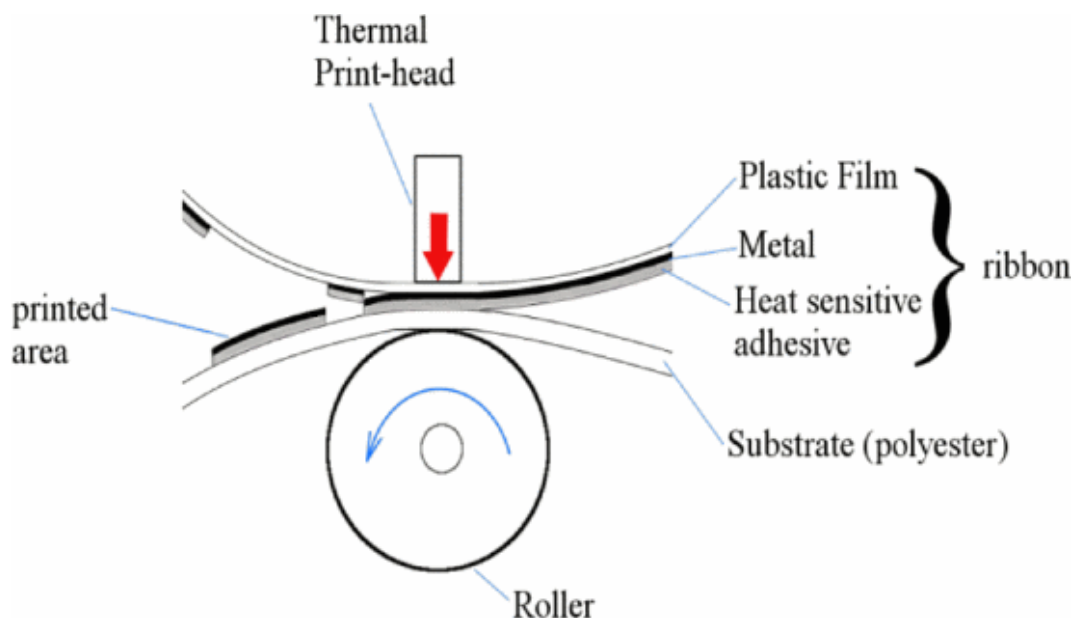


Figure 4. Thermal printing process [54]

Inkjet printing is a technology, where conductive ink is printed onto a substrate to make a printed device. Usually the conductive ink used is silver nanoparticle. The printer has printheads with tiny nozzles. Various factors decide the quality of printing for example,

temperature of ink, temperature of plate, jetting voltage and frequency. The drop spacing should be maintained such that is equal to the drop radius. This gives the pattern a good conductive layer [54][55]. Figure 5 shows how printhead controls the ink droplet formation on the substrate to make a conductive layer.

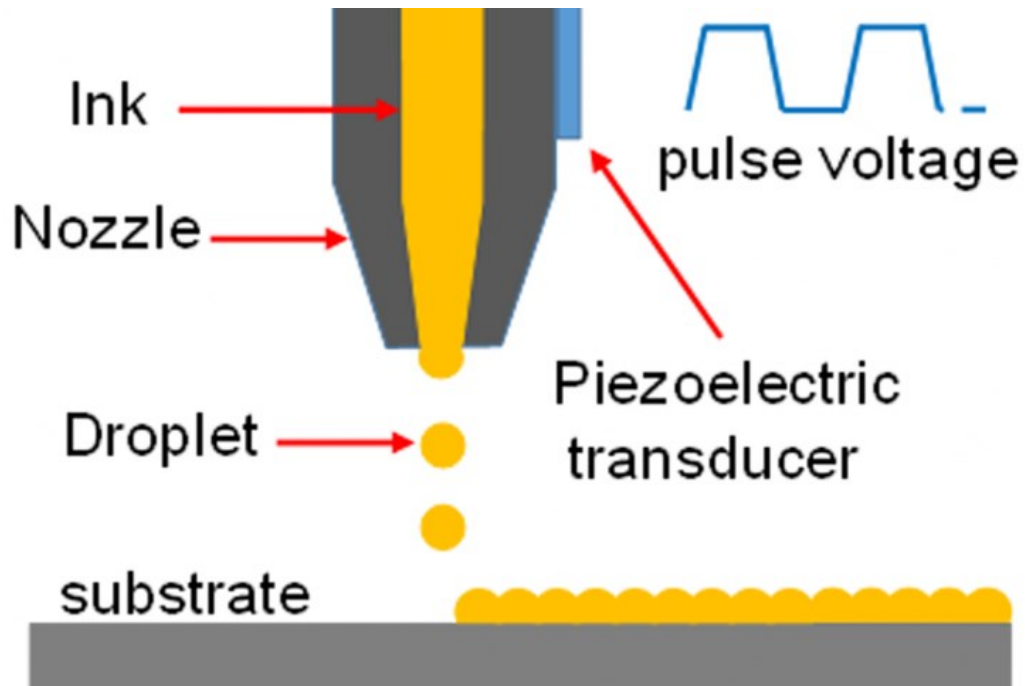


Figure 5. Inkjet printing method [59]

3D dispensing is a technology where thick layer of ink gets dispensed using a 3D dispensing system on a substrate. Any antenna model can be printed with any thickness directly on a textile surface. This provides the substrate with added versatility and flexibility [56][57]. Figure 6 shows a 3D dispensing system. It is a direct write system and uses a barrel to contain the ink. The barrel is air pressure controlled and it is dispensed using the tip.

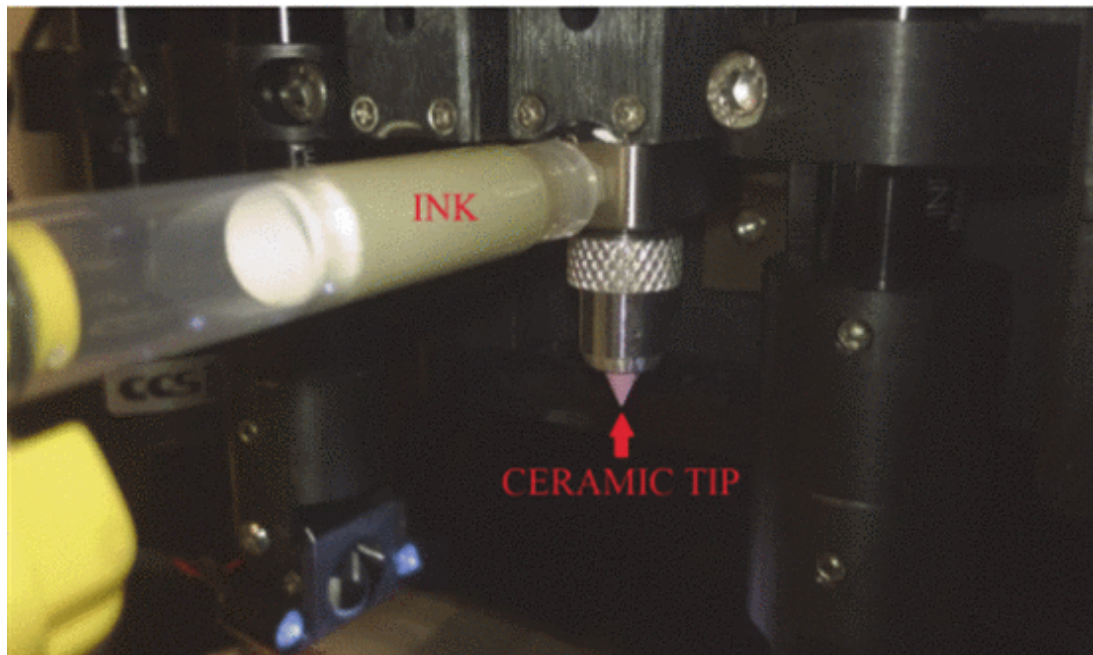


Figure 6. 3D dispenser with ink and nozzle tip attached [56]

Embroidery technology is where antenna pattern is formed by sewing conductive thread on a textile. The performance varies on many factors such as sewing pattern, sewing density, conductivity etc. The conductive thread is sewed using an embroidery machine which is computer aided [58].

Each technology has its advantages and disadvantages. Printing methods such as screen and inkjet printing provide us with another way of making conductive sections of an antenna [33]. Inkjet printing can be done on many kinds of substrates. But it is limited by the surface roughness of the substrate. Another limiting factor is the ink absorption. The substrates choice is restricted for thermal printing. Adhesive of thermal ribbon is not suitable for many substrates. A lot of material is wasted for thermal printing. Inkjet printing is good for saving ink on the other hand [54]. Garments may absorb ink with ease because of its porous nature and it makes then non ideal for printing [29]. In [33][36], a study was presented with antennas printed using inkjet. It showed that, if the textile is layered with a substance that is nonporous and suitable for the application, then the antenna can be printed onto the garment. Embroidery is not limited by the choice of substrates and specially it is highly suitable for fabrics. There is not any wastage of material. And embroidery can be used in many applications related to wearables. For this reason, embroidery was used for this study.

3.2 Embroidery in RFID

Clothing is something that a person wears to present his sense of identity and at the same time it serves as a way of protecting from the surroundings. It also holds necessary things that we require in our day to day life. Textile is the main source of the clothes that we wear, and their structure makes the clothing long lasting and washable at the same time. It also provides a lot of options in terms of texture. Conductive threads opened a new possibility in fabrication that is based on embroidery. They conduct electricity and hence they can be used for applications that unite embroidery and electronics. These kinds of threads may come in various flexible forms such as threads with metal coatings over polymer, metallic filaments or implanted with carbon-nanotubes [21][22].

Conductive threads transport electricity and they behave like cables. That's the reason they can be used for creating circuits. This means anyone can piece together a circuit just by sewing. These circuits provide flexibility and there is no need to solder. It is an easy and harmless method of fabricating circuits. But it can be very complicated and that's why state of the art embroidery machines is needed for this kind of fabrication [23].

Antenna pattern can be embroidered onto fabrics that do not conduct and this process of making tag is called embroidered RFID. The potential use for embroidered RFID is great, particularly in the wearable industry. Sewing antenna pattern onto nonconductive fabric is done by conductive thread. This way we can manufacture tag antennas on fabrics that work as UHF RFID systems. The applications are limitless. But in biomedical technology, the use can be acknowledged even more, because real time information such as heart rate, body temperature, etc can be gathered [3] [15-20].

A computer-controlled embroidery machine is used for fabrication process with the conductive thread. The circuits are turned into patterns that can be sewed onto. Digitally the stitching locations are fixed and then using the machine the threads are sewed onto single side of the desired fabric with precision [24]. The same technique is used for fabricating RFID antennas with conductive thread. The antenna design is transformed into antenna pattern and then sewed onto a non-conductive textile. Adding the IC to it transforms it into a RFID tag. This is the way embroidered Antennas are made and this made it possible for RFID to enter the world of textiles.

Another embroidery method known as double layer uses another layer over the original layer [25]. This is done to prevent pattern from discontinuation. This can enable variety of architecture applications such as interior, furniture designing. It can be used for wearable purposes too. The drawbacks include heating leading to uncomfortable wearing and it may require higher power.

A lot of work has been done in the field of fabrication using embroidery. RFID is one of them because it is very easy to design RFID tags using embroidered antennas and it has many applications. In [22], a RFID tag antenna design is proposed. Here, it is shown that the patterns if the sewing density is high can be treated the same way as a conductive layer of a uniform material. Antenna shaped like a logo is designed in [27] using conductive threads. In [26], the antenna designs are discussed on the potentials related to shape and structure. The downside of wearable RFID system is, the reduction of antenna efficiency because of human body. The high dielectric and energy dissipation constants mean there will be reduced performance and it possesses as a challenge [15].

Many researches have been done for figuring out the benefits of using conductive threads for making wearable antennas. Performance parameters such as directivity, efficiency, gain, input impedance etc., can be influenced by the design factors. Directivity can be enhanced by optimizing the pattern of thread sewing. Read range and bandwidth can also be increased by decreasing stitching density as it also lowers input impedance [44]. The thread density also has effects of antenna gain. As higher density may reduce effective conductivity, this can reduce the efficiency [22]. Another research shows the relation between thread's diameter and it's stitching density with radiation efficiency. As the thread diameter increases, it requires less stitching density to achieve the same or even better radiation efficiency [45].

3.3 Conductive Thread

A textile thread that carries electric current is conductive thread. They combine textiles with electrical wires. This kind of technology has been used in history even during the time of Thomas Edison. He used a carbonized thread as filament because it met the required resistance and longevity [43]. Conductive threads have many applications and its serves purposes like antistatic, electromagnetic shielding, wearables, e-textiles etc. They are not insulated and when sewed onto flexible textiles, it makes for a good conductive connection like wires [42].

Conductive threads have grabbed a lot of interest over the last years. Textiles are usually made from insulating materials like polymers and cottons. Textile threads are turned into conductive for several reasons. One is to gain the EM shielding effect. Electric load gathers on surface of insulated textiles due to poor conductivity. Turning the threads conductive makes it possible for load transferring and EM shielding. Another reason for conductive threads is using them as wires or connectors for various applications [47].

Conductive threads can be grouped into two categories. Firstly, there are intrinsic conductive threads. They are made from conductive fibres. Textiles are made from conductive materials like metals (gold, silver, nickel, steel) or graphite can come in various forms like wires or threads. They are injected in textile structure or used intrinsically. Each strand is made from the fibre that is physically conductive. Metal, graphite, conductive polymers, carbon nanotubes etc. are used to make these fibres. They have excellent conductance but possess some challenges. They have much higher weight and higher in cost. Also, their structure can damage the embroidery equipment since they are not as flexible and easy to use as typical textiles. Stainless steel is the most used and it offers low resistance. But this kind of threads are sensitive to ripping and very difficult for using in a sewing machine. During the procedure, it tends to break running through needles. Polyaniline, Polypyrrole, PVA, PA11 are few examples of intrinsic conductive polymers. They have good stability in terms of thermochemical and environmental perspective. Recently they have attracted a lot of attention due to their high conductivity. Their main characteristics are they are highly flexible, low in weight and have very good conductivity. Although they have good advantages, it's still used mostly in a research field due to their high cost [43][47].

Secondly, there are coated conductive threads. Conductive metals like copper, gold, silver or other elements like carbon are implanted or coated onto nonconductive textile cores to make this kind of threads conductive. The cores are usually made from cotton, polymers or nylon. These coatings are done using numbers of methods. Textiles are coated with metals or other conductive materials to achieve a hybrid of both worlds. Coatings done using galvanic method can achieve high conductivity. But they possess some challenges like having suitable substrate, low adhesion and resistance to corrosion. Another coating method is Metallic salt method. But this method has lower conductivity yield. When we coat the textiles with metals or other conductive elements, it adds multiple attributes to the thread. It improves the structure and adds conductivity to it. Thus, they can be used in applications in fields of medical, fashion, military, architecture etc. They combine functionality with aesthetics. This combination of textile core and coating makes it possible to use sewing machines. The resistance for this group varies depending on the material used for the coating and density of coating [43][47].

Conductive threads are usually uninsulated, and they come coated in various materials and ply number also vary. It is not as efficient as a wire but since it allows current to pass through and thus eliminating the need for circuit boards, we can use them for lots of applications [43]. Here is an example of a thread: 134/32 2ply thread. Here, 134 is the

denier weight, 32 is the filament number in each strand and 2 ply means strands number which is 2. Few examples of the industrial conductive threads in use are:

SwicoSilver is usually made by coating 100 percent silver onto a Polyethylene terephthalate filament. Silver is transported onto the filament using plasma metal process. This removes any need for adhesive layers and provides great conductivity, flexibility and durability. This makes the thread good for embroidering. They are also water resistant and washable. SwicoGold is the same as SwicoSilver but instead coated with 100 percent 24 karat gold. They provide similar conductivity; flexibility and it is also washable. Using Plasma metal method of coating any other stable and conductive metals can be combined with filaments giving the similar characteristics as SwicoSilver and SwicoGold. Fine inox wire is another type of conductive thread. It uses polyvinyl alcohol (PVA). PVA is mixed with Inox wire and it is available in dtex of 560. The polyvinyl alcohol is wrapped around the wire. When the process is finished, the polyvinyl gets dissolved leaving just the Inox product. Carbon fibres can directly be used such as Belltron. It has high conductivity and good performance. Carbon is also missed Polyester filament. This ensures that the thread is good for embroidering and easy to weave. Finally, there are polyamides that are coated with silver. Polyamides like Polyamide 6.6 or Polyamide 6 mono- and various other multifilament are coated by silver (Ag) and it is done by chemical method [60]. The conductive threads used for this study are silver coated polyamides.

4. TOOLS AND METHODS FOR TAG FABRICATION

This chapter presents the RFID and embroidery tools, techniques used, and the conductive threads used to make the tags.

4.1 The Antenna Design

The embroidery fabrication includes designing an antenna that is needed to be sewed using an embroidery machine. A design is selected for this thesis which will be used for all the tags that will be fabricated. The Figure 7 shows the dimensions of the antenna design. This same dimension is maintained and used for all the tags that are prepared. The whole dark area can be sewed with horizontal and vertical sewing. It makes the design very dense. For this thesis, single line embroidery was used. The embroidery machine sews a single line around the dark section. This makes the sewing density very low which helps with embroidery, but irregularities can make the antenna perform differently.

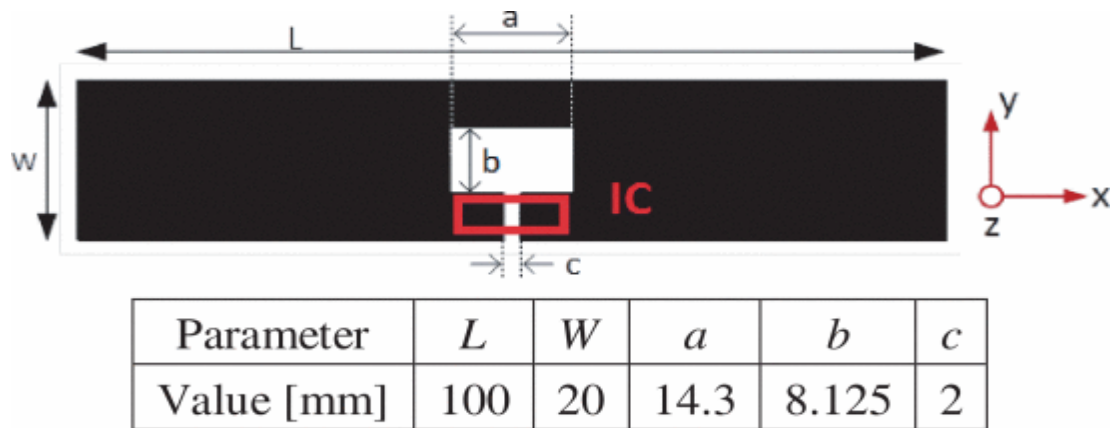


Figure 7. Tag antenna dimension [18]

Figure 8 shows a tag created using the same dimensions and using single line embroidery.



Figure 8. Tag created with single line embroidery

4.2 Embroidery Machine

For embroidering antenna onto the textile for the experiment, an embroidery machine is required. For the purpose, Husqvarna Viking machine was used which is available for commercial use. This machine can accurately sew the patterns that are required with its automatic printing system. The machine is shown in Figure 9.



Figure 9. Husqvarna Viking embroidery machine

The antenna structure is loaded onto the on-board system from a flash drive and it can be operated by its touch screen. The orientation, rotation, scaling and lot of other settings

can be changed from the display and then the tension and speed of the needle can also be changed beforehand. The textile is loaded onto a hoop and then attached to the arm of the machine. For sewing precise structures such as antenna, the machine is very important because dimensions of the antenna must be accurate. The antenna pattern is designed using a software specific to embroidery before it can be loaded onto the machine.

4.3 Conductive Threads

The six different threads that were provided are: 33/10, 33/12 Z-turns TR, 78/18, 110/34 Z 100 HC + B, 110/34 2ply HC+B and 235/34 HC. Here, the first number means Denier weight which is grams per 9000 meters. Higher number means more weight and, therefore, more conductive material in the thread. The second number is the number of filaments. ply means number of strands. HC means high conductive and B means anti-tarnish coating. All the threads used are from a company called Shieldex. They are experts in making conductive threads and yarns. For example, the 110/34 dtex 2ply HC was used for making the antenna. Its denier weight is 110 and 2 ply so conductive weight is 2 times 110 which is 220. It has also high conductive characteristics and anti-tarnish coating. First, problem was to find the resistivity of the conductive threads. It was not possible to exactly crossmatch from the given thread types that were given in the manufacturer website. So, it was matched with the possible or similar threads and found the following data. Table 1 shown the datasheet of the selected threads.

Table 1. Datasheet of the threads [51]

Thread	Thread name	Possible thread from the manufacturer	Linear resistance (Ω/m)
Thread 1	235/34 HC	235/34 dtex HC + B	< 500
		235/34 dtex 2 ply HC+B	< 100
		235/34 dtex 4 ply HC+B	< 50
		235/34 dtex 4 ply + HCB	< 100
		235/34dtex 4 ply +HCB	< 100
Thread 2	110/34 2ply HC+B	110/34 dtex 2 ply HC	< 500
Thread 3	110/34 Z 100 HC + B	110/34 dtex HC z-turns	< 3,000
		110/34 dtex 2 ply HC	< 500
		110/34 dtex 2 ply	< 6,000

Thread 4	78/18	78/18 dtex z-turns	< 25,000
Thread 5	33/12 Z-turns TR	33/12 dtex z turns	< 20,000
Thread 6	33/10	33/10 dtex rd z turns	< 50,000

4.4 Methods of IC Attachment

A tag requires an integrated circuit to work. Attaching this IC to the antenna is done after the antenna is sewed onto the substrate. Generally, there are 2 methods that are used to attach the IC (shown in Figure 10). One of those methods is using a conductive epoxy glue to connect the IC and the conductive threads in such a way that it only touches the IC pads and not the microchip. This method is simple and requires little to no practice. But it takes at least 6 hours for the glue to completely bind so the tag is not immediately ready for measurement. Another method is sewing the IC pads with the thread after the antenna is ready or during the antenna embroidery period. This method saves time but requires practice as the IC needs to be aligned and sewed properly and delicately.

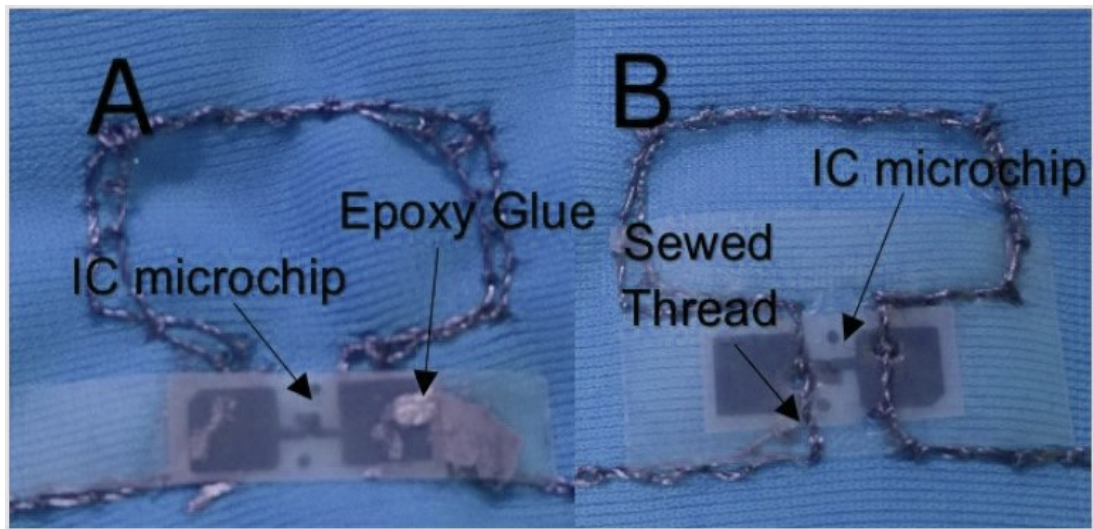


Figure 10. IC attachment methods A) with conductive epoxy glue B) sewing with thread

The IC NXP UCODE G2iL was used for the study. It is a RFID IC that has a microchip of -18 (15.8 μ W) turning on power. This microchip is coupled with two pads of dimension 3 x 3 mm² made from copper and attached on a film made of plastic. The film has a thickness of 45 μ m and the whole IC is 55 μ m thick [50]. Epoxy glue was used for attaching IC in this thesis.

4.5 Tag Preparation

For this study, the objective was to make 3 tags from the same thread. So, for 6 threads, the total number of tags required is 18. Due to some limitations of the thread 1, it was very difficult to fabricate more than one tag out of that thread. So total 16 tags were made and then tested for their performance. The tag preparation method is briefly described below:

The fabric used for all the tags were kept same. The very first thing to do is cutting the fabric according to the shape of the hoop and attaching it to the hoop so that the fabric is tightly in place and is ready for sewing as shown in Figure 11.



Figure 11. *Fabric inserted in hoop*

Then the sewing machine was turned on and operated using the touch screen. The hoop size was selected, and the machine aligned. After the alignment was done, the bobbin thread was inserted into its place using the same thread the antenna is going to be fabricated with and the hoop loaded with fabrics was attached to the arm of the machine. Then, the sewing machine was ready for loading designs.

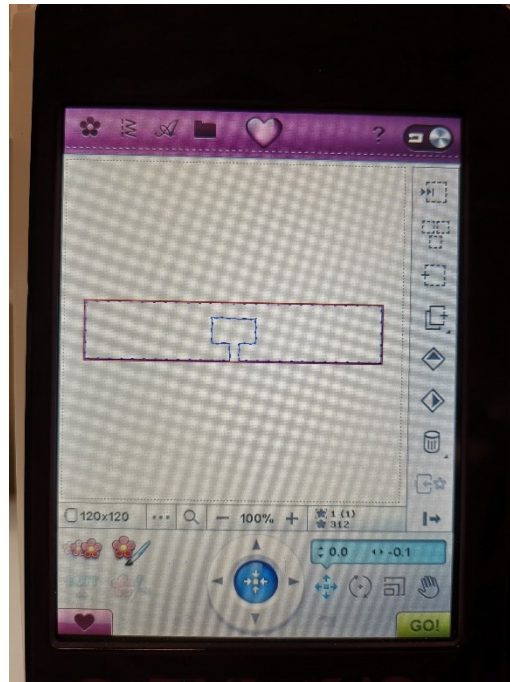


Figure 12. Loading the design onto the sewing machine

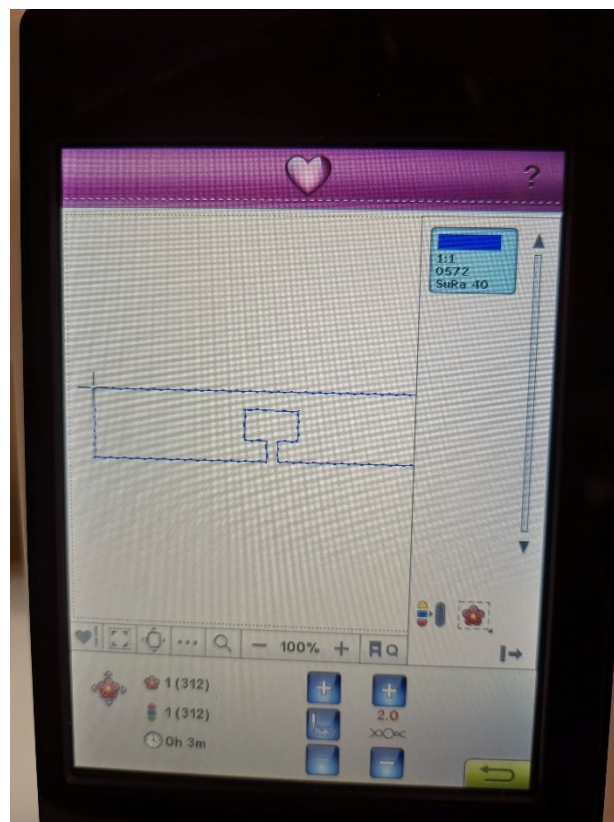


Figure 13. Setting sewing parameters for sewing.

The design file was loaded using a flash drive as shown in Figure 12. After the loading was complete, the design can be aligned, rotated and set its tension as shown in figure 13. This value determines how much further the needle will travel through the fabric before knotting. Several values of this is used for each thread to find the proper range for

the making the tags. Also, the speed of sewing can be set, and it is very vital. The speed needs to be the lowest for giving the threads less possibility to tear. After everything was set, the thread was needed to be installed. They were run through the machine and through the needle and now the sewing machine is ready for sewing as shown in Figure 14.



Figure 14. Embroidery machine ready for sewing.



Figure 15. Antenna being sewed onto the fabric

Then the sewing process starts. It takes about 2-4 minutes for the whole antenna to be sewed onto the fabric as shown in Figure 15. The threads were gently eased out of the

yarns for preventing the ripping. But when it ripped, the machine was stopped, the thread is again installed through the needle. Then few steps were reversed and started again until the design was completely sewed. This same process was repeated for making the 16 antennas. Next it was made sure there are no threads that short the circuit and extra threads that were sticking out are cut. Now the antennas were ready for attaching the IC as shown in Figure 16.

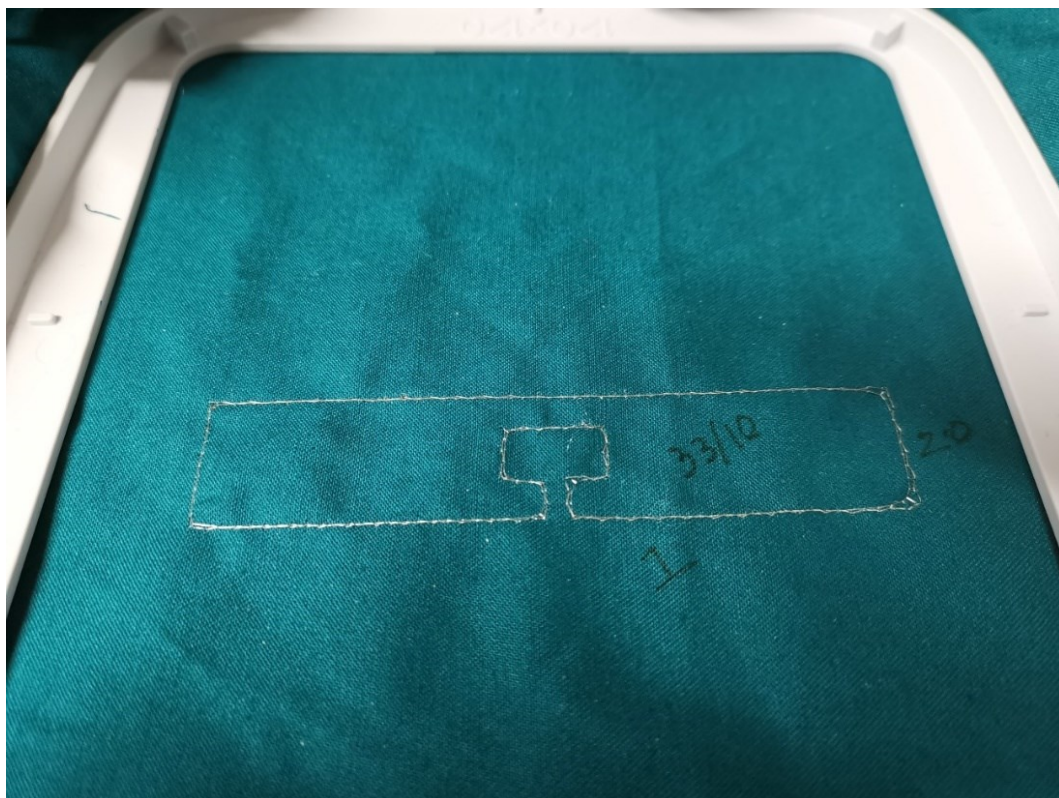


Figure 16. Antenna ready for IC attachment

Next the conductive epoxy glue was made ready for use. There are two part of this glue, A and B. Both were mixed in equal quantity and gently put on the thread where IC is going to be attached. Care needs to be taken so that there is not too much glue, or it might touch the microchip. After the IC was carefully placed, the tags were left overnight for the glue to bond completely with the antennas. Now the tags were prepared and ready for measurement.

5. MEASUREMENT AND RESULTS

This chapter presents the measurement equipment, methods and provides all the results and analysis.

5.1 Initial Tests

To maximize the tag read range, the most important thing is matching the input impedance of the tan antenna with chip impedance. For the chip used in this study, to achieve the best performance, a parallel RC circuit needed to be designed with resistance and capacitance of $R_{eq} = 2.85 \text{ k}\Omega$ and $C_{eq} = 0.91 \text{ pF}$ [50]. The purpose of this study is to test different threads provided to check how well they perform and what is their effect of resistivity on the thread. It is more difficult to design an antenna with the ideal impedance when embroidering instead of conventional method. Theoretically, the thread with the closest conjugate match compared to the IC will provide the best possible result. Keeping the fabric, methods and everything else constant, the performance based on the change of conductivity can be tested. From the section 4.3, it is seen that thread 1 and thread 2 has similar resistances and the resistance values are the lowest among all. It can be estimated that they will perform the best and the others have significantly higher resistances and their performance may be lower as well.

Since the datasheet does not provide accurate resistances for all the threads, measurements were done on them. This was done by calculating the resistance of 10 cm of each thread and then finding the resistance per meter. For each thread, 3 portions of 10 cm threads were used and taken the average.

Table 2. Measured thread resistances

Thread	Linear resistance (Ω/m)
Thread 1	173 ± 22
Thread 2	600 ± 54
Thread 3	1344 ± 78
Thread 4	2100 ± 485
Thread 5	718 ± 120
Thread 6	4433 ± 1200

Even though the exact resistances could be not be watched with the ones from the datasheets, a common pattern emerged. From the measurements, it is seen that thread

1 have the lowest resistance followed by thread 2, thread 5, thread 4 and thread 6. Practically it follows the same pattern as the datasheet but there is one exception. Thread 3 gave a higher resistance than expected.

The conductive threads used for this study vary in their weight, strength and thickness. The threads need to be robust, easily usable for embroidering purposes and provide the best performance.

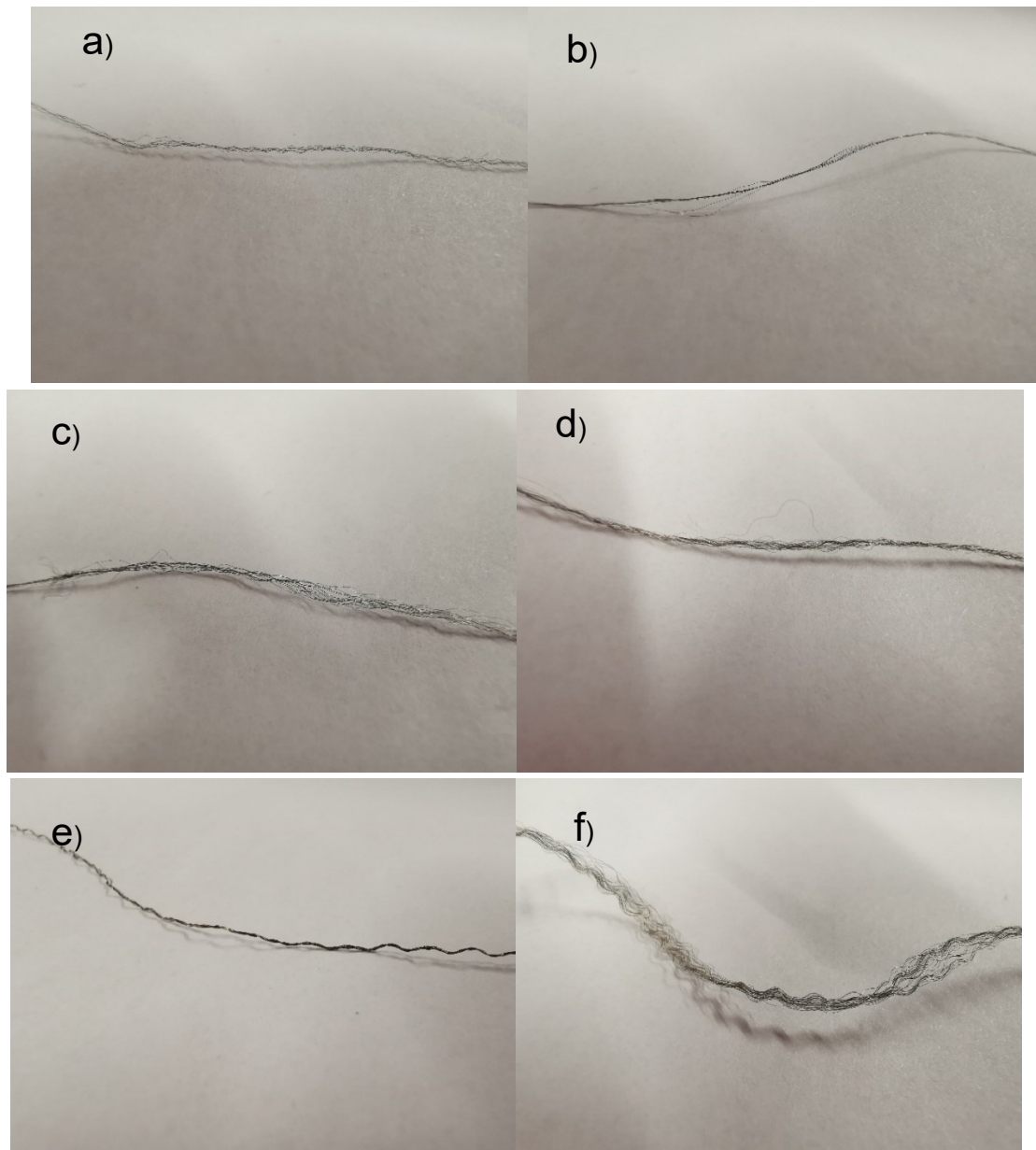


Figure 17. Close observation of the threads a) thread 6 b) thread 5 c) thread 4 d) thread 3 e) thread 2 f) thread 1

From Figure 17, it is seen that thicker threads have higher denier number. Thread 5 and 6 have the lowest thickness. Thread 4 and thread 3 have similar thickness and fall in between all the threads in term of thickness. Thread 1 here has the highest thickness.

Thread 2 has lower thickness even though having much higher conductive weight. Another thing to notice is how the filaments are rolled. it has an effect when sewing. The thread 1 has a loose structure and its filaments are exposed to getting stuck into objects. During the embroidery process, it can get stuck inside machine, and this also means it is difficult to work with. Out of all the threads, thread 2 has the best structure for embroidering followed by thread 5. But thickness is important because it is not desirable that the thread rips in the middle of embroidering. From the thickness point of view, thread 4, 3 and thread 2 should perform desirably during embroidery.

5.2 Measurements

Next part of the study includes taking measurements and that includes using some measurement tools. For taking measurements, anechoic chamber and tag reader was used.

A chamber that is designed in such a way that it is enclosed and the space inside is free from any echo and reflections from the wall inside is called an Anechoic chamber. It achieves this feat by absorbing all the EM radiation. The walls are shielded with materials that absorb radiation as shown in figure 18. This makes the chamber completely absorbent of all the radiations. It also protects the inside space by preventing any radiation from going inside the chamber.

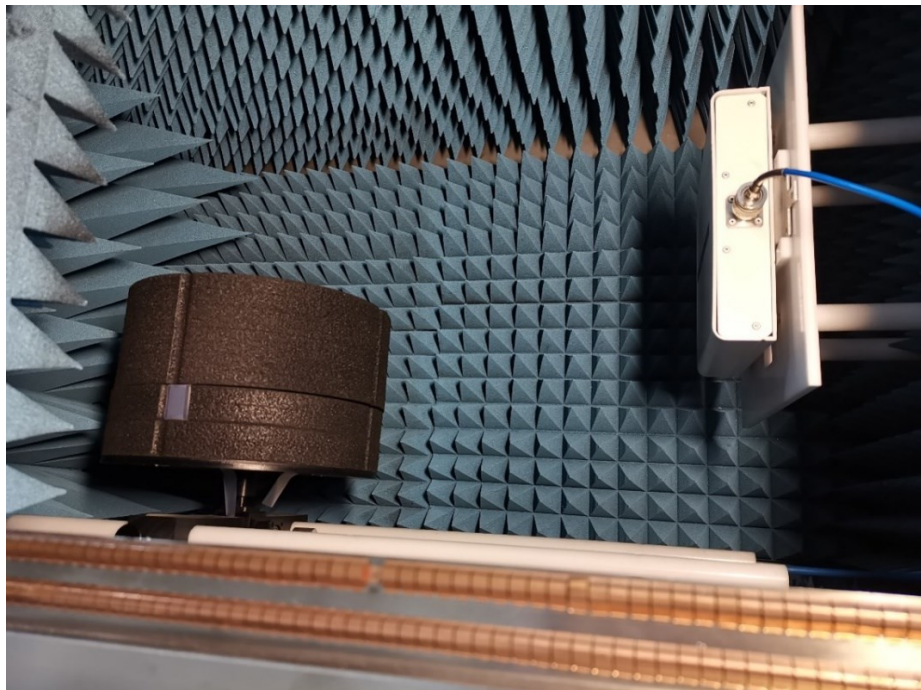


Figure 18. Inside of the anechoic chamber

The reader antenna produces radiation in all directions and this layer on the wall absorbs all the radiation. In the figure, the white device situated on the right side is the reader

antenna. The tag is placed on the round black foam in the left side of the chamber for testing. The object placed on the foam can be adjusted. It moves on its axis and can be rotated. This helps to change the angle of hitting the tag by EM waves. It can also be moved closer or further from the reader antenna. The best performance is gathered when the tag faces the reader directly and the IC is facing the same way.

For taking measurements, a tag reader was needed. Tagformance Pro is a testing device for RFID tags. It can be operated with the anechoic chamber and it has a software for measurement purposes. This reader is produced by Voyantic, a Finnish company. Various performance parameters can be measured such as read range, orientation etc. The whole system contains the software, the measurement equipment and its accessories. The device is shown in Figure 19. This device can help to tune RFID tags and NFC tags and measure their sensitivity. Other used include optimizing methods of tagging, benchmarking, studying material effect, analysing IC performance and memory, optimizing installation, grading performance etc. This device is compatible with HF and UHF RFID and NFC [48].



Figure 19. Voyantic Tagformance Pro reader [49]

Before taking the any measurements, the device is required to be calibrated. The reference tag shown in Figure 20 provided was used to calibrate the device every time it was turned on. The reference tag was attached to radiation absorbing foam and put inside the anechoic chamber. Then the chamber was closed, and the device was turned on. The computer with the software installed and attached to the reader device was turned

on and the software was opened. From the software the calibration was performed as shown in Figure 21, and it takes about a minute to complete the calibration. Then, the device was ready for taking measurements.



Figure 20. Reference tag

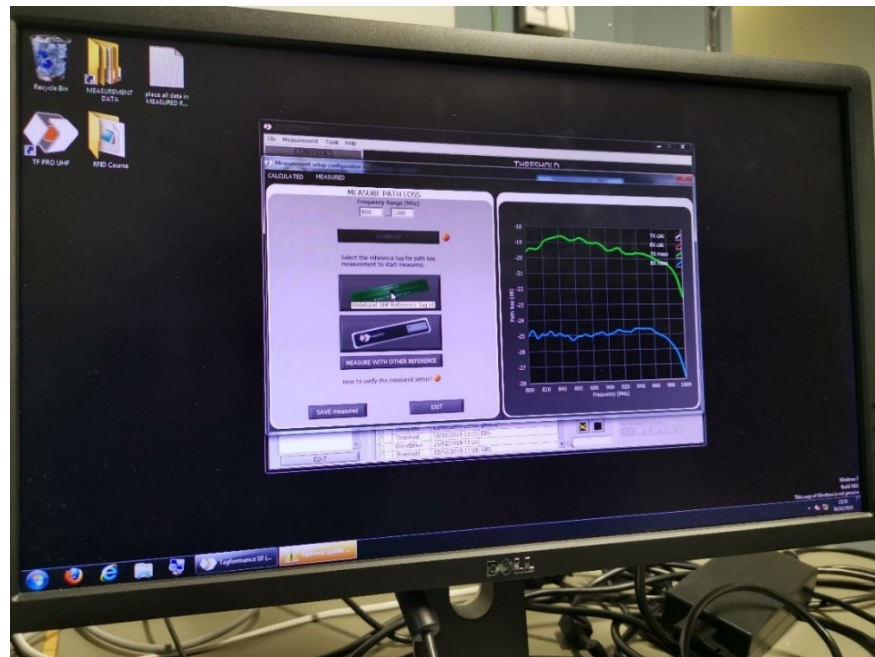


Figure 21. Calibrating the reader

The ready tags were attached to the foam the same way as the reference tag and they were placed inside the anechoic chamber as the next figure. They were placed facing the reader and at the middle of the circular table. Then the chamber was closed as shown in Figure 22, and measurements were taken for 800-1000 MHz.

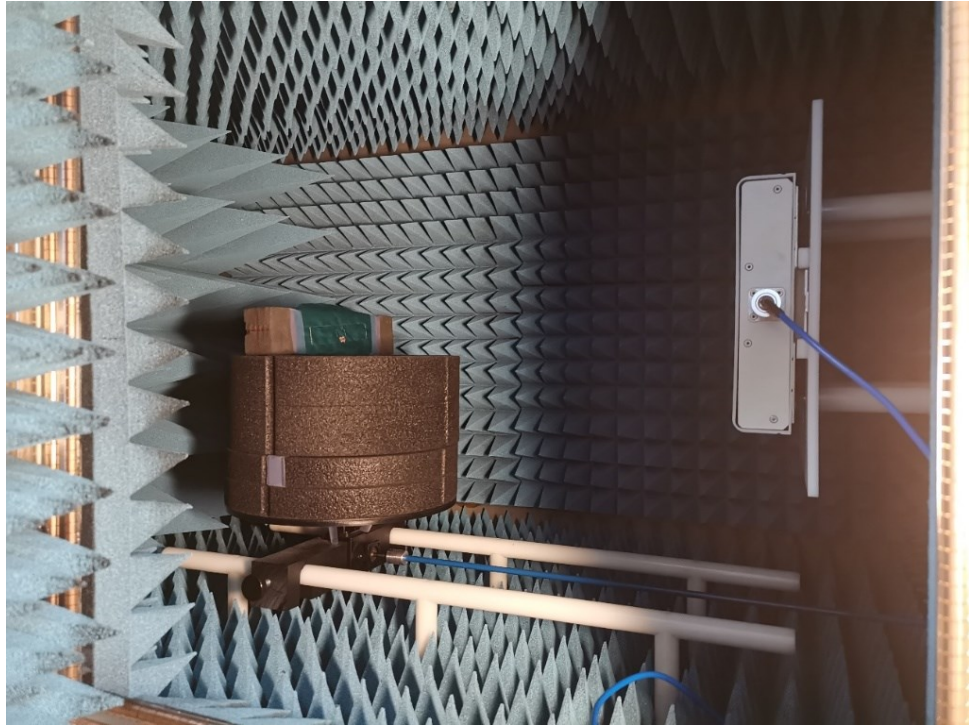


Figure 22. Tags placed inside anechoic chamber

After the measurements were taken, they were exported and saved onto flash drives. The focus is on read range and they are plotted on graphs. The measurements for each type of thread is shown in the same graph.

5.3 Results

Thread 1 has the highest conductivity and the highest read range. Unfortunately, the thicker and the more exposed filaments mean it's also the hardest thread to work with. It was possible to only fabricate one tag since sewing is very difficult with this thread. The thick and fibrous structure meant it was very difficult to get it through the needle. Then the second problem was the thread getting stuck inside the machine. The thread ripped during the second pattern and the decision was taken to move on to other threads. But the one antenna that was sewn is enough to provide with positive results that gave the highest read range of all the tested threads. But the thread is very strong, and it does not rip easily unless it gets stuck. The measurements were plotted in a graph and shown in Figure 23.

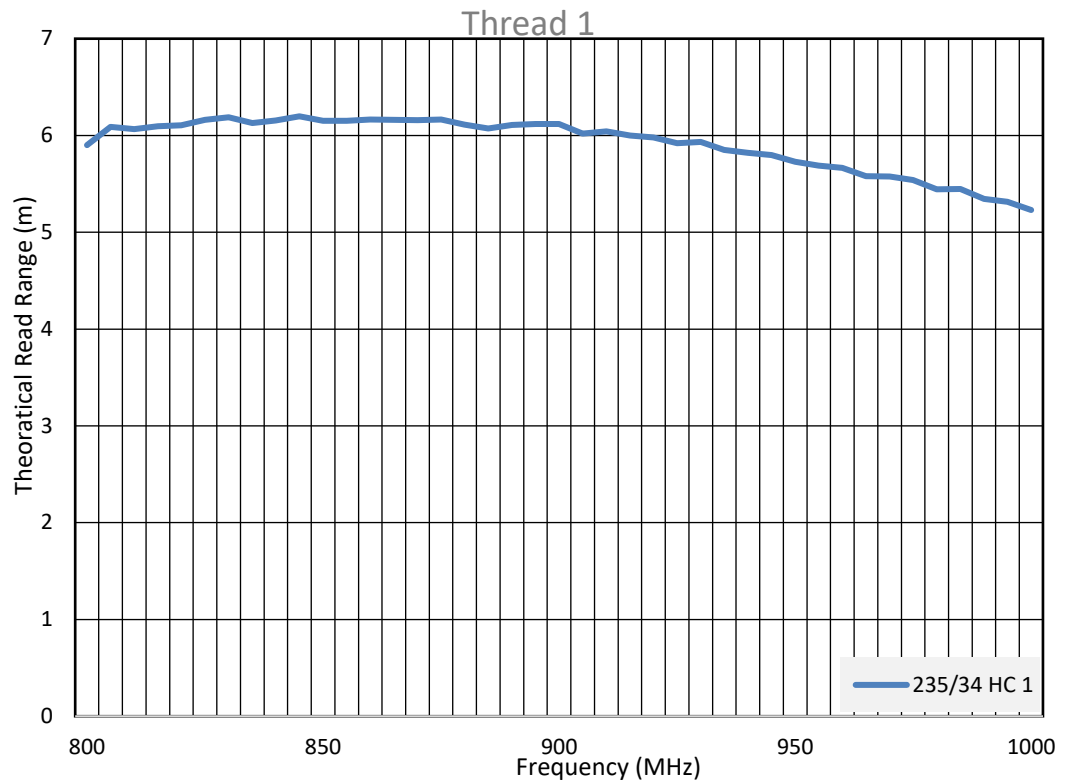


Figure 23. Measured read range for thread 1

The highest read range is 6.2 metres at 845 MHz. Besides the peak, the read range for other frequencies stayed around 6 metres. Few of the difficulties faced during using this thread are;

- a) Too thick to get it through the needle.
- b) Lots of exposed filaments and fibres that gets stuck inside the embroidery machine.
- c) The exposed fibres easily spread and can short the antenna.

The advantages are:

- a) Strong, does not rip easily.
- b) Very good conductivity and performance.

Thread 2 was by far the easiest thread to work with and the strength was balanced. During making the three antennas it did not break a single time and the read range was impressive as well. The measurements were plotted in a graph and shown in Figure 24.

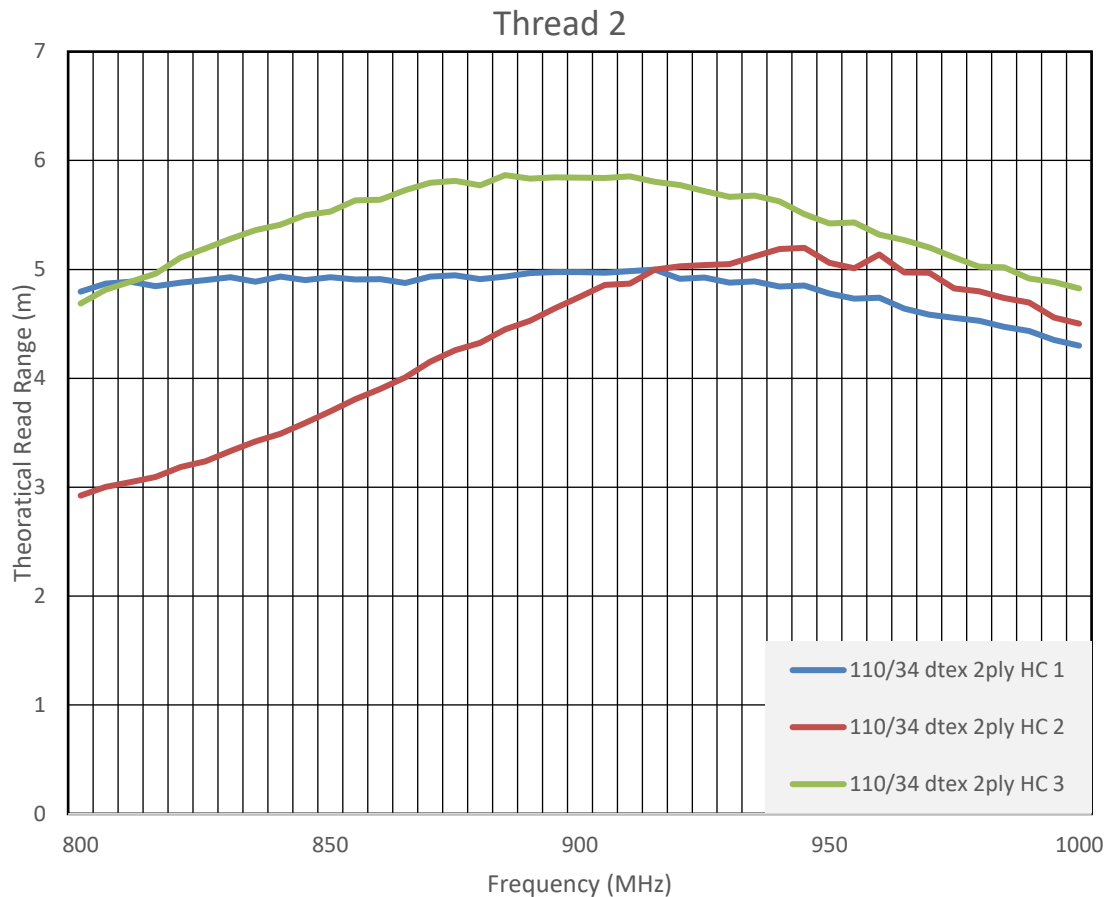


Figure 24. Measured read range for thread 2

The highest read range for this thread was 5.9 metres at 885 MHz and it was achieved with a tension value of 3.2. Except one of the tags, the read range is usually between 5 and 6 metres. Standard deviation is used to show how far apart the performances are from each other. This is done by taking standard deviation of the 3 read ranges at each frequency and taking the mean. For this thread the average standard deviation is 0.63 meters for its read range which shows the performance don't vary too much. Some of the advantages are,

- a) Good smooth structure that makes it easy to sew and does not leave much exposed filaments.
- b) The strength is good and does not rip easily.
- c) Very good conductivity and performance.

And there were no difficulties faced while working with this thread.

Thread 3 should have quite a good conductivity, but the thread wasn't the easiest to work with since it had exposed filaments and during the sewing these filaments would collect inside the embroidery machine and after sometimes the thread gets stuck inside the

machine and rips eventually. It happened 3 times in total. The measurements were plotted in a graph and shown in Figure 25.

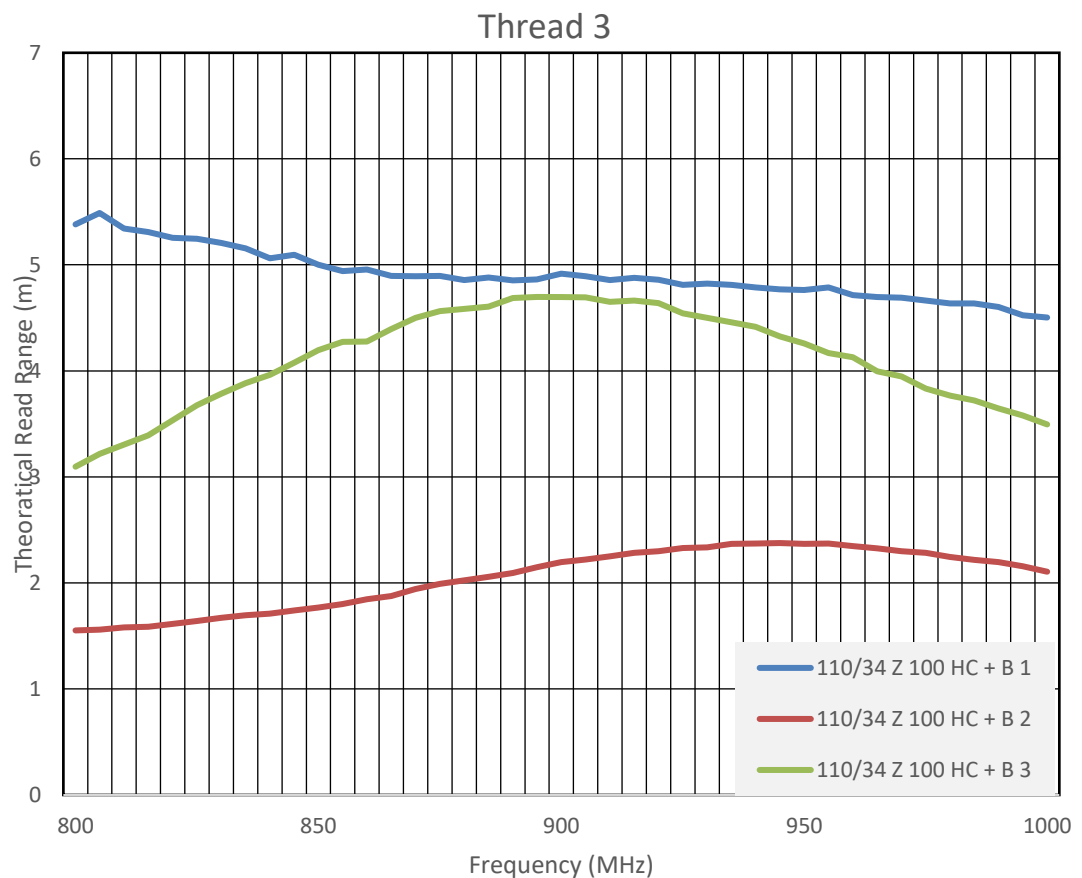


Figure 25. Measured read range for thread 3

The peak read range was 5.5 metres at 805 MHz. But besides the peak, the usual read range is below 5 metres and the performance of 3 threads are very different and inconsistent. Standard deviation here is 1.5 meters which shows the performance between 3 tags vary a lot. Some of the difficulties faced,

- Some exposed filaments that get stuck inside the sewing machine and rip.
- The threads are more fragile than expected.
- Exposed filaments mean they can short the antenna.

There are not any significant advantages to using this thread.

Thread 4 has less than average conductivity out of all the threads and thickness of this thread is also in the middle. It was quite comfortable to work with. During the process it ripped 3 times in total, but it does not have exposed filaments. The measurements were plotted in a graph and shown in Figure 26.

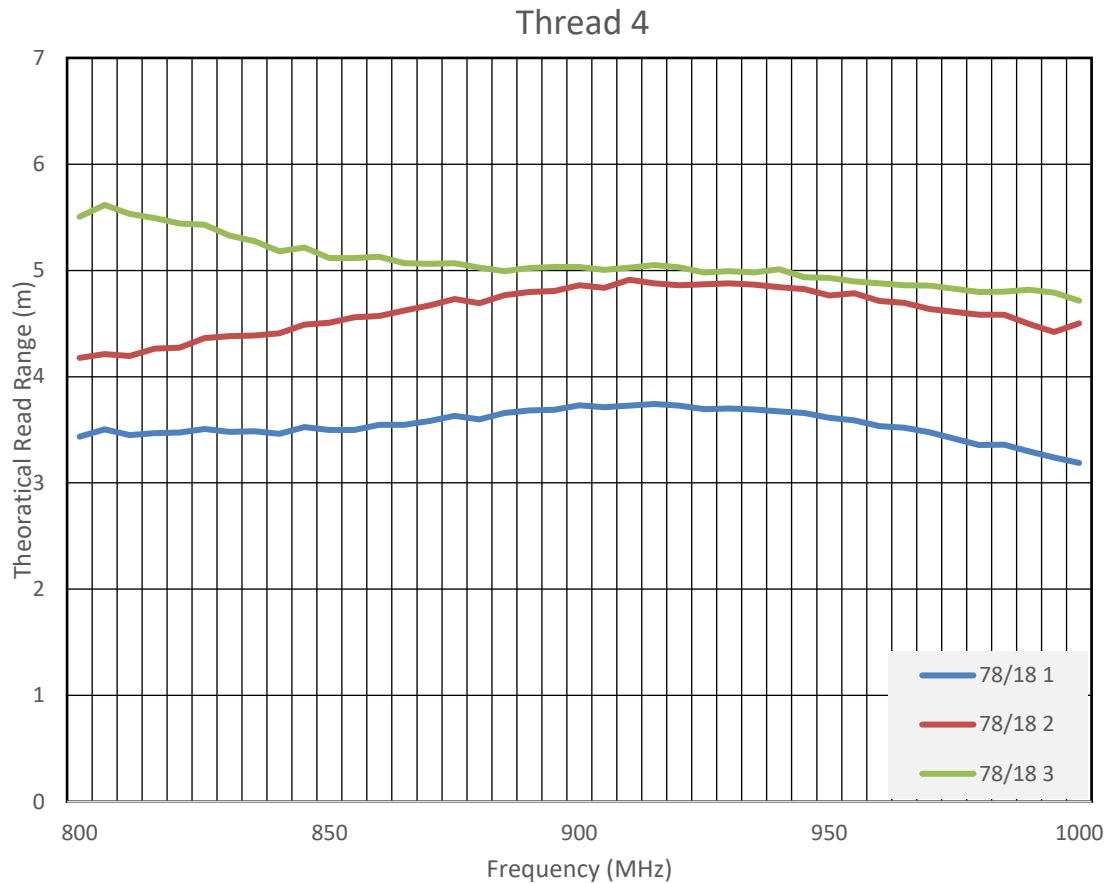


Figure 26. Measured read range for thread 4

The peak read range is at 5.6 metres at 805 MHz. The usual values are around 5 metres and the performance of 3 tags are consistent except one of the tags underperformed. The standard deviation here is 0.8 meters which is decent. The advantage of using this thread is:

- a) It is easy to work with.
- b) Consistent performance.

The disadvantages are:

- a) The thread tends to rip.
- b) Conductivity and performance are less than average.

The conductivity of thread 5 is 3rd highest and it's the second thinnest. Working with it was easy and it provided good performance, but the thin structure means it rips easily and it happened 4 times during 3 antenna fabrications. The measurements were plotted in a graph and shown in Figure 27.

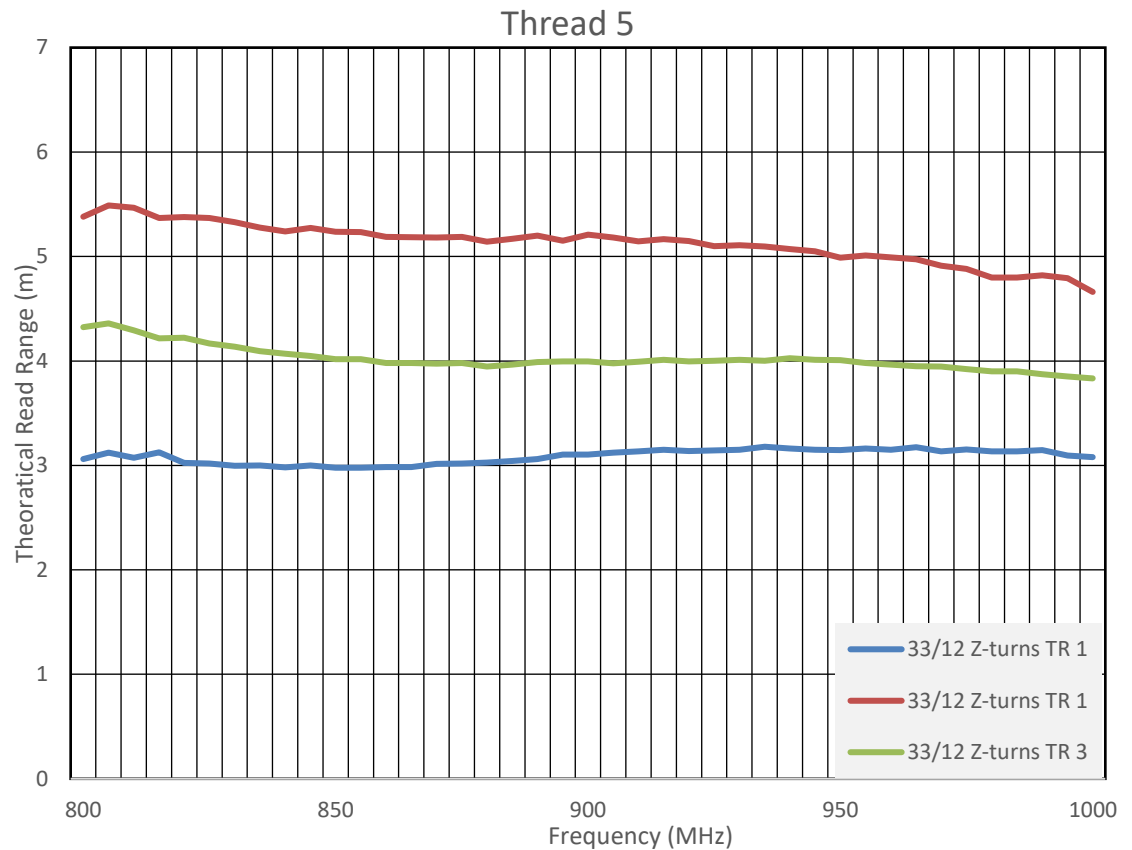


Figure 27. Measured read range for thread 5

The peak read range is 5.5 at 805 MHz. The read range plots have similar graphs, but each are 1 metre apart. The standard deviation is also 1 meter. The advantage of this thread is:

- a) It has high conductivity.

The difficulties of using this thread is:

- a) It has low strength since its rips easily.
- b) Very thin.

Thread 6 has the lowest conductivity and the thinnest of them all. Since it was very thin, it was necessary to use very low tension in the embroidery machine. Still the thread ripped 4 times during making 3 tags and as expected had relatively low read range. Unfortunately, during gluing process, one of the tags might have been compromised as it did not give any readings. So, another tag was fabricated, and its measurement taken. The measurements were plotted in a graph and shown in Figure 28.

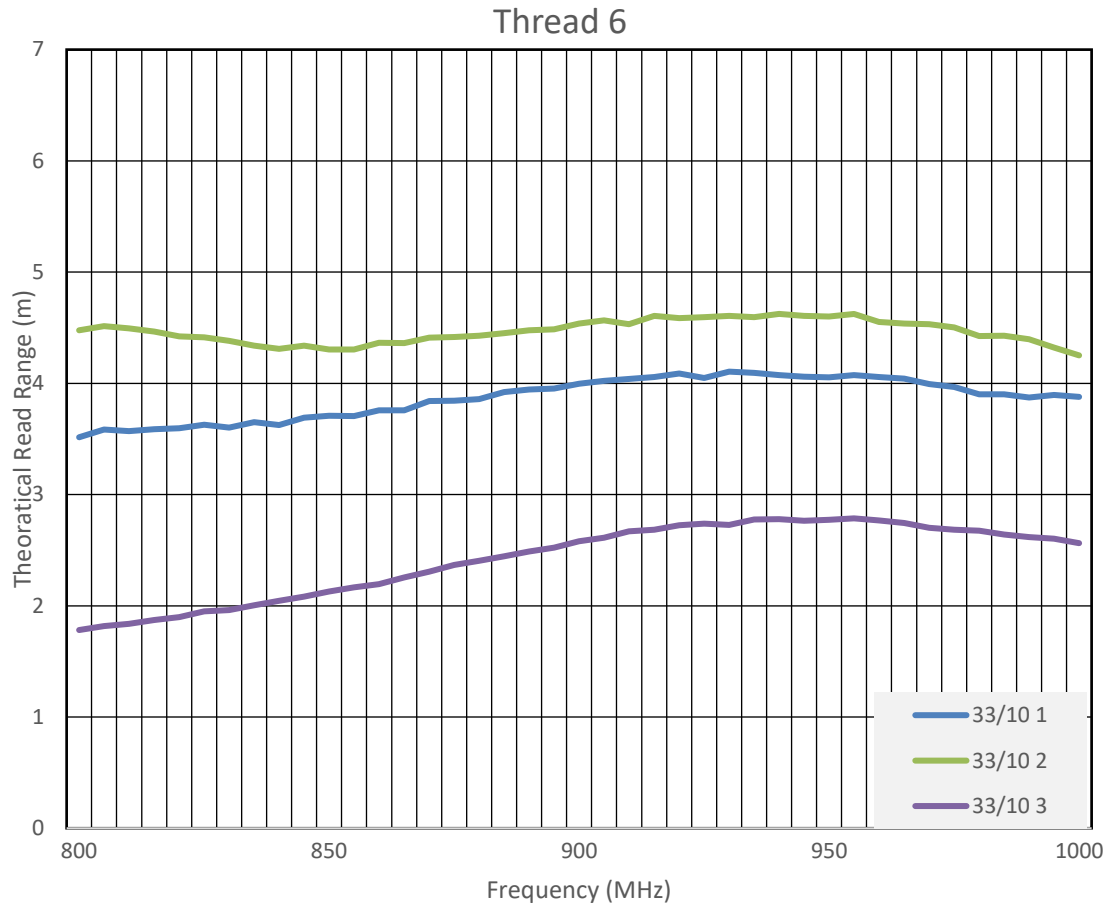


Figure 28. Measured read range for thread 6

The peak read range is 4.6 metres at 955 MHz. The Performances are somewhat similar and consistent, and the standard deviation is 1 meter. The main disadvantages are,

- a) Very thin and rips easily.
- b) Low conductivity and low performance.

There is no significant advantage of using this thread over the other ones.

5.4 Comparison and Analysis

From the graphs in section 5.3, it is easily distinguishable that thread 1 is the best performing and thread 6 is the lowest performing thread. Thread 2 tags also have very good read ranges after thread 1 tags. The rest three tags made from the rest 3 threads are very relatable according to read range and fall in middle. The highest average read range at US and Europe UHF central frequency along with some key characteristics of each thread is shown in Table 3.

Table 3. Comparison between the threads

Thread	Average read range at Europe central frequency (m)	Average read range at USA central frequency (m)	Peak frequency (MHz)	Key characteristics
Thread 1	6.2	6.0	845	-High conductivity and read range -Too Thick and exposed filaments
Thread 2	4.9	5.3	915	-High conductivity and read range -Good structure
Thread 4	4.4	4.6	915	-Good performance despite lower conductivity -Good structure
Thread 5	4.0	4.1	805	-Good conductivity and decent performance -Too thin and rips easily
Thread 3	3.7	3.9	915	-Unexpectedly low conductance and performance -Exposed Filaments
Thread 6	3.5	3.8	955	-Low conductance and performance -Too Thin, Rips too easily

The read range for two frequencies were considered. One at Europe central frequency for UHF RFID which is 866 MHz and the other is US central frequency which is 915 MHz. From the table, it is seen that there are some patterns emerging. As the threads get thinner, they rip easily and as they get thicker, they tend to be harder to work with as they get stuck inside sewing machine or too thick to push through the needle. Another thing to notice is, as the linear resistance of a thread increases, with it read range of the tag made from that thread decreases. There is one exception though. Thread 4 performed better for the read range for its measured resistance. The 2, 3 and 4 threads all reached their peak at 915 MHz for their best performing tags and they fall exactly on the US central frequency for UHF. Usually all the tags performed better for the US central frequency compared to Europe central frequency except thread 1. The clear winner in terms of read range only is thread 1 while thread 6 is the worst performing.

5.5 Discussion

The focus of this study is evaluating each conductive thread and optimizing the performance of the antenna by choosing the best thread for the purpose. Aside from performance, there are few other factors that influence this decision. The thread requires to be strong enough to survive through the sewing procedure, it needs to have good structure of filaments so that they are not exposed. Exposed filaments can get loose over time causing the antenna to short or even get stuck in other objects which may result in deformation of the sewed pattern. So, the challenge here is to choose the thread which is the most practical for embroidery and has the highest read range. Higher conductivity provided much better read ranges. Thread 1 has the highest conductivity and it provided the best range overall. But it has far too many disadvantages. During the fabrication process, it was possible to make one tag. The constant need to open up the embroidery machine for removing the stuck thread and cleaning the removed filaments stuck inside makes this thread very impractical to work with for the embroidery method currently used. So, it was necessary to look for the next option.

Tag made from thread 2 has very good read range compared to the rest and close to that of thread 1. But it has none of the disadvantages. It has the most convenient thread to work with. The performances were consistently high. But it also has the best structure and strength. It did not rip once while fabricating which no other thread could manage. Again, the peak frequency is 885 MHz and peak frequency for the average is 915 MHz in the spectrum for the tag antenna created with this thread. The other threads have few things to consider. The tags made from them provide less read range, the threads provide less strength for sewing purpose and none of them provide any significant advantage over thread 2. Perhaps using threads with much higher conductivity than this with similar structure might provide better results. But for the threads that the study was performed on, thread 2 (110/34 dtex 2ply HC + B) is easily the best conductive thread to use for optimizing the performance of the antenna as well as the most practical thread.

6. CONCLUSION AND FUTURE WORK

In this thesis, several conductive threads were evaluated for the purpose of making embroidered RFID antennas. The performance of tags made from each thread were analysed and the optimized selection is made.

At first, the resistance of each thread was measured. In this work, for the fabricated tags, tag substrate, antenna design, IC and fabrication method were kept consistent throughout. This way other factors affecting the performance were eliminated. The only parameter that can affect the tag performance is the conductivity of the thread. After that, 3 different tags were fabricated using each thread for evaluation. The measurements of wireless performance were taken of all the tags. Finally, the performances of all the 16 tags were analysed and compared to select the best conductive thread for wearable applications. Thread 1 resulted in the best performing tag, but it has many limitations. Embroidering with this thread is quite a challenge as discussed in Chapter 5. On the other hand, thread 2 has similarly good performance and the least challenging to fabricate embroidered antennas with. None of the other threads has any benefits over this thread and the tags made from them did not provide better results.

The goal of this thesis was to experiment with various conductive threads to realize the practical effects of changing the threads and conductivity on the embroidered antenna. For conventional RFID fabrication, the antenna material which is usually made from metal can easily be selected for its linear conductive nature. Embroidered RFID has a limitation, the conductive threads do not provide consistent conductivity over the different sections of its yarn. This means each tag will have different conductivity and it is very difficult to get an exact conjugate match for the IC used. The focus was optimizing the antenna performance for the antenna design used for this study by selecting the optimal conductive thread.

The thesis result will prove useful for anyone looking to find a conductive thread that provides the optimized performance for their purpose in embroidered RFID. In the future, this study can be revisited because the study can be expanded to better conductive threads and better tools. When fabrication methods get better and more advanced equipment are used, there will be more opportunities to evaluate embroidered RFID based on the conductive threads used to fabricate them. A machine that can handle difficult threads like thread 1 can open more possibilities to use thicker and more conductive threads for embroidery. This can lead to even greater read range and possibly better

antenna designs. Embroidered RFID still hasn't reached its full potential and better techniques will help us use other conductive threads like intrinsic conductive threads discussed in Chapter 3. Conductive threads are also getting better with time. Many types of conductive threads are being made which have significantly high conductive nature. Carbon nanotube and graphite are used to make conductive threads and intrinsic conductive threads have very low resistances and, in the future, when they will have the same structural integrity as the coated threads, further study can be performed. As the fabrication methods improve and conductive threads get better, it will eliminate many of the challenges we face today in embroidery RFID. The methods employed for this thesis may be expanded for future research and development.

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