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RELIABILITY TESTING ON WEARABLE TEXTILE-BASED UHF RFID TAGS

Master of Science thesis

Examiner: Prof. Leena Ukkonen and
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Virkki.
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ABSTRACT

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Due to their huge future potential in identification, monitoring, and sensor applications, textile-integrated radio-frequency identification (RFID) tags have been an active topic of research during the recent years. A passive, battery-free RFID tag is composed of an antenna and an integrated circuit (IC) and, when integrated into a textile material, offers a cheap, unobtrusive, and completely maintenance-free wireless platform for versatile body-centric systems. One of the key challenges to be addressed, before the large-scale deployment of these textile RFID components, is their ability to withstand continuous washing, which has been found to be a major reliability issue and is currently actively studied.

This thesis presents a washing reliability study of passive UHF RFID textile tags with three different coating materials. The tag antennas were fabricated by brush-painting silver ink on a 100 % cotton fabric. After attaching the ICs, the ready RFID tags were fully coated with three different protective coating materials: regular textile glue, white epoxy coating, and silicone rubber. The coated tags were washed 15 times in a household washing machine and tested wirelessly after each washing cycle for the total of 15 washing cycles.

Before washing, all tags exhibited good performance and attainable read ranges of about 10 meters, under the European RFID emission regulation. Based on the reliability test and the done measurements, all three protective coating materials can successfully protect the RFID tags from the effects of washing and especially the textile glue was found to be suitable coating for the brush-painted tags. Silicon rubber also can be said as a suitable coating. White epoxy glue coating does make the tags water resistant but it is constantly losing its ability of protection after each washing cycle and, in the long run, it can be said that it does not make the tags washable.

PREFACE

The master thesis, “Reliability Testing on Wearable Textile-Based UHF RFID Tags” was done in partial fulfillment of the requirement for the Master of Science degree in Wireless Communications and Networks major, in the Master’s Degree Programme in Information Technology at Tampere University of Technology. All the researches and investigations have been done in the Wireless Identification and Sensing Systems Research Group (WISE) under the supervision of Prof. Leena Ukkonen and Prof. Lauri Sydänheimo. I would like to thank my thesis examiners and supervisors, Prof. Leena Ukkonen and Academy Research Fellow Johanna Virkki., for all of their support, continuous guidance and for providing me an appropriate environment to complete my thesis. I am also thankful to all my colleagues in the WISE Group for their help and support.

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Tampere, July 2017

Aitzaz Haider Kazmi

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LIST OF ABBREVIATIONS AND SYMBOLS

TUT	Tampere University of Technology
EIRP	Effective Isotropic Radiated Power
RFID	Radio Frequency Identification
UHF	Ultra High Frequency
IC	Integrated Circuit
LF	Low Frequency
HF	High Frequency
Pth	Threshold power
dtag	Attainable free-space read range of the tag
GHz	Gigahertz
MHz	Megahertz
KHz	Kilohertz
Hz	Hertz
dBm	Power ration in decibels
Λ	Sensitivity of the reference tag
m	Meter
μm	Micrometer
V	Voltage
°C	Degree Celsius
μW	Micro Watts
mm	Millimeters

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1. INTRODUCTION

Due to their huge future potential in identification, monitoring, and sensor applications, textile-integrated radio-frequency identification (RFID) tags have been an active topic of research during the recent years. A passive, battery-free RFID tag is composed of an antenna and an integrated circuit (IC) and, when integrated into a textile material, offers a cheap, unobtrusive, and completely maintenance-free wireless platform for versatile body-centric systems [1-9]. Low manufacturing costs, easy installation, almost maintenance free operation and the amount of dependability are few of the major reasons which is why these RFID tags are gaining popularity in various topic of research.

One of the key challenges to be addressed, before the large-scale deployment of these textile RFID components, is their ability to withstand continuous washing.. Major reliability issue of the textile-based tag is to endure resistance against water, detergents and mechanical stress during the process of washing which is the area of focus and research in this study.

In this thesis, antennas for textile-based passive ultra high frequency (UHF) RFID tags were fabricated by brush-painting nanoparticle conductive silver ink on a 100% cotton fabric, the ICs were attached to these brush-painted antennas with a conductive epoxy glue, and the ready tags were coated with three different protective coating materials. To evaluate the reliability of the tags, they were washed 15 times in a household washing machine, using a commonly used 40 °C washing program with detergent and spinning, and tested wirelessly after each washing cycle.

The thesis is organized as follows: After this introduction section, the chapter 2 presents the background and the basics of RFID system, the components and their configuration, the RFID classification and focusing on passive UHF RFID textile tags. Chapter 3 presents various conventional RFID manufacturing techniques, explaining brush painting technique (technique used in this thesis study) in detail as well as our tag antenna design and the fabrication method of the tags. Chapter 4 presents the used coating materials and coating processes, the experiment itself and the wireless tag measurement equipment details. Chapter 5 presents and discusses the measurement results before and after the washing test and the last Chapter 6 summarizes the conclusions of this study and the future potential of it.

2. BASICS OF RFID

Every object, place, thing and person has a name or a number for identification, so that, we can recognize the object and if needed differentiate between the objects. Identification helps us in understanding the very existence of the object, its purpose, value and what we need to do with it. During World War II identification of the aircrafts flying in the sky was a major problem to the U.S which led to the non-recognition of Japanese bomber aircrafts flying towards the Pearl Harbor in 1941. German air force was pioneer in solving this problem of identification of their aircrafts by using passive backscatter radio link for identification. Passive means there is no energy source attached to the object being identified. The radar on the ground transmitted the radio signal which scattered back after hitting the object (in this case an aircraft) [1].

For quite a long time, and still now, barcode system has been used for identification and product tracking in supply chain management. Radio frequency identification (RFID) is a vital and integral part of our lives now. We use RFID in numerous applications daily to increase the efficiency and productivity. Such as, asset tracking, inventory and retail management, books tracking in libraries, fare collection at the toll gates, animal identification and tracking, electronic passports, luggage tracking, interactive marketing, access control systems, materials management, race timing in sports, public transport fare collection, anti-theft, parking systems, brand protection etc. RFID is gaining immense popularity in health care sector also by keeping track of the patients' access with in the vicinity and health records management. RFID system is fast, more robust and reliable than any other system used for object identification. Non line-of-sight ability, greater reading distance and onboard storage bring flexibility and capability to the RFID system, unlike barcode system [2], [4].

2.1 RFID System

"RFID is the use of radio communications to identify a physical object" [1]. RFID uses short-range radio technology to communicate identification information between a static location and a movable object or between several movable objects. RFID system has two ends, a simpler device at one end of the link and more complex device at the other end of the link. Tags or transponders are the simpler devices which are small, less complicated and inexpensive to attach to numerous objects which need to be identified and managed. Readers, interrogators, beacons are more complex and capable devices usually connected to a host computer or network. RFID frequency spectrum has frequency range starting from 100 kHz to 2.5 GHz but it might go up to 10 GHz in some cases [1].

Figure 2.1 shows a basic RFID system;

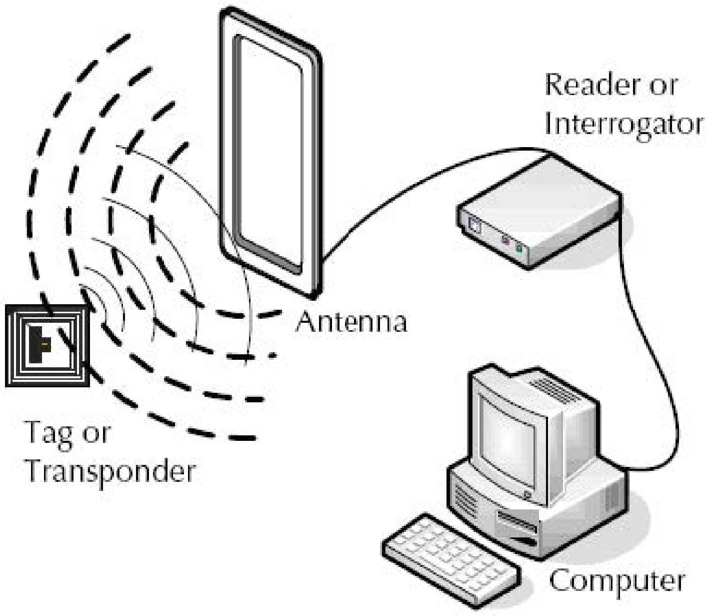


Figure 2.1 *Simple RFID system [1].*

Generally the reader has an antenna attached to it or, in some cases; it is attached via wire at a distance from the reader depending on the design and requirements. Reader antenna sends and receives the radio signals between the reader and the tag for communication and information exchange. Tags also have antennas which are attached directly to the tag; and an integrated circuit IC which controls the communication and holds the information about the tag. An unmodulated radio signal generated from the reader reaches the tag and backscatters a modulated signal to the reader in order to uniquely identify the object. Usually for better understanding, the signal carrying information from the reader to the tag is referred as the forward link or downlink and the signal carrying information from the tag to the read is referred as the reverse link or uplink. There might be possibility of the presence of multiple tags and readers near to each other in the real world applications [1-2].

2.2 Configuration and Components

A typical RFID system configuration consists of the same basic structural components among which the wireless communication takes place as shown in the Figure 2.2. These basic RFID components are:

- A tag or transponder
- A reader or interrogator
- A host computer

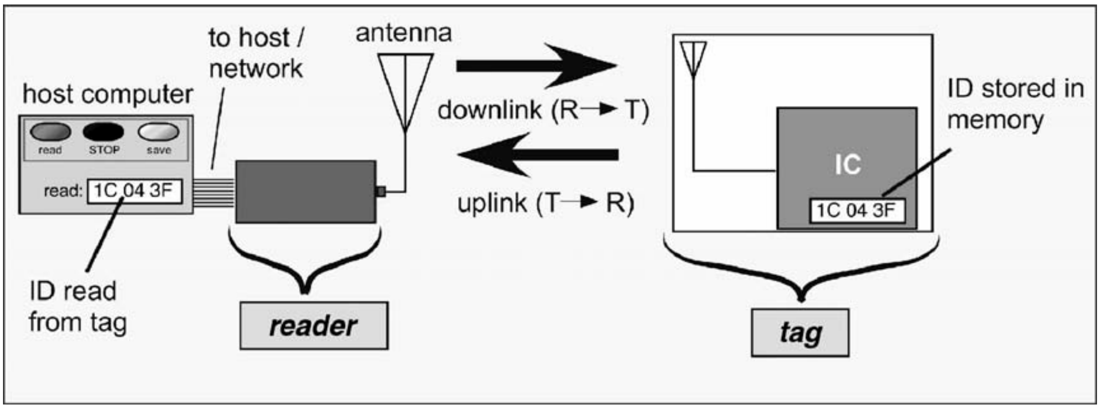


Figure 2.2 *Block diagram of basic components of a UHF RFID system [1].*

A tag contains the ID and is attached to the object. It consists of an IC and an integrated antenna. The IC holds the identity information within its memory unit. The size of the memory unit varies depending on the need and type of tag used for a certain application. The antenna is used to detect and respond to the signal coming from/to the reader. If the IC is read-only then we can only extract the information whatever it contains, however, if we have a read-write IC then we can not only extract the information for the memory unit but can also alter or write new information on the IC [1-3].

A reader transmits the radio signal to the tag using its antenna in order to extract the ID information from the tag. Reader transmission signal travels to the tag; some portion of this signal backscatters and reaches the reader. Transmitted signal has to be quite powerful and reader has to be sensitive because the energy is lost in travelling and in backscattering upon reflection form the tag. The reader is able to communicate with different application systems in order to resolve the information message received from the tag. For this purpose the reader is connected to the host network which demodulates the received signal and identifies the object [1-3].

Host computer is the control center for all kind of operations we want to perform on the tag and the reader. A computer host is used to display the message in human readable format where we can then utilize for different purposes such as; tag identification, management, access control and even for information modification [1-3].

In case, we have same antenna on the transmitter side which transmit the signal and intercepts the backscattered signal from the tag; such kind of reader system is known as monostatic. On the other hand, if we have two separate antennas on the transmitter side i.e. a separate antenna to transmit the signal towards the tag and the other separate antenna to intercept the backscattered signal from the tag; such kind of reader system is known as bistatic. Generally the transmitted signal has more power than the received backscattered signal. This is why the reader has to be quite sensitive in the reception/interpretation and in reading the reflected signal on the way back from the tag. These days the sensitivity of the IC attached to the tag is around -18dBm where as the sensitivity of the reader is around -80dBm [1].

2.3 Classification of RFID Tags

RFID tags are mainly classified in three different categories:

1. Passive tags
2. Semi-passive tags
3. Active tags

2.3.1 Passive Tags

Passive tags consist of an IC and an antenna. No internal power source is available at the tag for it to initiate the communication. It relies on the reader to initiate the communication. Energy from the radio signal generated by the reader excites the tag circuitry; tag gets operational and sends back the unique information contained within the tags IC using backscatter communication. Lack of power source means passive tags are very cheap to manufacture. Fewer component constructions mean size reduction, flexibility and virtually no maintenance is required [1], [5].

The IC is called the brain of an RFID tag stores all the unique information in its nonvolatile memory as there is no power available to the tag most of the time. Generally speaking, more the capacity of an IC to store data information more will be its cost. Tag antenna is used for radio communication and an encapsulation to contain these passive tags components can be made of plastic, glass, rubber or can be printed directly on to different materials. In our case, the antenna structure is brush painted on to a cotton fabric substrate and an IC is attached to it [1].

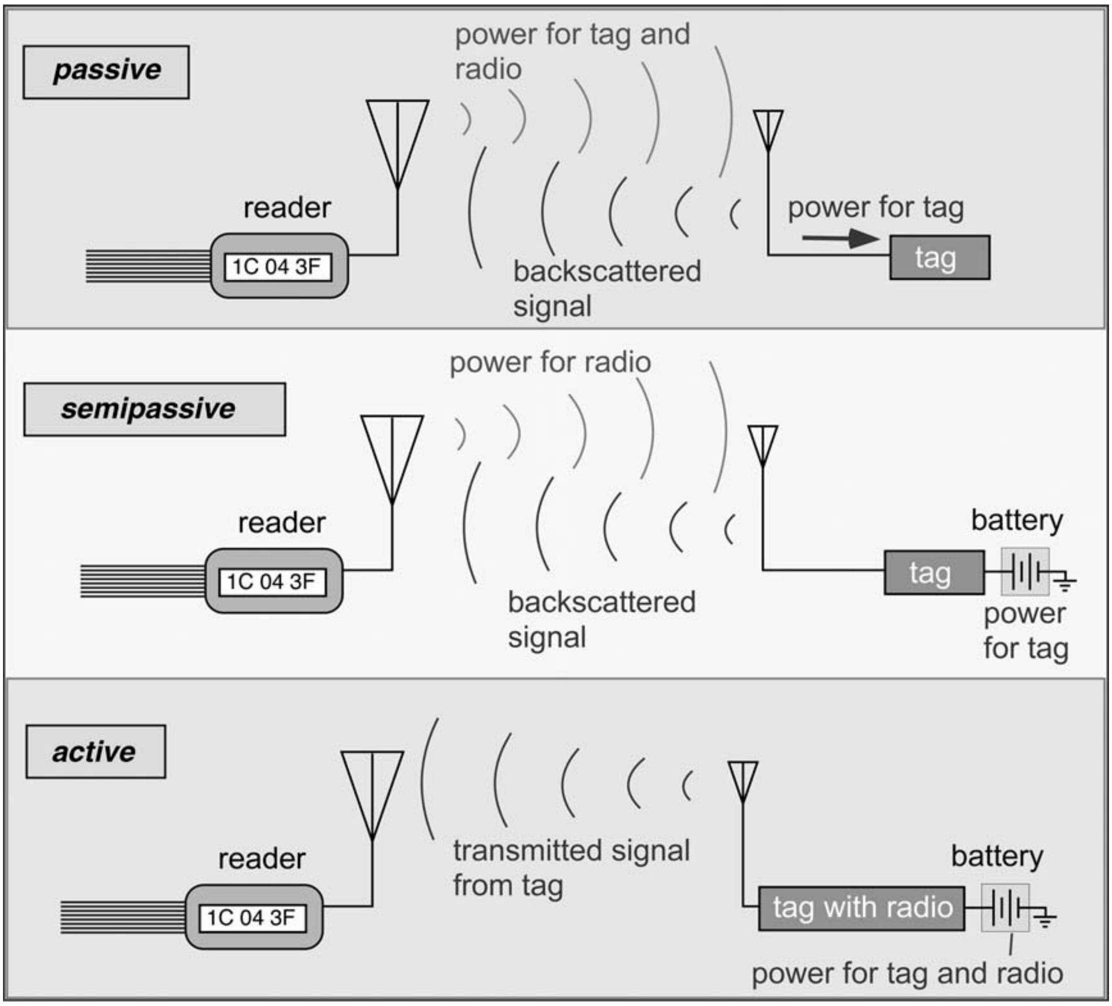


Figure 2.3 *Illustrative difference among each RFID tag type power configuration [1].*

2.3.2 Semi-passive Tags

Semi-passive tags are also known as battery-assisted passive tags. It consists of an IC, antenna and a battery. Energy source of the tag is used to power the tag circuitry however; it still cannot initiate the communication with the reader and relies on the reader to send a radio signal for communication to begin. Like passive tags, semi-passive tags also use backscatter communication for the uplink or tag-to-reader communications and sends all the information required by the reader. Semi-passive tags have read range in tens of meters as compared to smaller few meter range of passive tag and are more responsive upon interrogation. Addition of battery increases the size, cost and maintenance requirements [1].

2.3.3 Active Tags

Active tags have their own power source, IC, transmitter, receiver and the antenna. Battery source on the tag provides energy to the circuitry and antenna for communication with the reader and it can communicate at greater distances with the reader. On-board power do make active tags expensive, less flexible and they require maintenance incase battery runs out of power potential. Unlike passive tag, an active tag does not wait for the initiation from the reader to start the communication. Active tags can transmit the signal up to hundreds of meters even in the presence of external noise because of its capability of modulation techniques, such type of active tags are referred to as transmitters. The idea of transmitting information all the time regardless if there is a reader listening is simply the waste of energy source, so to address the issue the tags remains at sleep state meaning no data transmission unless there is an active request signal form a reader, such type of active tags are referred as transmitter/receiver [1].

2.4 Operational Frequency Bands

Identification and tracking information is sent wirelessly using the radio frequency electromagnetic waves in a typical RFID operation. Due to the limitations and availability in frequency spectrum and in order to avoid the interference among different radio channels, every wireless radio system is assigned a specific frequency band to carry out its operations. Broadly speaking, every region has different frequency ranges for the RFID communication purpose. Worldwide UHF RFID band allocation is illustrated in the Table 2.1 below: [1], [4-5]

Table 2.1 *UHF RFID band allocation.*

World Region	Frequency band for RFID (MHz)
EU, Russia, North Africa	865 – 868
USA, Canada	902 – 928
Brazil	902 – 907.5 and 915 – 928
South America (except Brazil)	902 – 928
South Africa	865.6 – 867.6 and 917 – 921
China	917 – 922
Japan	952 – 954
Korea	908.5 – 914
Taiwan	922 – 928
Hong Kong	865 – 868 and 920 – 925
Australia	918 – 926
New Zealand	864 – 868
Malaysia	866 – 869 and 919 – 923
Thailand	920 – 925
Singapore	866 – 869 and 923 – 925

The primary frequency ranges used in RFID are illustrated in detail in the Table 2.2 below: [5]

Table 2.2 *Primary RFID ranges and details.*

Frequency Type	Low Frequency (LF)	High Frequency (HF)	Active Ultra-High Frequency (UHF)	Passive Ultra-High Frequency (UHF)
Frequency	125 – 134 kHz	13.56 MHz	433 & 856 – 960 MHz	856 – 960 MHz
Approximate Cost ($)	0.50 – 5	0.23 – 10	25 – 100+	0.13 – 25
Read Range	Contact – 10cm	Contact – 30cm	30 – 100+ meters	Contact – 25+ meters
Examples	Animal tracking, Access control, Car Key-Fob, Applications with high volumes of liquids and metals	DVD shops, Library books, Personal ID cards, Poker/Gaming chips	Automotive dealerships, Automotive manufacturing, Mining and Construction	Supply chain management, High-volume manufacturing, Pharmaceuticals, Electronic toll collection, Item tracking, Racing timings, Asset tracking
Advantages	Better performance with applications including liquids and metals, Has global standards	NFC protocol, large memory, has global standards	Reading range is relatively large, reader has low cost, capacity to store large volumes of data, data transmission rates are high, can detect multiple tags at once	Favorably long reading range, less cost per tag, broad range and verity of tag sizes and types, global standards, data transmission rates are high, can detect multiple tags at once
Disadvantages	Very short read range, Data storage memory is quite less, Data transmission rates are low, Can detect very few tags at once, Production cost is high	Short read range, Data transmission rates are low, Can detect fewer tags at once	Tags cost much higher, Unable to carry via air transport if tags are actively transmitting, Probability needing a complex software, Higher interference from metal and liquids, No global standards	Usually associated with high costing infrastructure, Memory unit has small amount to contain data, Higher interference from metal and liquids

2.5 Passive UHF RFID Textile Tags

The concept of smart clothing and intelligent wearable has been around for well over a decade now. Antennas being part of clothing have particular requirements and specifications which should be taken into consideration at the time of implementation. Usually, the textile based tag have useful applications, such as, they are light weight, inexpensive, require virtually no maintenance at all and no setup is required [6]. The importance and relevance of all fabric antennas has been presented and discussed in detail in the international conferences [7-8].

RFID has bright and innovative future in wearable electronics with great potential in human benefit, welfare and healthcare applications [9-11]. Different kinds of electro textile materials have been experimented on to check the washing durability of the RFID tags in a normal everyday household washing machine with ordinary washing detergents at 40 °C [9] with a dipole antenna orientation. Researchers have adapted various methods for the manufacturing and utilization of RFID tags using conductive textile [12], using silver-coated yarn embroidered as side walls and part of the fabric [13] and using electro textile for better wave propagation in body area network [14].

3. BRUSH PAINNTING AND MANUFACTURING OF RFID TAGS

Manufacturing the passive UHF RFID tags via brush painting is an easy, cheap and less complicated procedure with promising results as we will conclude at the end of this thesis. The use of green, environment friendly and biodegradable materials, such as textile, paper, wood and cardboard is popular choice these days in manufacturing of printable wireless electronics. Especially brush painted silver passive UHF RFID tags has been studied with maximum achieved forward read ranges between 7.9 – 10.2 meters [15-16], [31].

Flexibility of the substrate used is also very important and useful for the future electronics, as we are trying to embed more and more electronics into the clothes and other materials, which we use in our daily lives. Flexibility of the passive UHF RFID tags provide the agility, freedom and ease of maneuvering about if attached to a movable object. Real life examples could be, attaching to integrating the textile based RFID into the clothes of a patient at the hospital so that when the patient reaches to a door, which he/she is allowed access to, will open itself or when the doctor reaches near a patient his/her medical history or related data will automatically appear on doctors tablet or other particular device using RFID. Similarly, it can be used for a mountain climber during his/her climbing activity in case of emergency if they get buried under an avalanche so their RFID tags can be scanned with a very powerful RFID scanner from a distance while flying above in the helicopter. Also it could be very useful to integrate an RFID tag to the clothes of a deep sea diver during his/her deep sea diving expeditions or exploration etc. In case of fire fighters, when they get trapped inside a building or some other tricky situation in which they get unconscious so they can be detected via RFID detector in those harsh environments etc etc…Hence there can be numerous examples, applications and situations in daily life in which we can get advantages from the flexibility and power of wireless communication technology.

Main focus of this thesis starts form heading 3.2 Brush Painting Techniques where the manufacturing process of textile base UHF RFID tags, methods, techniques, pros and cons, there dependability, ruggedness and flexibility is discussed in detail. Later on, textile base UHF RFID tags are coated with three various types of protective coatings. Afterwards, presenting and comparing the results for each of the methods involved in the whole process.

The effects of the fabrication methods on Passive UHF RFID Tag performance are studied in detail in [30].

3.1 Conventional Manufacturing Methods

Some of the most important and widely used conventional passive UHF RFID tag manufacturing methods are listed under:

1. Thermal printing
2. Inkjet printing
3. 3D dispensing
4. Sewing

Let us discuss each printing technique briefly.

3.1.1 Thermal Printing

In this method, the conductive ink is thermally transferred on to the printing substrate. A multi-layered ribbon is used which has three layers. First we have heat-sensitive acrylic adhesive, after that a thin layer of metal in the middle and in the end we have a plastic membrane. According to the desired antenna modeling shape, the thermal print-head heat-sensitively adhesive the thin metal for the ribbon on to the surface of the substrate [17].

This process is shown in the figure 3.1 below:

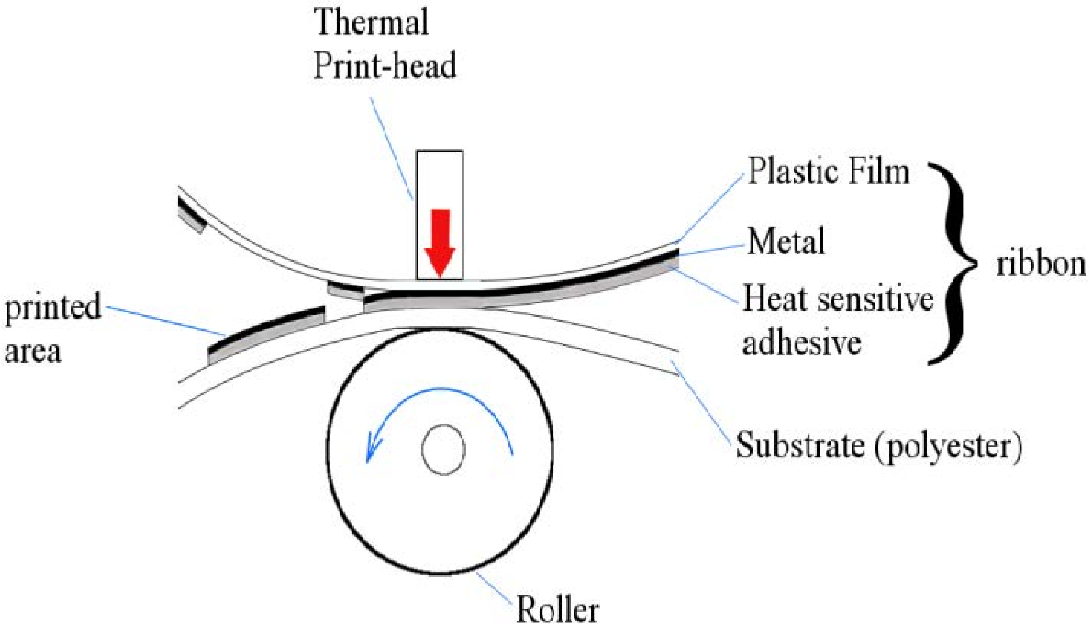


Figure 3.1 *Thermal printing process.*

Figure 3.2 shows a multi-layer ribbon typically used for thermal printing [18].

Figure 3.2 *Multi-layer thermal transfer ribbons [18].*

Figure 3.3 shows a thermal printed passive UHF RFID tag [17]

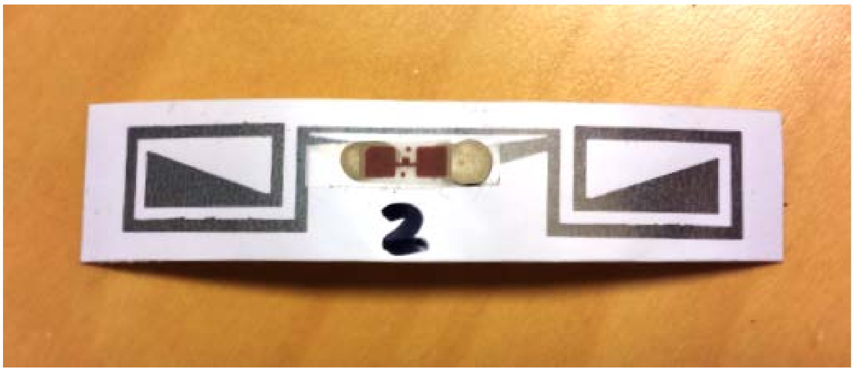


Figure 3.3 *Multi-layer thermal printed tag [17].*

3.1.2 Inkjet printing

In this method, the conductive silver nanoparticle ink is printed on the Kapton (substrate) with the average droplet radii of 45 µm using a Fujifilm Dimatix DMP-2831 material inkjet printer. The material inkjet printer is equipped with 10 pl print head nozzles. The quality of the print on any substrate is decided through various controlling factors including the temperature of the ink cartridge (40 °C), platen temperature (60 °C), jetting voltage (28 V), jetting frequency (9 kHz), as well as the pattern resolution. Ideally, the drop spacing should be the radius of the droplet for uniform thickness and a good conductive pattern. However, the drop spacing can be equal to the diameter of the droplet which will give us a continuous conductive pattern. In order to achieve higher thickness of the ink can be achieved by reducing the drop spacing lower than the droplet radius [17], [19].

A Fujifilm Dimatix DMP-2831 material inkjet printer is shown in the figure 3.4 [18]. An inkjet printed UHF RFID tag with silver conductive ink is shown in the figure 3.5 below:

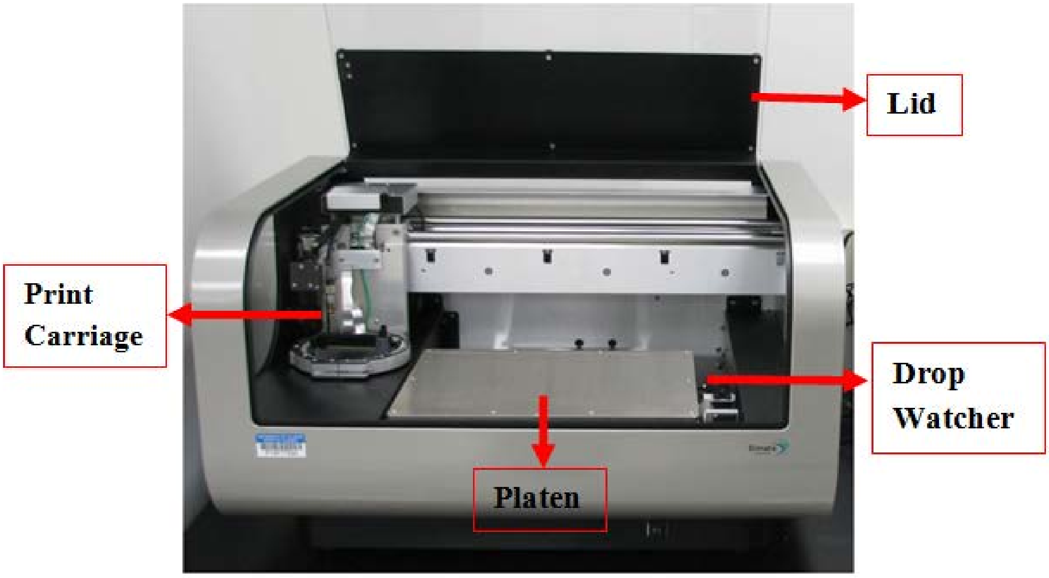


Figure 3.4 *Dimatix DMP-2831 material inkjet printer.*

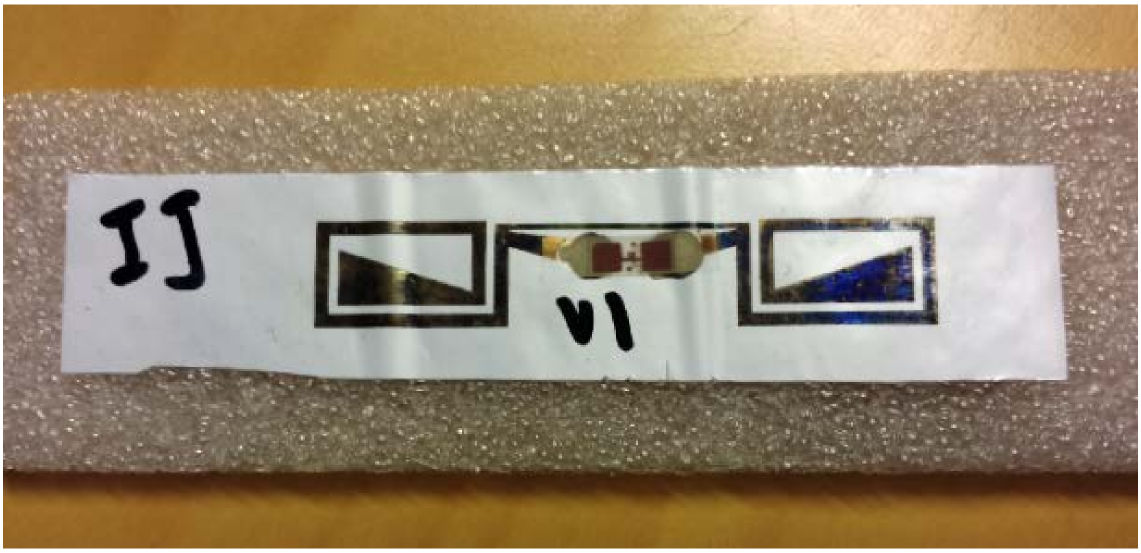


Figure 3.5 *Inkjet printed UHF RFID tag.*

3.1.3 3D Dispensing

In this fully digital method, a thick layer of water based conductive nanoparticle silver ink is dispensed using nScrypt tabletop series 3D direct write dispensing system, onto the porous and rough textile substrate to form the T-matched dipole antenna. Then the antenna is heat sintered for 30 minutes at 130 °C. Later NXP UCODE G2iL series RFID integrated circuit is attached via conductive epoxy [20].

Since it is a fully digital process, so we can model any thickness of the antenna. Dispense 3D print onto the surface of our textile substrate adding flexibility, versatility and rapidness to overall process. 3D dispensing not only allows us the control over the planer surface but also on 3D surface adding precision to meet the modern requirements in mobile communication antennas [21].

Figure 3.6 shows the picture of an nScrypt tabletop series 3D direct write dispensing system. Air pressure controlled barrel containing the conductive nanoparticle silver ink and the ink dispensing ceramic nozzle tip is highlighted for better understanding [20].

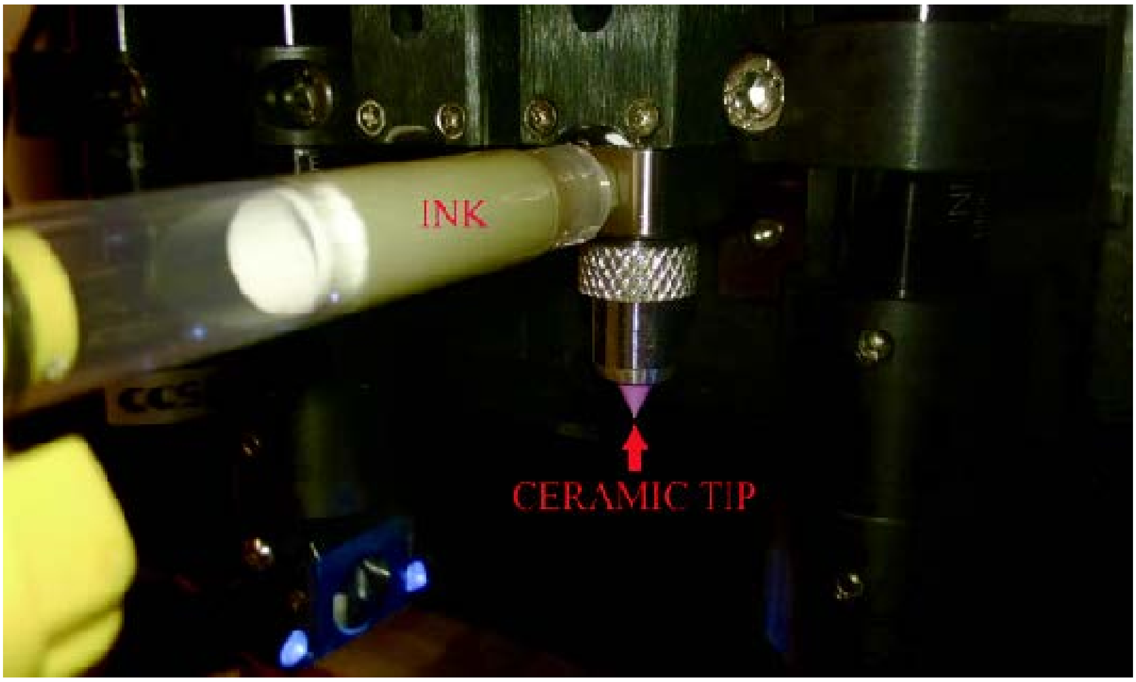


Figure 3.6 *3D dispensing system with ink barrel and nozzle tip.*

A fabricated sample tag is shown in the figure 3.7 below [20], with highlighted antenna dimensions, carrier fixture, printed fixture-antenna connection and microchip.

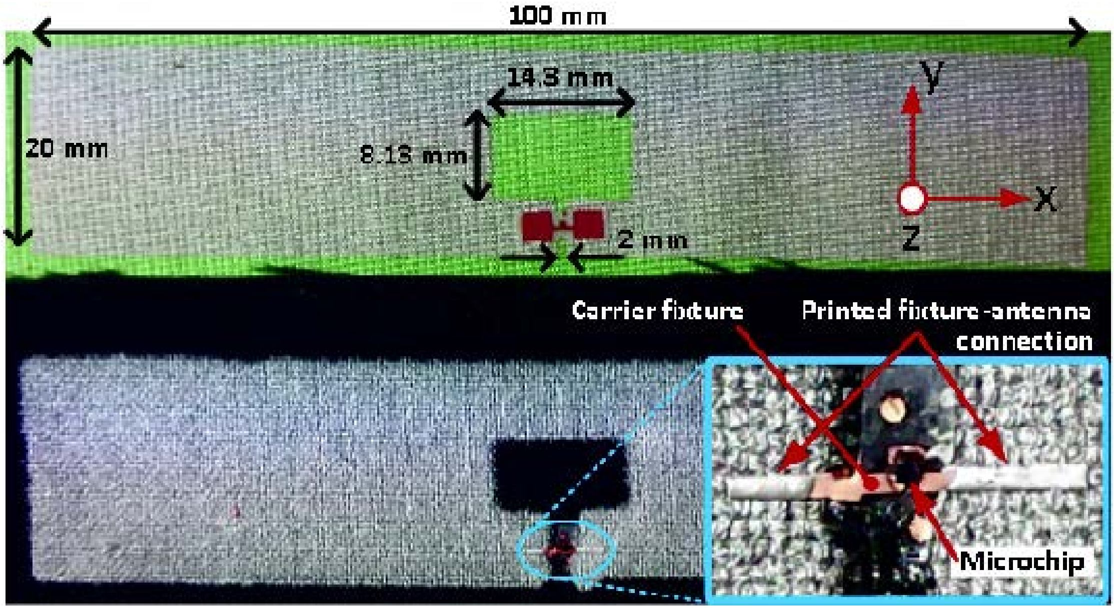


Figure 3.7 *Sample tag manufactured through 3D dispensing.*

To reduce the imperfections in the printing results, the antenna is chosen to be relatively wide (20 mm). However, the antenna length is kept (100 mm) as similar to most commonly manufactured commercial antennas [20].

3.1.4 Sewing

In this method, the conductive thread is weaved on to the fabric to form the antenna shape form to which the IC is attached to form a sewed or embroidered RFID tag. Various sewing patterns have varying results on the effective read range forward that is the free space read range. Study shows that if the sewing pattern achieves the read range of up to 7.5 meters if the sewing thread is sewed along the direction of current flow in the antenna [22].

Here in figure 3.8, the substrate is cotton and the thread is multifilament conductive thread Shieldex 110f34 dtex 2-ply HC [23]. A computer aided embroidery machine is used to sew the various Upper dipole (figure 3.8) and T-matched dipole patterns (shown in the figure 3.9) for study and comparing results against a copper dipole [22].

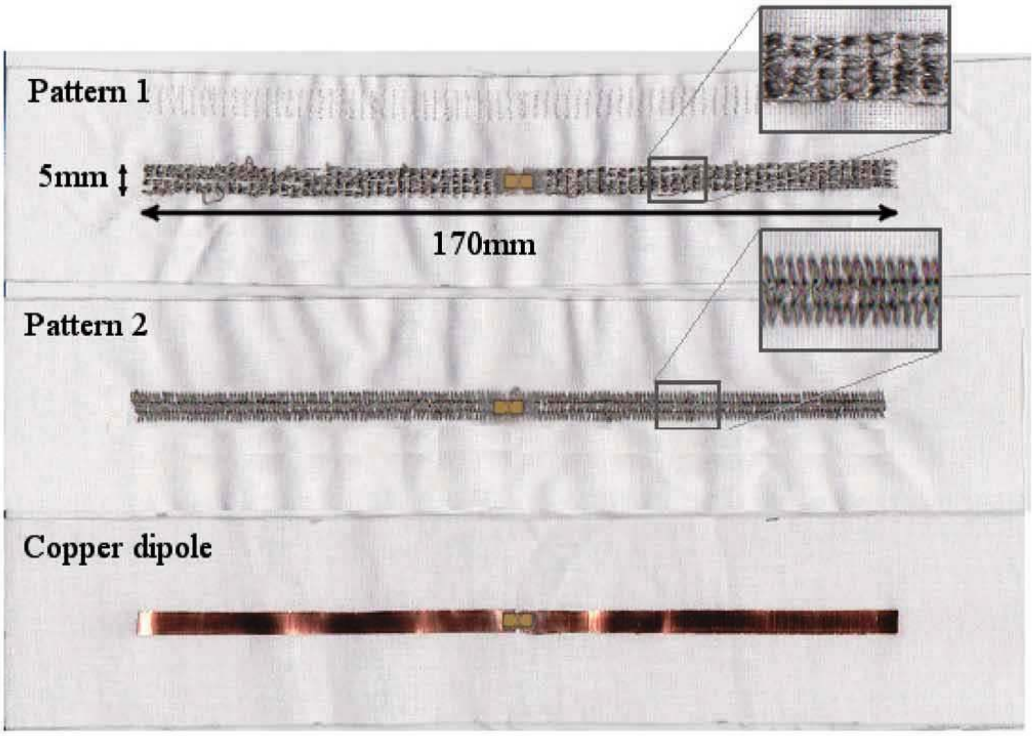


Figure 3.8 *Upper dipole and pattern variation in an embroidered tag.*

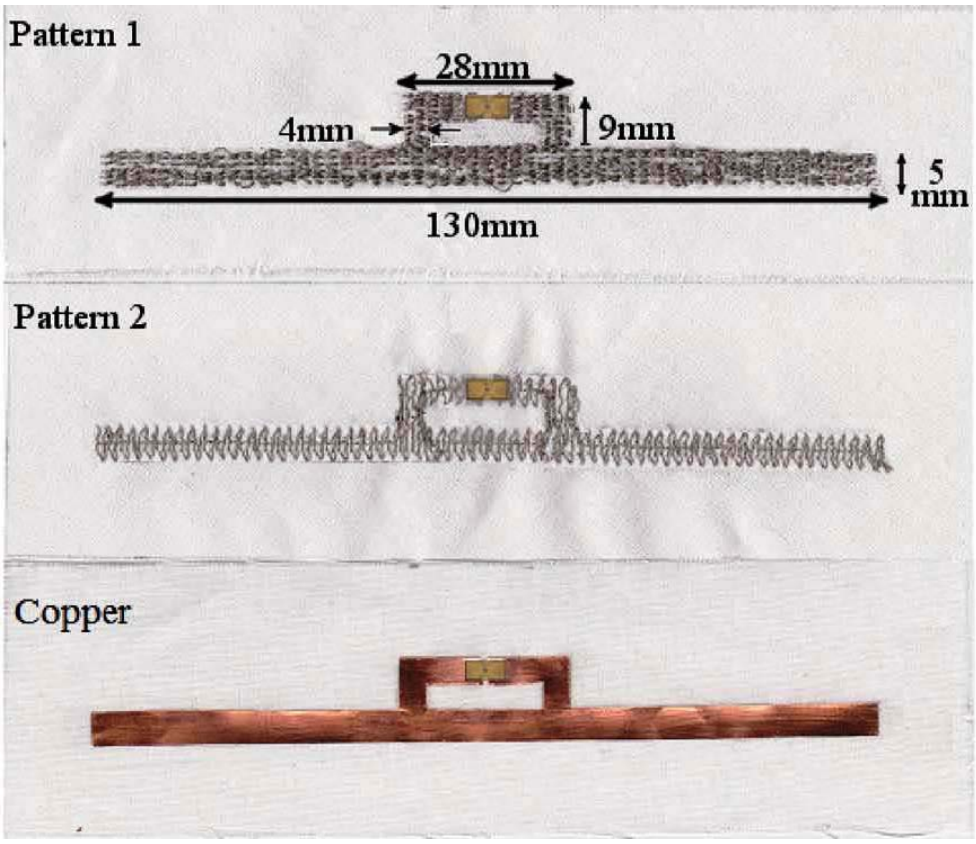


Figure 3.9 *T-matched dipole and pattern variation in an embroidered tag.*

Analyzing the performance of an embroidered conductive thread antenna fabrication, modeling methods, embroidered techniques, on-body effects on the read range of an RFID tag are discussed in [24]. Moreover, pattern variation, thread density variation, antenna dimension variation are discussed in the studies [25-29].

3.2 Brush Painting Technique

As mentioned earlier, the brush painting technique is the suitably efficient, least time consuming and far cheapest method in order to manufacture a textile base UHF RFID tags. The simplicity of this technique is the most appealing factor here, when we consider the real world scenarios of the manufacturing process, as compared to other common methods of the day such as inkjet printing the passive UHF RFID Tag [17], [19] and sewing the passive UHF RFID tag onto fabric method [22-23].

3.2.1 Type of Substrate

The choice of fabric to be used in the experiment was 100% cotton woven fabric, since it is the most common, cheap, easily available and widely used material across the globe. A think cotton fabric was used so that when the ink is applied on one side should not come out, between the woven pours, from the other side of the fabric. As from my earlier experiment, if the fabric is thin and the ink passes through the fabric onto other side then there is possibility of error in the read range. So, just to make sure that read ranges are correct with least amount of error margin, a thick 100% cotton fabric was used. Figure 3.10 shows the cotton substrate.

Figure 3.10 *100% Cotton substrate sample.*

3.2.2 Type of Ink

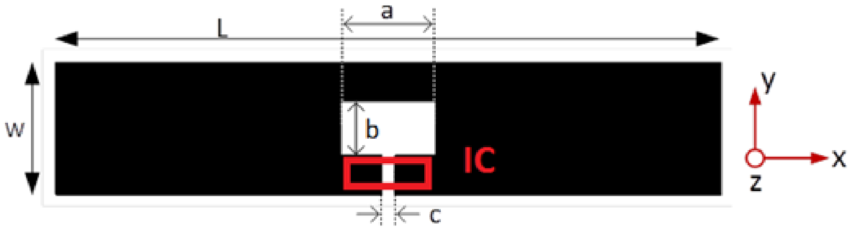
Ink used in the experiment is Metalon HPS-021LV [32] electrically conductive silver flake ink (shown in figure 3.11). A layer is applied on the face of the cotton substrate through a stencil (patterned from 1.5mm thick flexible plastic piece). One of the main reasons to use Metalon HPS-021LV electrically conductive silver flake ink is that it is designed to produce conductive traces on low-temperature to high-temperature substrates such as paper, glass, polyimide, and silicon [32].

Figure 3.11 *Metalon HPS-021LV electrically conductive silver flake ink.*

3.3 Tag Antenna Geometry and Type of IC

The tag antennas were chosen to be T-matched dipoles (structure shown in Figure 3.12), which is a very common class of antennas used in UHF RFID tags. The textile implementation has been studied thoroughly with simulations in [9], and this antenna geometry has been previously used successfully with textile tags fabricated by brush-painting on a fabric substrate [31]. Thus, this antenna, which has known, suitable properties was chosen also for this experiment, where the focus is to study the use of different coating materials and the washing reliability of the coated tags [33].

The RFID IC utilized in this experiment was NXP UCODE G2iL series IC that has a low wake-up power level of 15.8 µW (−18 dBm). The manufacturer had mounted the chip on a fixture with two 3x3 mm^2 pads, which can be connected to the antenna terminals (See Figure 3.12 and Figure 3.13).



Geometrical parameters in millimeters.

L	W	a	b	c
100	20	14.3	8.125	2

Figure 3.12 *The used tag antenna geometry and the placement of the IC.*

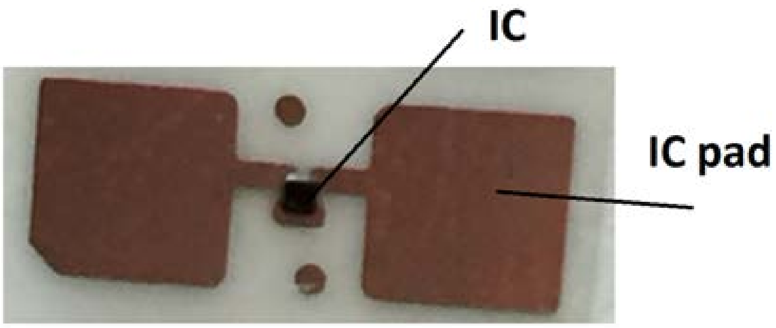


Figure 3.13 *NXP UCODE G2iL series IC.*

In the experiment, the ICs on each tag were attached to the brush painted antennas using Circuit Works CW2400 conductive silver epoxy [34]. Figure 3.14 shows a sample manufactured tag with IC attached to the dipole antenna.

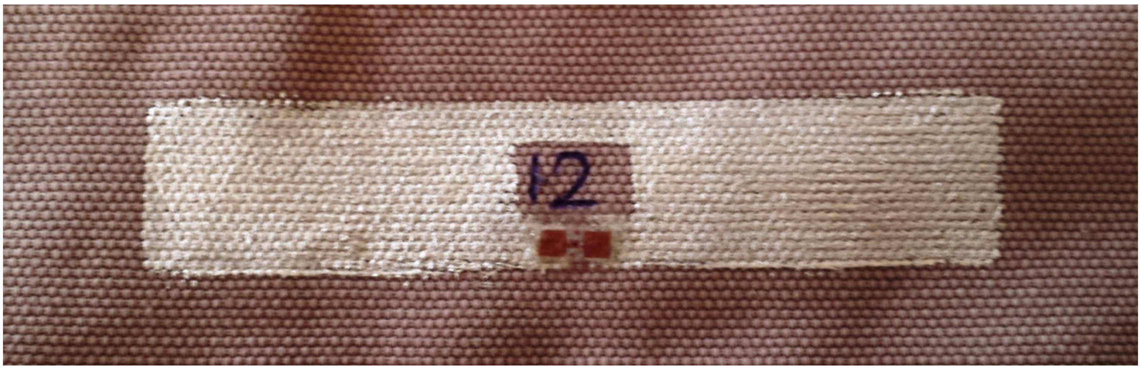


Figure 3.14 *A ready tag on the cotton fabric.*

3.4 Manufacturing Process

It was fairly a simple process to manufacture a passive UHF RFID tag. Process involves two basic steps which are as follows:

1. Painting
2. Sintering

Let us discuss them in detail one-by-one.

3.4.1 Painting

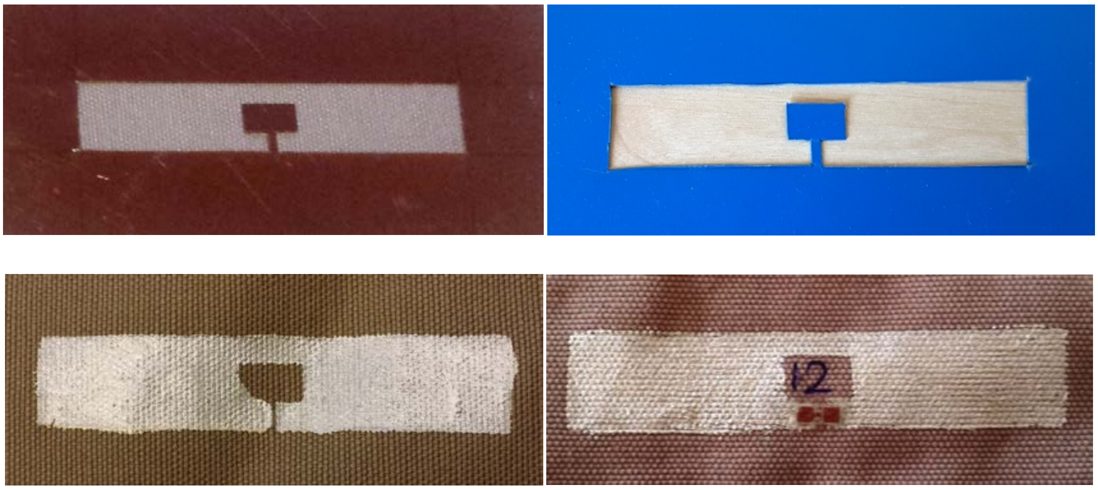
First using a pair of scissors, I cut a stencil out of Kapton material 50 µm thick (Shown in figure 3.15) according to the dimensions of T-matched dipole antenna. Then cut a suitable piece (5 x 8 cm) of cotton substrate and fixed it to the surface of the table using a masking tape (shown in figure 3.16) so that it should not move about when I am applying the conductive silver nanoparticle ink onto the substrate. Then I put my Kapton stencil on top of the substrate and fixed it firmly again using the masking tape. By using a simple painting brush (shown in figure 3.17) I have carefully applied a layer of Metalon HPS-021LV electrically conductive silver flake ink on the cotton substrate and the T-matched dipole antenna with desired geometrical dimensions is ready.

Figure 3. 15 *Kapton material 50 µm.*

Figure 3.16 *Regular masking tape.*

Figure 3.17 *Simple painting brush.*

To achieve accurate antenna dimensions while using a stencil made out of Kapton material was becoming a bit of a challenge as Kapton is very thin (50 µm thick) and bendy material. So the tags that I have made later on, I have used a 1.5mm thick and less flexible plastic material piece to make the stencil for painting the ink on the cotton substrate. This made the painting process considerably easy and smooth to achieve the accurate antenna dimensions. Figure 3.18(a) shows the tag antenna dimensions achieved using Kapton stencil. Figure 3.18(b) shows the required tag antenna dimensions achieved using flexible plastic material.



(a) (b)

Figure 3.18 *Tag antenna dimensions achieved using Kapton and plastic type stencil.*

3.4.2 Sintering

Once the painting process is complete, the tags were then heat sintered in a preheated oven (shown in the figure 3.20) at 140 ºC for 20 minutes to dry the silver nanoparticle ink. When the tags were heat sintered, the ICs were attached carefully to the antenna tag using Circuit Works CW2400 conductive silver epoxy (shown in the figure 3.19). For quick dry the IC attached tags were heat sintered in the oven at 70 ºC for 10 minutes. This is to quickly dry the conductive silver epoxy, since our cotton substrate can bear the heat easily, otherwise we can leave the conductive silver epoxy for four hours to dry at room temperature.

Figure 3.19 *CW2400 conductive silver epoxy.*

Figure 3.20 *Electric Oven for heat sintering.*

4. WASHING AND RELIABILITY TESTING EXPERIMENT OF UHF RFID TAGS

I have discussed the brush painting technique, manufacturing process and complete sintering technique for my UHF RFID tags in depth in the previous chapter 3. Now in this chapter 4, I will explain, firstly, the three basic protective coatings used to protect the tags so that they can be washed in an ordinary washing machine just like normal cloths with detergents without damaging the tags which is basically the goal of this thesis. Secondly, I will explain the conducted experiment and test equipment details. Sample tags are shown in the figure 4.1 below:

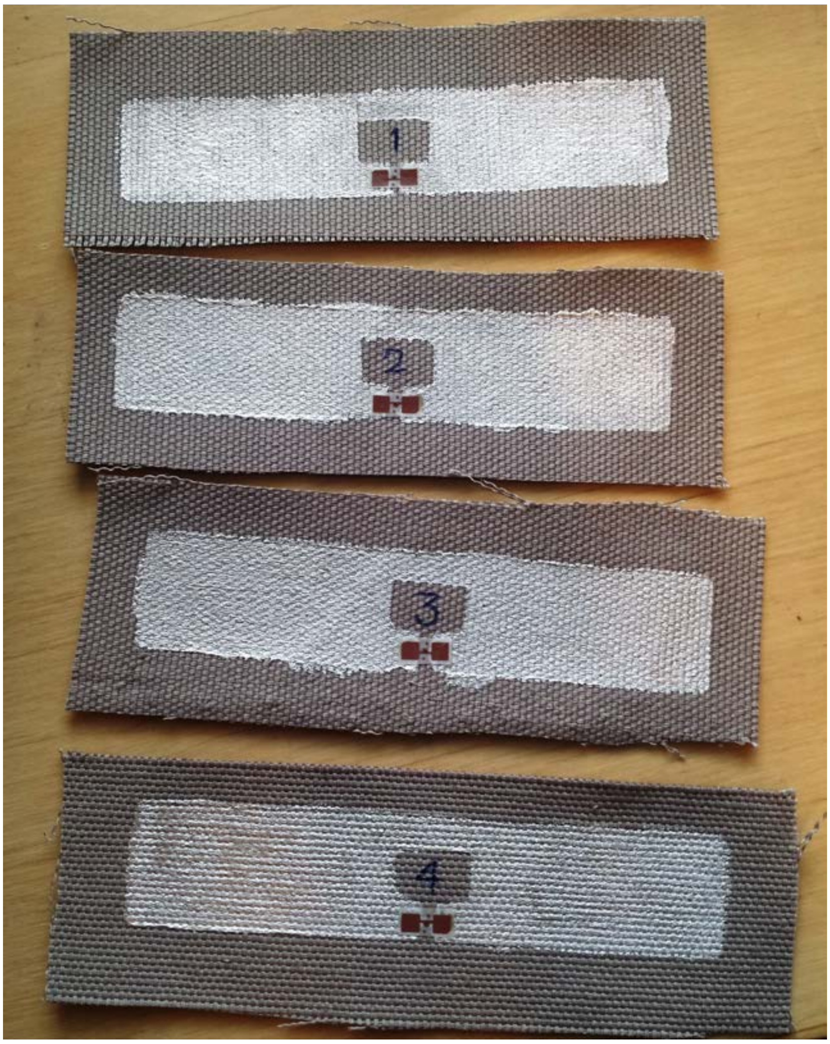


Figure 4.1 *Sample Passive UHF RFID Tags.*

These protective coatings make the tags reliable and tough enough to be used under normal daily life use conditions without compromising the read range and functionality of the tags. Hence the original purpose of tag is served here and preserved through these coatings as the results and discussion shows the achievements in the next chapter 5.

4.1 Protective Coatings

I have used three different types of coatings to protect the tags from water, detergent and stress/strain of the washing machine. These coatings are:

1. Textile glue
2. White Epoxy Glue
3. Silicon rubber (Sugru)

Now let us discuss each coating in detail individually by defining their characteristics, application method and process.

4.1.1 Textile Glue

I have used regular textile glue called Gutermann Creativ HT2. These types of textile glues are quite cheap and generally are easily available from the nearest superstores. It is very good at bonding with different fabric threads and materials. It dries quickly and the bond between the materials is permanent. Textile glue bond remains fairly elastic. It is washable to 40 ºC which is needed for the experiment. The elastic nature helps preventing any major damage to the tag itself [35]. Textile glue used is shown in the figure 4.2 below:

Figure 4.2 *Textile glue Gutermann Creativ HT2.*

The process of applying the textile glue on the ready passive UHF RFID tag was fairly simple. I put a tag on the table and squeezed the glue out of the tube on to the surface of the tag so that the complete surface tag area is fully covered in the glue. Always make sure that no surface of the tag should remain uncovered by the glue. It generally takes couple of hours to completely dry the textile glue but since I have applied quite a generous amount of glue, so in order to fully cover the tag surface, I left them for about 4-5 hours to fully dry at room temperature (typically 20-25 ºC). Figure 4.3 shows the tags with the textile glue applied to them.

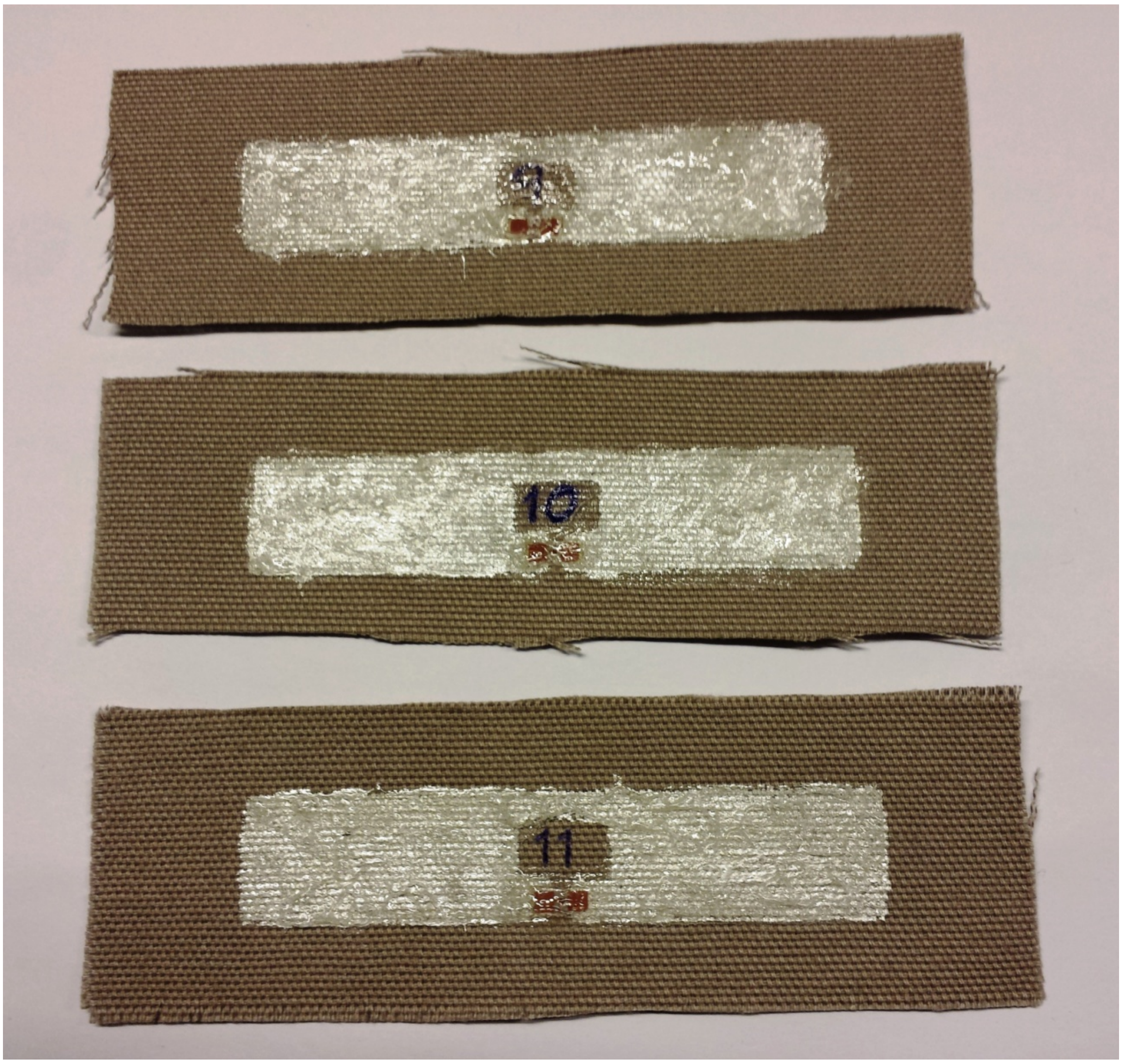


Figure 4.3 *Single side textile glue coated passive UHF RFID tag.*

Similarly, when one side of the tag was completely dry, I cut the tag with a pair of scissors with the same length at the tag antenna geometry with length 100mm and width 20mm (See figure 3.11 for compete tag antenna geometry details) and applied the textile glue on the back of the tag exactly the same as before. The goal here is to completely submerge the tag in the textile glue so that during washing process the water must not be able to reach the IC.

Once the textile glue dries and now the tag is completely covered in textile glue, we are ready to take measurements and also to start the repetitive washing process of the tags for the experiment.

4.1.2 White Epoxy Glue

Regular white glue (2^{nd} type of protective coating material) was also pretty good choice to be used as a protective coating for the UHF RFID tags. The white glue used here in this experiment was ESL 243 White Epoxy Coating. This white glue is screen-printable, thermo-setting, epoxy coating which is non-permeable to the solvent attack when fully cured [36]. White glue used is shown in the figure 4.4 below:

Figure 4.4 *White Epoxy Coating.*

A regular ethanol based thinner was used to adjust the viscosity of the white glue appropriately so that it can be applied easily to the tags. I have fully covered (almost submerged) the tags with the white glue so that there should be absolutely zero probability for the water to reach the IC which would intern damage the functionality of our UHF RFID tags. The process of applying the white glue to the tags was fairly simple. I took a fare portion of white glue from the container and put it into a disposable plastic cup. Then added the thinner to the cup and stirred the contents to reduce the viscosity of the glue to a fairly medium level (let us say a bit less viscous than the honey). Here I would like to mention the importance of viscosity of the glue because if the glue is thin then one might not notice while applying the glue but after drying process results are not great as shown in the figure 4.5 below:

Figure 4.5 *Less viscous white glue coated and dried UHF RFID tag.*

Here (as seen in the Figure 4.5) the glue was not thick enough to protect the tag and once it was dried in the oven, it appears to be in the form of little chunks/patches on the tag. So again a good viscous solution of white glue is recommended.

Then I took a simple painting brush to apply the glue thoroughly on the RFID tags on one side, then put the coated tag or dried in to the electric oven (shown in figure 3.16(b)) at 115 ºC for 40 minutes. The long drying time and the low drying temperature (recommendation from the coating manufacturer: drying in 125 ºC for 10-15 minutes, curing in 150 ºC for 5-15 minutes) were chosen because of the low temperature endurance of the tag IC.

Similarly, when one side of the tag was dried, applied the white glue on the other side (in order to fully protect the tag) using painting brush and dried in the electric oven under similar conditions for optimum and equal results. Fully white glue coated and cured tags are shown in the figure 4.6 below:

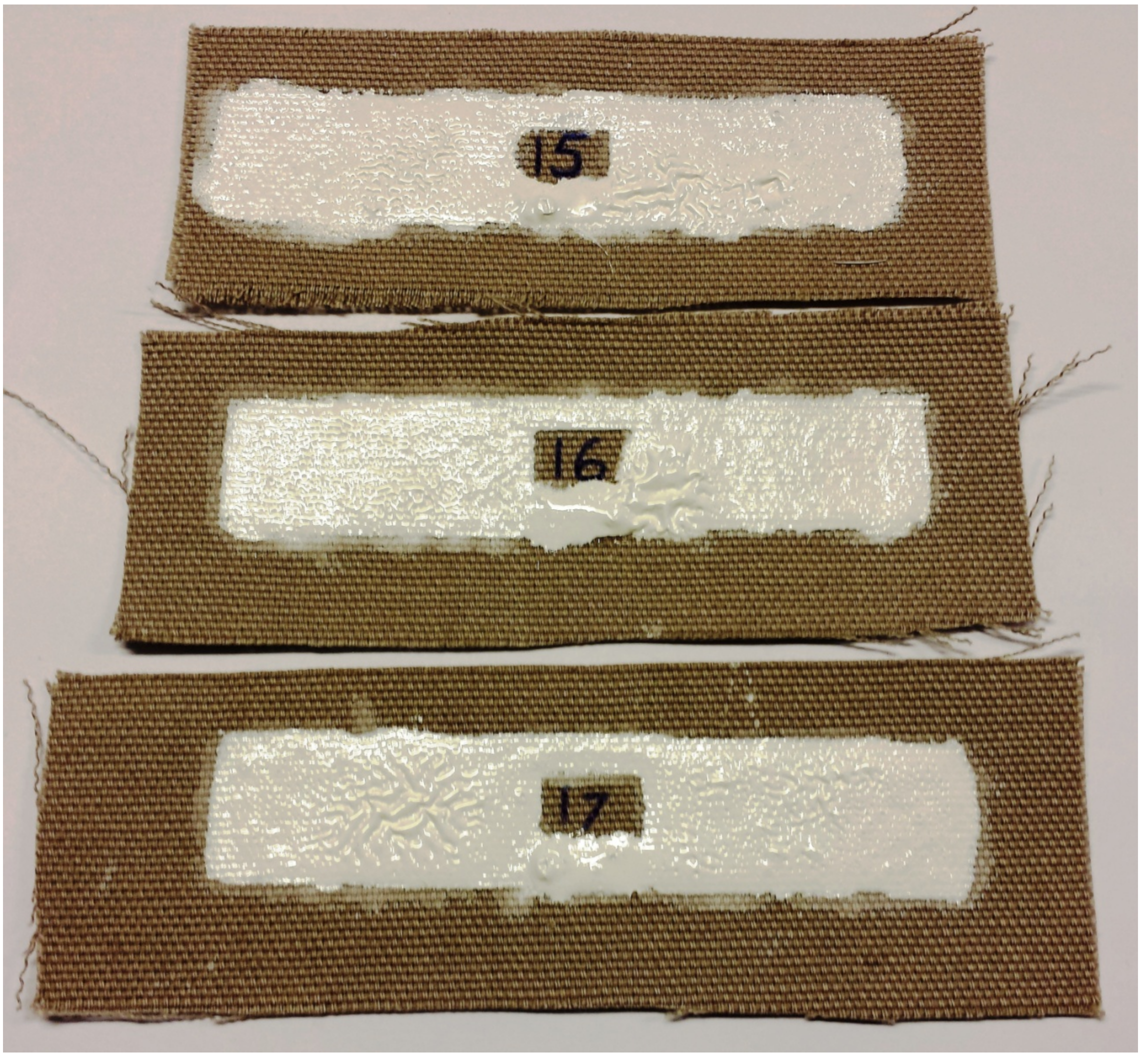


Figure 4.6 *Single side white glue coated passive UHF RFID tag.*

4.1.3 Silicon Rubber (Sugru)

Silicon rubber was one of the most interesting coating materials used in this thesis. It gave me the most amazing and promising results in this study. The results are discussed in the next chapter 5. Silicon rubber used here, comes with the name of Sugru. It is a very interesting, playful, most flexible and robust coating material of the three coatings. It bonds with almost every kind of materials around us. Super flexibility and mould ability is main strength of sugru. It is a multi-purpose silicon rubber which resembles with the modeling clay. It cures to a rubber like texture upon exposure to the air. It remains plasticity in nature for almost 30 minutes once you take it out from its air tight packing. Figure 4.7 shows the packing of the coating material used below:

Figure 4.7 *Silicon rubber coating material.*

It self cures at room temperature within 24 hours approximately. It has a soft touch slightly flexible grip able texture. It is water proof, dishwashing and detergent safe material. It is a great heat insulator. According to the specification of the product, it can bear the temperature changes from -50 ºC to 180 ºC [37].

The process of applying the sugru coating is fairly simple. First I cut the ready passive UHF RFID tag according to the tag antenna geometry, then applied a generous amount of sugru coating around it so that the tag is covered in the coating material completely. Then I left it to dry at room temperature for almost 16-20 hours. Sugru is quite sticky to the hands when molding or trying to apply to the cotton fabric substrate. I tried my best to apply an even layer of the material around the tag in order to get perfect measurement results. Figure 4.8 show a read passive UHF RFID tag covered in the sugru coating below:

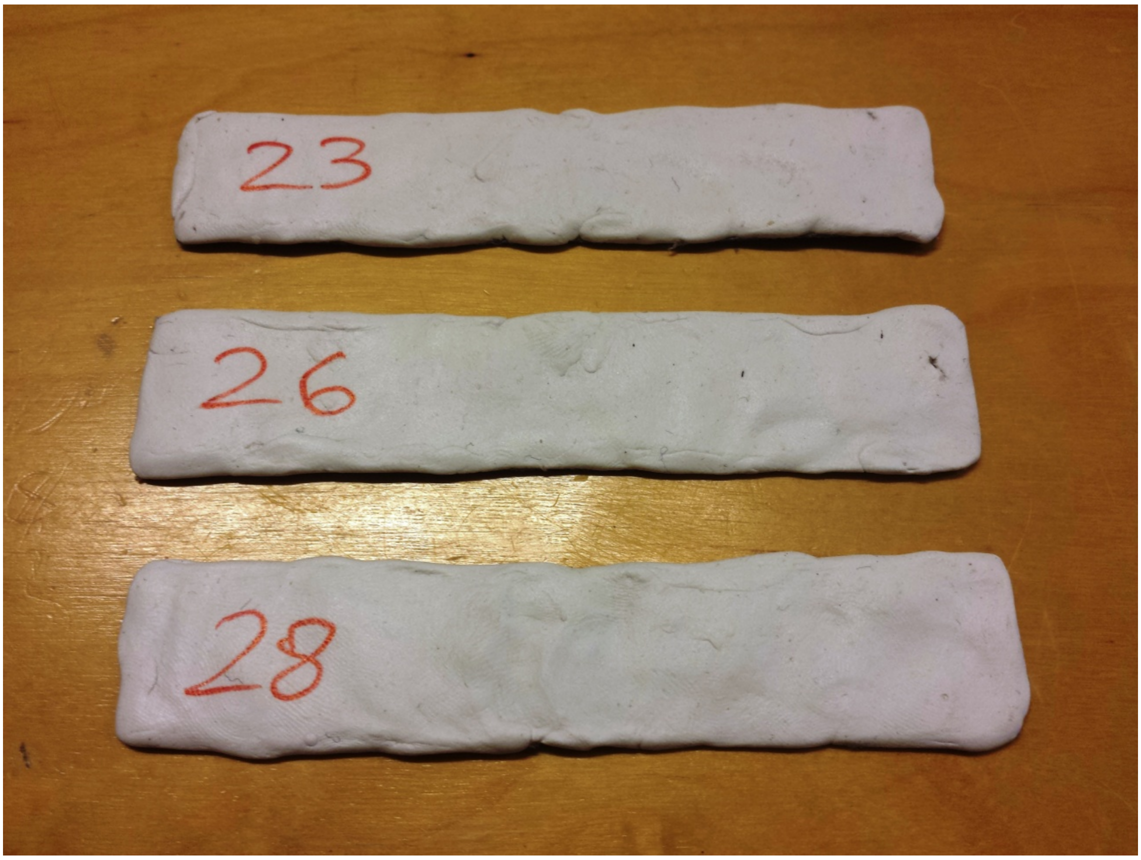


Figure 4.8 *Single side silicon rubber coated passive UHF RFID tags.*

Now I have total of nine samples of passive UHF RFID tags with three samples of each type of coating material ready to be washed in the washing machine. I chose three samples of each coating type because the redundancy will provide the accurate confirmation of washing behavior for each coating material and thus helping with the confirmation of the results.

4.2 Reliability testing experiment

To check the washing reliability of the passive UHF RFID tags, I washed these tags in the washing machine with a regular detergent at 40 ºC for 45 minutes. Then I let them dry over night at room temperature and took the read range measurements. Similar process was repeated in total of 15 times in order to see the effects of washing reliability of the protective coatings used on these UHF RFID tags.

Since the inside of the machine is quite big as compared to the size of the tags so I used a washing bag (Shown in the figure 4.9) so that the tags can easily be collected from the washing machine (shown in the figure 4.10) easily.

Figure 4.9 *Washing bag used to contain UHF RFID tags.*

Figure 4.10 *Washing machine.*

4.3 Wireless Measurements Equipment

The performance of the tags was assessed with wireless measurements through 800 MHz to 1000 MHz, by using Voyantic Tagformance RFID measurement system. The measurement system consists of three main parts which are:

1. Anechoic chamber
2. RFID reader
3. Tagformance software

Anechoic chamber is where we place our tag to take the measurements. This anechoic chamber is connected to a reader/interrogator which is then connected to a computer, on which the Tagformance software runs.

4.3.1 Anechoic Chamber

Anechoic chamber is an enclosed space which is designed so that there are no reflections and no echo from the chamber walls because it absorbs the electromagnetic radiations. In this chamber, the electromagnetic waves are completely absorbed without any reflections from its walls because the walls are covered with radiation absorbing materials. Anechoic chamber also prevents any electromagnetic waves entering the chamber from the surroundings. Figure 4.11 shows the inside of the Voyantic Tagformance Anechoic chamber.

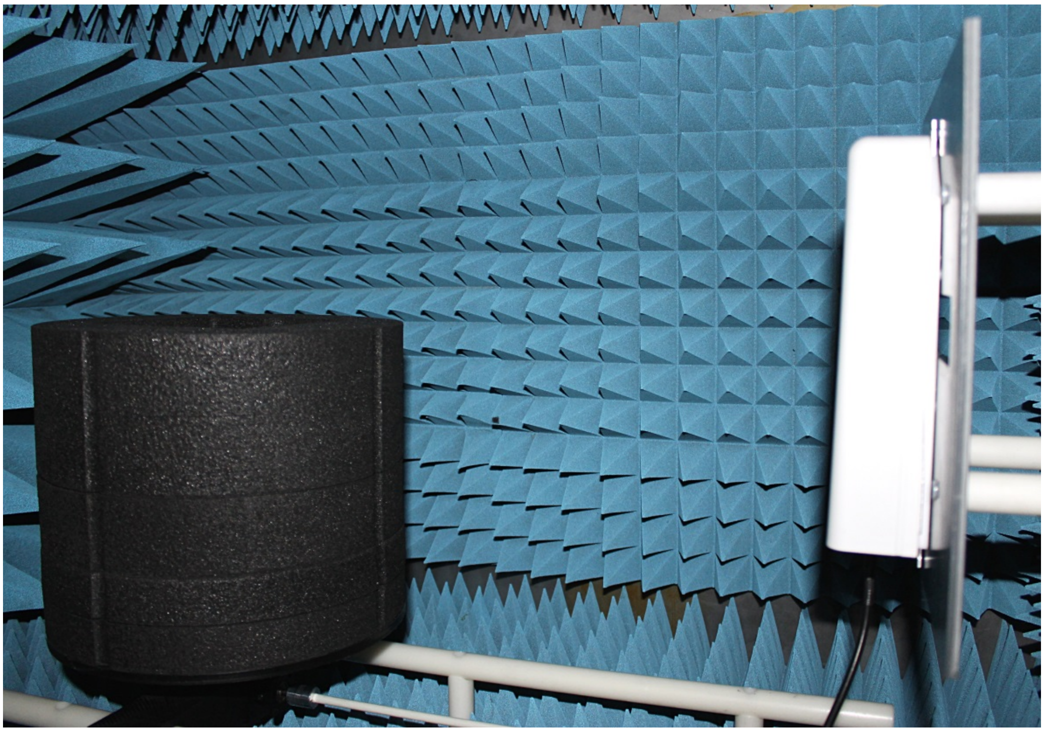


Figure 4.11 *Inside view of Voyantic Tagformance Anechoic chamber.*

Blue elongated cone like shapes mounted on the walls are covered with radiation absorbing material and their purpose is to cancel/absorb all the electromagnetic waves produced by the RFID reader antenna which is mounted on the right (in white colour) in the figure 4.11. The black cylindrical piece of foam is where we place our RFID tag which needs to be tested. This black cylindrical object is adjustable such that it can be moved near and far from the reader antenna plus it has rotational motion to adjust the angle at which the electromagnetic waves emerging from the reader will hit the IC of the RFID tag. For optimum result, the RFID tag's IC must face directly towards the tag reader antenna.

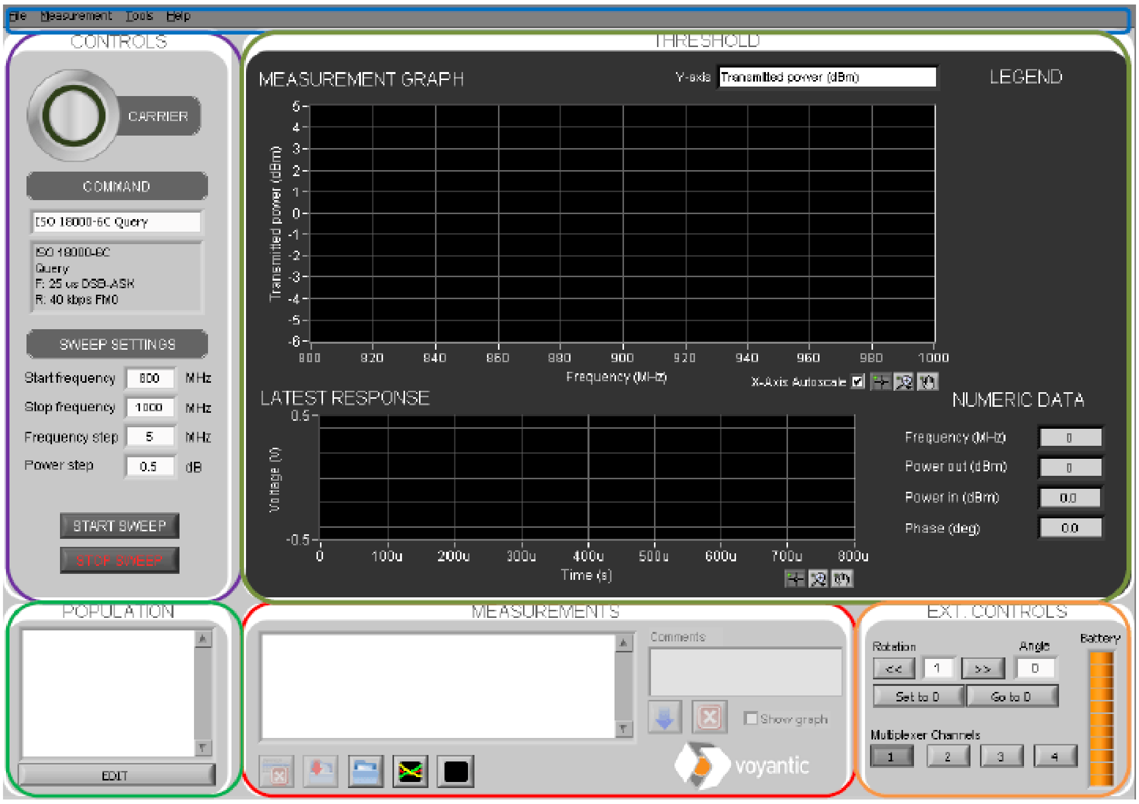
4.3.2 RFID Reader

Figure 4.12 shows the Voyantic Tagformance RFID reader. It generates the range of frequencies and controls the power and transmission and receiving functions. It is then connected to the computer which runs the Tagformance software.

Figure 4.12 *Voyantic Tagformance RFID reader.*

4.3.3 Tagformance Software

From this software we control and adjust the various measurement parameters, record, play and store our RFID measurements, basically operate our measurement setup. Figure 4.13 shows the basic Tagformance software interface below:



ISO 18000-6C Query

ISO 18000-6C
Query
F: 25 us DSB-ASK
R: 40 kbps FM0

Start frequency 800 MHz
Stop frequency 1000 MHz
Frequency step 5 MHz
Power step 0.5 dB

Y-axis Transmitted power (dBm)

X-Axis Autoscale ☑

Frequency (MHz) 0
Power out (dBm) 0
Power in (dBm) 0.0
Phase (deg) 0.0

☐ Show graph

Rotation 1
Angle 0

Figure 4.13 *Tagformance Software Interface.*

5. RESULTS AND DISCUSSIONS

In this chapter, I will discuss the results and RFID tag measurements. The performance of the tags was assessed with wireless measurements through 800 MHz to 1000 MHz, by using Voyantic Tagformance RFID measurement system. The tags were measured before the coatings were applied, after coating, and after each washing cycle. The performance of the assembled tags was analyzed based on the measured threshold power (P_{th}), which is the minimum output power of an RFID reader to activate the tag under test at a given distance, which can be measured using RFID readers and testers with adjustable output power. Power step to find P_{th} was 0.1 dBm and the frequency step was 1 MHz. Because the measured threshold power depends on the measurement site and hardware, we used the attainable free-space read range of the tag (d_{tag}) derived from Pth to provide universal tag characterization. The d_{tag} is based on the measured threshold power of the tag under test and a system reference tag as given in equation 5.1:

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\Lambda}\frac{P_{th*}}{P_{th}}}, \tag{5.1}$$

Where, Λ is a parameter (unit: watts) describing the sensitivity of the reference tag of the measurement system and P_{th*} is the measured threshold power of the reference tag. In this article, we report all the read range results under the European RFID emission regulation: EIRP = 3.28 W in the direction of the positive y-axis as shown in Figure 3.12. In general, the yz-plane is the omnidirectional plane of the dipole antenna where the read range is approximately equal in all directions. In all measurements, the dipole tag was aligned for polarization matching with a linearly polarized reader antenna [33], [38].

5.1 Silicon Rubber Coated Results

Figure 5.1 shows the condition of silicon rubber coated tags after 15 washing cycles. Three sample tags were coated with silicon rubber coating in total for redundancy but the only tag with the best measurements results presented in Figure 5.2. Here no big difference was in read range was observed out of three sample tags.

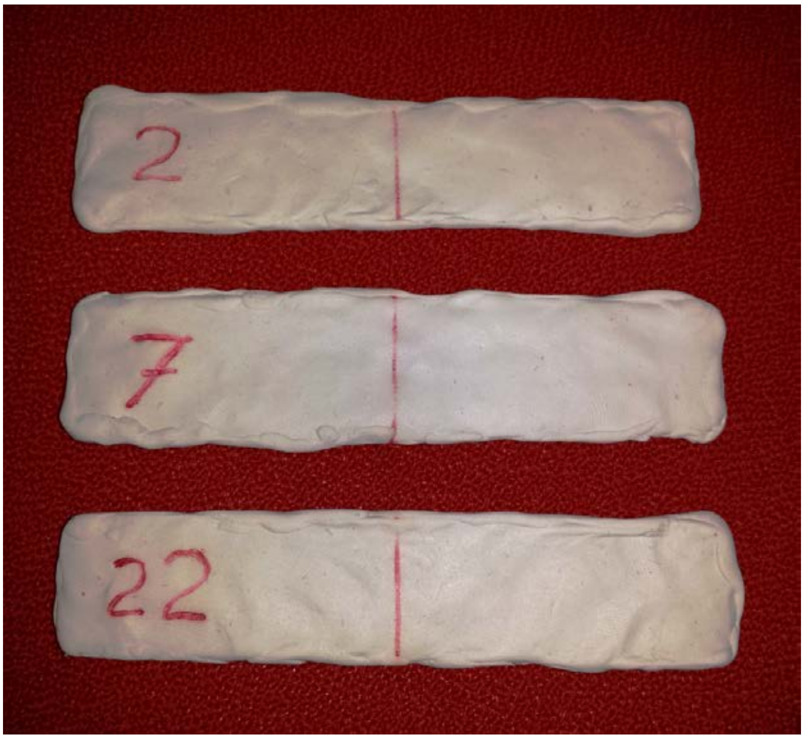


Figure 5.1 *Silicon rubber coated tags after 15 washing cycles.*

The silicone rubber coating caused a major downward shift in the frequency of the peak read range. The other two coatings, that is, textile glue and white glue did not have as significant effect on the tag performance. The silicone rubber was found to be a potential future coating material for washable brush-painted RFID tags: after 15 washing cycles the peak read ranges were still around 9 meters, which is about 1 meter less than the original peak read range of 10 meters. Figure 5.2 shows the achieved free-space read range results of the silicon rubber coated tags before washing and after washing.

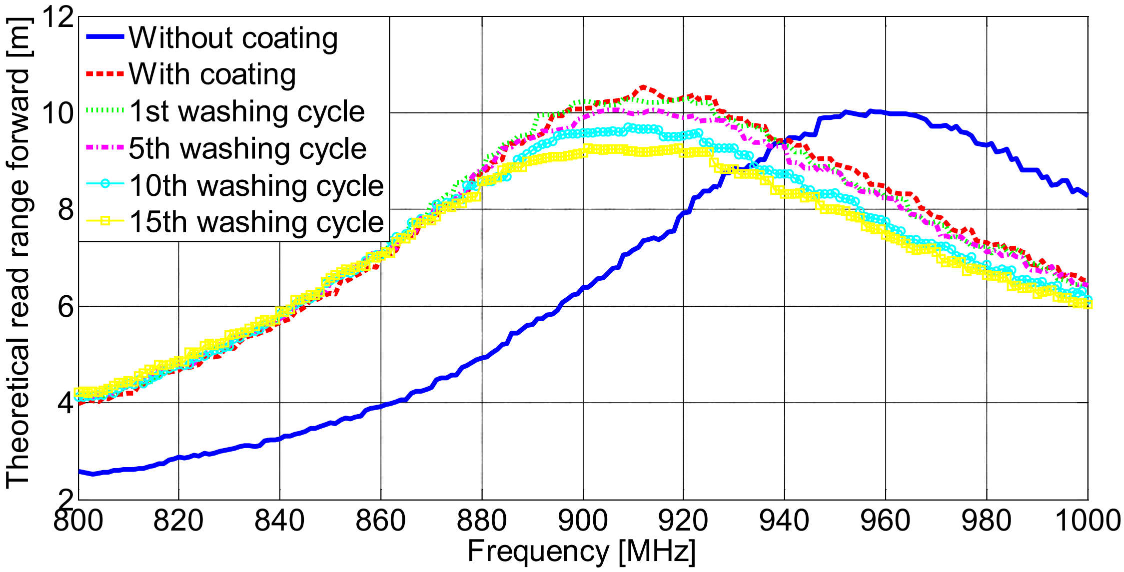


Figure 5.2 *The attainable silicone rubber-coated passive UHF RFID tags performance before and after washing.*

5.2 White Epoxy Coated Results

Figure 5.3 shows the condition of white epoxy coated tags after 15 washing cycles. Similarly, three sample tags were coated with white epoxy coating in total for redundancy. The only tag with the best measurements results presented in Figure 5.4. Here again, no big difference was in read range was observed out of three sample tags.

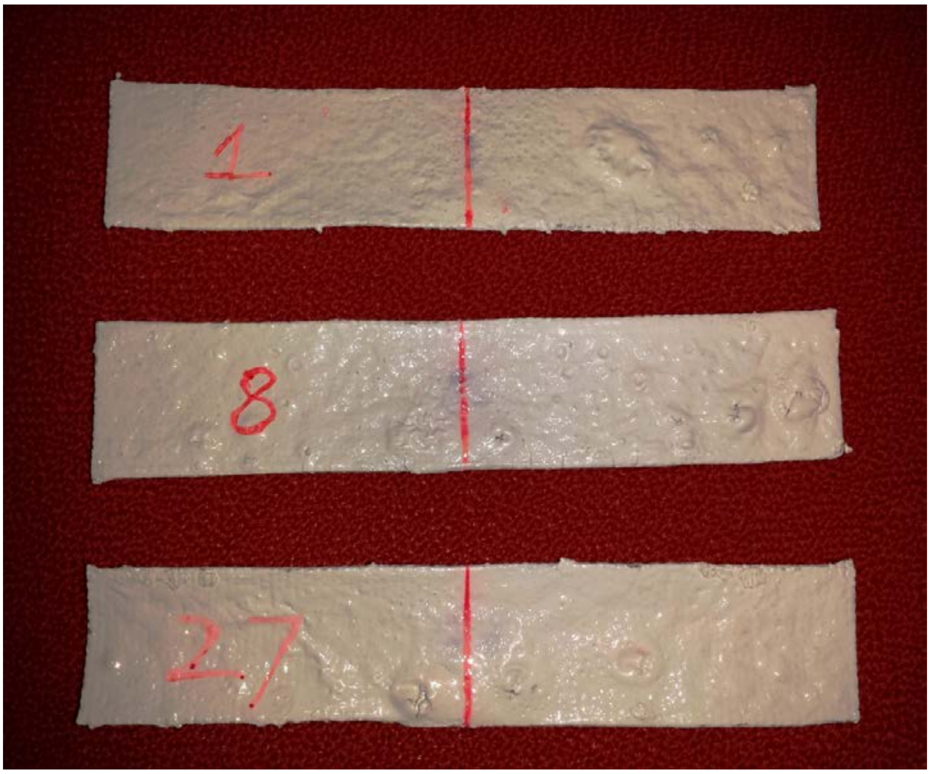


Figure 5.3 *White epoxy coated tags after 15 washing cycles.*

The read ranges of the epoxy-coated tags (shown in Figure 5.4) started to steadily decrease after each washing cycle, and after 15 washing cycles the peak read range was about 7.5 meters. Thus, the epoxy coating can be considered to help the tags to endure washing, but it does not make them washable.

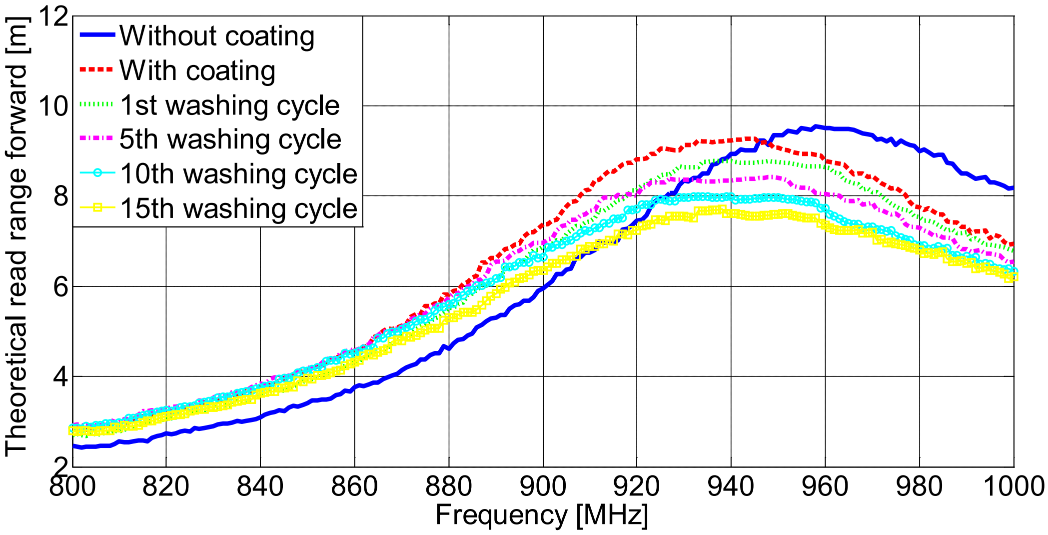


Figure 5.4 *The attainable white epoxy glue coated passive UHF RFID tags performance before and after washing.*

5.3 Textile Glue Coated Results

Figure 5.5 shows the condition of textile glue coated UHF RFID tags after 15 washing cycles. Similarly, three sample tags were coated with textile glue coating in total for redundancy. The only tag with the best measurements results presented in Figure 5.6. Here again, no big difference was in read range was observed out of three sample tags.

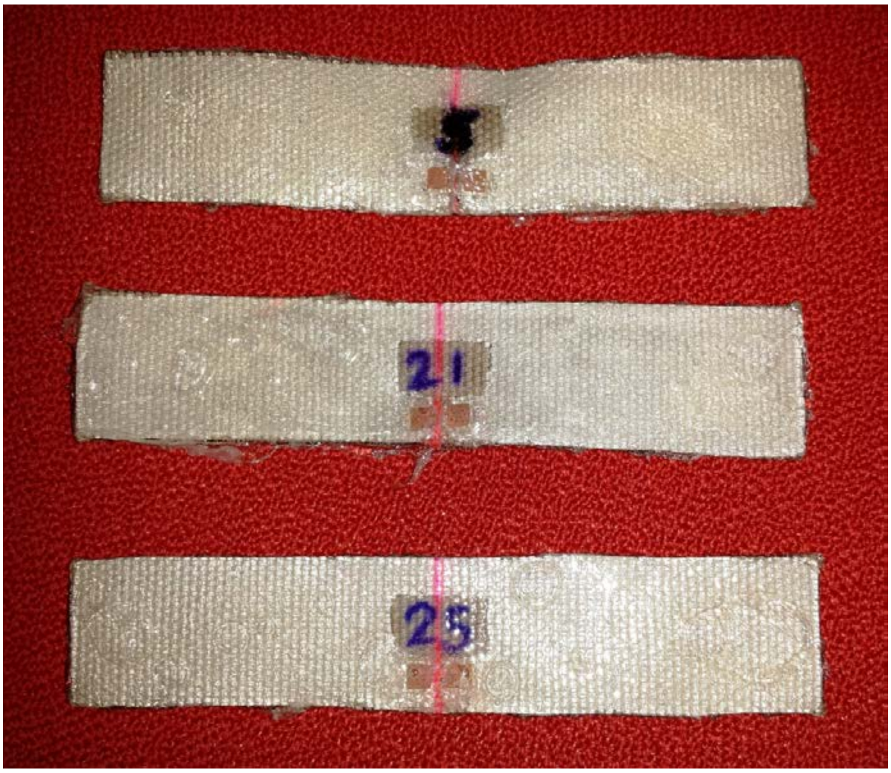


Figure 5.5 *Textile glue coated tags after 15 washing cycles.*

Based on the measurements, washing did not have such a negative impact on the textile glue-coated tags (measurement results shown in Figure 5.6). After 15 washing cycles, the textile glue-coated tags still achieved similar peak read ranges than originally, and the frequency shift was very small.

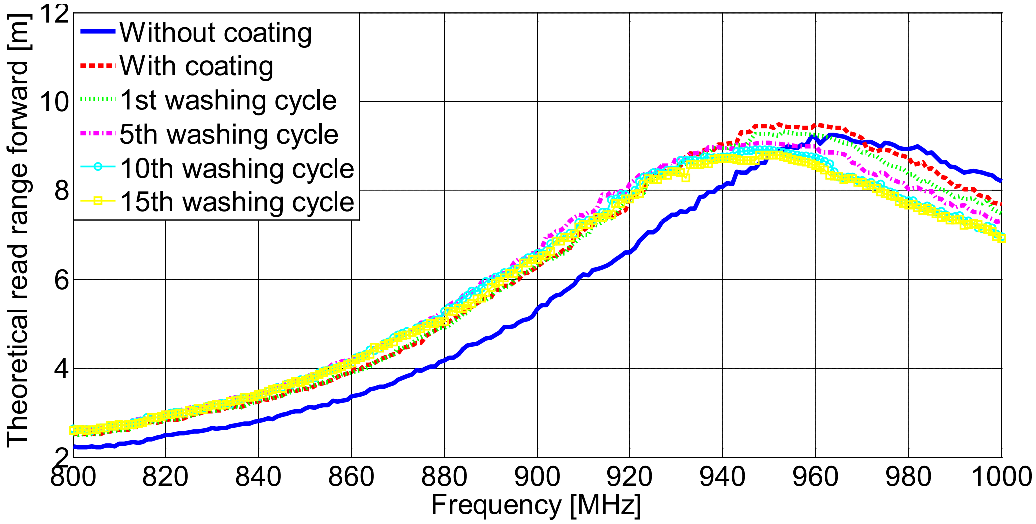


Figure 5.6 *The attainable textile glue coated passive UHF RFID tags performance before and after washing.*

5.4 Coatings Comparison

Overall, the under achieving coating was the white epoxy glue as shown in the results earlier in this chapter. Textile glue coating was the best among others as it was with the least decrease in read range from first washing cycle till the last fifteenth washing cycle. However, the silicon rubber coating gave us the highest read range of 9 meters after 15 washing cycles.

Table 5.1 shows the comparison between the three coating types based on the read ranges in detail.

Table 5.1 *Read range comparison for each coating type.*

Coating type	Without coating (meters)	With coating (meters)	1st washing cycle (meters)	5th washing cycle (meters)	10th washing cycle (meters)	15th washing cycle (meters)
Silicon rubber	10	10.2	10.1	10	9.7	9
White epoxy glue	9.7	9.3	8.8	8.3	8	7.9
Textile glue	9.5	9.6	9.5	9.2	9	8.9

Table 5.2 illustrates the decrease in the reading range of UHF RFID tag from first washing cycle till the 15th washing cycle. With the help of this table it is easy to figure out which coating type has the most potential and in my opinion it is the textile glue if it were to be used to make the wearable textile based tags washable.

Table 5.2 *Maximum variation in peak read range.*

Coating type	Maximum variation from peak read range after 15 washing cycles (meters)
Silicon rubber	1
White epoxy glue	1.8
Textile glue	0.6

As a conclusion, all three protective coating materials can quite effectively protect the RFID tags from the effects of moisture and from the mechanical stress during washing. Especially the textile glue was able to protect the tags: the reduction in the read range was only about 5 % over the 15 washing cycles. The achieved results are very promising for future wearable applications requiring continuous washing.

It should be noted that some commercial UHF RFID laundry tags are already available on the marked, e.g., Fujitsu WT-A522 UHF RFID Laundry Tag [39] and TAGSYS' LinTRAK UHF Tag [40].

6. CONCLUSION AND FUTURE WORK

This chapter summarizes the thesis, shows the prominent results, and proposes the potential future work and research aspects.

6.1 Conclusion

Textile-integrated RFID tags are among the key components enabling future wearable wireless devices and body area networks which is a huge step forward in the concept of Internet of Things (IoT). In this Master’s thesis, the impact of washing on passive UHF RFID tags fabricated by brush-painting silver ink on a 100 % cotton substrate. The fabricated tags were coated with three different protective coating materials and their reliability was studied by washing them 15 times in a household washing machine at 40 ºC for about 40-45 minutes. The tags were wirelessly measured before coating, after coating, and after each washing cycle.

Regular textile glue coating was found to be a potential protective coating for the brush-painted tags, as they were able to maintain the peak read ranges of 9 meters after 15 washing cycles. Also the silicone rubber coating was found to protect the tags very well indeed and even after the last washing cycle it had retained the same peak read range of 9 meters just like the textile glue.

Now, white epoxy glue was also found to protect the tags from the effects of moisture, detergent, and mechanical stresses during washing fairly well. Although a consistent and a fairly large drop in the peak read range of 1.8 meters was found at the end of last washing cycle and it is fair to say that white epoxy glue coating indeed protect the tags rather well and make them to endure washing but not washable, if compared to the other two coating types.

6.2 Future Work

In the future research, after these preliminary washing tests, standardized conditions defined tests for textile tags domestic uses can be addressed. In addition, optimization of the antenna to be used near the human body is also an important future topic.

7. PUBLICATIONS

1. “Performance of Textile-Based UHF Passive RFID Tags after Recurrent Washing”, Aitzaz Haider Kazmi, Johanna Virkki, Toni Björninen and Leena Ukkonen, IEEE Antenna and Propagation Society (APS) 26 June – 1 July 2016, Puerto Rico, US.

2. “A Reliability Study of Coated Materials and Brush-painted Washable Textile RFID Tags”, Aitzaz Haider Kazmi, Muhammad Rizwan, Lauri Sydänheimo, Leena Ukkonen and Johanna Virkki, IEEE 6th Electronics System-Integration Technology Conference (ESTC) September 13 – 16, 2016, Grenoble, France. (Won Best Poster Award)

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