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DAWOOD SHUAIB
PERFORMANCE EVALUATION OF TEXTILE BASED PASSIVE
RFID ANTENNAS AS WEARABLE SENSORS
Master of Science Thesis

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ABSTRACT

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Conformal and stretchable wearable sensors provide real-time information about individual's health conditions. There are lot of vital signs and parameters of the human body that are supposed to be sensed by the sensors like, body movement, body temperature, Electrocardiogram (ECG), Electroencephalogram (EEG) etc. Hence, there are lot of health tracking devices available in the market for different purposes. One of the most important sensors are the hydration/moisture/humidity sensors. These sensors are required for the health fitness and for the medical care of the patients. However, as far as the skin sensors are concerned, they are facing one important challenge, which is to have better contact with the body to have better results to analyze as well as providing ease and comfort to the patient/user. In this work, Radio frequency identification technology (RFID) has been used to achieve and overcome the challenge. Since RFID is a prevailing technology in which a microchip in a label used to transmit data when the label is exposed to radio waves. RFID technology can easily be understood by the concept of student cards used in our university where student cards are working as the Tag and the readers planted on the door slots read them. The data/information read by the reader is stored in the database for every specific tag (transponder), to be accessed it later. Passive Ultra-High Frequency (UHF) RFID tags are here used as moisture sensors. The tags for the mentioned challenged used here for different application as stated before, are specifically textile tags. There are two types of textiles (Substrate) that have been used; cotton, which is organic in nature and stretchable synthetic textile, which is a mixture of viscose and polyester. The IC chip containing the information is attached on the antenna that is designed on the substrate which is acting as a Tag (Sensor), one with glue and the other with embroidery. The most specific part is the tag is embroidered with silver thread, which is conductive in nature. Hence embroidery is the fabrication method as well as the vital part of making the tags. The embroidery is accomplished with the help of domestic sewing machine. To get different results, different embroidery designs have been used; single line (less dense), horizontal embroidery and vertical embroidery. Moreover, six tags are fabricated using cotton substrate and two tags are fabricated using stretchable substrate, both substrates have IC antenna attached with sewing as well as glue as mentioned before. When the

fabricated sensors (Tags) were tested in the anechoic chamber, all the sensors have different behavior with different read ranges as well as different peak frequencies. The objective was to test the humidity/moisture evaluation on the sensors. Hence, the sensors were very well exposed to the moisture and were tested again. The sensors with less dense embroidery (Single Line) were more wet than the dense embroidery (vertical and horizontal designs), hence, making the frequency more affected in terms of putting the frequency at lower level in the less dense embroidered sensors than the dense ones. After being dried up, after 48 hours, the sensors were almost back the initial read range values. Therefore, the frequency difference between the initial read ranges and the moist read ranges is of vital importance and all the tags are having different behaviors. As the tags are textile in nature and are embroidered like a simple cloth, they are easy to wear and have very better contact with the body to have better results in terms of moisture evaluation. So further fabrication technique in the prospect of UHF RFID has multiple applications e.g. wounds sensor inside the bandages, soil moisture sensor, moisture/humidity leakage sensor etc. Hence, they have very vital advantages, which include that they are passive, cost-effective, and simple.

PREFACE

The Master Thesis “Performance Evaluation of textile based passive RFID antennas as Wearable sensors” is performed as a requirement of Masters of Science degree in Information Technology with a major in Communication Systems and Networks, in the Department of Electronics and Communications Engineering at Tampere University of Technology. All the researches and investigations take place in the Wireless Identification and Sensing Systems Research Group (WISE) under the supervision of Johanna Virkki and Leena Ukkonen.

I would like to say thanks to my supervisors Johanna Virkki and Leena Ukkonen, for guidance and support during my thesis. I would also like to say thanks to my seniors and colleagues working in the lab, who helped me every time whenever I had any issue or ambiguity.

Especially thanks to my parents for their intellectual, moral and financial support, which allowed me to converge my attention on thesis rather than on personal obstacles.

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1. INTRODUCTION

*"[RFID] is about research, development, education and developing new markets."
- Sal Iannuzzi (November 7, 2014)*

In our daily life, interaction with different types of entities plays an important part that help us to develop our social and physical capabilities. Social interactions contribute towards improvement of our transferable skills and provide a path to live our life in a more sophisticated way. On the other hand, physical interactions come under the umbrella of quantum mechanics where heterogeneous types of interaction are used to recognize different types of objects and understand the encompassed environment in terms of its value and magnitude. Since detection and categorization of objects remains the core subject of research because of its involvement in business and daily life therefore, more efforts have been made in the past couple of decades in order to provide an advanced state of the art detection and categorization methods that can improve the competitiveness of the European industry [1] [2]. Among many refined technologies, some of them are barcode, radio-frequency identification detection (RFID), near field communication and Bluetooth.

In the current competitive market where market call for the more advanced, mature, sustainable and innovative technologies to meet the global economic objectives, used of RFID technology becomes vital. RFID is an advanced detection technology that observe and detect objects using radio waves. Because of its numerous fruitful applications, longer queues in the grocery stores has been dispersed that not only reduced the human power requirement but also contribute to the economic improvement. Currently, this technology is used in different fields of life such as tracking of vehicles, airline passenger's management, preventing theft of vehicles, collecting tolls and taxes without stopping, having authorized entry to the buildings, controlling access of vehicles to gated communities and providing ski lift access [3].

In the aforementioned technology, tags are used to establish a path for the communication with an electronic reader in order to detect objects or any other application depended obstacles. The typical purpose of these tags is the product tracking and identification. Generally, the reader is connected to a central database in order to provide scanned object information through electromagnetic waves. RFID tags consists of an Integrated circuit (IC) microchip and an antenna and are categorized into three major types: active tags, passive tags and semi-passive tags [1].

RFID technology is an emerging technology that is evolving day by day. Generally, to introduce the RFID technology, there are some pros and cons [3]. Some of the advantages are:

- Capability of reading tags from a greater distance than barcodes.
- The tag provides more edibility in term of no in-line of sight requirement.

- RFID tag designed with limited memory storage that can be used to store information. It stores data up to 2 KB, whereas, a barcode can read just 10 - 12 digits [3].
- From security prospective, it is better than barcodes as it cannot be easily replicated.
- In supply chain management, RFID systems play a key role hence it provides more sustainability.
- The reading time required by RFID tags is much smaller as compared to barcode. Approximately 40 RFID tags can be read at the same time.
- The maintenance cost or human's interaction time is minimum.
- RFID tags are reusable and rugged as they are protected by a plastic cover.

Contradictory to the above advantages and despite of the huge amount of efforts made of researchers, it has not completely replaced other competitive technologies such as barcode because of the limitation associated with it [3]. Some of the disadvantages are:

- RFID proves to be too expensive for many applications as compared to other tracking and identification technologies.
- RFID reader struggle to read the information passing through liquid or metal products.
- Possibility of occurrence of the tag collision since numerous tags in the same area respond at the same time.
- Non-standardization of RFID signal frequencies [2].
- Poor read rate can occur if the reader and receiver are not properly aligned [2].
- RFID technology ultimately involves software that allow users to be identified by a central database. This infrastructure potentially be under attack by hackers.

In the last couple of decades, RFID technology has been evolved rapidly and recently; it has been used extensively in personal area network (PAN) and body area network (BAN). PAN consist of devices that communicate with each other in pre-defined limited area. In PAN, any given RFID system can read and process the data from any mobile device by using any RFID reader [4]. The data transmitted by the RFID tag may provide information about the identification, location, price, color or about the date of product purchase. Some of PAN based applications include industrial control in which sensors measure temperature, humidity and position of items in a production facility, communication of information to a production control system, electronic product code used in supply chain applications and exchange of temperature and humidity sensor data in a pre-defined environment.

In contrast to the above PAN, Body Area Networks has also gain their importance especially for advanced and future applications. Theoretically, BAN is an expansion of PAN in which devices are enabled to communicate with each other while they are implanted on the human body [4]. Unlike PAN devices that requires high power consumption, it composed of smart and low-powered heterogeneous wireless devices that are attached to a moving body. BAN along with wearable sensors have diagnostic, as well as monitoring applications. Currently, BAN using wearable sensors is used in a number of modern healthcare applications with the objective to improve the supervision capability of patients such as collection of biological information from the users in order to maintain their optimal health status as well as for diagnosis and therapeutics monitoring. Presently, pa-

tients can be comfortably monitored at home while carrying out their daily activities normally and in parallel, the medical staff have the opportunity to monitor several patients simultaneously. Since the number of out-stationed patients are increasing dramatically therefore, there is a demand of monitoring innumerable patient at a single point of time without geographical constraints [4]. Such type of ambitions can only be achieved with the use of well-organized PAN or BAN along with the modern and advanced RFID tags.

In modern applications, wearable sensors are used in BAN to achieve sophisticated healthcare objectives. Conformal and stretchable wearable sensors provide vital real-time information about individual's health conditions. In the last few years, extensive research and development has been done to merge wearable sensors with the human body. The goal of this huge research is the ability to enhance wearable sensors to sense parameters of the human body such as body movement, body temperature, ECG, EEG etc. Hence, many health-tracking devices have been marketed for different purposes. Out of these many, humidity or moisture sensors are of great importance. These sensors are vastly used and required in health fitness and medical care applications [4]. As far as the skin sensors are concerned, they are facing one important challenge, which is to have better contact with the body to achieve better results as well as provide ease and comfort to the patient/user. In this thesis, radio frequency identification technology has been used to achieve and overcome the challenge. Since RFID is a prevailing technology, in which a microchip in a label used to transmit data when the label is exposed to radio waves [5].

This thesis is divided into following chapters: Chapter 2 contain worthy literature about RFID systems while Chapter 3 focuses on the methodology of RFID Sensors. In Chapter 4, fabric based wearable sensors are discussed and Chapter 5 highlight the components of measurement, Chapter 6 focuses on the measurements and results whereas Chapter 7 contains final analysis including future work of the obtained results.

2. RFID SYSTEMS

RFID technology is a contactless and short distance wireless communication that applies radio waves to identify and track objects. RFID technology has the ability to surge as well as guard the lives of human beings and modernize the way companies establish business. It is used to track and monitor the physical world commodities spontaneously and with abundant precision. Because of its clear advantages to any of its competitive technologies, it is also used abundantly in supply chain business, defense systems, oil and gas, healthcare and security matters [1]. Due to its numerous application in every aspect of life, the analogous research activities have been booming especially in the last couple of decades. The prime motivation behind this increased research activity is the demand of an innovative technology that can track and detect objects at a much faster rate and in a reasonable amount of time. Since RFID is a solution to such problems therefore, its usage has been observed increased dramatically. According to the statistics, the growth of RFID market is likely to increase from \$3 billion in 2005 to \$25 billion in 2020 [6]. It has the capability to reveal about the structure, geographical position and other important properties of any understudy object. With the competence to tag any item with an inexpensive antenna chip and later reader reads the tags, its usage is increasing globally. It has endless applications but are limited in fact, only by the fantasy of the user.

2.1 History

RFID Technology is relative new technology. According to some available data, this concept was first used in the military plan during World War II. The main player Americans, Japanese, British and Germans were all utilizing radar to warn the potential planes while they were quiet far away. The problem with using such radar was that there was no way to differentiate between enemy and a country's own pilots returning from a mission [7]. To solve this problem, the Germans discovered and observed reaction of radio signal in the cases where pilots turned their planes as they about to reach the base. Such methods alerted the radar crew on the ground hence provide the basic solution to a huge military problem. This is essentially considered the first passive RFID system designed and used in real time application [2].

Later, with the advancement made, the British established the first active Identify friend (IFF) system where a transmitter is mounted on British planes [7] as shown in Figure 2.1. On receiving signals from ground based radar stations, it eventually starts broadcasting a signal back that recognized the plane whether as friend or foe. After the successful use in the air defense sector later, it has been used intensively in many other applications in the early 1960's. During this period, scientists in the Japan, Europe and United States boosted their research in this field [2]. In parallel, companies began commercializing products based on this technology such as anti-theft systems that used radio waves to control if an item had been paid for or not and electronic article surveillance tags which are still used in packaging industry nowadays.

The 1990's era was an important period for RFID development and research since it maxim the extensive scale utilization of electronic toll collection in the United States and the deployment of over 3 million RFID tags in railways in North America.

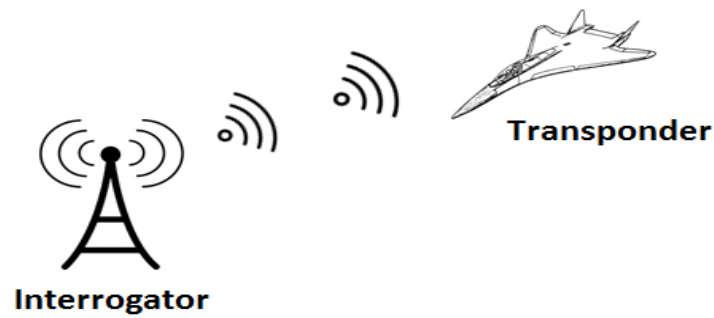


Figure 2.1 Identification of Friend or Foe System

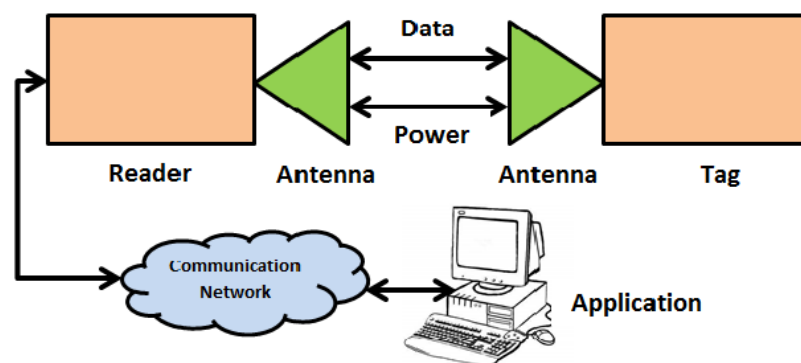


Figure 2.2 Architecture of RFID systems

Additionally, companies in Europe such as Micro design, Alcatel, CGA, Bosch, Baumer, Philips and Tagmaster were became active in the RFID race [8]. Innovative work did not back off and later on out of the blue, valuable microwave Schottky diodes were manufactured on a consistent CMOS incorporated circuit. This advancement allowed the development of microwave RFID labels that contained just a solitary integrated circuit, a capacity beforehand restricted to inductively coupled RFID transponders. Books started to seem dedicated particularly to RFID innovation.

2.2 Components of RFID System

RFID systems consist of two portions, a transmitter (also known as RFID reader) and one or more transponders (also known as RFID tag). In a basic RFID system, tags are associated to all objects that are needed to be identified and followed up. An RFID reader is a network connected device with an antenna that leads data as well as power commands to the tags. The RFID reader perform like an access point for RFID tagged objects so that the “tag” data can be made available to business customs. The transmitter communicates electromagnetic waves to transfer data. Generally tags constitutes of some valuable information, which is used for the tracking and identification. However, the RFID tag is used for the exploration of parameters related to environmental around the tag. RFID tags are usually movable and linked distantly via RFID readers. The readers used to read the tags and they are generally coupled to a device which a user can interact.

2.2.1 RFID Reader

The RFID reader is utmost significant component of the RFID system. RFID readers is used in order to obtain identification, location and other information about the device or product to which the tag is embedded in. Generally, any RFID reader is a combination of two subcomponents: transmitter and a receiver. Job of the transmitter is to provide proper communication channel, relevant frequency, baseband, signal information, efficiency, high edibility and precision [2]. In contrast to this, receiver is used to provide high sensitivity in order to detect smallest possible signal and good selectivity of frequencies. RFID readers are further divided into two categories.

- RFID read-only readers: Such devices can only query or read information from a neighboring RFID tag. These readers are immobile and used for different stationary applications.
- RFID read-write readers: They are also called as encoders, such devices read and write (change) information in any RFID tag. These RFID readers can be integrated with a barcode printer to print "smart labels ". Smart labels have a Universal Product Code (UPC) on the front and RFID tag fixed on the back.

Components of RFID Reader

RFID reader composed of many additional components such as antenna, power splitter, mixers, low noise amplifiers, clock, filters, attenuator, power amplifiers and RF oscillator. Out of all these, the most important is the antenna. The reader utilizes an associated antenna to seize tag's data as shown in Figure 2.3. RFID readers normally use full-duplex communication while interacting with the tags where the received data is passed to a computer for processing. There are several multiple types and sizes of RFID readers. Readers can be attached in a stationary location like in a factory or combined into a mobile device such as a movable or handheld scanner. They can also be embedded in vehicles and electronic devices.

Together, RFID readers and antennas used to read tags. Reader antenna change electrical current into electromagnetic waves, which are radiated into space so that they can be received by a tag antenna and alter again to electrical current. It is important to mention here that the best antenna selection varies according to the environment and particular application for the solution. Linear and circular-polarized antennas are most common types of antenna. Antennas that radiate linear electric fields have long ranges but they are subtle to tag orientation [2]. Linear antennas face trouble in reading the tags taking tag placement or angle into account. On the other hand, antennas that radiate circular fields are less sensitive to orientation but are not capable to send enough power as that of linear antennas.

The distance between the RFID reader and the tags also determines the antenna that it required to be read. The reading distance is known as read-range. Reader antennas work in both "near-field" (short range) and "far-field" (long range). In near-field applications, the read range is less than 30 cm and the antenna uses magnetic coupling so that the reader and tag can transmit power [2]. However, the read-range of the tags is not affected by the presence of dielectrics such as water and metal. In far-field applications, the read-range

is more than 30 cm and extended to several tens of meters. Far-field antennas use electromagnetic coupling and dielectrics can decline communication between the reader and tags.

2.2.2 RFID Tag

RFID tags are small microchips with integrated memory with antenna coil. It is the basic source for analyzing, detecting and identifying goods and they are used for calculating the properties of any object. Tags always snoop for a radio signal that is sent by a RFID reader. When a RFID tag receives a request, it replies by transmitting its specific Identification Code (ID) code and remaining data back to the reader. Use of RFID tags is increasing dramatically and the reason is the production and research at huge level making them cheap recently. RFID tags can be either passive, active, or semi-passive that are differentiated in terms of power usage. Tag is also embedded with an antenna in order to collect energy and channel [2]. Usually, the bigger the area of tag antenna is, the increased energy it will be capable to gather and the tag will have further read range. There is no ideal antenna for every applications. Antenna specifications are defined by the application. Some tags are adjusted for a specific frequency band whereas others might be adjusted for worthy performance when integrated to objects that may not perform well for wireless communication (such as metals and certain liquids). Antennas can be manufactured from a number of materials that can be stamped, etched or printed with vapors deposited onto labels or even with conductive ink [2]. Tags containing a single antenna are not as consistent as those with multiple antennas are. Tags with single antennas have orientation that leads to “dead-zones” whereas tags with multiple antennas are able to remove such dead-zones and rise its reading capacity but needs a particular chip. As discussed in chapter 1, there are three types of RFID tags: passive, active and semi-passive tag, which are explained below,

Active Tags

Active RFID tags contains its own source of power and a transmitter. The received power is used for the operation of electronic circuit and to broadcast essential signals to the reader for further processing. For a typical RFID tag, the power last for approximately 3 to 5 years. The schematic diagram of an active tag is shown in Figure 2.4. Active tags are available in two different types: transponders and beacons. In the prior type, the reader sends a signal first and then the transponder will a send a signal back. In the later type, tag will not wait for the reader's signal but broadcast a signal after every 3-5 seconds. Transponder tags are considered very efficient because they conserve battery life. Active tags apart from providing long range, it has the property of resistance to noise and improved operational suffer from short life, cost and large size [2]. They require longer charging time and maintenance due to battery. Active tags are normally used for tracking animals or objects due to long-range capability.

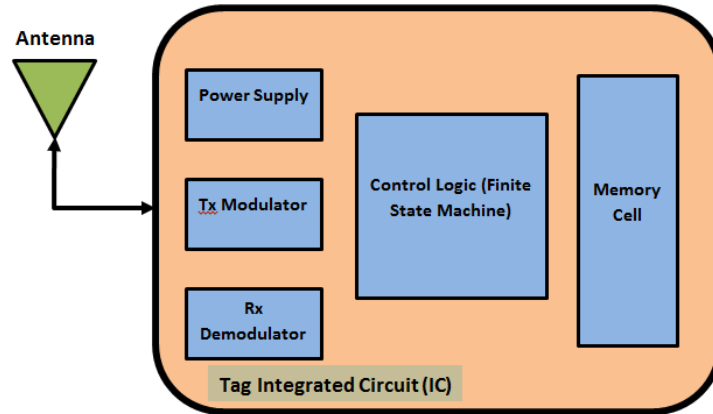


Figure 2.3 Schematic Diagram of Active RFID Tag

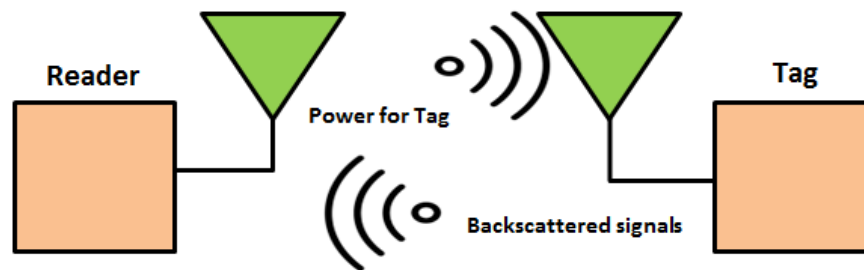


Figure 2.4 Schematic Diagram of Passive RFID Tag

Passive Tags

Among RFID tag family, passive tags are the most used in the practical applications. In general, they are the simplest in design. Unlike active tag, passive tag does not contain any power source or battery and its electronic circuit functionality depends on the strength of the broadcast reader RF signal. The reader sends energy to an antenna that converts that energy into an RF wave, which is then received by the passive tag antenna and re-converted into energy waveform [2]. The schematic diagram of a typical passive RFID tag is shown in Figure 2.5. Currently, passive tag is further categorized into different types on the basis of temperature, size, material and embeddable properties. The foremost purpose to use passive tags is their simple design, no power requirement and low cost. In contrast to this, its reading speed is slow and normally, it takes 25 to 50 milliseconds to complete its reading process. Another issue faced by the passive RFID tags is the weak security [2]. Due to less amount of available power, logical and computational resources are minimized that bounds the operation of composite security algorithms.

Semi-Passive Tags

Semi-passive tag is nothing but designed from a combination of active and passive tag. The semi-passive tag works like passive tag, by means of the reader signal to cause a reply from the tag. The major difference is the absence of the battery for a power source in the semi-passive tag in order to power electronics that are used in combination with off-board sensors such as a thermal sensor instead of generating a reply [2]. Hence, active tags, it requires a power source to operate the electronic circuitry but unlike the previously

mentioned tag, the power is not generated by any installed battery but by the transmitter antenna. In semi-passive tag, the sensor reading integrated into the tag that return the signal along with the tag serial number. Semi-passive RFID tags provide more edibility and reliability in term of battery requirement, size and complexity but at the same time, semi-passive tag has the limitations in terms of slow read speed and short read distances.

2.2.3 Reader and Tag Antennas

Antenna is the most essential component in any RFID system since it is used for the transmission as well as receiving of meaningful signals. Voltage is induced in the antenna while transmitting signal, which is mainly, depends on the operating frequency. Typically, small inductively coupled antennas utilize the fertile core to rise up the antenna's inductance. In RFID systems, there are different types of antenna used that is typically depends on the nature of application. Out of many, some of the important types are linear, circular, bi-static and monostatic [9]. Linear antennas operate when the tag orientation is known and fixed in advance [2]. The tag and reader antennas should be matched in polarization while circular-polarized antennas are used when the tag orientation is unknown in advance. Bi-static antenna consists of two ports where the transmitted signal is being transmitted through one port and the received signal with the other port [2]. The monostatic antenna is the most common antenna and has single port. The transmitted and received signals are operated through a common port [2].

2.3 RFID Frequency Distribution

RFID systems around the globe operate in low frequency (LF), high frequency (HF) and ultrahigh frequency (UHF) bands. RFID system that operates at a lower frequency has shortcomings in term of shorter read range and slower data read rate but have the advantage to read on metal or liquid surfaces. On the other hand, system that functions at a higher frequency has faster data transfer rates and longer read ranges but exposes to interference. The LF band covers frequencies from 30KHz to 300KHz. Due to this frequency band, it provides a short read-range of 10 cm and slower read but comparatively less sensitive to radio wave interference. Typical LF RFID applications include access control and livestock tracking. The LF spectrum is not taken for granted for a real global application due to very small difference in power levels and frequency throughout the globe [2].

The HF band ranges from 3 to 30 MHz. Due to such a unique frequency band, it provides the reading ranges between 10 cm and 1 m but experience more interference to radio waves. Typical HF RFID is commonly used for data transfer, payment and ticketing applications. There are multiple HF RFID standards such as the ISO 15693, ECMA-340, ISO/IEC 18092, ISO/IEC 14443A and ISO/IEC 14443 standards. The UHF frequency band ranges from 300 MHz to 3 GHz [10]. In this study case, UHF range of 800 MHz to 1000 MHz is used. The reading range of UHF systems can be as long as 12 m, and a faster data transfer rate but more sensitive to interference. Practically, UHF tags are cheaper and easier to produce than LF and HF tags. Wide variety of applications utilize UHF RFID, ranging from wireless device configuration, to pharmaceutical anti-counterfeiting, to retail inventory management. Several recent RFID projects are utilizing UHF contrary to LF or HF, leading UHF as the fastest growing section of the RFID industry.

2.4 Application

In the current world, RFID systems are used in a number of application because of its unmatched features such as simple structure, reading of electronic product code from a distance and scanning capability without any physical contact. Some of its applications out of many are listed below [11] [12],

- The implementation of RFID products in medical applications is reaching maturity in many areas. Due to the well-optimized structure of the tags currently, it is used for the tracking of the medical equipment and enables automated data entry that resulted in the minimization of medical mistakes. Furthermore, HF tags are used for short ranges (less than 3 inches) and used in tissue, blood and other critical fluids samples. UHF has a long range of detection therefore; it has been used for the location of the devices, inventory management and tracking and identification of patients.
- In hospital, an emerging problem is the lack of well-organized infection control methodology. Use of the RFID technology can be a good approach to address this problem. RFID tags are deployed to patients and staff in order to trace people or patients with a potentially dangerous infection such as HIV/AIDS, TB, Anthrax, MRSA, Smallpox etc. [11] With the help of central database where all the important information of patients is stored, RFID tag scanner generates an alert to the staff or ordinary people when they encounter a person affected by any serious infection.
- In medical world, another an important application attached with this technology is its usage for the tracking and locating of the medical devices hence enables staff member to rapidly response to the location of the critical medical devices. Furthermore, use of different equipment in an operation can be optimally managed in advance. By applying RFID in hospitals for automating inventory management, it not only reduces the overhead but also minimize the duplicate supplies of critical inventory.
- In medical Laboratories, RFID is used to track tissue or fluid samples. As fluid samples pass through numerous preparation steps, through RFID they can be automatically tracked, reducing errors from data entry or mishandling. The final samples can be automatically attached to the patient record stored in a central hospital database.
- RF tags are also used to secure the stock and make it possible for people to use self-service checkout machines. For checking books in or out of a library using one of those machines, an RFID chip stuck inside the book's cover and it is used to know which book has been borrowed with a specific identity without scanning any barcode.
- The specific competence of RFID technology is to identify each item. Such feature came up with bulk of opportunities in supply chain management and inventory by presenting better visibility to item location, improved inventory accuracy, increased ability to track and trace, better consumer protection and decreased shrinkage. [12]

3. SENSORS

In our daily life, measurement of physical phenomena in a more automatic and sophisticated way is sometime critical that becomes more problematic when such operations need to be performed in a risky environment. To face such harsh constraints, sensors come into play. Sensor is nothing but an electronic device, which detects the actual results and then transfers it to electrical signals. A specific apparatus or MCU later interpret these signals. It can also be defined as a device, which provides a user-friendly output in response to a specific input. A sensor can be thought of as an automatic switch that perform several functions in automated manufacturing and material handling systems for example, it can be used to determine if an object is present or not, a tool is broken or if product is running down a conveyor line. In a factory, a sensor can be used to detect a problem on the line and stop the line automatically [13]. Similarly, in our home, it can be used as a security device that detect window or door opening and closing. In short, sensors have contributed significantly to recent advances in manufacturing technology that can make a process or system more automated and removes the need for human operators to monitor and control the situation.

In the current modern world, sensors are used in every aspect of science and engineering. Currently, it is used in all aspects of life including surveillance, security, safety, monitoring and awareness. Sensors are key component for large scale applications being used for safety, monitoring and process control. They are also being used centrally in medicine for diagnostics, monitoring, critical care, and public health [14]. Generally, sensors are divided into three major categories [13].

- Physical sensors: They are used for sensing properties such as temperature, pressure, ow, stress, strain, position, particles or force.
- Chemical sensors: They used for concentration or identity of a chemical substance like ethanol, carbon monoxide, gasoline or other molecules.
- Bio-sensors: They are used for sensing biologically active substances.

There are a number of sensors with distinct features available in the present market therefore; proper study is required before the selection of any sensor is made practically. The general criteria for selecting any sensor for any type of application are:

- Accuracy
- Cost
- Environmental condition
- Range
- Calibration
- Resolution
- Repeatability

In the current competitive age where demand for every commodity is increased dramatically, use of the sensors has been increased in parallel. Some of the well-known and modern function of the sensors in different aspects of engineering are given as follows [13].

- In this modern technology era, sensor is widely used in all branch of the textile industry [13] [15]. Without applying of sensor technology, efficiency of the machine will be decrease, wastage will be increase hence, overall cost will be increase. Besides, accident can be occurred without using sensor in textile machine. The sensors used in textile industry are fully able to apprehend physiological data provided by the human body. The design of these sensors is also capable to properly embed in daily usage garments. In this way these sensors will help users to organize their vital signs and to help them to keep track of their health (such as weight, blood pressure, heart rate).
- Today's smart phones utilize a wide array of accelerometers, gyroscopes and various other sensors in their designs. These sensors are currently being integrated into premium-grade smart phones but are also becoming more common in mainstream phones or wearable such as fitness trackers.
- Today in automobile industry, a number of sensors are used with different functionality. Most cars have a sensor which tells about the throttle, manifold pressure sensor, camshaft, engine coolant temperature sensor, mass air flow sensor, crankshaft position sensor, and an oxygen sensor. They also contain EGR sensors, detonation sensors and intake air temperature sensors.
- Similar to above industrial sector, sensors are also used by the construction industry. Building materials may include lumber, natural and synthetic boards, steel beams, concrete or any other material used in the building of residential and commercial structures. Acuity products may be used in any number of dimensional measurement applications that relate to the manufacturing of building materials and equipment. Short-range sensors may be used to measure the height of architectural paves so that all materials mate properly and according to specification.
- Sensors are also widely used at paper and pulp plants. Various different processes require sensors such as pulp slurry under extreme temperatures, corrosive chemicals and pressure conditions. Therefore, it is necessary to find out stable and accurate results to properly control the processes without compromising the performance of plant operation [13].
- The quality, consistency and reliability of production systems are critical to the development and manufacture of pharmaceuticals. Pumps, fans and motors form the core of most production systems that required sensor in order to function at peak efficiency for extended periods and with minimal maintenance. Vibration monitoring sensors are being used as an essential tool to ensure system efficiency, precision and repeatability.
- Whether it is the pharmaceutical, cosmetics, food or consumer goods industry, packaging requirements are as varied as the products we deal with every day. Packaging equipment uses many types of sensing technologies in linear and non-linear motion-control applications. For every bottle that needs to be filled, for every carton that needs to be folded and for every bag or box that needs to be sealed, one can find a sensor at work.

- Due to harmful working environment and remote location of thermal power plant sites, it is dangerous and time expensive to operate and maintenance. As the demand for power increases, increasing safety and reducing operating and maintenance cost plays a vital role in increasing the reliability of the power plant. As the thermal power plant should work for 24 hours and 365 days, it is not possible to monitor the parameters in site at each and every moment [16]. Hence remote monitoring is required. For this purpose, temperature sensor, pressure sensor, ow sensor, level sensor, revolutions per minute (RPM) sensor, PH sensor, vibration sensor and Voltage sensor are used.

3.1 Types of Sensors

In real life, there are numerous applications with distinct objectives. Since the motive of every application vary in term of magnitude and applicability therefore, in the present industrial market; there are many sensors available with varying capabilities. Out of many available, some of the most important sensors are listed below [13] [17] [18].

Current Sensor

Current sensor is used to detect electric current and generates a conserved signal. It is very crucial to analyze the current for different vital instrumentation systems. Before the sensors current sensing technique was used to analyses the current control. But now with the development of sensors technology, new current sensors are emerging with new topologies to sense and monitor the current to boost the performance of the system [5].

Magnetic Sensor

Magnetic sensors used in electronics circuits typically decode the megantically-encoded information and then converts it into electrical signals.

These devices are becoming more and more popular because of its usage in different fields of solicitations such as movement of direction, position sensing, and velocity. One main reason for their popularity in electronic design is the contact free operation, reliable design and requires very less maintenance [5].

Temperature Sensor

The most common physical measurement is temperature sensing. We can easily find the implementation of these sensors in our daily life implementations, such as refrigerators, electric ovens, air conditions and thermostats of home heating solutions. They are also used in PCB boards, in industrial controls room such as in calibration laboratories and data centers. Most of the times there temperature sensors are the passive devices that does not require any electrical power to operate such as resistance temperature detectors, thermistors and thermocouples [5]. Out of them Thermocouples are the commonly used sensors, as they does not require annihilation signals.

Pressure and Strain Sensors

Industrial and manufacturing systems rely heavily on pressure sensors and strain gages for the measurement and control of gases and weights. Pressure sensors typically used to measure air, gas or fluid pressure. Other applications include its usage in automotive and ergonomic sector [5]. For example, edible pressure sensors are used in designing products such as mattresses and automotive seats.

Position Sensor

Position sensors are basically used for the measurement of distance travelled by the body. How far the body has moved from its reference or initial position is sensed by the position sensor and often the output is given as a feedback to the control system that in return takes the appropriate action. Motion of the body can be rectilinear or curvilinear hence, accordingly; position sensors are classified into linear and angular position sensors. Position sensors are used for detecting motion in large systems such as aircrafts, ships and industrial systems. Angular position sensors which measure motion in as many as three axes is used to measure vibration in machines for predictive maintenance or in aircraft wings for test [5].

Humidity Sensors

Numerous ecological tests executed as a major aspect of item portrayals depend on testing over a scope of humidity [16]. Humidity sensors are used for the measurement of humidity in applications such as aviation, weather and other scientific applications. In our homes appliances, humidity sensors have found their way into refrigerators [5].

Inductive Sensors

These sensors are used for the non-contact detection of metallic objects. They recognize metal items without connection and are described by a long administration life and outrageous toughness. The sensing range of an inductive sensor is dependent on the type of metal being detected. With the latest ASIC technology, these sensors offer the ultimate in precision and reliability [5].

Light Sensors

A light sensor is an electronic device used to detect light. There are several ways to detect light using this electronic equipment. Every cell phone and digital camera has a light-sensing array for taking photos. Engineers use other light-sensitive components such as photo-resistors, photodiodes and photo-detector in all kinds of applications. Photo-diodes are particularly useful as a detector of light in fiber-optic networks [5].

Mass flow Sensor

Mass flow sensor is used to examine the mass flow-rate of air and the temperature of air entering an engine. This sensor measures the volume of air as well as adjusts for its flow towards the engine. There are two normal plans of mass flow sensor utilized as a part of the present vehicles. One produces a variable voltage yield (analogue) and alternate creates a frequency yield (digital) [5].

Oxygen Sensor

Oxygen sensor is a device that detects the amount of oxygen to mix with the proportion of oxygen in other chemical mixtures or liquid that is being analyzed. Every new car produced in late 80's have an oxygen sensor. This sensor is a piece of the outflow control framework and bolsters information to the engine management controller. The objective of the sensor is to enable the motor to keep running as proficiently as could be expected under the circumstances and to deliver as couple of emanations as would be prudent [5].

Moisture Sensor

Moisture sensors are used to measure the water content. The quantity of water vapors in air can disturb human respiration and many industrial manufacturing processes. The existence of fumes of water also influences various chemical physical, and biological processes [5]. Moisture detection in industries is crucial, as it may affect the businesses, product cost, health and safety of the personnel. Consequently, moistness detecting is critical particularly in the control frameworks for modern procedures and human solace [13].

Governing or observing moisture is of utmost prominence in many industrial & domestic applications. In semiconductor industry, humidity level need required properly control & monitoring during vapor processing. In medical applications, stickiness control is required for respiratory gear, sterilizers, hatcheries, pharmaceutical handling and natural items. Mugginess control is additionally essential in compound gas sanitization, dryers, stoves, film parching, dad per and material creation and food preparing. In agriculture, moist detection is very important protect the plantation, soil condition etc. For local applications, moisture control is required for living environment in buildings, cooking control for microwave ovens etc. [13]. In every such application and numerous others, stickiness sensors are utilized to give a sign of the humidity level. Currently, numerous number of various moisture sensors are available in market [15].

3.2 UHF RFID Tags as Moisture Sensors

With promptly increasing ageing inhabitants around the globe and growing amount of cognitively weakened older people, deprived liquid intake is now the common problem [19]. Researchers tried to measure humidity and moisture by permitting an RFID tag to interrelate with humidity and permitting others to work independently without interference [20]. Common approaches for automatic monitoring of moisture sensing are attached battery-powered sensors to users [21] or to objects [22] [23] in light of their ability to give data rich sensor information. These sensors are cumbersome, upkeep inclined (i.e. require battery substitution or energizing) and costly. In consequence, they are inappropriate for applications concerned with older people. For the high performance of RFID tag on body and under the guidance of IEEE 802.15 standard for the body area networks, the UHF frequency band is chosen for the measurement [24]. UHF RFID labels are tiny, reasonable and has an unending lifetime making them perfect possibility for subtle observing of human conduct in true settings [25] [26]. These labels can be effectively inserted into ordinary articles, making potential outcomes for clients to do their typical schedules with no changes.

4. FABRIC BASED WEARABLE SENSORS

In the present fast growing technological age, term “Smart Textiles” is used excessively in recent healthcare and other industrial applications. It leads us to a broad field of products and studies that outspread the functionality and benefits of common fabrics [27]. Smart textiles can be defined as textile products such as filaments and fibers, yarns composed with knitted, woven that can relate with the environment/user. The margining of textiles with the electronics results in e-textiles that are used for the growth of smart materials which can accomplish a wide range of functions, found in inflexible electronic products nowadays [28]. Smart textiles will work as a source of increasing social welfare and they can open ways to essential reserves on welfare budget. As the living standard of the humans is increased along with progressions in artificial intelligence, telecommunications, electronics, complex computing and prominent development in cardiovascular chronic diseases (such as angina, hypertension and arrhythmia), it leads to the evolution of wearable fabric/textile-based biomedical health monitoring systems [29]. Such moveable and pervasive wearable monitoring provide the world an opportunity to track human being physical activities (e.g. calorie burned, step count) and keep record of their health condition. In this respect, wearable sensors are designed in order to unobtrusively measure large and small strains and transmit data accurately to any Bluetooth enabled device, without the need for constant recalibration. They can be used as a tracking device that can be worn for a few hours to provide better care for patients connected to medical devices for weeks. Moreover, these sensors enable smarter technologies are also used for the measurement of the body motion to enable new methods of sports training. [30]

4.1 Introduction

Smart wearable electronics are used for monitoring the physiological and biomechanical signals of human body and are used for personalized healthcare. Recently, wearable electronics have gained focus along with the growth of flexible and stretchable electronics as well as the quick spread of movable devices [31] [32] [33] [34]. Those devices are of a vital attention for the assortment of physiological and electro-physiological information extracted from the body of a human, with application such as very sensitive pressure sensors, epidermal electronics based on inorganic semiconductors [31], strain sensors, organic electronic devices laminated on the skin [32] [33]. They can match human skin [34], active-matrix mechanical sensor arrays for electronic skins [34] and multipurpose electronic patches in order to diagnose and rectification of movement sicknesses [35]. However, many flexible electronics manufactured until now rely on long wires to connect them to the external power source, which minimize their ability to move. Working of wearable sensors is shown in Figure 4.1.

Wearable sensors are used to monitor body's physiological response to exercise and the kinematic aspects of performance. To monitor this in a natural way, there is a need for integrated sensors that are comfortable, wearable and straightforward to use. Textile based sensors which are compatible with textile manufacturing processes can be a possible solution [36]. There is different type of textile based wearable sensors available that can be used for different application for example, pH sensor which collects and analyses sweat in real-time, piezo resistive sensors which respond to body movement such as

breathing and foot plantar pressure, strain sensors capable of measuring knee flexion/extension of patients with anterior cruciate ligament rupture etc. Initially, studies about intelligent textiles focuses on smart materials while in a later on, research is done about the different methods that merges these smart materials to textile materials. These smart materials are incorporated into the textile structure by different technologies. In real time applications, these are widely used in BAN to detect and measure different physical and environmental factors.



Figure 4.1 Wearable Sensor Working [36]

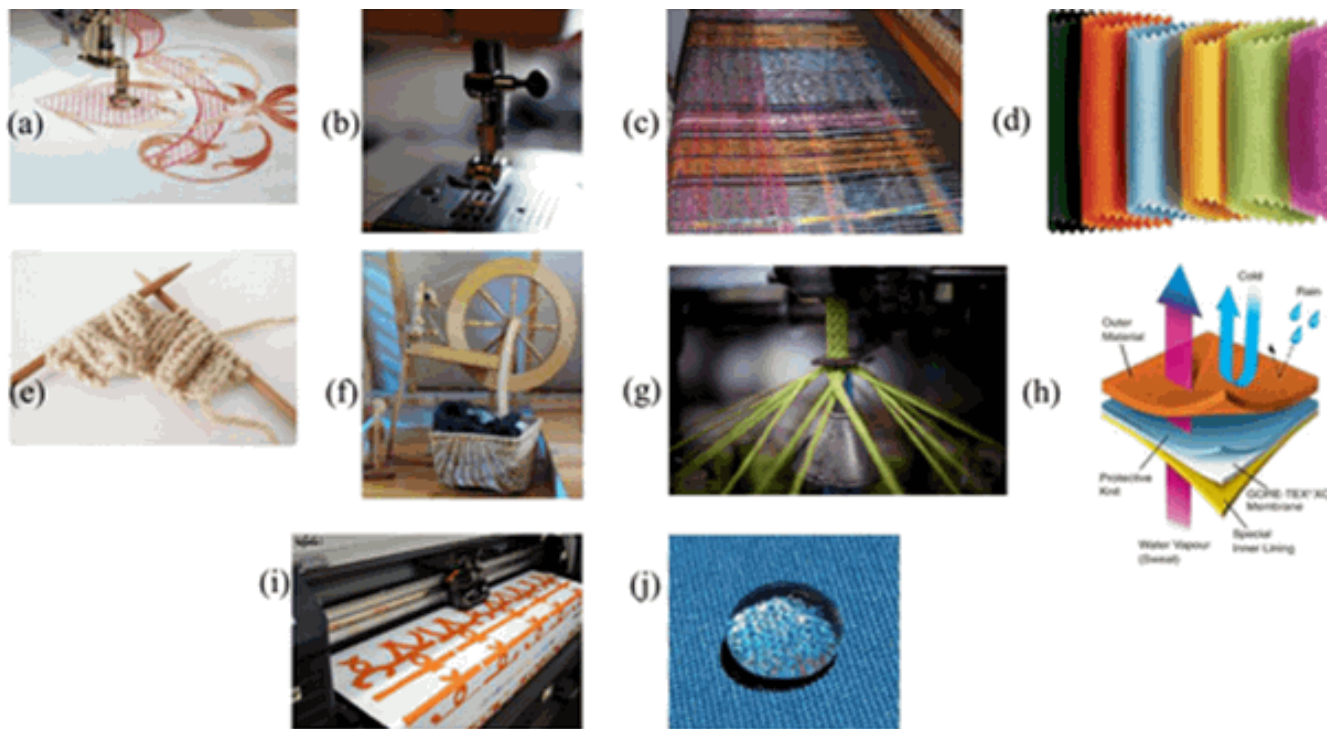


Figure 4.2 Different kinds of textile/fabric manufacturing and treatment (a) Embroidery (b) sewing (c) weaving (d) non-woven (e) knitting (f) spinning (g) braiding (h) coating/laminating (i) printing and (j) chemical treatment [29].

Wearable sensors in body area network

In Chapter 2, body area network is discussed where different electronics equipment such as sensors or RFID tags, which are attached to the human body, are used to detect the physical and mental behavior of concerned commodity. Body sensor network systems can help the people by providing healthcare services such as medical monitoring, memory enhancement, control of home appliances, medical data access, and communication in emergencies [37]. Practically, BAN system consists of various nodes attached to different body parts. These nodes are responsible for communicating with each other and transmitting the data to any remote server [38]. A node is subdivided into a sensor, an actuator and a personal digital assistant. Sensor is the most important part since it includes a memory unit for data storage and an antenna for transmitting and receiving the collected data [39]. Wearable antennas are one of the wearable sensors working in BAN (WBAN). Traditional antennas that were non-flexible were difficult to integrate into BAN systems compared with the flexible wearable antennas. In order to use any wearable antenna in a BAN system, following conditions need to be considered.

- Compact and light weight
- Flexible and retain their shape
- Radiation away from the human body
- Stable characteristics in the human body vicinity

For applications where, wearable antenna is required to be operated near the human body, it requires necessary performance characterization. In 2004, detailed analysis of antenna performance near human body was presented [40]. The antenna performance was analyzed near upper part of human chest and arm. The results showed that the antenna can operate near human body with sufficient return loss.

WBANs in medical field consists of wearable and implantable sensor nodes that can sense biological information from the human body and transmit it over a short distance wirelessly to a control device worn on the body or placed in an accessible location. The sensor electronics must be miniaturized, low-power and detect medical signals such as electrocardiograms, photoplethysmograms, electroencephalography, pulse rate, pressure and temperature. The gathered data from the control devices are then transmitted to remote destinations in a wireless BAN for diagnostic and therapeutic purposes by including other wireless network for long-range transmission. The schematic diagram that show working of WBAN is shown in Figure 4.3.

WBAN health monitoring systems allow the individual to follow closely the changes in her or his vital functions and provides a feedback for maintaining optimal health status. If integrated into the tele-medicine system, such systems can alert medical personnel when life threatening changes occur. In addition, patients may benefit from continuous long-term monitoring as a part of a diagnostic procedure. We can achieve optimal maintenance of a chronic condition or can be monitored in the recovery period after the acute event or surgical procedure. Long-term health monitoring can capture the diurnal and circadian variations in physiological signals.

The use of WBAN for monitoring various health-related biometric parameters in everyday activities is attracting more interest recently. Many people are familiar with the use of devices such as wearable heart rate monitors and pedometers for medical reasons or as

part of a fitness regime. Interest in the use of such wearable systems for personal health and rehabilitation has increased as part of a wider initiative for increasing the input of the individual or patient in their own care [41]. It is believed that this could help in reducing the strain put on healthcare systems of aging populations, rising costs and increasing incidence of chronic diseases requiring long-term care. While the growing success of sensors that monitor the physical properties, relatively little has been done in the field of wearable chemical sensors that can be used for real-time daily monitoring of bodily liquids such as tears, sweat, urine and blood [42].

The first stage of the architecture includes number of wireless nodes of medical sensor that are integrated into WBANs. The second stage includes the personal server application that runs on a personal digital assistant, cell phone or home personal computer. Once the WBAN network is configured, the personal server application manages the network, taking care of channel sharing, time synchronization, retrieve and process data. Finally, if a channel of communication for the medical server is available, the personal server establishes a secure connection to the medical server and sends reports that can be integrated into the user's medical record. Other applications of WBAN includes wearable bio-potential acquisition system, wearable smart shirt and artificial retina for blind people etc. Along with the much development made in this field of science, there are also some challenges faces by this modern concept. Although the number of research efforts is focusing on various technical, economic and social issues, many technical hurdles remain to decide whether to acquire a flexible, reliable, secure and energy efficient WBAN. Currently, some of the open challenges faced by this technology are security, privacy, and user-friendliness, ease of deployment, scalability and mobility.

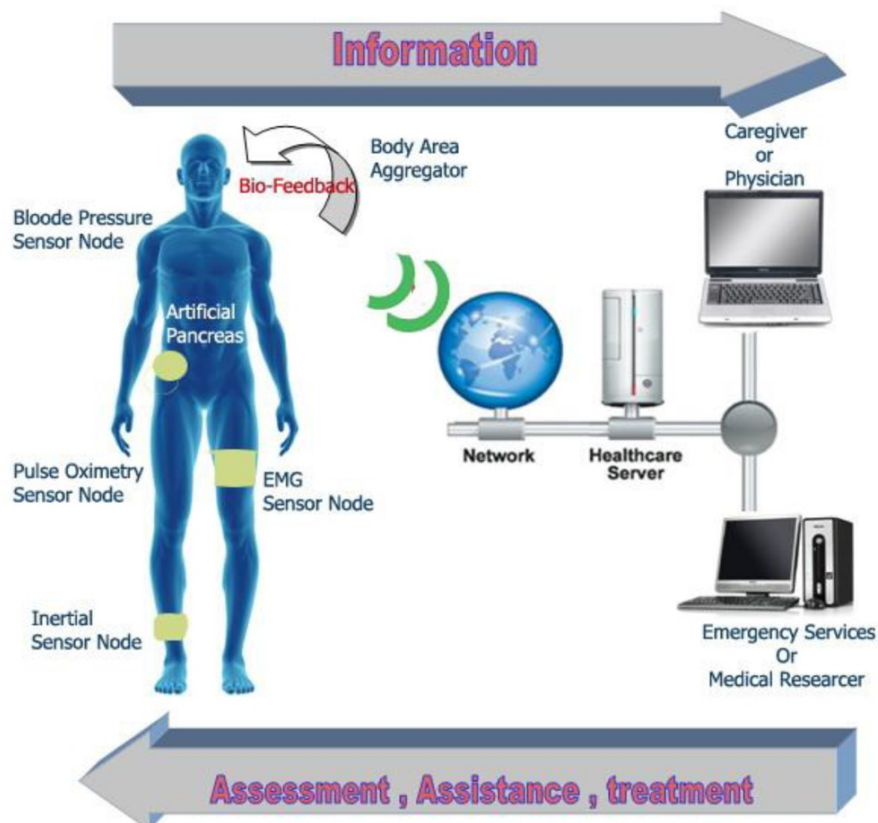


Figure 4.3 Wearable Sensor in BAN [37]

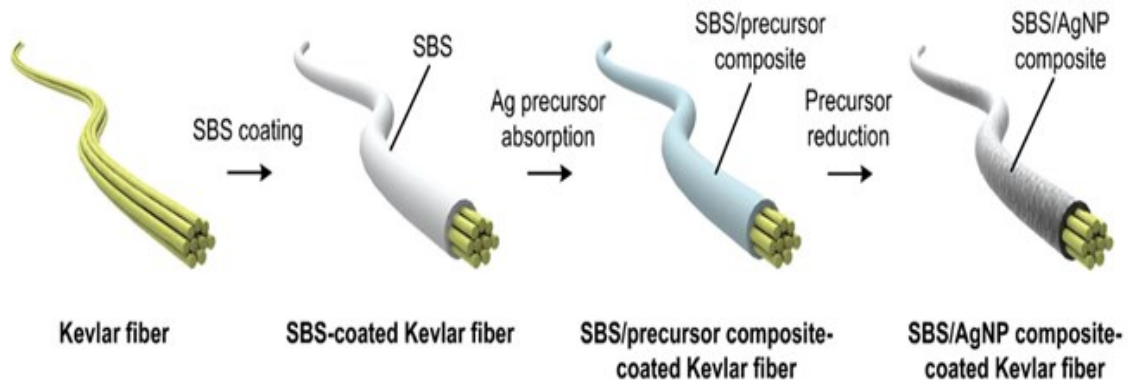


Figure 4.4 Conductive Fibers Setup [43]

4.2 Types of Fabrics

In the present scientific world, one of the most emerging field is the convergence of both electronic components and textile that resulted in “E-textile”. These new designed product falls into the category of intelligent systems that has the ability to sense and behavior according to the provided environment. Smart textile has gain importance recently and has many valuable applications in medical monitoring applications such as hear beating rate monitoring, rehabilitation of athletes and assistance to emergency to first responder. Over the past decade, many techniques and materials have been used in order to utilize and realize smart textiles [30]. Some of the well-known fabrication techniques are listed in detail as under.

Conductive Fibers

Conductive fibers which have excellent conductivity and stability. The conductive fibers were fabricated by coating highly stretchable polymer on the surface of poly (p-phenylene teraphthalamide) fiber, followed by converting a huge amount of silver (Ag) ions into Ag Nano-particles directly in the stretchable polymer as described Figure 4.5. The conductive fibers provide superb electrical property of 0.15 ohm/cm owing to the dense electrical connection of the Ag Nano-particles and the good stability against repeated external deformations of 3,000 bending test as shown in Figure 4.6. [43]

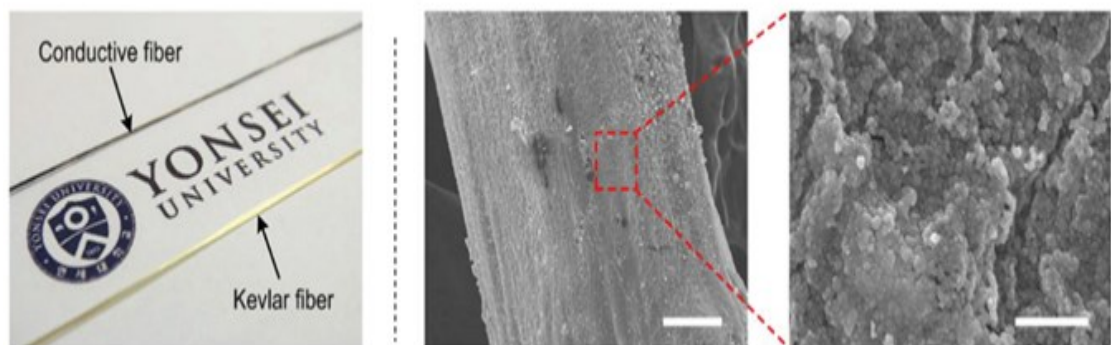


Figure 4.5 Conductive Fiber Internal Structure [43]

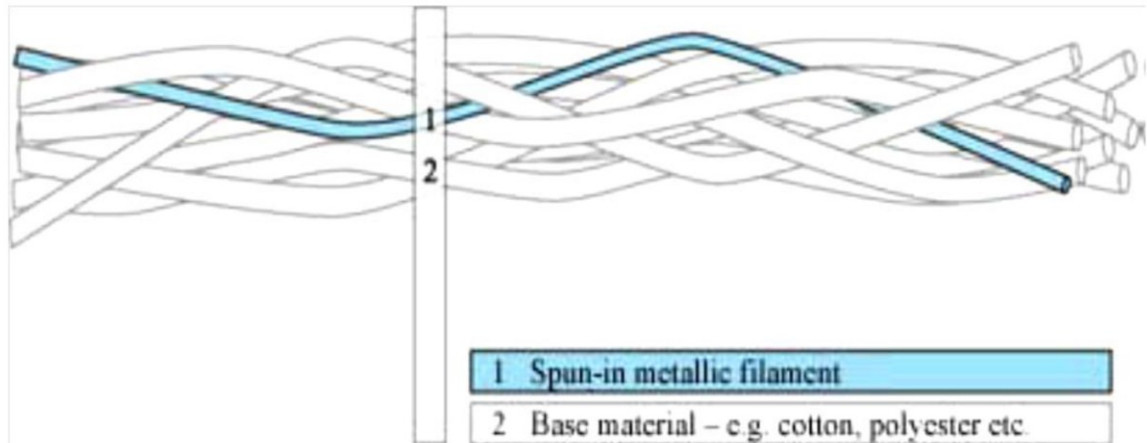


Figure 4.6 Schematic of Conductive Fiber Twisted with the Normal Fibers. [29]

Initially, conductive threads were mainly used in technical areas: clean room garments, military apparel, medical application and electronics manufacturing [44]. Conductive fibers play a significant role in aerospace, microelectronics, medicine, precision vehicle and automotive industry because their electric properties recently [30]. Currently, different multi-nationals company are involving in this type of business. The company Swiss-Shield (Flums, Switzerland) specializes in producing metal mono-filaments which are incorporated into base yarns like cotton, polyester and poly-amides. The metal mono-filaments are made from copper, brass, bronze, silver, gold, aluminum, for instance. The following Figure 4.7 shows a typical conductive yarn with base fibers and a metal mono-filament twisted around them [45].

Conductive Fabrics

Conductive fabric offers the softness and malleability of fabric while taking care of electrical properties. It is mainly used in projects where a soft, flexible and sometimes washable circuit is required. It is also used for creating low profile switches in projects where manufactured and hard conductive materials are not appropriate.

There are different ways to produce electrically conductive fabrics. One method is to integrate conductive yarns in a textile structure, e.g. by weaving. However, the integration of conductive yarns in a structure is a complex and seldom a uniform process as it needs to be ensured that the electrically conductive fabric is comfortable to wear or soft in touch rather than hard and rigid. Conductivity can be established with different thread types [27]. Another possibility to achieve a conductive fabric is to attach a conductive structure to a ground structure by using the embroidery technique. In 2000, the Massachusetts Institute of Technology Media Laboratory researches were the first to propose a way of stitching patterns that can define circuit traces, component connection pads or sensing surfaces designed with traditional CAD tools for circuit layout [46].

A challenge, associated with conductive fabric is that it erodes over time that impregnate with metal. Sometimes this metal and fiber bond is not the strongest, so it wears down and wears off through use. Depending on which metal is used, it will oxidize since it is not properly insulated therefore, different insulation ways are practiced overcoming such a problem [30].

4.3 Additive Fabrication Methods

In recent years, there has been considerable research effort devoted to the development of new fabrication methods for wearable sensors to fulfil the requirements of future technology and in return, much progress has been achieved. Fabrication processes are categorized into two classes: impact printing and non-impact printing. Printed techniques can be classified into four traditional methods which are used for the fabrication of wearable sensors devices: screen printing, flexographic printing, ink-jet printing and brush printing.

Screen-Printing

Screen-printing is one of the simplest and most cost-effective technique used for fabricating electronics due to its ability to produce patterned, thick layers from paste-like materials [47]. This technique is based on a woven screen that has different mesh sizes. The screen printing procedure comprises the printing of a viscous paste through a patterned fabric screen that is usually followed by a drying process. To produce a printed pattern, a squeegee blade is driven down forcing the screen into contact with the affixed substrate. This in turn forces the ink to be ejected through the exposed areas of the screen on the substrate thus; the desired pattern is formed [48] as shown in Figure 4.7. Material, which is used for fabrication of squeegees, include rubber or other polymeric materials.

Currently, three different screen-printing methods are used in industry: flat, cylindrical and rotatory. Flatbed is the simplest and most common screen printing method while cylinder screen-printing has similar features to that of flatbed except that the pattern is deposited as the substrate rotates while attached to the screen roll. In rotary screen, ink and squeegee assembly are rotated inside a rolled screen where impression cylinder produces pressure to substrate [49]. Using screen-printing, several RFIDs have been prototyped successfully. The idea to develop such screen printed RFID antennas as wearable antennas. As well as washable for future reliability as such wearable antennas can get dirty and sweaty [50]. However, there are some problems associated with this technique including the limited control over the thickness, number of passes, resolution of the printed patterns and layer consistency [47] [51].

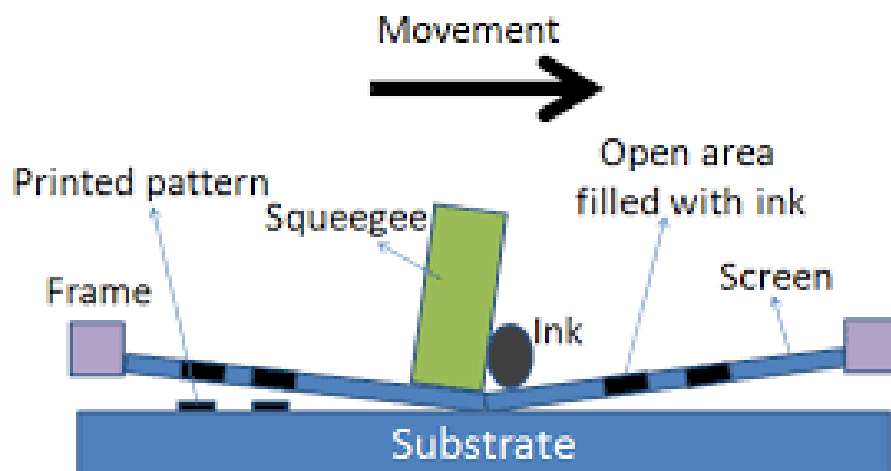


Figure 4.7 Illustration of the Screen-Printing Process. [50]

Flexographic Printing

Flexographic printing is a roll-to-roll printing technique [52]. It is a simple process since it only involves inking the protruding surface of the matrix and bringing it in contact with the substrate [53]. An image is produced by a print making process where a protuberating surface of the printing plate matrix is inked while the recessed areas are free of ink. The main components of this printing process are a plate cylinder, an impression cylinder, an anilox roll and an inking unit. The plate cylinder is made of rubber or photopolymers. The imaged areas on the plate cylinder are raised with respect to the overall surface of the plate cylinder. The image is transferred from the plate cylinder to a substrate through the use of an inking unit. The inking unit first transports the ink particles onto the anilox roll, which is metered with the assistance of a doctor blade that wipes the excess ink from the surface of the anilox roll. In the next step, the raised parts of the plate cylinder will receive the ink from the anilox roll because the non-image areas are not raised with respect to the surface of the cylinder since they do not receive the ink. The image on the plate cylinder is transferred to the substrate by the use of an impression cylinder [51]. Due to its relatively fine resolution, low cost and high throughput; flexography gained a great interest by RFID antenna manufacturers. Flexographic printing like other techniques is effective method of fabricating UHF RFID antennas [52]. The process schematic diagram is demonstrated in Figure 4.8.

Inkjet Printing

Inkjet printing is a non-impact printing process that does not use image carrier or mask. This new technology utilizes conductive ink on different Nano-structural materials such as silver nanoparticle based ink. This is one of the very reliable and moderate method to develop UHF RFID passive tags for wearable purpose [52] [54] [55]. It is divided into two types: continuous inkjet and drop on demand inkjet [51]. In continuous inkjet printing, a continuous stream of ink droplets is generated during the printing process. This stream is electronically controlled in a process where a high voltage and electrostatic field is formed that can detect ink droplets from an image area to a non-image area [55]. The detected ink is directed back into the printer. In comparison, a drop on demand inkjet printing generates ink droplets only on the desired locations to form the images [56]. Drop on demand inkjet printing techniques use either thermal or piezoelectric techniques to jet individual drops of ink. Printing quality depends mainly on the ink characteristics such as viscosity, surface tension and particle size [57]. The surface topology of the substrate, the platen temperature and the print head parameters are also important factors [55]. The process is shown in Figure 4.11. This process is very easy and durable for wearable antenna applications as the inkjet printing is very uniquely demonstrated process but the quality of ink and flow depends on its reliability.

Brush Painting

Brush painting is a versatile, simple and fast method which enables mass production in the future. The method not only reduces the process steps in RFID tag manufacturing but also minimizes the need of conductive ink material because it is dispensed directly to the brush [58]. This not only reduces the cost but also it is more environment-friendly, especially when compared to the widely used etching process. The manufacturing process

involves only two steps: painting and sintering. This novel fabrication method offers great competitiveness in future wearable RFID tag manufacturing and an appealing alternative to screen-printing. This process offers durability and flexibility to fulfill the requirement for wearable antenna. This process is also extended to develop flexible and stretchable antennas on 3D printed substrate [59]. The process is shown in Figure 4.12. Brush painting has been previously successfully used for fabrication of tag antennas on fabric substrate with silver Nano-particle ink and on wood substrate with silver and copper Nano-particle inks [60]. Moreover, silver brush painting also gives the reliability of UHF passive tags to work as environmental friendly and reliable devices [58] [61].

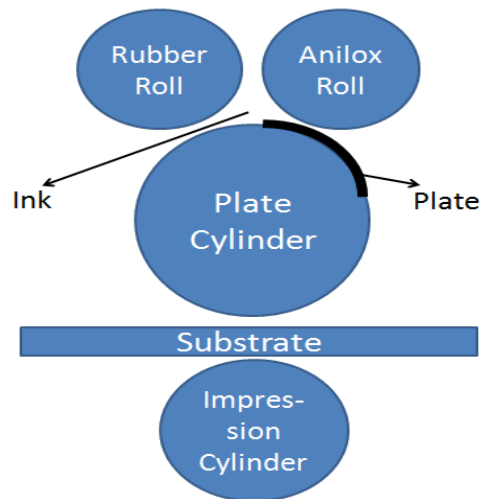


Figure 4.8 Flexographing [50]

4.4 Embroidery Based Fabrication

Textile is the main source of clothing that is used to convey a sense of the wearer's identity provides protection from the environment and supplies a convenient way to carry all the paraphernalia of daily life. The woven structure of textiles and spun fibers makes them durable, washable, and conformal while their composite nature affords tremendous variety in their texture, for both visual and tactile senses. In embroidery based fabrication, conductive threads are used for electric connectivity. Several flexible conductive materials have been introduced in literature, including fibers having polymer cores and metallic coatings, yarns bundled with thin metal laments and yarns/fabrics embedded with carbon Nano-tubes [30] [62]. Conductive thread can carry current in the same way as the wires do, hence; it can be used to create an electronic circuit. This allows the user to sew a circuit together, creating flexible circuits that require no soldering. In some textile-based applications, this is the most practical tool to maintain the hang of the fabric, as well as educationally, it is a very safe and intimidating way of fabrication. For such fabrication, sophisticated sewing machines are used [63].

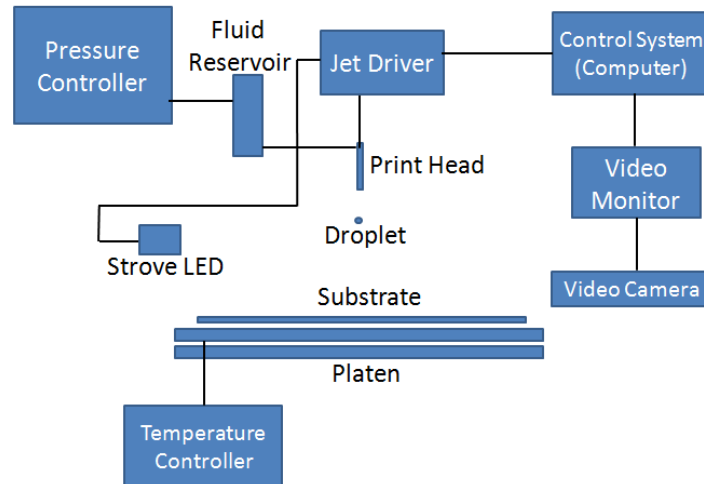


Figure 4.9 Inkjet Printing [50]

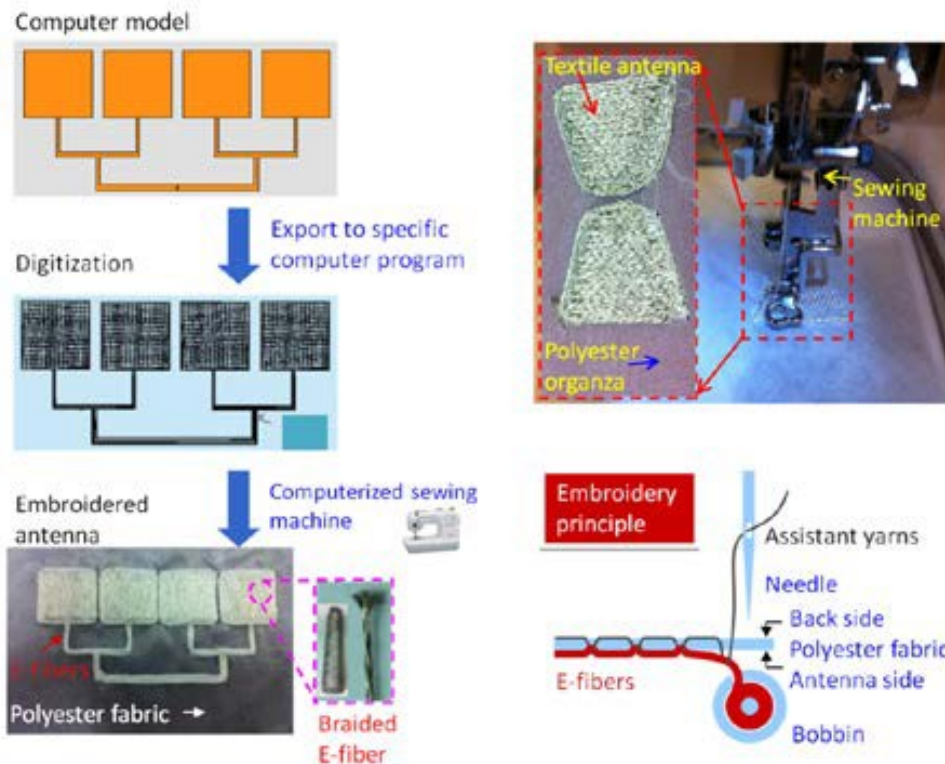


Figure 4.10 Fabrication of Embroidered Textile Surface [53]

There are variety of sewing machine that can be used for this purpose [64] [63]. Some of them are:

- Brother Domestic Embroidery Machine line: This machine work best for conductive thread but often creating a break in the thread [65].
- Brother Entrepreneur PR-650: It works well because it accepts the metallic novelty thread needle whereas the professional machine does not have such a functionality [65].
- Brother Industrial Machine: This machine work best for the conductive thread in comparisons with other industrial machines [65].

Embroidery process was adopted for the E-fibers using a computerized sewing machine. As shown in Figure 4.10, antenna and circuit designs were translated into embroidery patterns, followed by digitization of the stitching locations. E-fibers were precisely and firmly couched onto only one side of the textiles [65]. As such, possible abrasion damage of the metallic fiber coatings is avoided since the E-fibers did not go through the textile. To explore E-fiber viability in constructing multilayer RF circuits, a process for multilayer micro-strip circuit structure was also developed using pins made by E-fibers. The embroidery process was tailored to achieve high conductivity of the E-fiber textile surfaces. Initially, 332 strands of E-fibers were bundled to form thicker threads [30].

Concurrently, double-layer embroidery was employed to apply a second layer of E-fiber surface atop the first one to form the conductive patterns [66]. The resultant physical discontinuities in the embroidered surface was minimized. This type of fabrication can be deployed in a variety of ways. They can enable many different interior decorating, furniture and architectural applications as well as they have wearable applications but constraints exist regarding power requirements and potential discomfort associated with resistive heating.

Embroidery based Fabrication is a hot research topic where mature work has been done so far to provide more advanced features based research in this field of science. For example, in [67], authors discussed antenna designs focusing on aesthetic qualities relating to geometry and shaping based on this technology. In [68], the author proposed logo-shaped antenna using embroidered E-threads. Similarly, in [62], an embroidery tag antenna is designed, with electromagnetic simulators we can treat the complex embroidery pattern as a uniform conductive material layer when the pattern is sewed densely.

5. MATERIALS AND METHODS

In this chapter, every component, materials and methods used for the fabrication and measurements of the tags is explained in detail.

5.1 Measurement Tools

This measurement was conducted with two of the RF measurement tools, one is the measurement cabinet for the measurement and analysis of the tag and other is the reader to analyze the performance of the tags in terms of read ranges in UHF range. All the measurements are done in dry and moist phases of each of the fabricated tag.

5.1.1 RFID Measurement Cabinet

To measure and analyze RFID tags parameters in a suitable way, anechoic measurement chamber is used. It is the product of a Finnish company Voyantic, based in Helsinki. Anechoic chamber absorbs the radiation by means of the Radiation Absorbent Material (RAM) to provide the space, which is independent from echo and reflection. However, in the large anechoic chamber, testing of aircraft can also be accomplished [69] [70].

Tagformance Anechoic measurement chamber as appeared in Figure 5.1 is an economical anechoic chamber, which contains discretionary functionalities of automatic tag rotation of objects with a maximum mass of 10 kg utilizing its software, to watch the radiation pattern and affects as a result of various orientation on the execution of RFID tags. External measurements of the chamber are 120 x 80 x 80 cm, RFID chamber contains following [69].

- Quick Release Antenna with the capability to alter polarization up to 90 degrees.
- Standard Patch or Wideband Antenna for the UHF.
- RF cables and Directional Couplers.
- Shielding Effectiveness up to 90dB.



Figure 5.1 Voyantic Anechoic Chamber for Tagformance [57]

5.1.2 Tag Reader (Tagformance Pro)

Tags performance for specific parameters and ranges especially the read range is measured by the reader, Tagformance Pro, manufactured by a Finnish company Voyantic. Tagformance Pro system consists of a Tagformance Pro measurement device, one or more software packages, and accessories that complete the system [71]. It is used to verify tuning and sensitivity of RFID and NFC tags, study the effects of materials, orientation and tag proximity, define optimal tagging methods, benchmark tags, optimize RFID installations, analyze tag memory and chip performance and analyze and grade performance of tagged item. It is very well compatible with measuring cabinet and its relative measurement kit. Moreover, it is a measurement device for RAIN RFID, HF RFID and NFC as a whole [71]. Voyantic Tagformance Pro is shown in Figure 5.2.



Figure 5.2 Voyantic Tagformance Pro Reader [58]

5.1.3 Sewing Machine

The process by which the tags are fabricated is by the process of sewing. In order to sew the substrates, a common domestic modern sewing machine is used. Specifically, the sewing machine as shown in Figure 5.3, used here for the purpose of fabrication is named



Figure 5.3 Husqvarna Viking Sewing Machine [72]

as Husqvarna Viking which has a special edition termed as Designer Ruby [72]. The manufacturer of the company is the Swedish Company based in Husqvarna, Sweden.

5.1.4 Measuring Balance

To measure the mass of Tags at different phases of experimentation is required in the whole methodology. In order to measure the mass, a measuring electronic balance with Capacity of 120 g and Readability of 0.1 mg / 0.0001 g is used. The said balance is Sartorius ED1245 as shown in Figure 5.4, manufactured by Sartorius, which is pharmaceutical, and laboratory equipment supplier [73].



Figure 5.4 Sartorius Measuring Balance [73]

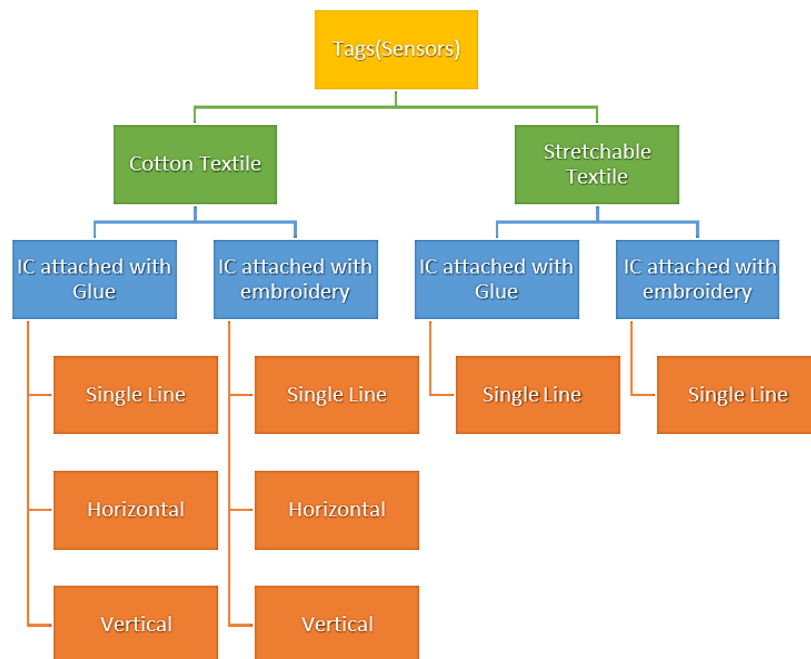


Figure 5.5 Classification of Tags (Sensors)

5.2 Fabrication of RFID TAGS

RFID tags are basic components of any RFID system; they are also basic sensor for all of the measurements. In our case, as tags are used to evaluate the effect of moisture/humidity on them, it is quite important to study tags resistance to the environmental parameters. In order to keep high performance, their wearable capability and to allow them working in the perfect way, when exposed to the moisture, selection of the tags, substrate and their fabrication technique is quite significant decision [74].

For the high performance of RFID tag under the influence of the moisture and under the standard of IEEE 802.15 for the body area networks, the UHF frequency band is chosen for the measurement [75]. Some advantages of UHF frequency band include transmitting more amount of energy via small size of antenna, capability to transmit signal to longer distance, utilization of single loop antenna and capability to nullify electronic noise [76]. The classification of the tags w.r.t the substrates selection and designs of embroidery is presented in the Figure 5.5.

5.2.1 Textile Substrates

Textile substrates used are of two types, which are different in nature and properties as shown in Figure 5.6. Cotton is one the two textile substrates, which are used here for the fabrication of the sensor. Cotton as shown in Figure 5.6 is organic in nature and natural cellulose fiber.

Table 5.1 Properties of Cotton [77]

<i>Specific Gravity</i>	<i>1.54</i>
<i>Elasticity</i>	relativity low
<i>Dielectric Constant</i>	3.9-7.5
<i>Resistivity</i>	order of 10^9 ohm/cm ³
<i>Moisture regain</i>	7-8% at standard conditions

The second type of textile used is the stretchable textile which is synthetic in nature and mixture of viscose and polyester. This fabric shown in Figure 5.6 is synthetic in nature, having characteristics like good absorbance, machine washable, excellent strength, stretchable, not easy to sew. [77]

The two used textiles for the fabrication of tags are different in nature and properties. Cotton is very less flexible than the stretchable one. In fact, the stretchable one is flexible in both directions while cotton cannot be stretched in any direction. Cotton is also thinner and weaker than the stretchable fiber. Moreover, cotton very easier to handle and sew than the stretchable textile. It is easy to sew many designs on cotton while it is very difficult to handle the stretchable textile on the sewing machine, making it limited for the embroidery designs to sew on it.

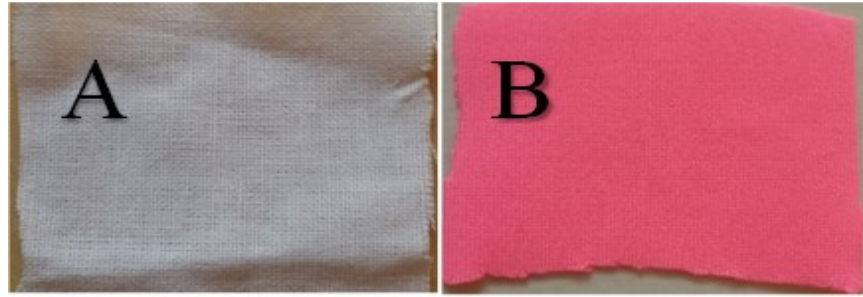


Figure 5.6 Different Textile Substrates (A) Cotton Substrate in white color (B) Stretchable Substrate in Orange color

5.2.2 Embroidery Thread

As discussed before, the method used for fabrication of the tags is embroidery with the help of sewing machine and thread used for the method is of vital importance. The thread used for embroidery is multifilament silver plated thread (Shieldex multifilament thread 110/34 dtex 2-ply HC), which is 99% Silver [78].

The thread as shown in Figure 5.7, used for whole process is Silver, which is conductive in nature. The diameter of thread is approximately 0.16 mm. Important physical properties of Silver thread are given in Table 5.2.

Table 5.2 Electrical Properties of Shieldex Silver multifilament thread [79] [80] [81]

Resistivity ρ ($\Omega \cdot \text{m}$) at 20 °C	1.59×10^{-8}
Conductivity σ (S/m) at 20 °C	6.30×10^7
Temperature Coefficient (K^{-1})	0.0038
Linear Resistance/Meter (Ω/m)	< 500



Figure 5.7 Bundle (Cartridge) of Shieldex Silver multifilament thread

5.2.3 Embroidery Design

The fabrication process includes the embroidery with the help of sewing machine as discussed in section 5.1.3. The embroidery includes three different designs of sewing for the cotton substrate and one embroidery design for the stretchable substrate as shown in Figure 5.9. Since due to very flexible nature of the stretchable, it is difficult to sew such substrate, which limits it to one embroidery design as discussed in section 5.2.1 and Figure 5.5. It should be noted here that single line embroidery is very less dense, while vertical and horizontal embroidery designs are very dense as it can be seen in Figure 5.9.

Tag Dimensions

Dimensions of tags are given below in Tables 5.3a and 5.3b along with diagrams in Figure 5.8 for cotton and stretchable tags respectively.

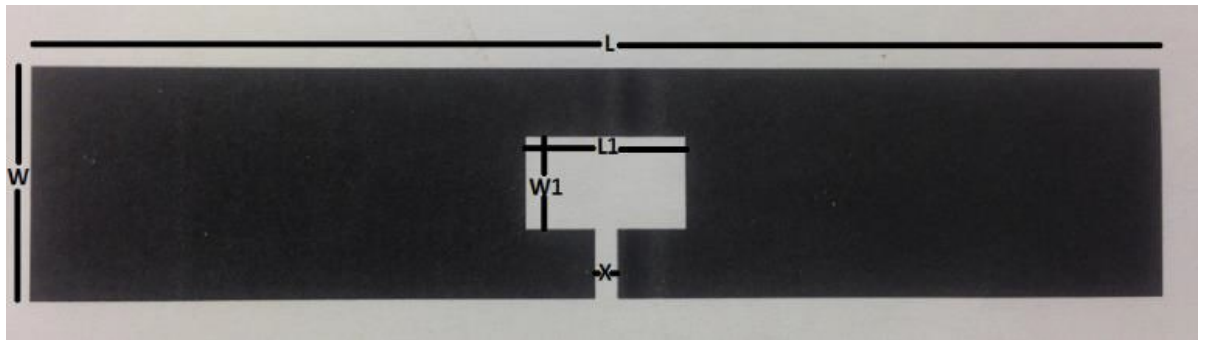


Figure 5.8 Tag Dimensions

Table 5.3 Cotton Tag Dimensions

Parameter	L	W	W1	L1	X
Value (mm)	100	20	14.3	8.125	2

Table 5.4 Stretchable Tag Dimension

Parameter	L	W	W1	L1	X
Value (mm)	105	20	14.3	8.125	2

It should be noted from the tables mentioned above; that the length L for the cotton tag is 100 mm and for the stretchable tag is 105 mm. It is because the stretchable tag is very flexible and it is very difficult to handle the substrate during the sewing embroidery. Hence, the length L is more in stretchable tags than the cotton tags to deal with the sewing fabrication more conveniently

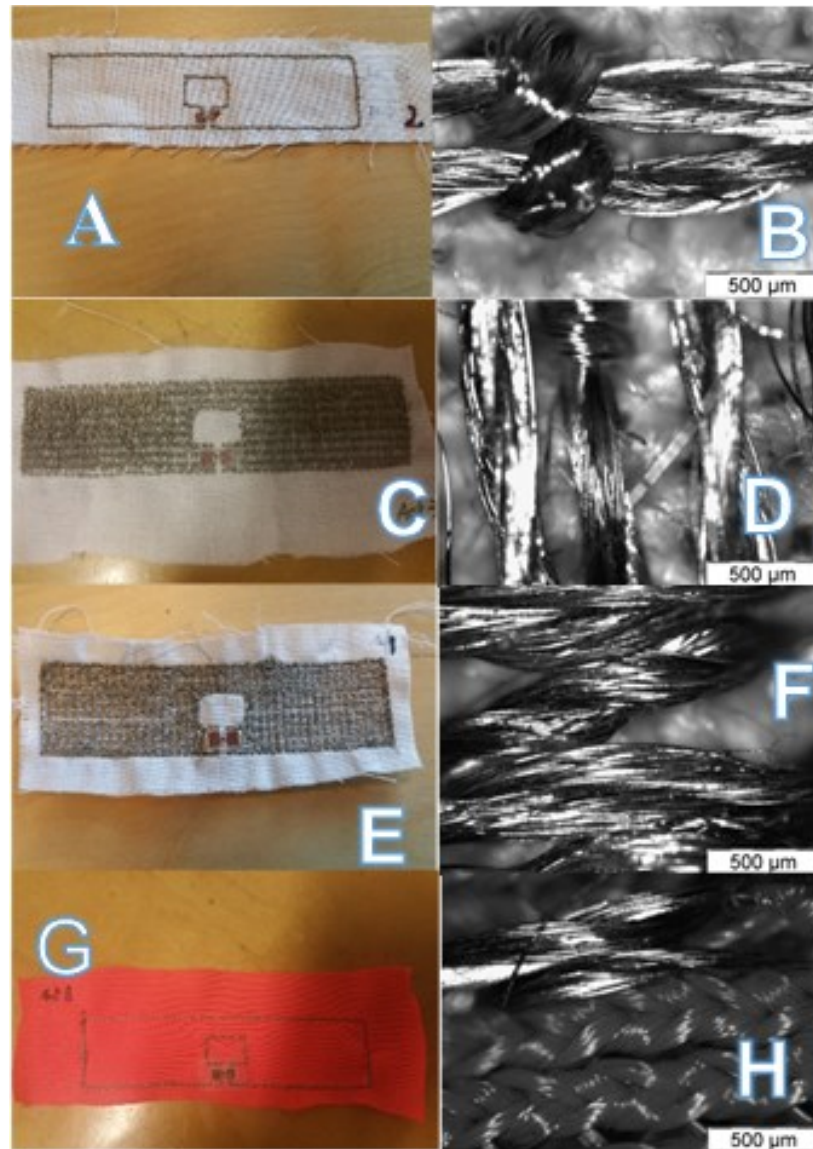


Figure 5.9 Embroidery Designs on cotton and stretchable substrate (A) Cotton substrate with single-line embroidery (B) Microscopic vision of single-line embroidery silver thread and cotton substrate (C) Cotton substrate with Vertical embroidery (D) Microscopic vision of Vertical silver thread embroidery and cotton substrate (E) Cotton substrate with Horizontal embroidery (F) Microscopic vision of Horizontal silver thread embroidery and cotton substrate (G) Stretchable substrate with single-line embroidery (H) Microscopic vision of single-line embroidery silver thread and stretchable substrate

5.2.4 Methods of IC Attachment

The whole process includes the attachment of IC microchip on the embroidered substrates of cotton and stretchable respectively. In order to attach ICs on the embroidered textile substrates, two methods are used. One method used here to attach the IC is with the conductive epoxy glue as shown in Figure 5.10. Other method used in the process is to attach the IC with the silver thread by the method of delicate sewing as shown in Figure 5.11.

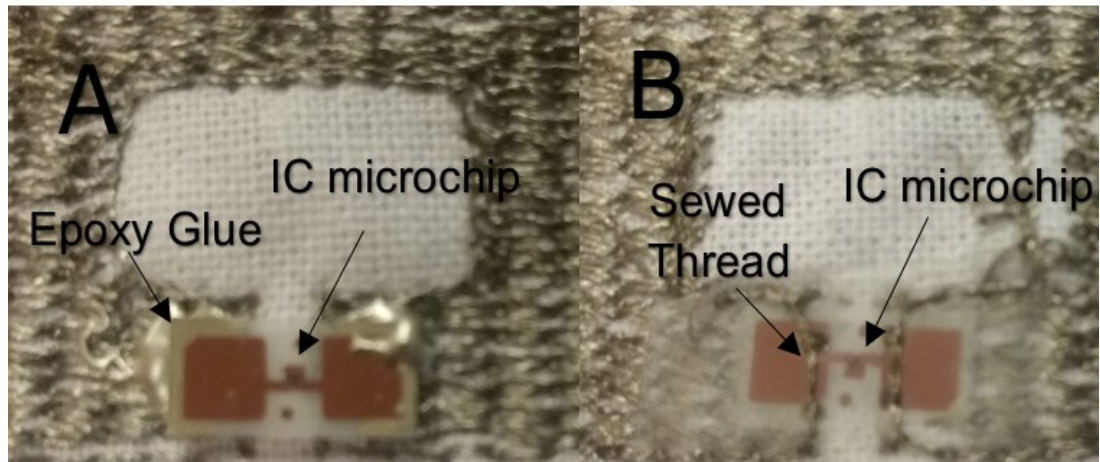


Figure 5.10 Methods of attaching IC on cotton embroidered substrate (A) Conductive Epoxy Glue (B) Delicate Sewing

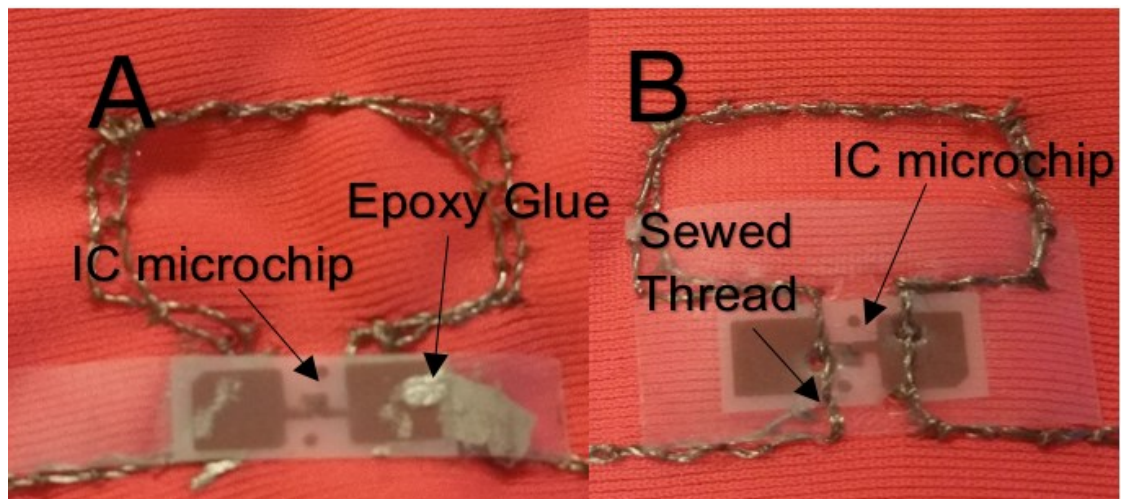


Figure 5.11 Methods of attaching IC on stretchable embroidered substrate (A) Conductive Epoxy Glue (B) Delicate Sewing

5.2.5 Fabricated Tags (Moisture Sensors)

The entire fabrication of tags includes,

- Selection of Substrates (Cotton and Stretchable)
- Embroidery on the substrates of various designs using the sewing machine
- Attaching the Microchip on the embroidered antennas

The steps mentioned results in the formation of Tags that are supposed to be the humidity sensor. They were initially tested and will be discussed in Chapter 6, as well as their performance was evaluated as hydrated sensors and will be discussed in Chapter 7. After successful fabrication of the tags, performance of all tags is examined and the best ones are chosen. There were about two to three tags for each design are manufactured and some are not working and some are not well manufactured. After going through the performance of the tags eight tags; six tags on cotton substrate and two tags on stretchable substrate, are carefully chosen to work as the humidity or moisture sensors as shown in the hierarchy in the Figure 5.5.

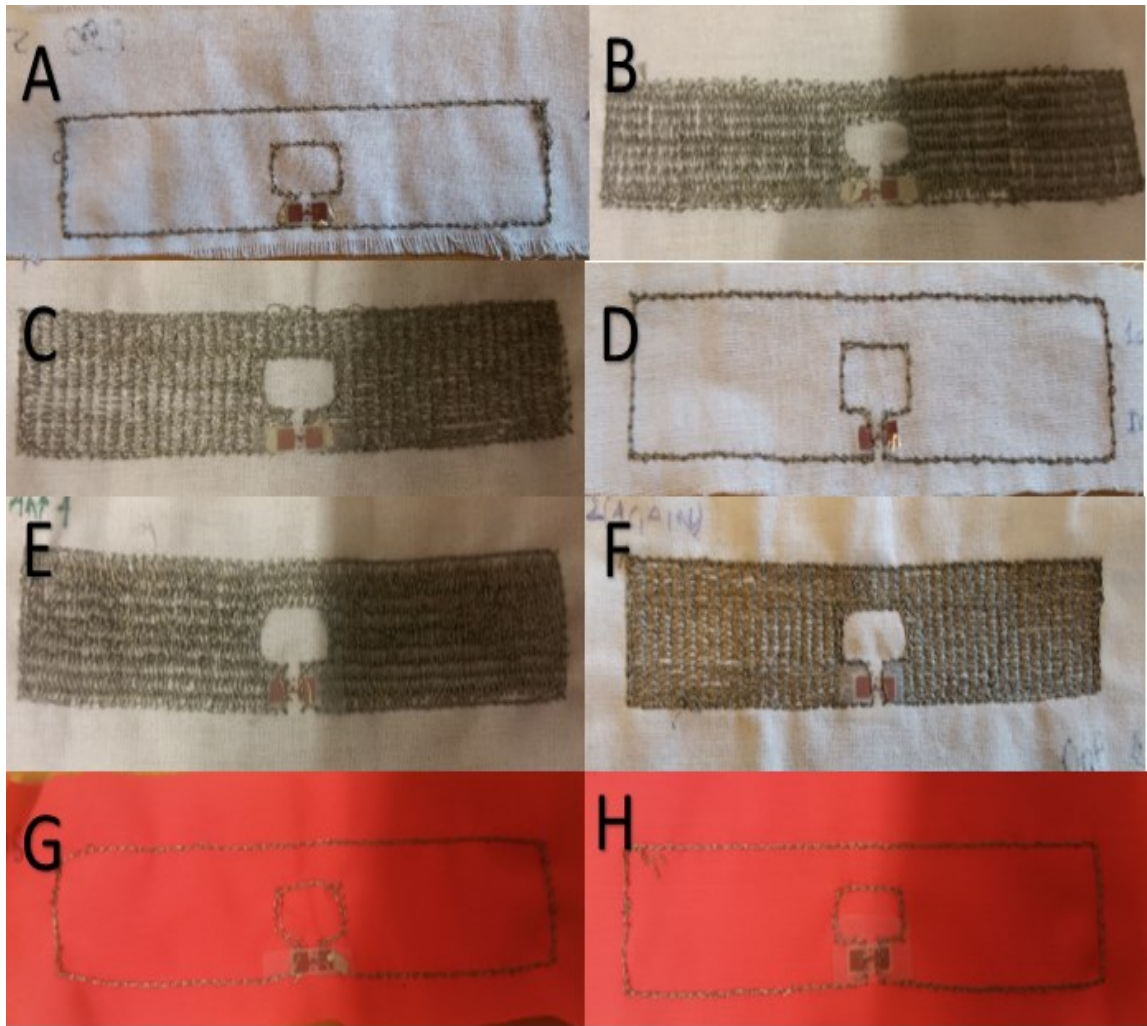


Figure 5.12 Fabricated Tags (Sensors) (A) Single line embroidered tag with IC attached with epoxy glue on cotton (B) Vertical embroidered tag with IC attached with epoxy glue on cotton (C) Horizontal embroidered tag with IC attached with epoxy glue on cotton (D) Single line embroidered tag with IC attached with sewing thread on cotton (E) Vertical embroidered tag with IC attached with sewing thread on cotton (F) Horizontal embroidered tag with IC attached with sewing thread on cotton (G) Single line embroidered tag with IC attached with epoxy glue on stretchable substrate (H) Single line embroidered tag with IC attached with sewing thread on stretchable substrate

The real-time fabricated tags as the UHF RFID sensors, which are selected to be the best tags out of all the fabricated ones are shown in Figure 5.12. Moreover, as it is mentioned earlier in this chapter that convenience to sew is the vital reason that limits the stretchable tags to only single line designs of embroidery as they are quite difficult to handle.

6. MEASUREMENTS

In order to evaluate the performance of all RFID tags in details, with the respect of the effect of humidity level on the tags, RF measurements for the required parameters on the fabricated passive RFID tags are performed. The sum of all measurements provides us sufficient details to get the conclusive relation between the performance of RFID tags with the initial performance, checking the effect of moisture and humidity level. It must be mentioned here again that 5 to 8 tags of each type with different substrate and different embroidery pattern are fabricated and best of them are selected after initial read range readings to perform moisture test on them.

Tags are examined using Tagformance for preliminary parametric analysis, which helped in getting better impression and working information of tags. After that, the initial weight of the tags is determined using the balance mentioned in chapter 5, which then are exposed to the moisture and analyzed again and in the end their performance is finally measured and analyzed when they are dried from the moisture.

6.1 Initial Results (Read Range)

Using the Tagformance Pro reader system including closed chamber and tag reader, read range of each of the fabricated RFID tag is measured; read range of each tag provides us strong idea about peak frequencies where the tag is working at the particular maximum peak read range and about the maximum possible spectral range. Read range R_{tag} of RFID tag is specified by:

$$R_{tag} = \frac{\lambda}{4\pi} \sqrt{\frac{EIRP}{P_{tag}}}$$

In the equation given above, $EIRP$ = equivalent isotropic radiated power transmitted by the antenna, P_{tag} = tag sensitivity and λ = wavelength.

To calculate R_{tag} at a specific frequency, we can get the value of $EIRP$ and P_{tag} by reader, value of λ can be calculated by the inverse of frequency. The results mentioned in the study case are correspondent to $EIRP = 3.28$ W, which is the emission limit in Europe [82]. Hence, theoretically by putting all of values in the above equation we calculate read range of the RFID tag at a specific frequency [83]. Tagformance RF chamber is used to measure the read ranges of RFID tags, read-range is examined by aggregating the power of the RFID tag and analyzing received power. Read range is measured between 800 MHz to 1000 MHz of UHF spectrum as shown in Figure 6.1 and Figure 6.2.

The Read Ranges vs Frequency plot of cotton RFID Tags is shown in Figure 6.1. The maximum read range is achieved by single-line glued of 8 m between 890 MHz and 900 MHz. Others have maximum read range from 5 m to 7 m at around 970 MHz. The Read Ranges vs Frequency plot of stretchable RFID Tags is shown in Figure 6.2. Between 940 MHz and 950 MHz the maximum read range of almost 8 m for single line glued tag. In case of single line embroidered tag, the maximum read range is 7.3 m between 910 MHz and 930 MHz.

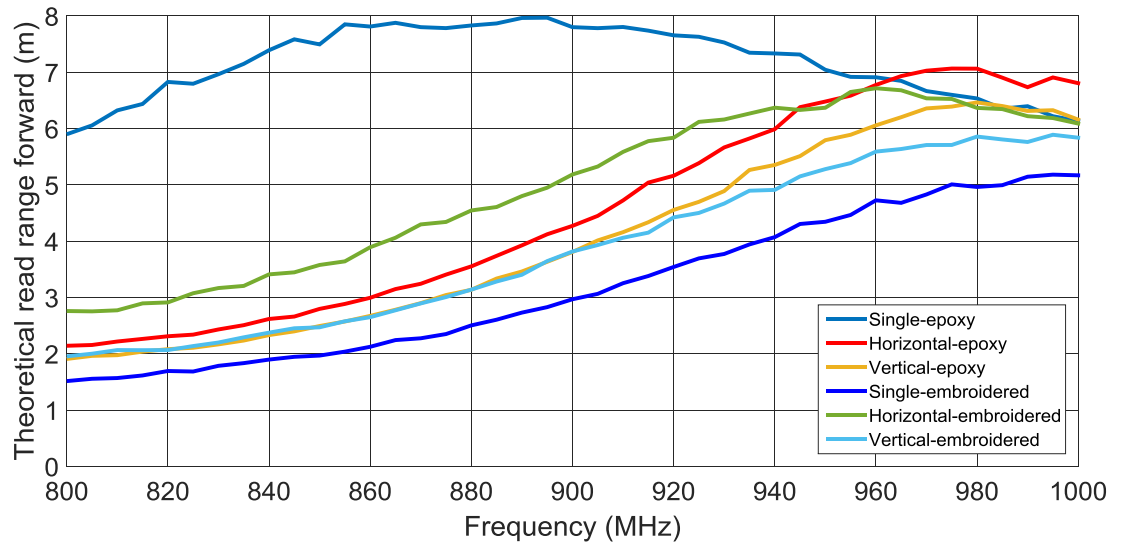


Figure 6.1 Initial Read Ranges of the Cotton RFID tags

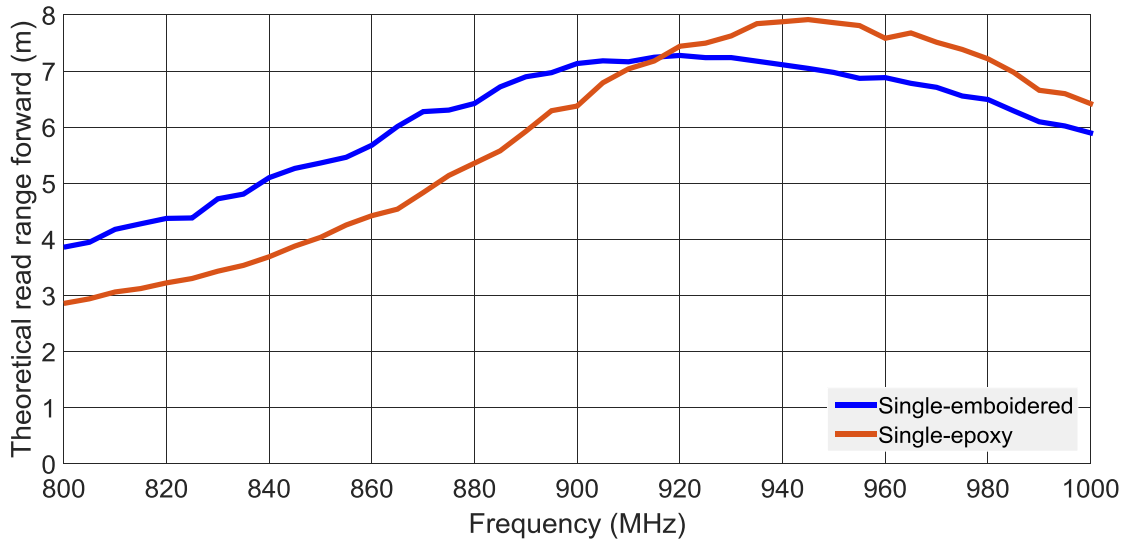


Figure 6.2 Initial Read Ranges of the Stretchable RFID tags

6.2 Moisture/Humidity Testing and Evaluation

The initial Read Ranges of the fabricated tags leads to the final phase of the experiment. The phase is to evaluate the performance of the RFID tags to check the effect of moisture/humidity on them. In order to do the humidity evaluation and experimentation on the fabricated RFID tags to make them work as humidity sensors, all the RFID tags are very well exposed to the moisture using the spray bottle. A very considerable amount of water is sprayed on each tag to be tested via the water spray bottle. After making the Tags moist, their performance is evaluated in the Tagformance closed chamber. After getting the read ranges of the moist RFID tags, the final step is to make them dry. Since, all the experiment is done in the room temperature, the moist tags are dried for almost 48 hours. After the mentioned time for the RFID tags to be dried up, their performance is

evaluated in the Tagformance closed chamber for the last time. Hence, the experimentation and the evaluation of the RFID tags in three phases (Initial, Moist, and Dry) leads them to work as the humidity sensors.

6.2.1 Effect of Moisture on Read Range of Cotton RFID Tags

As discussed in chapter 5, there are six RFID tags, which are fabricated on cotton fabric. All these RFID fabricated/embroidered tags are evaluated in terms of their performance in three phases as discussed earlier. In the whole process, the most vital part along with the evaluation of the performance is to measure the weight of the tags. So, a measuring balance as mentioned in chapter 5 is used to measure the weight of the tags. In order to check the effect of humidity on cotton RFID tags, the moisture absorbed by the tags and the amount of weight increased by the moisture is of great importance. Table 6.1 shows the initial weight of the tags and the percentage of increment after the tags are exposed to the moisture. It can be seen from the table 6.1 that the RFID cotton tags are so well exposed to the humidity/moisture that the weight of moist tags is more than the initial weight of the tags.

Table 6.1 Tags weight in different phases of cotton tags

Tags (Sensors)	Initial Weight of Tags (g)	Weight of Moist Tags (g)	Difference (g)	% increase of weight
<i>IC Attached with Sewing-Single Line</i>	0.6647	1.4392	0.7743	116%
<i>IC Attached with Sewing-Vertical</i>	1.2269	3.1762	1.9493	145%
<i>IC Attached with Sewing-Horizontal</i>	1.2545	2.5517	1.2972	103%
<i>IC Attached with Glue-Single Line</i>	1.1413	2.3964	1.2551	110%
<i>IC Attached with Glue-Vertical</i>	1.7437	3.5923	1.8486	106%
<i>IC Attached with Glue-Horizontal</i>	1.3505	2.7784	1.4279	105%

Since, all the cotton RFID tags are different w.r.t the embroidery designs and the ways of attaching the IC. Hence, different response to the moisture can be observed. Especially, the response can easily be differentiated in terms of less dense (single line embroidery) and more dense (Vertical and horizontal embroidery). Each plot for cotton RFID tags contains the read ranges of initial, moist and dry phases against the frequency from 800 MHz to 1000 MHz.

Figure 6.3, Figure 6.4 and Figure 6.5 represents the plots where IC is glued on the tag for single line embroidered, vertical embroidered and horizontal embroidered respectively.

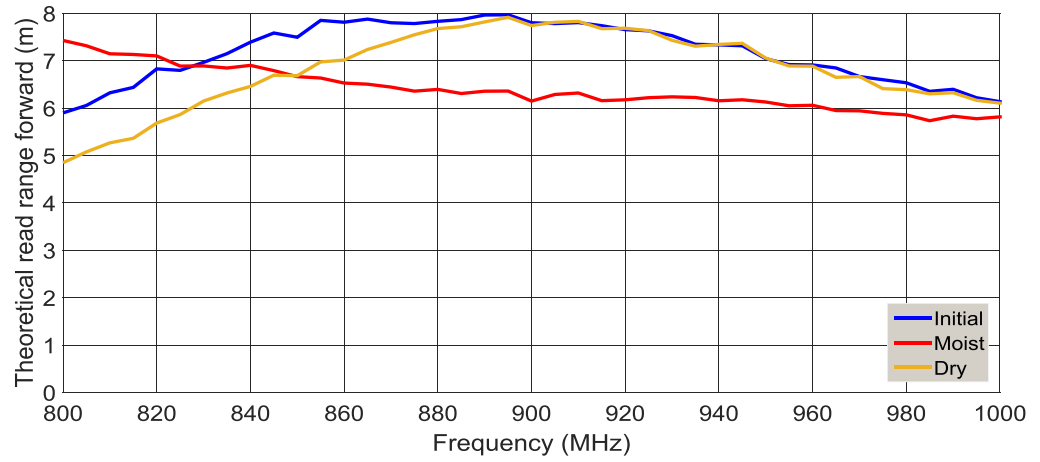


Figure 6.3 Effect of moisture on Cotton Single line embroidered RFID tag with glued IC

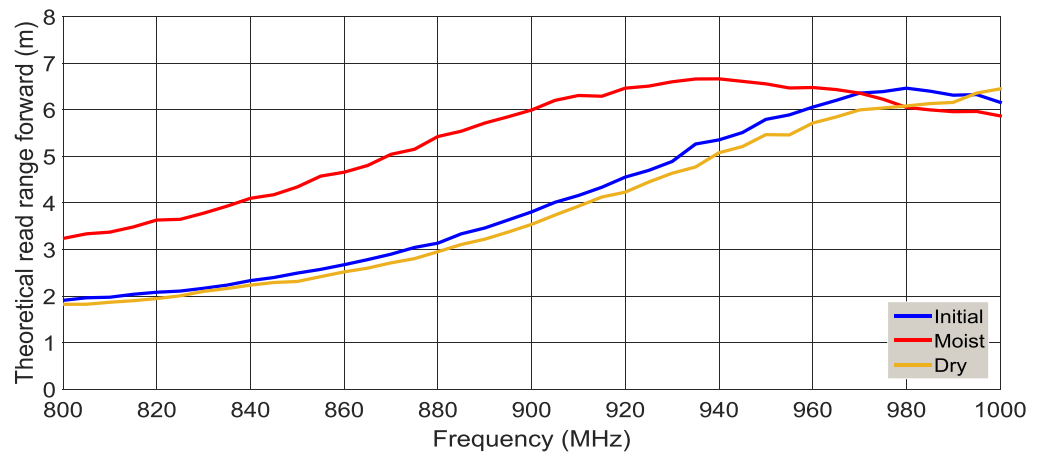


Figure 6.4 Effect of moisture on Cotton Vertical embroidered RFID tag with glued IC

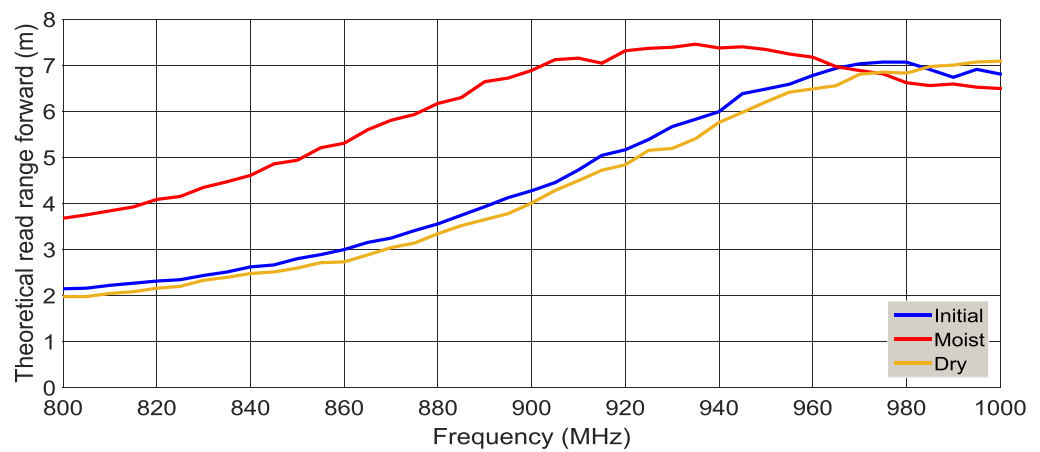


Figure 6.5 Effect of moisture on Cotton Horizontal embroidered RFID tag with glued IC

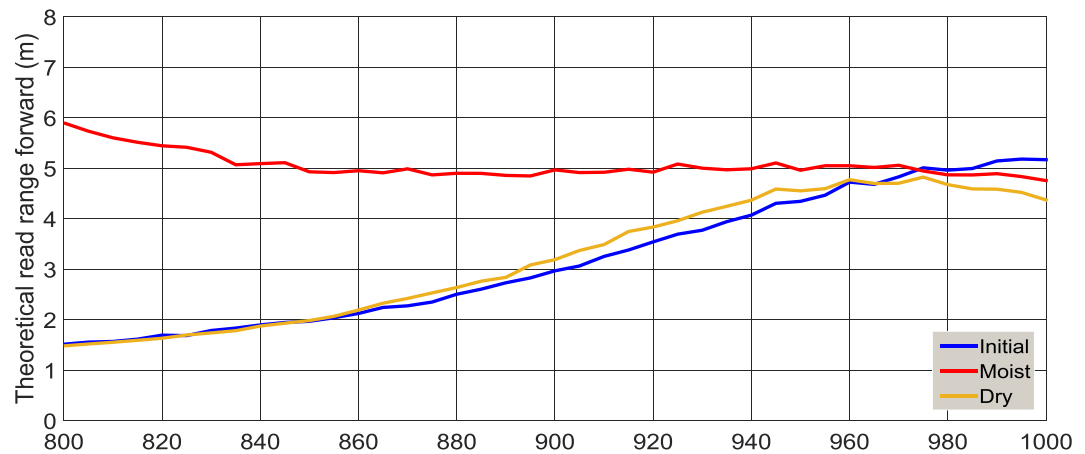


Figure 6.6 Effect of moisture on Cotton Single line embroidered RFID tag with sewn IC

It can be seen in the Figure 6.3 that at 800 MHz, the difference between the initial and moist plots lines is a slightly more than those in Figure 6.4 and Figure 6.5. It is because the threads in the less dense tag is more exposed to the moisture than those in dense embroidered tags and hence are more affected by the moisture. It leads to shift the frequency more backwards. Because of this reason the read range for the moist plot is quite less than the initial and the dry plots in single line embroidered than later two graphs. Moreover, after the tags get dried, the maximum read range is approximately approaching the initial maximum read ranges in all three designs for IC glued tags making them to work as the humidity/moisture sensors.

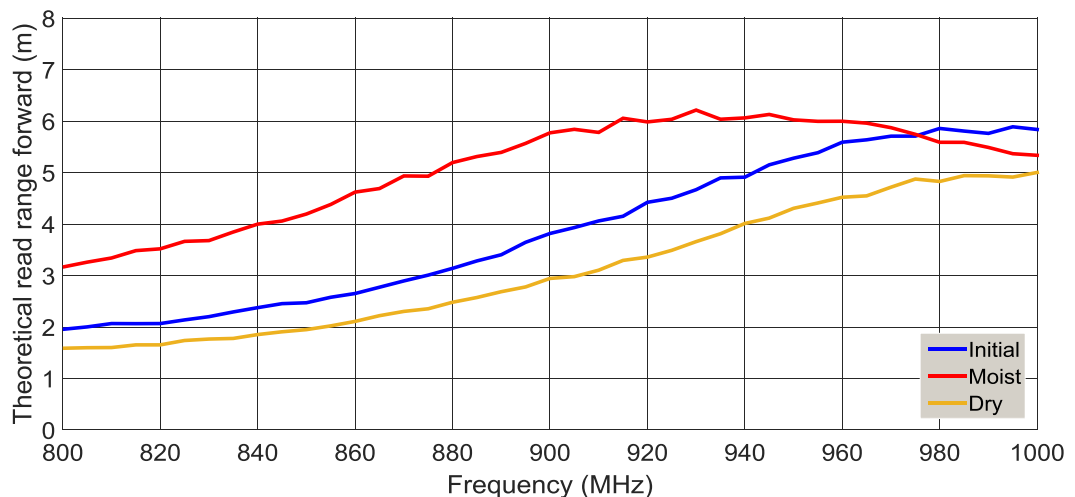


Figure 6.7 Effect of moisture on Cotton Vertical embroidered RFID tag with sewn IC

The plots where IC is sewn on the tag for single line embroidered, vertical embroidered and horizontal embroidered are shown in Figure 6.6, Figure 6.7 and Figure 6.8 respectively.

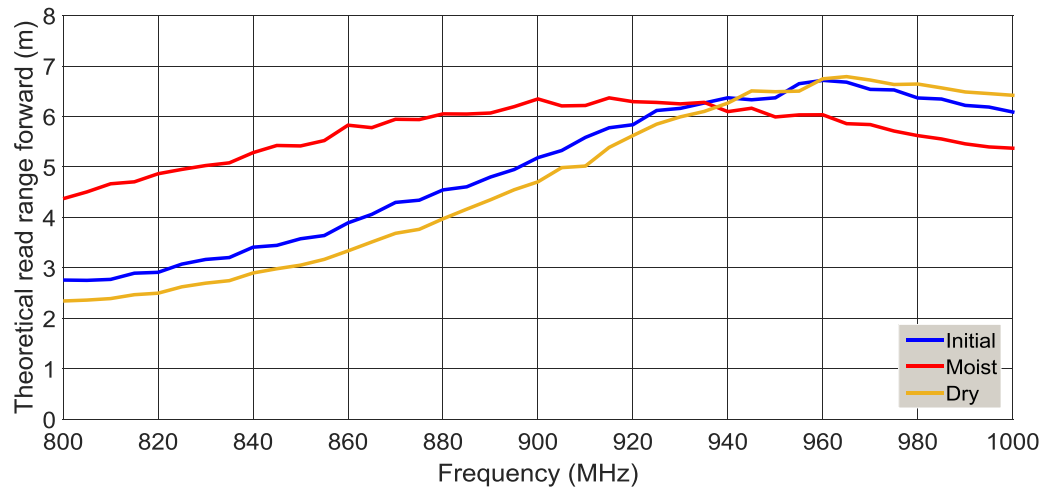


Figure 6.8 Effect of moisture on Cotton Horizontal embroidered RFID tag with sewn IC

It can be seen in the in Figure 6.6 that at 800 MHz, the difference between the initial and moist plots lines is far more than those in Figure 6.7 and Figure 6.8. The reason is same as discussed before that the single line embroidered is very less dense threaded than vertical and horizontal embroidered tags which may let some threads in dense embroidered tags less moist which leads them to be less effected by the moisture. In addition, the maximum read ranges for the moist plot in later three figures is slightly more than the initial maximum read ranges and for dried plots, the maximum read ranges is less or slightly less than the initial read ranges and for the dried tags the plots approaching the initial read range trend.

It must be mentioned here again that the all the six cotton tags are all different from each other so each has different read ranges in all three phases but trend for the moist plot is same as frequency is shifting more backwards in the single line embroidered tags.

6.2.2 Effect of Moisture on Read Range of Stretchable RFID Tags

For the stretchable substrate RFID tags, there are two tags fabricated as discussed before. Table 6.2 shows their weight and measurements on the measuring balance during the initial and the moist phases. It can be seen in the table that the tags are very well exposed to the moisture/water that the percentage of their increase of initial weight indicates the moist tags weight is double than the initial weight of the tags likewise cotton RFID tags.

Table 6.2 Tags weight in Different phases of stretchable tags

Tags (Sensors)	Initial Weight of Tags (g)	Weight of Moist Tags (g)	Difference (g)	% increase of weight
IC Attached with Sewing-Single Line	1.4979	3.0652	1.5673	104%
IC Attached with Glue-Single Line	1.2027	2.7431	1.5404	128%

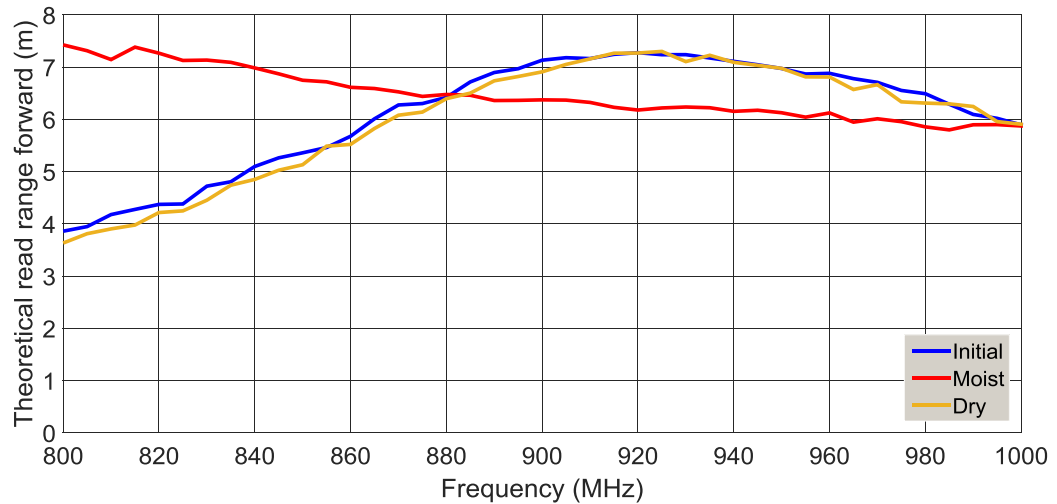


Figure 6.9 Effect of moisture on Stretchable Single line embroidered RFID tag with sewn IC

Since, both stretchable tags are less dense embroidered RFID tags i.e. they have single line embroidery on them, which leads them to be exposed and reacted very well to the water or moisture. The final plot for the stretchable RFID tags on which IC is attached with the help of sewing method is shown in Figure 6.9 and Figure 6.10 shows the plot for the RFID Stretchable tag where IC is glued on the antenna.

It can be seen from both the figures that the maximum read range is approximately equal to the maximum initial read range but it is slightly decreasing with the increase of frequency from 800 MHz to 1000 MHz. In addition, the dry plot in green in both figures is showing the read range along mentioned frequency, which is also quite same as the initial read range plot. It means that the tags are working very similar after being dried up to the raw form of the RFID tags. Hence, keeping in view the performance, these tags work very well as the moisture sensors.

The most vital point to be noted here from the figures is that the difference of read ranges between the initial and the moist at 800 MHz is quite notably big. It is because of the reason that both tags are less dense and the conductive threads on them are very well exposed to the water making them more conductive and shifting the frequency more backwards in the moist condition. Hence, in the initial and the dry stages, the frequency plots are same and restored with the same peak read ranges but, moist condition can be distinguished from the other two phases of the tags.

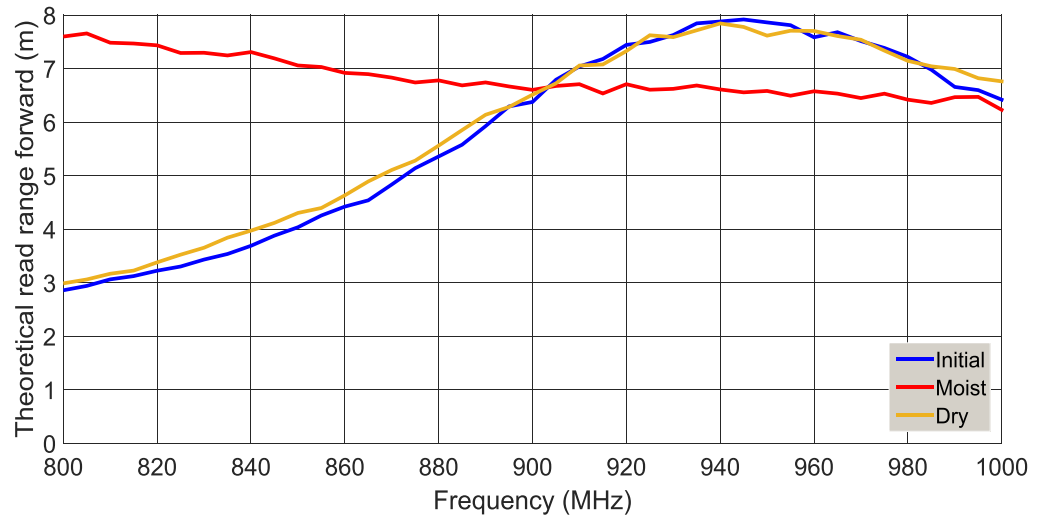


Figure 6.10 Effect of moisture on Stretchable Single line embroidered RFID tag with glued IC

6.3 Discussion and Analysis

The results of the study case describes about in depth performance of RFID tags and their performance as the humidity/moisture sensors in specific. Since all the tags are different from each other in terms of their fabrication techniques and design, so their performance as a humidity sensor in UHF is also differentiating from each other in the Initial (raw), moist and the dry phases. As far as frequency shift is concerned, Figure 6.11 gives the general analysis of the performance the tags. The results show that all the tags when exposed to moisture, give the considerable amount of frequency shift. When the single line (less dense) sensors are exposed to the moisture, a big shift in the frequency is seen for both the cotton and stretchable sensors. However, the dense sensors give a less frequency shift when they are exposed to the moisture. Because, the dense tags are less wet when expose to the moisture as compared to the single line tags.

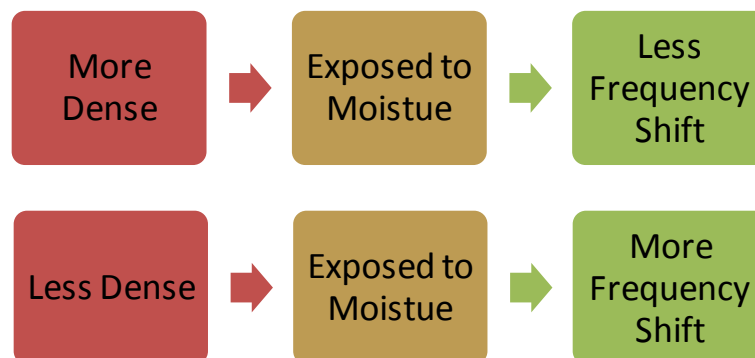


Figure 6.11 Analysis and evaluation of the moisture/humidity effect on the RFID tags

Table 6.3 *Frequencies of Fabricated Sensors on Peak Read Ranges*

Tags (Sensors)	Initial		Moist		Dry	
	Peak Fre- quency (MHz)	Peak Read Range (m)	Peak Fre- quency (MHz)	Peak Read Range (m)	Peak Fre- quency (MHz)	Peak Read Range (m)
IC Attached with Sewing-Single Line (Cotton)	990	5	810	5	970	4.8
IC Attached with Sewing-Vertical (Cotton)	980	5.8	930	6	990	5
IC Attached with Sewing-Horizontal (Cotton)	960	6.8	900	6.3	970	6.3
IC Attached with Glued-Single Line (Cotton)	890	8	800	6	890	8
IC Attached with Glued-Vertical (Cotton)	980	6	940	6.8	1000	6
IC Attached with Glued-Horizontal (Cotton)	980	7	940	7.5	990	7
IC Attached with Sewing-Single Line (Stretchable)	920	7	810	7.2	920	7
IC Attached with Glued-Single Line (Stretchable)	940	8	810	7	940	8

Table 6.3 shows the frequencies at their respective peak read ranges of each of the manufactured sensor. The peak read range varies from 5 m to 8 m in three stages of measurement. They are increased or decreased from 0.2 m to 0.8 m in some tags depending upon the moisture affecting the conductivity in the moist phase. When the tags gets dry, the peak read ranges is more less the same as that in the initial results. The same is can be observed in the case of frequency on the peak read range. However, there is a big difference in peak frequencies of initial and moist phases of each tag. This frequency shift is more in case of single line embroidered tags than the dense embroidered tags. The single line cotton sensor has peak frequency 810 MHz (Initial 990 MHz) and 800 MHz (Initial 890 MHz) for sewed IC and glued IC respectively in the moist condition. However, single stretchable tags for both sewn IC and glued IC shows the peak frequency of 810 MHz in

moist condition, whereas their initial peak frequencies are 920 MHz and 940 MHz respectively. The difference in peak frequencies between initial and moist stages for other tags ranges from 40 MHz to 50 MHz. Hence, addition of moisture gives them the big shift due to the increased conductivity. As a result, they can work as moisture sensors with an appreciable read range for a passive UHF tag. Hence, peak frequency is almost restoring to the initial value with almost the same peak read range in the dry phase for each of the tags so they can be used again.

The phenomenon arises through variations in humidity level around the sensor, as a water drop generates capacitance among themselves and RFID tag antenna, triggering an alteration in impedance, hence, affecting the performance.

Conclusively, it can be analyzed by the results given in Table 6.3 that cotton sensors show irregular behavior in terms of peak read ranges and frequency shifts. However, they have somehow restored to their initial phase when dried up but, peak read ranges and frequency shift is varying from sensor to sensor giving inconsistent behavior. Whereas, the stretchable sensors are showing a regular behavior as their peak read ranges and peak frequencies are restored to the same initial phase after they are dried up. Also, in wet conditions both parameters are also showing very regular change in both of the tags. Hence, stretchable sensors show promising and consistent results as compared to the cotton sensors. As far as wearable characteristic is concerned the polymer stretchable tags also show more convenience as compared to cotton sensors because they are stretchable.

7. CONCLUSION AND FUTURE WORK

In the study case, performance evaluation of the Passive RFID tags using two different types of textile fabrics (Cotton and Stretchable polymer) is done. Effect of water/moisture/humidity on the manufactured RFID tags is analyzed.

Different types of designed embroidery are used on both cotton and polymer stretchable textile fabrics giving the variety of sensors in respect of fabrication techniques. After analysis, they all work as the humidity/moisture sensors giving the very acceptable results of all the sensors as all of them restore to their initial frequency peaks after they dried up.

The performance of all the sensors is analyzed in three stages. First, in the raw form or the initial stage, second is in the moist form after the tags are exposed to the moisture and third and last stage is when the sensors are completely dried up.

Cotton sensors give results suitable but irregular results to analyze the moisture, as peak frequency in the moist phase is very different from initial and dry phases and it is varying from sensor to sensor as mentioned in Chapter 6, but they are quite easy to fabricate and less challenging.

On the other hand, one of the most stimulating effect examined in this study case is the performance of RFID tags fabricated using a stretchable textile. Since they are stretchable in nature, RFID tags fabricated on stretchable textiles give us very good read ranges and very good performance in all three stages than the cotton sensors as both the sensors a regular and consistent results but embroidery on such fabric is quite a challenge as it is stretchable.

The major goal and motivation behind the fabric and embroidered moisture sensors is to provide ease and comfort to the patient and the user. Cotton sensors are not stretchable whereas the stretchable are quite flexible in wearing. Using the sewing machine, the silver thread is sewn on the substrates in different designs. The thread used also make the tag unbreakable and can be folded in any direction. Therefore, they give better contact with the body and hence give better results to analyze.

Moreover, along with the medical applications, such moisture sensors can also be utilized for applications such as, moisture sensor in the soil and to detect very minute leakages from the water pipes or other hydration sources.

In the future, this method can be extended to different other textiles and different conductive threads as well as different embroidery designs which may lead to more variety of sensors and more application for users. Since, the main challenge in the study is fabrication method i.e. embroidery particularly in the case of stretchable substrate so, better embroidery techniques can be used to overcome the limitations on difficult textiles. However, effect of liquids other than water with different dielectric properties can be used in the future to evaluate the moisture effect.

Moreover, the method used in this study case, can be extended and used to make sensors to analyze different parameters of the body like blood pressure, heart rate etc., giving such sensors more extension for future studies techniques, research and development.

8. PUBLICATION(S)

“The Possibilities of Embroidered Passive UHF RFID Textile Tags as Wearable Moisture Sensors”, Dawood Shuaib, Leena Ukkonen, Johanna Virkki, Sari Merilampi, Tampere, IEEE Serious Games and Exhibition for Health, (IEEE SEGAH-2017), Perth, Australia

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