Tampere University

XIAOCHEN CHEN

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ACADEMIC DISSERTATION
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Supervisors	Johanna Virkki, Adj. Prof. Tampere University Finland	Leena Ukkonen, Prof. Tampere University Finland
Pre-examiners	Ahmad Hoorfar, Prof. Villanova University United States of America	Will Whittow, Dr. Loughborough University United Kingdom
Opponents	Hendrik Rogier, Prof. Ghent University Belgium	

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The Design, Fabrication and Practical Evaluation of Body-centric Passive RFID Platforms

Xiaochen Chen

Abstract

Passive ultra-high-frequency (UHF) radio-frequency identification (RFID) technology is increasingly being recognized as a compelling approach to utilizing energy- and cost-efficient wireless platforms for a wireless body area network (WBAN). The development of WBANs has stimulated a lot of research over recent years, as they can offer remarkable benefits for the healthcare and welfare sectors, as well as having innovative sports-related applications.

This thesis is to evaluate and develop the RFID tags used in an integrated wearable RFID platform working in a realistic environment. Each of the wearable antennas were specifically designed for a target part of the body, such as the back or the hand. The antennas were manufactured in different ways, using copper tape, electro-textiles (E-textile) and embroidered conductive threads. After they had been produced, the tags were subjected to on-body measurement and reliability tests. The reliability tests were performed under tough conditions in which the tags were stretched, for instance, or exposed to high humidity and washing. Our results show that the tags can perform well when worn on-body in a harsh environment.

This thesis provides several integrated solutions for wireless wearable devices. By different RFID antenna design and fabrication methods, the RFID tag can be used as the moisture and strain sensor with lightweight, small size, flexible pattern and great daily-use reliability.

Preface

This study was carried out in the Wireless Identification and Sensing Systems (WISE) Research Group at the BioMediTech Institute and the Faculty of Biomedical Sciences and Engineering at Tampere University of Technology (TUT) during the years 2016 to 2018. The research was funded by the Academy of Finland and the Nokia Foundation, whose financial support is gratefully acknowledged.

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I wish to thank all my friends for their support and encouragement. I would like to thank my dear Han He for all his support, kindness and encouragement during this thesis. Most of all, I would like to thank my parents for their unconditional love and constant support.

Tampere, August 2018

Chen Xiaochen

Contents

List of Symbols and Abbreviations

3D	3-Diamention
E-textile	Electro-textile
EPDM	Ethylene-propylene-diene-monomer
HF	High Frequency
HFSS	High Frequency Structure Simulator
IC	Integrated circuit
IoT	Internet of Things
LF	Low Frequency
RFID	Radio-frequency identification
UHF	Ultra-high-frequency
WBAN	Wireless body area network
MHMS	Mobile health-monitoring system

List of Publications

I. X. Chen, L. Ukkonen, and T. Björninen, Passive E-textile UHF RFID Based Wireless Strain Sensors with Integrated References, IEEE Sensors Journal, Vol. 16, No. 22, 2017, pp. 7835-7836.

II. X. Chen, A. Liu, Z. Wei, L. Ukkonen, and J. Virkki, Experimental Study on Strain Reliability of Embroidered Passive UHF RFID Textile Tag Antennas and Interconnections, Journal of Engineering, Vol. 2017, Article ID 8493405, 2017, 7p.

III. X. Chen, L. Ukkonen, and J. Virkki, Reliability Evaluation of Wearable Radio Frequency Identification Tags: Design and Fabrication of a Two-part Textile Antenna, Textile Research Journal, Published online before print, DOI: https://doi.org/10.1177/0040517517750651.

IV. X. Chen, S. Ma, L. Ukkonen, T. Björninen, and J. Virkki, Antennas and Antenna-Electronics Interfaces Made of Conductive Yarn and Paint for Cost-Effective Wearable RFIDs and Sensors, In Proceedings of IEEE International Microwave Symposium, 4-9 June 2017, Honolulu, HI, USA, 2017, pp. 827-830.

V. X. Chen, L. Ukkonen, T. Björninen, and J. Virkki, Comparison of E-textile Dipole and Folded Dipole Antennas for Wearable Passive UHF RFID Tags, In Proceedings of Electromagnetics Research Symposium, 19-22 November 2017, Singapore, 2017, pp. 812-817.

VI. X. Chen, H. He, Y. Lu, H. Lam, L. Ukkonen and J. Virkki, Fabrication and Reliability Evaluation of Passive UHF RFID T-shirts, In Proceedings of International Workshop on Antenna Technology, 5-7 March 2018, Nanjing, China, 2018, 4p.

VII. X. Chen, H. He, L. Ukkonen, and J. Virkki, Embroidered UHF RFID Moisture Sensor Tag on Dishcloth Substrate, In Proceedings of IEEE Antennas and Propagation Society Symposium on Antennas and Propagation, 8-13 July 2018, Boston, Massachusetts, USA, 2018, 2p.

VIII. X. Chen, H. He, J. Xu, T. Wang, L. Cheng, L. Ukkonen, and J. Virkki, Fabrication and Practical Evaluation of Glove-integrated Passive UHF RFID Tags, Accepted to IEEE International Conference on RFID Technology and Applications 2018.

IX. X. Chen, H. He, L. Ukkonen, J. Virkki, The Effects of Added Clothing Layers on the Performance of Wearable Electro-Textile UHF RFID Tags, In Proceedings of URSI Atlantic Radio Science Meeting, 28 May-1 June 2018, Gran Canaria, Spain, 2018, 4p.

1 Introduction

Passive ultra-high-frequency (UHF) radio-frequency identification (RFID) technology is increasingly being recognized as a compelling approach to utilizing energy- and cost-efficient wireless platforms for a wireless body area network (WBAN). The development of WBANs has stimulated a lot of research over recent years, as they can offer remarkable benefits for the healthcare and welfare sectors [SanA10] [Mar07] [Gro13] [Mer16] [Tso14], as well as having innovative sports-related applications [Tso14] [Sal10].

Traditionally, Low Frequency (LF) and High Frequency (HF) RFID systems have been used for on-body and implanted applications [Fis05] [Occ10] [Yan08]. In these frequency bands, although the signal can overcome the presence of human body-tissue, the systems are limited by their short ranges and very low data rates [ISO433] [ISO960] [ISO2.45]. By utilizing UHF RFID technology, comparable on-body sensing, measurement and identification can be achieved unobtrusively over longer distances and at higher data rates [Nam03] [Ali05] [Phi05]. An RFID tag can achieve some sensing functions simply by adding the required sensors, or it can be used as a self-sensing element to monitor a number of physiological parameters (stretching, moisture and temperature, etc.). One of the earliest examples of the successful application of this technology is presented in [Nil03]. In this study, several readers were combined with additional “reference RFID tags” to detect the location of target RFID tags in an indoor environment. Another study [Occ10] improved the human tracking system with wearable RFID sensor tags. A wearable RFID-enabled sensor node for continuous biomedical monitoring was investigated in [Yan08]. This sensor node can easily be used in real-time monitoring and medical monitoring applications. A pulse and temperature mobile health-monitoring system (MHMS) was introduced in [Wuy09]. Here it was shown that the target parameters can be measured and then transmitted to mobile devices using RFID technology. In [Pat16], it was shown that a wearable, passive-strain RFID sensor can be used for monitoring basic physiological activities such as breathing.

An RFID system typically has three parts: a host computer, an RFID reader and an RFID tag. This study focuses on the design and testing of the RFID tag antenna and antenna-IC interconnection.

There are three main categories of RFID tags; passive, semi-active and active tags. Passive tags do not need batteries, so they are longer-lasting and lighter than the other two types [Max05]. The tag's antenna plays an important role in sustaining the RFID's performance, especially its reading range [Hal06], so this was used as the target parameter for assessing the performance of the tags studied here.

Although the idea of pervasive wearable intelligence has many appealing applications, there are several challenges that have prevented it from gaining widespread acceptance. For example, the cost-efficiency and reliability of the tags need to be improved for commercial use. Regarding cost, for example, the price of the silver ink used in [Heh18] was 3.57 euros per gram, and as about 5g of ink was needed to fabricate each tag, at about 18 euros per tag, the costs would be prohibitive for commercial use. For textiles, the nickel-plated Less EMF Shieldit Super Fabric (Cat. #A1220) which was used in this thesis cost US $670 per roll (0.5 m x 30 m). Only about 0.02 m x 0.1 m material was needed to fabricate one antenna, so as the conductive thread only costs about one euro per gram, and as one contour dipole antenna requires less than 0.05 grams of thread, the cost of the materials needed to manufacture a tag is greatly reduced (about 0.1 euros for E-textile antenna and 0.05 euros for embroidered antenna apiece).

Wearable devices integrated into garments have to be washable, and they also have to withstand severe stretching and bending. Previous studies have examined this problem. A graphene-based RFID textile tag that was still readable after 100 harsh bending cycles was studied in [Akb16]. Unfortunately, the tag could not endure even the first stretching cycle, as cracks appeared on the printed antenna body after the first stretching test. In [Kel12] [Bjö14], plastic-coated RFID tags were tested in a washing machine, and the study showed that the tags' reading ranges were clearly attenuated by the washing cycles. Besides the problem of washing the garments, the tags often have Integrated Circuits (IC), which can even be affected by human sweat.

Thus, the design of the tags is crucial. In [Man12] [Toi13] and [Rak14], all of the tag designs had problems arising from either the failure of the IC or practical interconnection problems. [Kio14] introduced a stretchable E-fiber antenna working at 915 MHz using a wire to connect to the signal source. In this case, the IC attachment technique still had a reliability problem. Furthermore, an E-textile patch antenna on a cotton fabric substrate suffered from a notable shift in its operational frequency due to moisture [Her10]. So, none of the clothing-integrated RFID tags so far reported in the literature are robust enough for everyday use. There are also challenges in designing a passive RFID antenna that can work on the human body. The dielectric properties of the human body have notable effects on electrical conductivity and polarizability, so an antennas' radiation performance is reduced because some of its energy is dissipated through the interaction between the antenna's electromagnetic fields and those of the human body. In [Pat16], it is clearly demonstrated that human body-tissue can have a significant effect on the performance of an antenna worn by a human.

1.1 Aim of the thesis

The aim of this thesis is to develop and evaluate RFID tags and sensors for a textile-integrated wearable RFID platform working in a realistic environment, such as for a worker in a warehouse, for example. To design the wearable antennas specifically worn on a target part of the body, such as the on the back of a glove. To manufacture the antennas in different ways, using copper tape, electro-textiles (E-textile) and embroidered conductive threads. After they had been produced, the tags were subjected to on-body measurement and reliability tests. The reliability tests were performed under stringent conditions in which the tags were stretched, for instance, or exposed to high humidity and washing. Our results show that the tags can perform well when worn on-body in a harsh environment.

1.2 Objectives and scope of the thesis

The main objective of this research is to look at effective fabrication methods for producing reliable, textile-integrated passive RFID tags and sensors, mainly through the utilization of E-textiles and embroidered conductive threads. Furthermore, another objective is to optimize the tags' design so that they can easily be integrated into clothing. Therefore, the tags have to be easy to make, perform well when worn by a human, and be wearable. The conclusions are based on the robustness and reliability of the tags. The structure of the whole research project is shown in Figure 1. The objectives of the thesis can be summarized as follows:

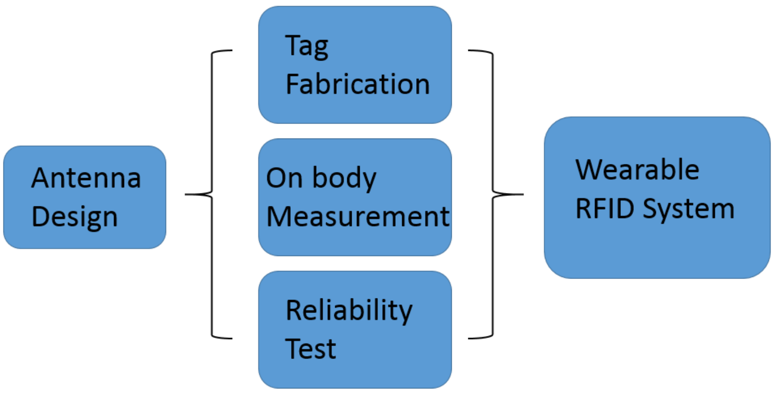


Figure. 1. Structure of the study.

- to find practical ways of manufacturing textile-integrated wireless electronics using cost-effective materials such as E-textiles and conductive thread
- to design textile-integrated passive UHF RFID sensors
- to optimize the wireless platforms for different parts of the body, such as the back or the hand
- to test the tags' robustness under the harsh conditions typically required of such devices, such as the high humidity and mechanical stresses caused by washing the tagged garments
- to test ready-made RFID tags worn on-body in different working environments, such as in an office.

1.3 Structure of the thesis

This thesis is based on work carried out for nine publications, and is divided into seven chapters. The structure of the thesis is shown in Figure 2. Chapter 1 introduces the aims, the results, the structure of the thesis and the author's contributions. Chapter 2 explains the basics of RFID technology and measurement methods and describes the challenges faced in producing wearable RFID technology. Chapter 3 deals with the design of the antennas used in this research and describes the conductive properties of the materials utilized for the substrate and antenna body. Chapter 4 presents the manufacturing methods used to produce the wearable RFID tag antennas, and Chapter 5 describes the realistic environments that were used to test the reliability of the tags, which include on-body and in-air measurements. Chapter 6 draws conclusions from the results of the research and presents some ideas for the direction of future research into passive wearable UHF RFID technology. The structure of the thesis is summarized in Figure 2.

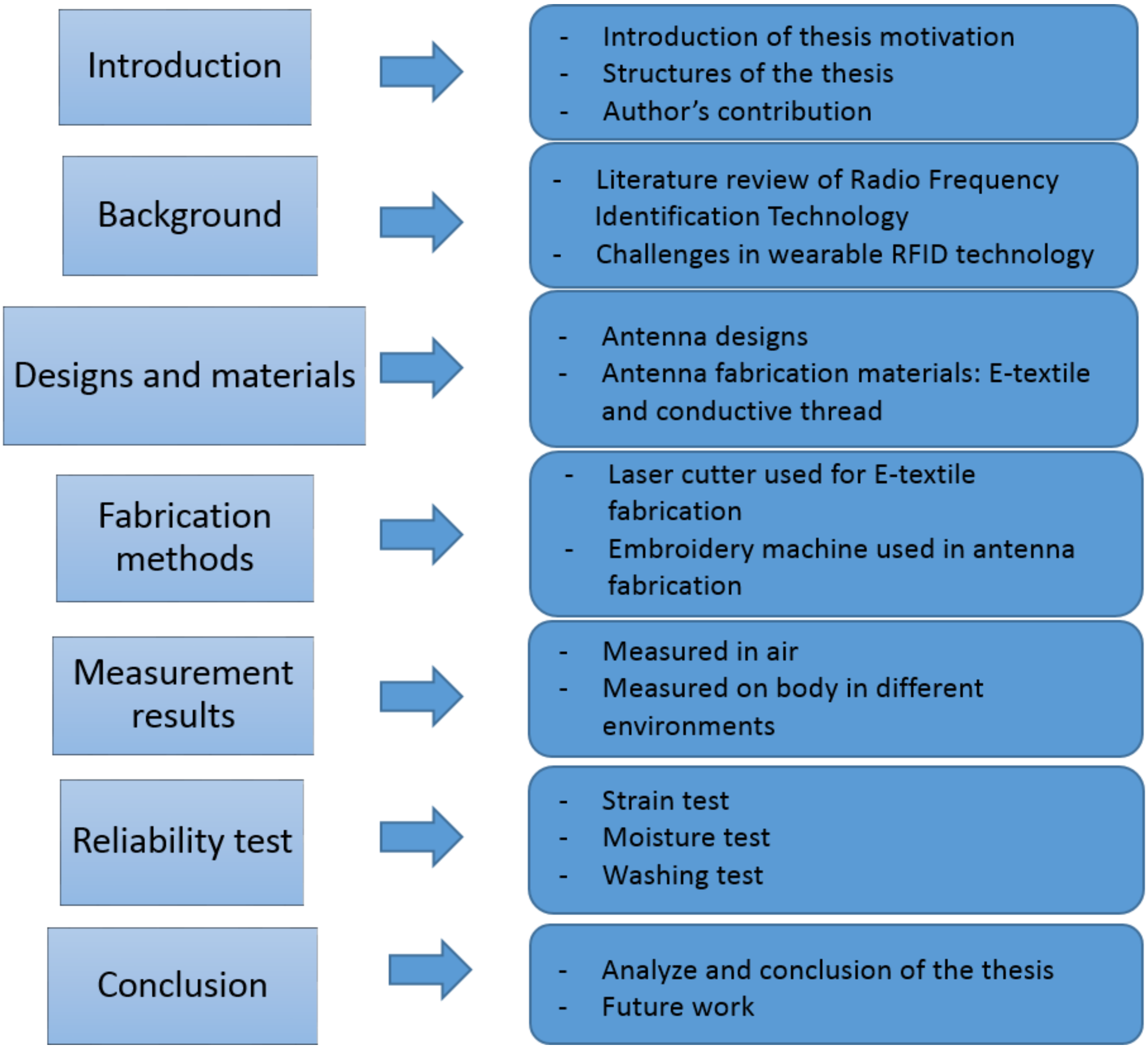


Figure. 2. Structure of the Thesis.

1.4 Author's contribution

This thesis is based on collaborative research carried out over years and reported in nine publications. The contributions of the author are as follows:

Publication I. The author was the main contributor to this paper and was responsible for the design and simulation of the antennas, and methods for their manufacture. The author also made the tags, carried out all the measurements, analyzed the results and wrote the original manuscript, which was later revised with the aid of the co-authors, Toni Björninen and Leena Ukkonen.

Publication II. The author was the main contributor to this paper and was mainly responsible for the simulation of the antenna and for designing methods for embroidering the antenna-IC attachment. The antenna bodies were made with the help of the co-authors, Aruhan Liu and Zhigang Wei, who also contributed to the main measurements. The results were analyzed by the author. The original manuscript was written by the author and revised with the aid of the co-authors, Aruhan Liu, Zhigang Wei, Leena Ukkonen and Johanna Virkki.

Publication III. The author was the main contributor to this paper and was responsible for the design and simulation of the two-part antenna, the fabrication of all the antennas, and the wireless measurements. The results were also analyzed by the author, who wrote the original manuscript, which was later revised with the aid of the co-authors, Leena Ukkonen and Johanna Virkki.

Publication IV. The author was the main contributor to this paper and was responsible for the fabrication of an embroidered tag with an embroidered IC connection. A conductive-paint tag was also fabricated with the aid of one of the co-authors, Johanna Virkki. The author completed all the measurements, analyzed the results and wrote the original manuscript, which was revised with the aid of the co-authors, Shubin Ma, Leena Ukkonen, Toni Björninen and Johanna Virkki.

Publication V. The author was the main contributor to this paper and was responsible for the fabrication of the tags and their measurements. The author collaborated with Toni Björninen on the design of the antenna, but all the test results were analyzed by the author, who wrote the original manuscript, which was revised with the aid of the co-authors, Leena Ukkonen, Toni Björninen and Johanna Virkki.

Publication VI. The author was the main contributor to this paper and was responsible for the reliability of the experimental design. The tags were made and tested by the co-authors, Yao Lu and Heihung Lam. The results were analyzed by the author, who wrote the original manuscript, which was subsequently revised with the aid of the co-authors, Han He, Yao Lu, Heihung Lam, Leena Ukkonen and Johanna Virkki.

Publication VII, The author was the main contributor to this paper and was responsible for the design and simulation of the antenna and the fabrication of the tags. The measurements were completed with the aid of one of the co-authors, Han He. The results were analyzed by the author, who wrote the original manuscript, which was revised with the aid of the co-authors, Han He, Leena Ukkonen and Johanna Virkki.

Publication VIII, The author was the main contributor to this paper and was responsible for the design and simulation of the antenna, and the fabrication methods used to implement the tag's innovative design. The author completed all the measurements with the aid of Jinxiong Xu and Han He. The results were analyzed by the author, who wrote the original manuscript, which was revised with the aid of the co-authors, Han He, Jinxiong Xu, Tao Wang, Lianglun Cheng, Leena Ukkonen and Johanna Virkki.

Publication IX, The author was the main contributor to this paper and was responsible for the experimental design and fabrication of the tags. The measurements were completed with the aid of one of the co-authors, Han He. The results were analyzed by the author, who wrote the original manuscript, which was revised with the aid of the co-authors Han He, Leena Ukkonen and Johanna Virkki.

2 Background

RFID is a wireless radio communication technique that can be used to identify a physical object [Dan08]. This technology enables remote identification without the need for line-of-sight communication [Roy06]. The great advantage of RFID tags over traditional bar codes is that RFID tags can carry more information and can even sense environmental factors, such as humidity, temperature and stretching [Roy06]. In addition, an RFID reader can recognize many tags at the same time.

2.1 Introduction to RFID

This section will introduce the basic science behind RFID systems and tags using RFID operational-frequency bandwidths.

2.1.1 An RFID system

A typical RFID system usually consists of an interrogator, also known as a reader, a transponder, as known as a tag, and a controller, which is always a host computer. Antennas are attached to both the reader and the tag, and these are used for converting the voltages into electromagnetic waves, and vice versa, as shown in Figure 3.

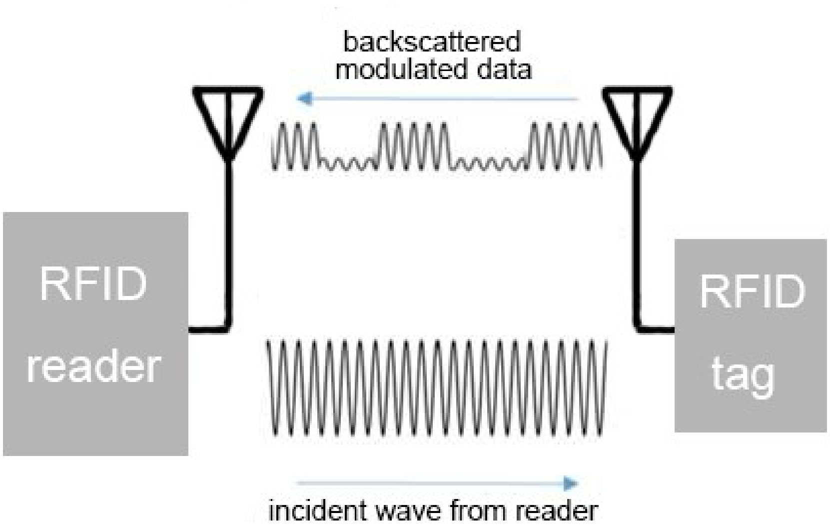


Figure 3. The backscatter modulation principle of passive RFID technology [Dob08].

The tag has an integrated circuit (IC) which is used to store identification information and to transmit data to the reader. The reader is usually connected to a host computer, which handles the data. The operator can control the reader through the host computer, and can store the data or display information on the computer screen.

An RFID system utilizes modulated backscatter to communicate the data between tag and reader [Lan05]. Data transfer between the tags and the reader consists of three steps. Firstly, the reader sends an unmodulated signal to the tag. Then, the tag reads the internal data and changes the loading on the tag antenna in a coded manner according to the stored data. The signal reflected from the tag is thus modulated with this coded information. Thirdly, this modulated signal is received by the reader, then demodulated using a homodyne receiver. After decoding, the tag's information can be displayed on the host computer. The data is amplitude-modulated for transmission from the reader to the tag [Lan05]. For example, RFID-based tags can be used in supply chain management system in a practical working context for tracking the information of cargos [Hop18].

2.1.2 Classification of RFID tags

RFID tags can be categorized into four different types: active tags, semi-passive tags, passive tags and ultra-passive tags [Dan07].

Active tags use a battery to power the transmission of data to the interrogator and thus they can communicate over a distance of several kilometers. They also have large memories and are more resistant to environmental interference. However, because they are battery-powered these tags have several serious drawbacks. Not only are they larger and more expensive than passive tags, but their durability is obviously limited by the battery-life (two to seven years) [Dob08].

Semi-passive tags have an on-board battery but it is smaller because semi-active tags also get energy from the interrogator. The on-board battery powers the tag's integrated circuit, and to transmit data. The read ranges, means in which distance the tag can be read by the reader, of semi-passive tags are much lower than for active tags, (10 to 100 meters) and they also suffer from the same problems as active tags.

Passive tags do not have an independent power source or an on-board radio transmitter. They utilize the power they get from the reader to transmit data. When the interrogator sends a signal to the passive tags, the energy of the signal can be used by the tag to backscatter data to the reader. This technology means that passive tags are always smaller and cheaper than the other two types, but their read ranges are reduced. Nevertheless, passive RFID tags are the most widely-used type.

Ultra-passive tags, known as chip-less tags, do not contain a silicon microchip on-board [Ven11]. This kind of tags do not store the information in microchips [Chan13]. By eliminating the use of silicon IC chips, chip-less RFID tags can offer more competitive price than normal silicon IC based tags. These tags have been used for simple functions, such as identification and tracking [Mcv06] [Mcv10] [Pre10] but also for sensing [Ven15] [Ven16]. Thus, these tags can be expected to take a larger role in the future.

2.1.3 Operation frequency

RFID systems communicate via electromagnetic waves in specific frequency bands [Kla03]; 100 kHz to 5 GHz, as shown in Figure 4. The frequencies utilized by RFID vary in different regions so it is vitally important to ensure that there is no other interference signal in the same frequency band that can affect the communication radio link of the RFID system. Therefore, in general RFID systems can only be used in specific frequency bands which are reserved for particular cases.

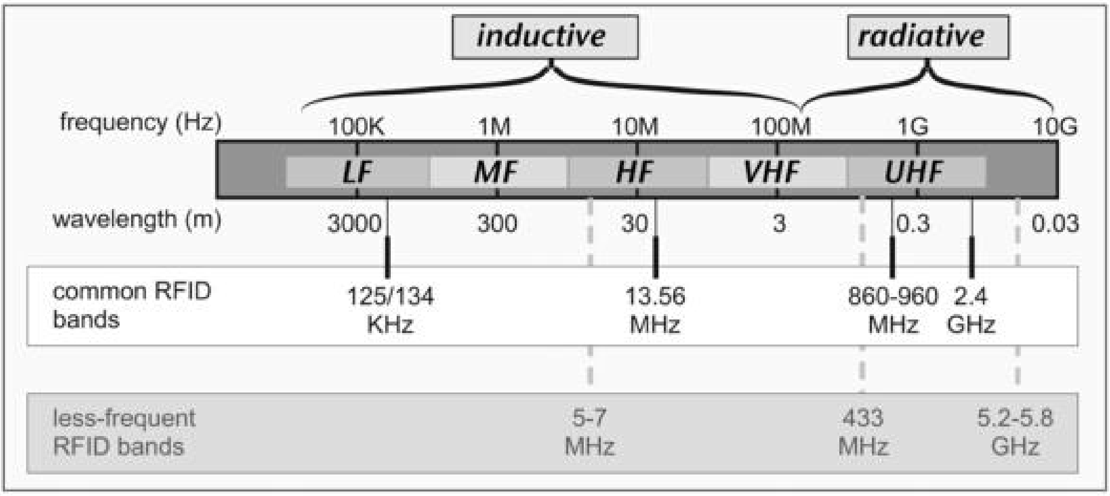


Figure 4. Wireless frequency band [Dob08].

The most commonly utilized RFID frequency bands are 125/134 kHz, 13.56 MHz, 860 – 960 MHz and 2.4 – 2.45 GHz. The RFID systems that use the 125/134 kHz bands, i.e. low-frequency (LF) bands, are referred to as LF systems. Those that use the 13.56 MHz frequency band are high frequency (HF) systems while those which use 900 MHz and 2.4 GHz are referred to as ultra-high-frequency (UHF) systems. The operating frequency bands of different countries are shown in Table 1. The microwave bands from 2.4 GHz – 2.45 GHz are unlicensed and are widely used for industrial, medical and scientific radio communication.

The wavelength (λ) depends on the frequency (f). The speed of electromagnetic waves is equal to the speed of light, c = 300000000 meters per second (m/s). Therefore, the relation between the wavelength, the speed of light and the frequency is:

$$\lambda = \frac{c}{f},$$

Thus, RFID systems have a common wavelength of from 2000 m to 12 cm. Because of the limitation of the size of the tag, the antenna lengths of body-worn RFID can be anything from 0.01 m to 1 m (emphasizes the breadth of the range). In LF and HF systems, the wavelength is much larger than the size of the antenna. Typically, the readers and the tags are inductively coupled. This means that almost all the transmitted energy is around the reader antenna, and this drops sharply the greater the distance between them. In UHF and microwave systems, whose antenna sizes match the wavelength, radiative coupling can be used. This means that the tags can be detected at the furthest reach of the reader’s range, so radiative-coupling systems have a greater range.

Table 1. RFID operation frequency bands in different countries.

Region	Frequency band [MHz]
Europe	865.6 – 867.6
United State, Canada	902 – 928
China	920.5 – 924.5
Japan	916.7 – 920.9

2.2 The applications of passive UHF RFID

Nowadays, passive UHF RFID systems have a wide range of applications due to the fact that passive RFID tags do not need an on-board battery, which reduces their weight and enhances their durability. RFID tags not only have a much longer read range than bar codes, but neither do they require line-of-sight access to read the tag. In addition, RFID readers can communicate with multiple RFID tags simultaneously. A reader can thus collect a great deal of detailed information in one pass, without having to scan each product separately, which offers a number of time-saving applications.

Examples of the fields in which passive RFID can be used include:

- Tracking cargoes, (already used by major retail chains such as Wal-Mart, K-Mart and similar companies) [Hop18].
- Access control. By identifying employees' ID cards, the RFID system can readily be used for speedy and efficient access control [Bri08], such as the access control system of Tampere University of Technology.
- Animal tracking (it has been used for a long time in the breeding industry and is now starting to be used for pets) [Kim10].
- Vehicle tracking and security systems as the example in [Baj12].
- Healthcare applications as the example in [Pat16].

Three of the major fields for RFID applications are described in more detail with examples in the following sections.

2.2.1 RFID-based sensing

RFID is a promising technique for making low-cost self-sensing sensors [Mar10] [Occ11a] [Sip16]. As studies in this thesis have mainly been aimed at human wearers, only on-body sensing systems are listed below. There have been several examples of these over the last few years [Mar09] [Ros15]. The RFID sensors are usually based on two different sensing methods: the first of these is an RFID tag with a traditional sensor attached, or integrated into the tag IC; and RFID tag in which the sensing ability is integrated into the tag structure. All the sensors used for this study are self-sensing elements and do not need any extra sensor components. [Publication I] achieved novel referenced strain sensors for unambiguous readout while [Publication VII] presented an embroidered moisture sensor tag made of dishcloth and conductive yarn. These kind of sensors have many advantages. They are lightweight, maintenance-free and their antennas can be fabricated from flexible conductive materials which makes them soft. Thus, they have great potential for the fabrication of wearable RFID devices. One study has shown that RFID technology has a high potential for detecting additional information about the attached object, such as its physical state and its time-evolution, without the addition of any embedded sensors or the need for any local power maintenance [Occ11b].

RFID tags made from conductive yarns could be the answer to the design of wearable sensors. In [Pat16] a wearable strain sensor was used to monitor human activities, such as contraction, limb movements and respiration. The study showed how the sensor was used to capture contractions or respiration when worn on the human body, as shown in Figure 5. The preliminary strain sensing was analyzed using a typical mannequin used for medical training. The work focused on using the sensor as a wireless monitoring system for human respiration, which has obvious applications for healthcare. For instance, a child’s breathing can be monitored in order to detect symptoms of apnea, and may thus be used to prevent acute cardiorespiratory arrest [Pat16]. The existing devices used to monitor a child breathing have to connect to a mobile device with WIFI or Bluetooth, which requires a battery that needs to be charged regularly [Mimo]. An RFID tag sensor would eliminate the need for a battery, so a knitted antenna can achieve strain sensing and can be used for the wireless monitoring of breathing as shown in Figure 5.

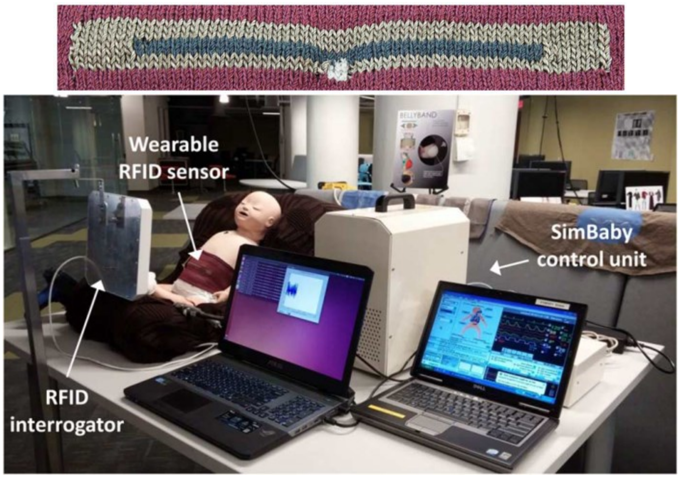


Figure 5. Passive RFID breathing monitoring system [Pat16].

Another example of a medical application for an RFID sensor, STENTTag, in [Occ11b] is passive vascular monitoring, as shown in Figure 6. As passive RFID systems can be used in self-sensing equipment, a possible application for the proposed sensing paradigm could be monitoring in-stent restenosis. The RFID sensing system monitors any repeated narrowing of the vessel, which can be caused by an abnormal accumulation of tissue inside the lumen of the implanted stent. The RFID system can sense the decrease in flow. By recording the sensors' response at different times, over intervals of days or even hours, a map of the geometrical or chemical changes in the vessel can be generated. Therefore, the system shows that STENTTag is sensitive to changes in physical processes.

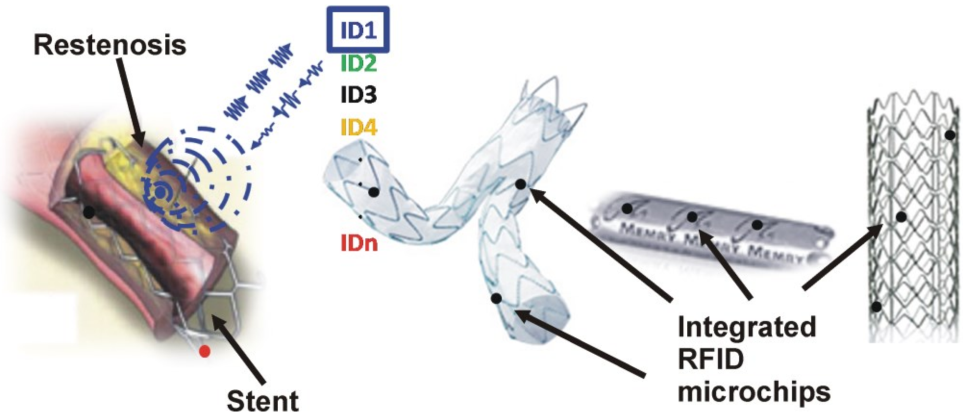


Figure 6. RFID in-stent restenosis monitoring system [Occ11b].

2.2.2 RFID in supply chains and logistics

Supply chain management is a field which can clearly benefit from the use of RFID technology. RFID technology can provide suppliers, manufacturers, distributors, and retailers with accurate real-time information, such as what products are in the supply chain and where they are [Bha04]. Many commercial and industrial companies, such as Wal-Mart and Target, have already investigated the feasibility of using RFID systems in their supply chains [Leu07] .

In Figure 7, Shenzhen Hopeland Technologies CO. Ltd presents an example of an RFID-based supply chain management system in a practical working context [Hop18]. In this system, the RFID tags are attached on products during manufacture. These tags can store all the required information related to the attached products. Then, the tagged products are shipped to a warehouse. As they pass through the warehouse, the tag reader registers them and sends the data to a control center. This allows the host computer to record the quantities of products going in or coming out of the warehouse, and thus to help organize the storage of products in the warehouse [Hop18]. Finally, the information stored in the products' embedded with RFID tags can be used to locate the products when they enter a distribution center, allowing them to be sorted quickly and efficiently. The system can also help with the timely and accurate dispatch of the goods to retail outlets [Hop18].

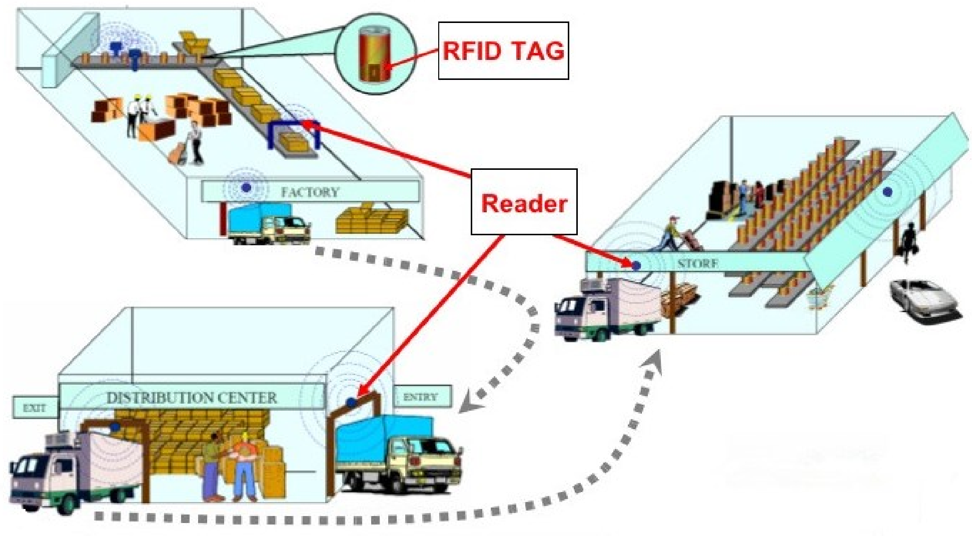


Figure 7. An example of passive UHF RFID in supply chain management [Hop18].

Figure 8. shows an RFID tag integrated into a roll of paper [Ukk07]. The paper industry urgently needs an automated identification system which can carry the identification code of any particular reel throughout its whole life cycle. Barcode identification systems are already used in the paper industry to identify rolls of paper, but as these must be attached to the surface of an object, they disappear when the outer wrapping of the paper roll is removed. However, RFID tags can be attached safely to the surface of the reel core, between the core and the paper. In this way, the identification code record in the RFID is retained throughout the lifecycle of the reel, from the paper mill to the end-user. Thus, rolls of paper can be tracked in real time which is a real benefit for the paper industry. Knowing the origin of the reel throughout its life cycle would also improve quality control.

Using RFID in such a way would result in more efficient and automated identification and improved quality control throughout the whole supply chain and life cycle of paper reels [Mic05][Sch05], which will also bring cost benefits.

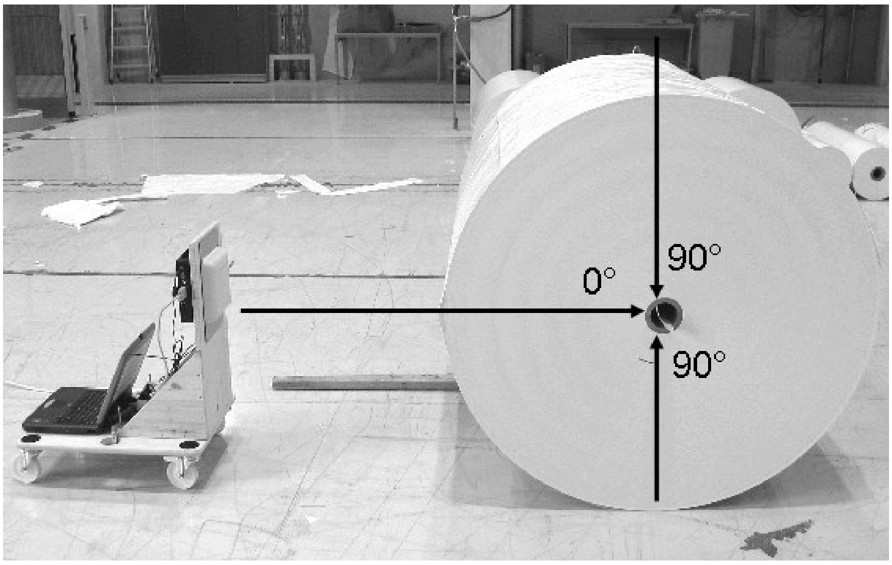


Figure 8. RFID measurement system, the measured paper reel and the measuring directions at the paper mill [Ukk07]

2.2.3 Human tracking

Passive RFID technology is also attracting considerable attention for tracking humans. For example, the remote tracking of the elderly or the disabled in the healthcare sector. Furthermore, RFID tags can be used to track the path and ensure the safety of patients in hospital [Naj11, Per12b]. Another application could be in schools. In a recent study [Lin10], wearable tag-embedded bracelets or wristbands were used to monitor pupils' attendance and to locate the positions of individual children within a school's premises. Wearable RFID technology plays an important role in building an efficient yet unobtrusive tracking system for all of these applications.

Figure 9 shows an RFID patient-tracking system designed by Borda Technology for use in indoor environments, such as hospitals and health centers, [Bor18]. Wearable RFID Tags containing personal information are issued to all patients to be worn on-body all the time. To detect these tags, RFID readers are installed in the premises at key points in rooms, stairways and corridors. Thus, whenever the tagged patients pass by a reader, the tag will be recognized and its location will be recorded. This system enables real-time location of all the patients so that medical staff can be instantly at hand should the need arise.

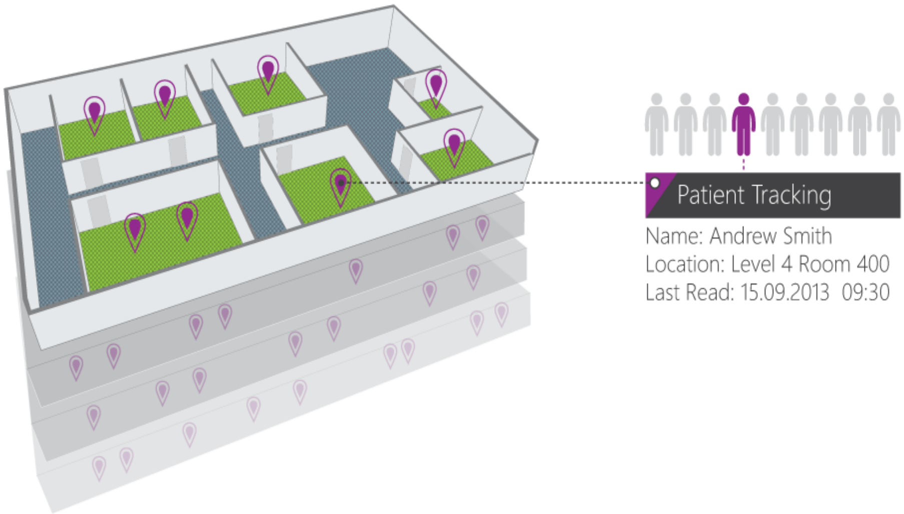


Figure 9. A RFID-based real-time patient tracking system [Bor18].

2.3 The challenges for wearable RFID solutions

Designing a passive RFID antenna that can work on the human body is challenging. Human body-tissue can have significant effects on an antenna [Pat16], and different parts of the body have different effects on the wireless performance of an RFID device [San07]. In addition, the size of these wearable devices is obviously limited by the size and shape of the part of the body on which it is worn [Tan03].

If an RFID device is to be worn comfortably by a human, it must be flexible and miniaturized in order not to inhibit the movements of the wearer. There are several materials that can be used to make wearable antennas. For instance, the wearable antennas can be made from thin and uniformly metallized conductive sections, woven or knitted conductive sheets, and they can also be embroidered or inkjet- or screen-printed on to a garment [Par16] [Kel12] [Whi14] [Tso14]. If only a few antennas need to be fabricated, then metallized materials such as copper tape are the fastest method. However, in a commercialized industrial environment where large quantities of antennas are required, textile antennas are more suitable because the manual work needed with copper tape antenna would slow the process down. Generally, copper tape antenna is useful in an experimental environment, but it is often not scalable to the practical requirements of commerce and industry. Woven or knitted conductive sheets can produce a more durable and flexible antenna than copper tape. However, these materials should not come into direct contact with human skin since the conductive human tissue will reduce the performance of the tags. Therefore, with this technique a non-conductive substrate is needed to insulate the conductive E-textile antenna from the human body. This entails using some type of glue to combine the conductive sheet and the substrate, which involved one more fabrication step [Loe06]. Inkjet and screen printing can also be used to make the conducting sections of wearable antennas [Mer09]. However, textiles are not ideal printing substrates since they are porous and can easily absorb the ink [Pat07]. Inkjet-printed wearable antennas were presented in [Liy12] [Whi14]. This study showed that the antenna could be printed onto a textile substrate if the surface of the substrate-part textile of the garment is coated with a suitably non-porous substance. With 3-dimensional (3D) printing technology, the conductive ink can be printed on to a textile substrate, but the price of the conductive ink is still high [Cao15] [Heh18]. In [Vir16], a screen-printed antenna was produced on an elastic textile substrate. However, after a cyclic strain test, the read range of the tag had clearly been attenuated by the harsh treatment. [Kaz16] showed how a brush-printed tag can be fabricated on a textile substrate, but the coating material was too thick and inflexible to be worn comfortably on the human body.

A wearable antenna must be able to tolerate a wide variety of conditions and treatments. For example, it must be able to bend and stretch and tolerate all the movements and conditions experienced by the human wearer. It must be water-resistant, i.e. washable. This is a challenging requirement because a wearable antenna, if it is to be part of the wearer's daily wardrobe, has to go through the regular clothes-washing cycle many times before the wearer will dispose of it. The IC must also be very well protected. [Man12] [Toi13] showed that even a high-humidity environment can disable an IC when it is worn on a human, so the mechanical stresses that occur in a washing machine mean that any wearable RFID device must have a very well-protected IC [Wan15]. A washing test in [Toi13] indicated that a wearable textile RFID tag can be given a protective coating to withstand washing. However, as reported in [Kel12] [Bjö14] [Fuy15], after washing tests, the read range of plastic-coated RFID tags were clearly attenuated as the plastic coating deteriorated. In [Kaz16], brush-painted textile tags were coated and tested after repeated washing cycles. The results of these tests showed that there are coating materials which could protect the tags in a washing machine, although their coating was thick and non-stretchable. A graphene-based RFID textile tag, which remained readable even after 100 harsh bending cycles was studied in [Akb16]. However, the tag failed the stretching tests completely since cracks appeared on the printed antenna body after the first stretch. [Publication II] has also shown that mechanical stresses can break a conductive glued IC interconnection. There have been a number of ingenious designs for wearable RFID tags, but so far none of them have been developed into a practical device that can be easily manufactured into a garment, and can withstand all the harsh conditions that the garment will undergo in its lifetime.

2.4 Solution: textile-integrated RFID platforms

2.4.1 E-textile

Embroidered antenna made from electro-textiles (E-textiles, see Figure 10) could meet all the above requirements and thus pave the way for the seamless integration of the wireless tags needed for RFID applications into wearable garments. Previous studies had shown that E-textiles, such as Lycra (used in [Ooc14]), Cordura® fiber yarns (used in [Ouy05]) and Less EMF Stretch Conductive Fabric Cat. #321(used in [Lon15]), are lightweight, flexible and easy to handle, so an antenna made from an E-textile will incorporate all the characteristics of that textile. One drawback with earlier studies was the cost. The silver ink used in [Heh18] was 3.57 Euro per gram, so at that price the material costs for one tag would be about 18 euros, which would be too high for most commercial applications. However, the nickel-plated Less EMF Shieldit Super Fabric (Cat. #A1220) studied here costs 670 dollar per roll (0.5 m x 30 m). As only about 0.02 m x 0.1 m material is needed to make one antenna, the cost of materials is greatly reduced. Furthermore, this E-textile can easily be cut into the required antenna body. With all these attractive features to its credit, the question was, could an E-textile be used to manufacture a practical and commercially-feasible wearable antenna? The details of how such an antenna can be fabricated with our E-textile will be described below.

Figure 10. Different kinds of E-textile materials.

2.4.2 Embroidery

Embroidery with conductive yarn is a simple manufacturing method with great possibilities due to its compatibility with various textile materials [Act14] [SanB10] [Hua06] [Sal04] [Gup10] [Zha12]. In embroidery, we have full control of the conductive pattern through shape, stitch density, and stitch type [Hua06] [Tro06]. In addition to fabricating conductors and antennas, sewing is also a highly effective method for embedding electrical interconnections into textiles. Conductive yarn can be embroidered onto a variety of materials. Using normal colored thread, a traditional embroidery machine can produce any shape or pattern dictated by the control computer. All that needs to be changed in order to embroider a conductive antenna onto a garment while it is being manufactured is to substitute the normal thread with conductive thread. Figure 11 shows the simplicity of a working embroidery machine. As long as the cloth-based substrates and the yarns are suitable, embroidered antennas are almost as flexible and lightweight as the rest of the garment.

Therefore, embroidered antennas look like a great way of fabricating wearable RFID tags. Electronic embroidery technology has various advantages over other fabrication methods, such as inkjet printing, not least because embroidery machines are already used throughout the clothing industry. This means that integrating embroidered antenna into garments on an industrial scale would be commercially feasible. Embroidered antenna can easily be attached to cloth substrates and, as mentioned above, the material and production costs are low, much lower than for the ink-jet technique, for example. Embroidered antennas are ideal for making linear antennas as any electric current will naturally flow through a single strand of a conductive yarn rather than through the non-conductive cloth around it. This is not so easy with copper tape, for example.

Another advantage of the embroidery method is that the computerized embroidery machines already in use in the industry can easily reproduce the geometrically precise antenna bodies which have been tested in an experimental environment. [Cha13] has shown that almost any structure can be embroidered by copying the original shape. This makes it relatively easy to integrate this RFID technology into our current industrial infrastructure. Fractal antenna technology was studied in [Ahm12] in order to design wearable textile antennas. These experiments resulted in attractive and compact designs, but the embroidery was only accurate to approximately one millimeter. However, another study has shown that computer-assisted embroidery can partially overcome this problem [Tso14]. With regard to attaching an IC to an embroidered antenna, [Publication II] has shown that glue is not the only technique. In our study, an embroidered IC-antenna connection was used in stretchable RFID tags. The embroidered IC attachment was more reliable and stretchable than the glued one [Heh18].

Figure 11. Embroidery machine and conductive thread.

2.4.3 Coating the tags

RFID tags can be given a protective coating to improve their robustness and reliability after going through a harsh environment such as a washing machine or a dryer. It has been clearly demonstrated that high humidity or mechanical stress will impair the performance of wearable tags [Toi13] [Wan15], so coating the tag antenna and IC is an obvious solution. Different coating materials have tested in various studies [Scar12] [Fuy15] [Kel12] [Kaz16]. In [Publication XI], a variety of RFID tags were coated with a stretchable protective encapsulant and tested after both washing and drying cycles. As far as the authors are aware, this was the first stretchable coating material to be used for RFID antenna fabrication. The tags were integrated onto T-shirts and the on-body measurements which were conducted to test the reliability of the coated textile tags showed that this coating protected the tags well against the demanding conditions of everyday use.

3 Designs and Materials

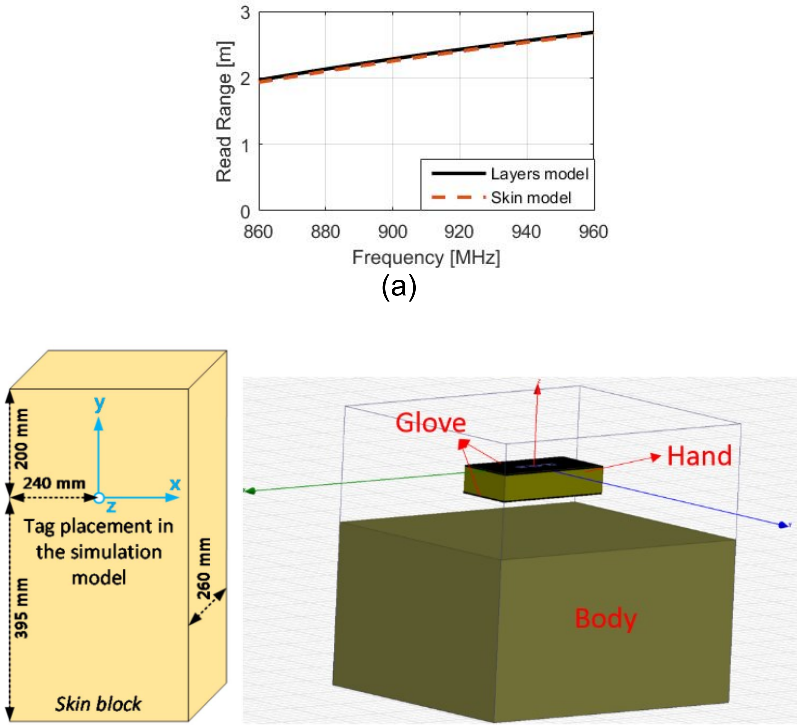
This chapter introduces the antenna structures used for this thesis. It itemizes and illustrates all the materials and methods used in the manufacture of the antenna, and compares them.

3.1 Antenna design

Antenna simulation is a vital procedure in antenna optimization [Bou15]. In order for a wearable RFID system to function, the antennas not only have to resist interference from the human body, but they must not interfere with the movements of the wearer, so they must be light and flexible, while remaining highly reliable. The first stage in the creation of such an antenna was carried out with the simulation software, ANSYS HFSS (High Frequency Structure Simulator). ANSYS HFSS is a 3D electromagnetic simulation tool for designing and simulating electronic products at high-frequency [HFSS]. The simulations were aimed at optimizing the dimensions of the antenna in order to achieve the longest possible read ranges for the tags in limited human-body area. The simulations also indicated the current density in a particular antenna body. This meant that fabrication methods for different parts of the antenna could be controlled according to the current density. In this thesis, the antennas were designed and evaluated by simulations before the actual measurements. In the simulations, the optimization of the tag read ranges were based on “trial and error”.

A model was used in the simulation to account for the influence of the human body. A rectangular block which had the dielectric properties of the human skin was used to enable rapid evaluation of various antenna configurations. The other layers of the tissue on human body may also affect the backscatter radiation. However, the effect is not significant, as shown in Figure 12 (a), which presents the delicate change of read range when simulated by skin model and layers of skin-muscle model. The more complex human tissue model will be used in future for the antenna design to get the more accurate results when necessary. Figure 12 (b) shows the simplified model of the human torso used in the antenna modelling.

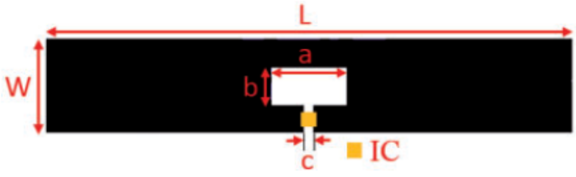
Figure 12 (b) also shows a glove-tag antenna simulation model [Publication VIII], in which two cubes (200 × 100 × 30 mm and 480 × 400 × 260 mm) were used to simulate the human hand and torso with a 120 mm gap between them. The hand part was set to model bone in HFSS while the hip was set to model skin. The top and bottom sides of the simulated hand tissue were covered with a 2.5 mm thick sheet of polymide material to simulate the glove material.



(b)

Figure 12. (a) Compared simulation result between layers model and skin model; (b) Human body simulation model upon back and hand with body.

Five different antenna body patterns designs were used in this work. The antenna bodies, which had different sizes and structures, were evaluated for different functions and for use in diverse environments. The first structure was used to test the antenna and the reliability of the IC interconnection of an embroidered RFID tag. The size of the antenna body and the current density in the HFSS simulation with an input current of 0.57 W are shown in Figure 13.

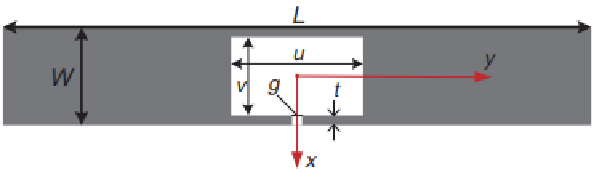


a	b	c	W	L
14.3 mm	8.125 mm	2 mm	20 mm	100 mm

Figure 13. The structure and current density of dipole antenna.

This kind of antenna has a good read range in air and was thus a good candidate for testing of the manufacturing features and the reliability of different fabrication and connection methods. As shown in Figure 13, the current has higher density around the feeding loop and lower density at the farther end of the antenna body. Therefore, the loop area was the most critical part in the fabrication of this antenna.

The final dipole RFID antenna, which can be adapted to work around the human body, was bigger than the original one used in earlier experiments. The size and the structure of this bigger dipole is shown in Figure 14. In the simulation, the current density plot was similar to that of the basic dipole. This antenna had a broad working bandwidth when worn by a human.



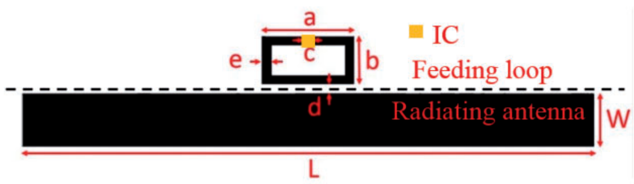
DIPOLE WITH INDUCTIVE LOOP MATCHING

t	*g*	*L*	*W*	*u*	*v*
2 mm	2 mm	120 mm	20 mm	27 mm	16 mm

Figure 14. The structure and current density of big matching loop dipole antenna.

A two-part antenna has a separate radiating antenna and feeding loop. The structure and size of this antenna is shown in Figure 15. The purpose of evaluating the two-part antenna against the basic dipole antenna was to improve reliability so that the antenna can work as the sensor in a self-sensing component. This antenna body will undergo a lot of stretching and bending when the tag is integrated into clothing. For a one-part RFID tag, while these changes affect the conductive properties of antenna body, the matching between the antenna and IC may change correspondingly, thus influence the antenna performance. In addition, the IC is vulnerable to high-humidity or stress in the sensed environment. The two-part design allows the antenna-IC attachment to be unaffected by these conditions as long as the small feeding loop is fabricated into a rigid structure. In this case, the radiating antenna body which needs to endure mechanical stresses can still be flexible. Thus, a two-part antenna could have been more reliable as a self-sensing sensor.

The current density on each part on the antenna when 0.94 W was delivered to the antenna is shown in Figure 15. The loop had a higher current density than the radiating antenna. Thus, when manufacturing the antenna, a more conductive material should be used to fabricate the feeding loop. In order to improve the utility of the sensor, the radiating antenna could be made with other materials with different physical features, such as a stretchable conductive sheet or a water-absorbing textile material.



a	b	c	d	e	W	L
21.6 mm	11.3 mm	2 mm	2.5 mm	1.9 mm	12.6 mm	165.7 mm

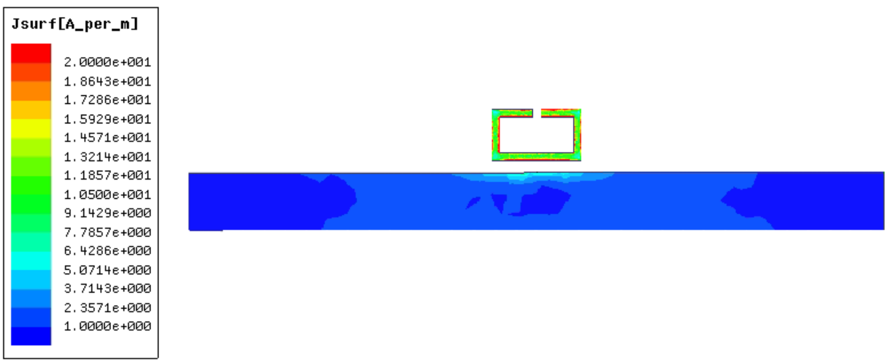
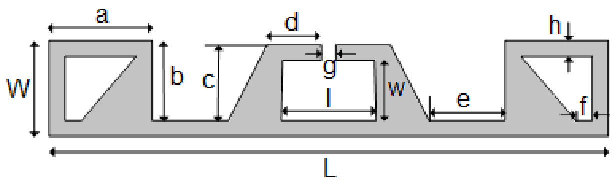


Figure 15. The structure and current density of the two-part antenna.

The structure and size of an antenna which was specifically developed to be worn on a glove is shown in Figure 16 [Ata14]. This antenna was worn by humans and can be utilized for authentication or indoor tracking. Designing the glove tag antenna was challenging due to the size limitation and the required good performance near different parts of the human body. In practice, the back of a worker’s glove has only a very limited area to which an antenna can be attached. In this case, the normal dipole in Figure 13 was tried first. However, this antenna structure was oversize comparing to the hand. The “trial and error” method was used in antenna design. The antenna body was changed to be shorter but the read range reduced significantly. Then, some inflexions were added to the antenna body to increase the antenna performance. The result showed that the added inflexion could improve the read range. Next, the optimization in ANSYS was used to find the best antenna inflexion size to maximize the read range at the target frequency. Since the conductive material of the antenna cannot be allowed to touch the skin, the fabrication of the antenna directly onto the glove was challenging. A wearable tag attached to a glove needs a highly flexible and conductive material for the antenna body. Figure 16. shows the performance of the glove antenna when 0.15 W was delivered to the antenna. The current was high-density around the matching loop and nearby patterns.



W	**L**	**w**	**l**	**a**	**b**
13.1	76	8.3	12.9	14	10.9
c	**d**	**e**	**f**	**g**	**h**
12.3	7.4	10.4	2.3	2	2.1

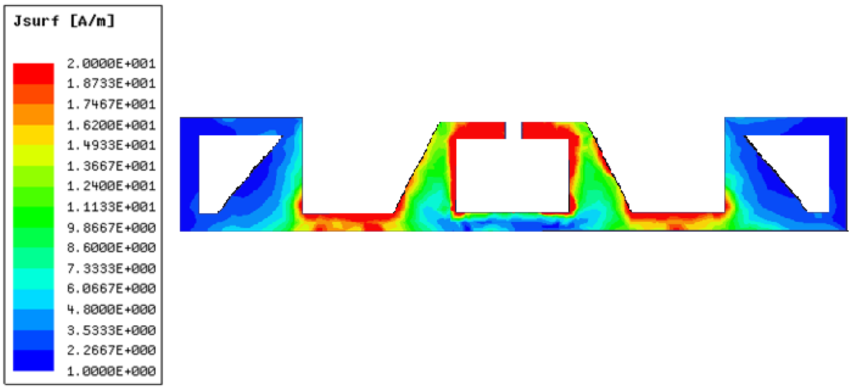


Figure 16. The structure and current density of glove-integrated antenna. The dimensions are in millimeters.

3.2 Materials

3.2.1 Substrate materials

The substrate and the antenna are the basics in the fabrication of any textile RFID tag. The selection of the right materials for these components is of crucial importance. The use of low loss materials can increase the efficiency of a wearable antenna, but the substrate should also be flexible. In addition, the dielectric properties of the substrate can vary with the frequency. Typically, textiles have a low relative permittivity. Non-conductive textile materials can reduce the surface waves and improve the antenna impedance bandwidth with low permittivity relativity. The effects of different materials as substrates have been studied by many researchers. In [Tso14], four different substrates were designed and tested: wash cotton, curtain cotton, polyester and polycot. The results of these experiments showed that, of the four materials tested, the antenna with the polyester substrate had the best performance in terms of gain and efficiency, and the lowest loss tangent. It was also shown that the firmness of the textile substrate influenced the performance of the antenna. Fluffy materials can easily be compressed which means that the substrate will vary in thickness.

In order to fabricate our E-textile antenna, 2 mm thick EPDM (Ethylene-Propylene-Diene-Monomer) cell rubber foam was used as a substrate, as shown in Figure 17 [Publication III] [Publication V]. The dielectric constant and loss tangent of EPDM are 1.26 and 0.007, respectively, at 915 MHz. In on-body tests it was shown that this non-conductive material can insulate the antenna from the human body and thus decrease its influence on the performance of the tag. For the RFID tags integrated onto T-shirts, the cloth of the T-shirt was used as a direct substrate [Publication VI].

Figure 17. EPDM material.

100% cotton woven cloths were used as the substrates for the non-stretchable embroidery antenna part in [Publication III], and the painted antenna in [Publication IV], as shown in Figure 18. This soft, freely-breathing, skin-friendly material is commonly used in the garment industry. The woven cotton fabric is non-stretchable so it can retain the antenna's structure after manufacture. Thus, cotton has great potential as a substrate material for embroidered flexible wearable RIFD devices. Two knitted elastic cloths, as shown in Figure 18, were used as the substrate for the embroidered antennas. Both of them were used in [Publication II] as a stretchable substrate on which to fabricate the flexible embroidered tags. [Publication III] used the white elastic band as the substrate for the stretchable antenna radiation pattern. The red elastic band was thinner and softer than the white one. These two materials can both be strained to 200% of their original length and then revert automatically to their original shape. Such an elastic band has a long lifetime as it can endure more than 1000 stretching cycles. All of these substrates are normal materials used in the garment industry. Even the thin dishcloth shown in the middle image in Figure 18, which was very cheap, could be used as a substrate for the moisture sensor in [Publication VII] as shown in Figure 18. Similarly, the common work glove made from a knitted nylon material shown in the bottom image was used as the substrate in [Publication VIII].

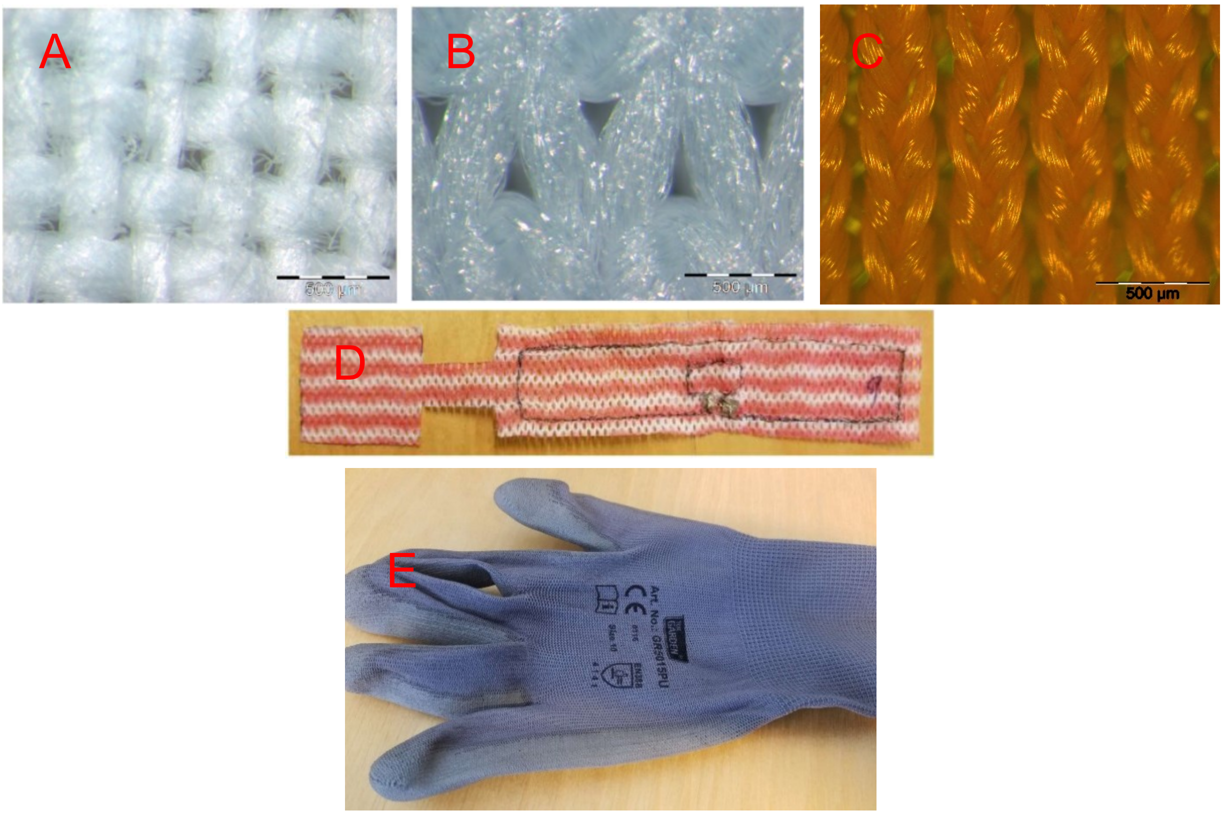


Figure 18. Substrate materials. A: woven cotton fabric, B, C: knitted elastic cloth, D: dishcloth and E: work-glove.

3.2.2 Conductive materials

Conductive electro-textile materials were nearly always used to create the antenna bodies. A copper woven E-textile, Less EMF pure copper polyester taffeta fabric (Cat. #1212) was used in [Publication I] with the antenna body shown in Figure 19. This E-textile is a copper-plated polyester-based material which has 0.08 mm thickness and approximate 0.05 ohm/square sheet resistance. It is as easy to cut and sew as many ordinary fabrics [Copper].

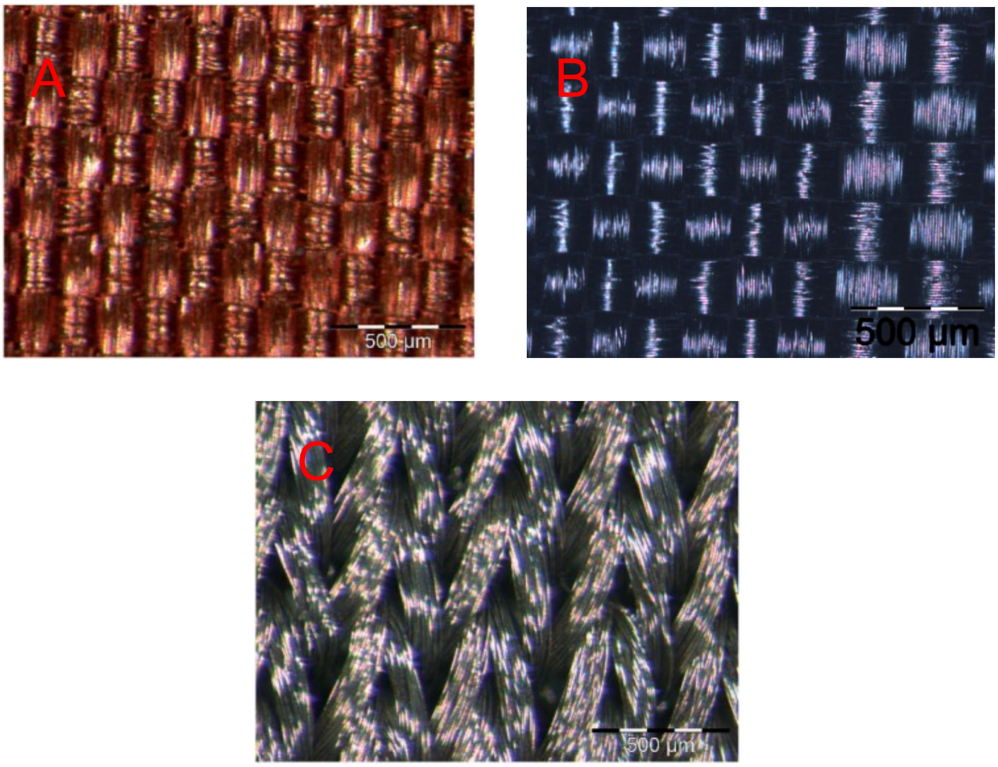


Figure 19. Microscopic pictures of the E-textile materials. A: copper woven E-textile, B: nickel-plated E-textile, C: silver-based E-textile.

Another frequently used E-textile material was nickel-plated Less EMF Shieldit Super Fabric (Cat. #A1220) used here in [Publication V] [Publication VI] [Publication VIII] [Publication IX]. This electro-textile has a sheet resistance of approximately 0.16 ohm/square and is 0.17 mm thick. It has hot melted glue on the back and can thus be easily ironed onto versatile textile substrates [Nickel].

A stretchable silver-based E-textile, Less EMF stretch conductive fabric (Cat. #A321), was used to manufacture the stretchable antennas required for devices such as strain sensors [Publication I] [Publication III]. This fabric is a commercially-available stretchable knotted silver textile, with 0.4 mm thickness and less than 1 ohm/square sheet resistance in its unstretched condition. At maximum stretch, this E-textile can extend to 200% of its original length [Silver].

For the embroidered antenna, the conductive multifilament silver-plated yarn (Shieldex multifilament thread 110/34 dtex two-ply HC) was used to embroider the antenna body in [Publication II - VII] as shown in Figure 20. The DC linear resistivity of the yarn is 500 ± 100 Ω/m and the diameter is approximately 0.16 mm [Yarn]. This yarn can be used by any standard embroidery machine, so the antenna could be made by the automatically at the same time as the garment.

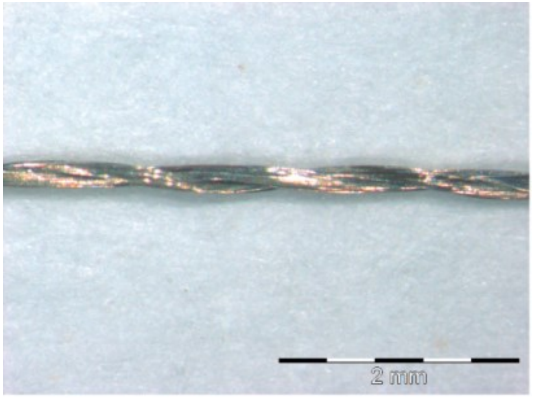


Figure 20. Conductive thread.

Copper is an excellent conductor and is of course widely used in the electrical industry. Thus, copper tape was also used to fabricate the reference tags. In this study, the copper tape antenna were used as a yardstick for assessing the performance of the embroidered textile antennas.

Conductive paint was also used in this study as a possible antenna material [Publication IV]. The paint was Bare Conductive's nontoxic, solvent free, water soluble Electric Paint [Bare] provided by the manufacturer in a 10-ml tube as shown in Figure 21.

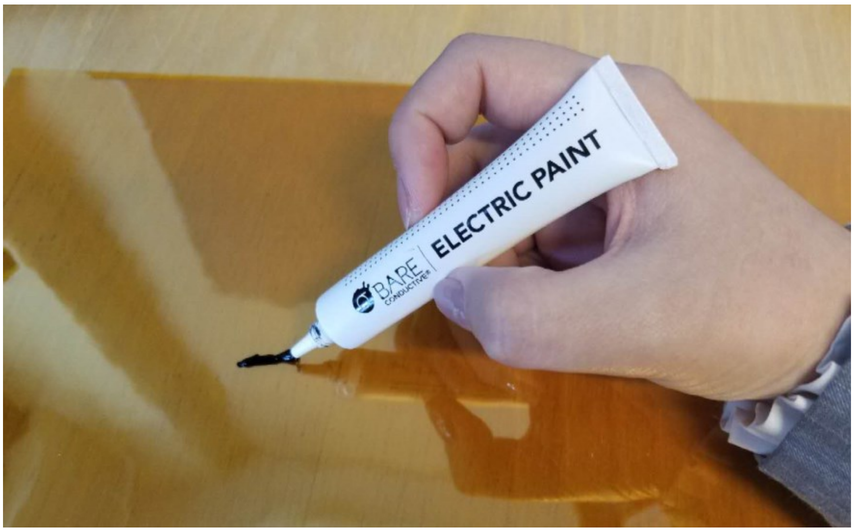


Figure 21. Conductive paint.

4 Fabrication Methods

4.1 E-textile tag

The antenna body for the E-textile RFID was cut from the E-textile. Scissors and a laser cutter (Epilog Fusion Laser Model 13000, as shown in Figure 22) were used to cut the E-textile fabrics, which were then attached to the substrates or garments. In this case, 30% of the maximum power of 75 W was used. The textile antenna bodies were glued to the substrate with textile glue, tape or were ironed on directly [Publication V].

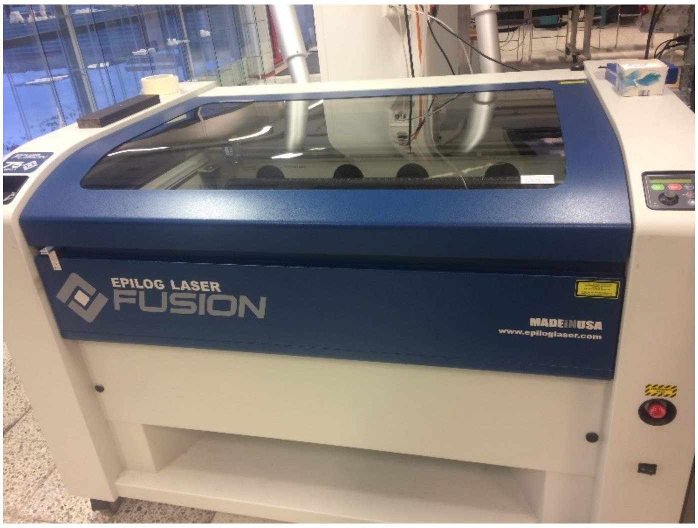


Figure 22. The Epilog Fusion laser cutter.

Some ready-made textile tags are shown in Figure 23.

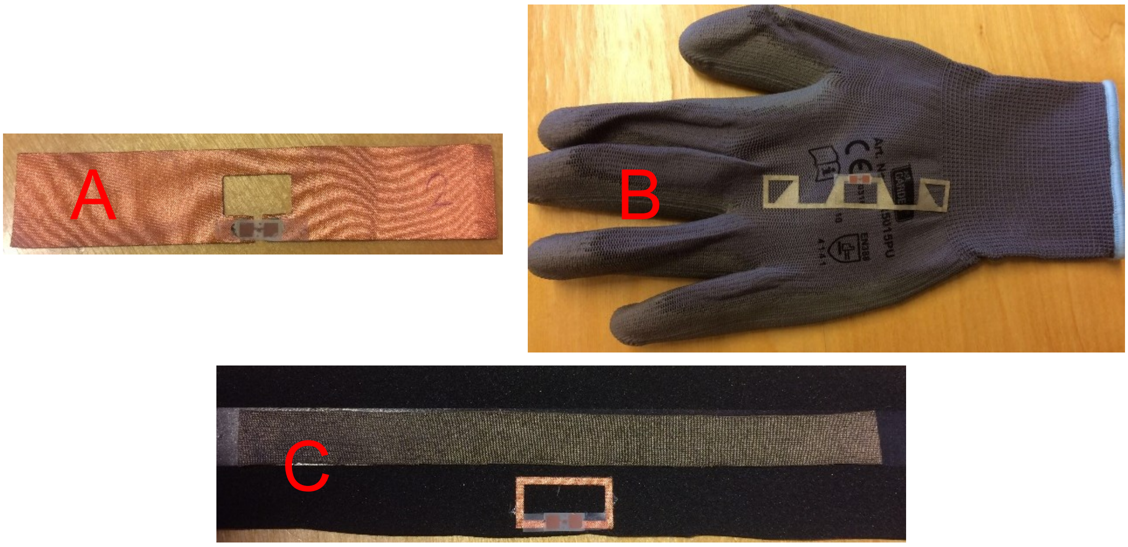


Figure 23. Ready-made E-textile RFID tags.

Figure 23 A shows a copper textile dipole antenna. Figure 23 B shows a nickel textile antenna integrated on a normal working glove [Publication VIII]. The antenna was attached to the glove by the adhesive coating on the back of the material. Figure 23 C consists of two separate parts: the upper part is a silver-base stretchable radiation antenna body and the lower part is a copper textile feeding loop. With this type of structure, the two separate parts can have different characteristics, for example here the radiation antenna is flexible while the feeding loop has a rigid configuration. The separate antenna was integrated onto the EDPM substrate using plastic-base double tapes. All of the textile antennas were cut with the Laser Cutter and then attached to the IC with conductive glue [Publication III].

4.2 Embroidery tag

The commercially available Husqvarna Viking sewing machine shown in Figure 24 was used to embroider the antenna onto the fabric substrates in this study. The structure of the antenna was designed using 5D embroidery software which was then downloaded into the embroidery machine. The antenna body can be embroidered onto the cloth substrate according to the chosen design, as shown in Figure 24.

Figure 24. Husqvarna Viking sewing machine.

Three different sewing styles were used in order to see if the stitching had an effect on the wireless performance of the embroidered antenna. The styles used were vertical sewing, horizontal sewing and contour sewing [Publication II]. In each structure, as the resistance along the conductive yarn is lower than it is along the adjoining yarns, the currents generally flow along the single conductive yarn rather than over the other untreated yarns. As Figure 25 shows, with vertical sewing the thread tends towards a vertical direction, and therefore, so does the current. With horizontal sewing, the thread is horizontal so the current flows in a horizontal direction over the designated area, as shown in Figure 26. With contour sewing, it is only necessary to sew the outline of the designed figure, as shown in Figure 27. This sewing style has many advantages as it saves on materials, is highly efficient and is easy to design. The current flows along the thread of the contour as shown in Figure 27.

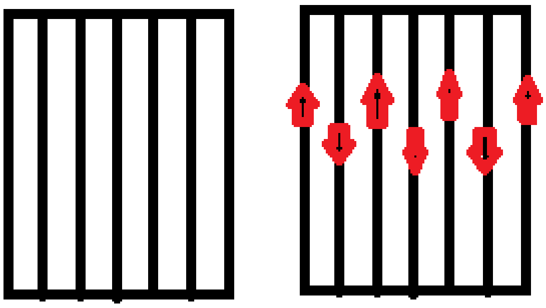


Figure 25. Vertical sewing.

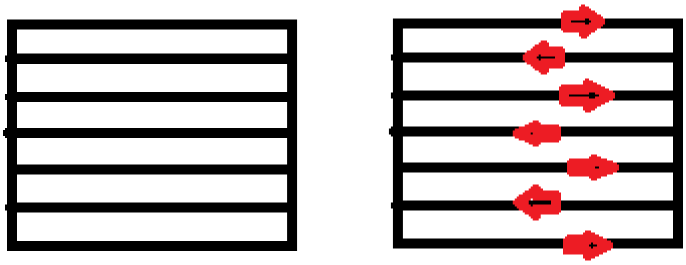


Figure 26. Horizon sewing.

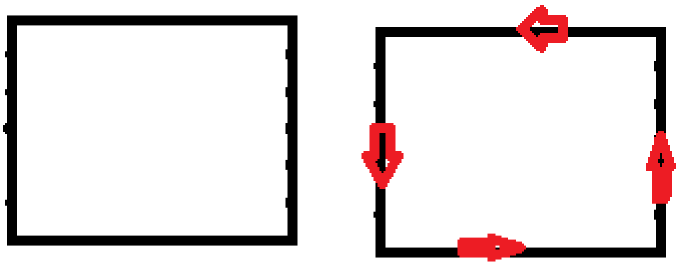


Figure 27. Contour sewing.

Some embroidered tags with different sewing styles are shown in Figure 28-29.

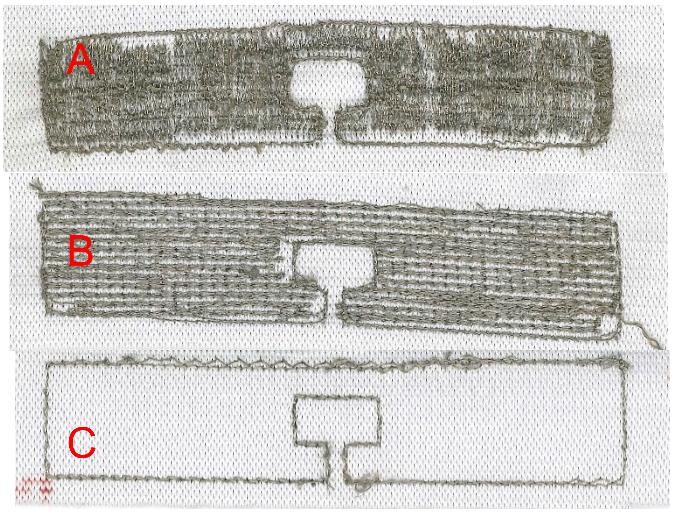


Figure 28. Ready-made embroidered tag by vertical sewing (A), horizontal sewing (B) and contour sewing (C).

Figure 29. Ready-made glove tag conductive face (left) and non-conductive face (right).

Figure 28 shows tags made using three different sewing styles. (A) shows vertical stitching, (B) shows horizontal stitching, and contour sewing is shown in (C). The wireless performance of the different sewing styles has been discussed with details in [Mor12]. As the result, the contour sewing reduced the wireless performance of the dipole antenna slightly. Since contour sewing requires much less conductive thread to fabricate an antenna comparing to the full-sewing antenna body, it is a method worth studying further. However, it cannot directly be used for example to fabricate a patch antenna, but different type of sewing patterns need to be considered. The wireless performance comparison of the different sewing tags will be discussed later [Publication II]. Figure 29 shows the an antenna embroidered directly onto a glove. This antenna combined contour and horizontal sewing methods. For example, a non-conductive bobbin thread was used to fabricate the embroidery structure for the inside face of the glove, as this face of the glove would bring the antenna into direct contact with the skin, which is conductive tissue. In this case, the non-conductive backing on the inside face of the glove protects the antenna from contact with the skin.

4.3 Other fabrication methods

4.3.1 Textile materials combination antenna

Figure 30 shows a dipole antenna manufactured from two different E-textile materials, copper E-textile and stretchable E-textile combined with conductive thread. This was utilized as a strain sensor. In this study, the antenna continued to work when stretched and was able to sense the length of strain. In this case, only the material used for the antenna body need be stretchable. In fact, the matching loop part needs to be stable to maintain the matching between the antenna and IC, and interconnection with the IC via the conductive glue. So, a non-stretchable material should be used for the matching loop part. In this study, the stretchable and non-stretchable E-textiles were combined by embroidery with conductive thread, which satisfied the requirements.

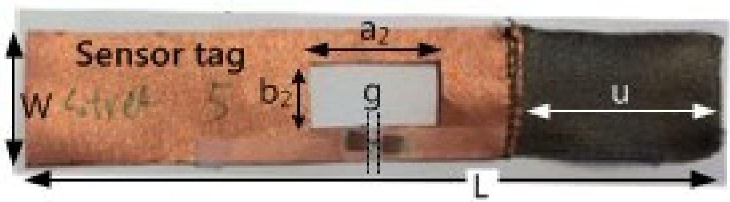


Figure 30. Two materials combination dipole antenna [Publication I].

4.3.2 Conductive paint

The conductive paint antennas used in this study were usually made by hand, unlike the copper tape antennas which had to be fabricated with a vinyl cutter. Laser cutting was not feasible because it needs such a high laser power output, so the (Summa D60R) vinyl cutter, in which an automated blade cuts out the outlines of the antennas on copper tape was used. Some ready-made tags are shown in Figure 31. The conductive paint tag was draw by hand on the cotton substrate to reveal the contours of the antenna. The thickness of the paint was about 1.5 mm and the surface resistivity of the conductive paint is approximate 55 ohms/square at 50 microns layer thickness [Bare]. The copper tape was cut by the vinyl cutter and then stuck on the EPDM substrate.

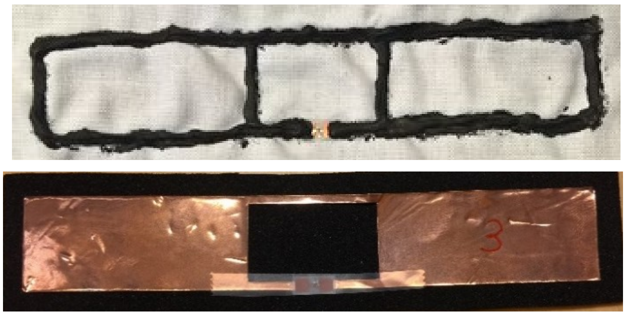


Figure 31. Ready-made conductive paint tag (top) and copper tape tag (bottom).

4.4 IC attachment

The RFID IC (integrated circuit) used in this study was the NXP UCODE G2iL RFID IC, provided in a fixture made of copper on a plastic film with 3 × 3 mm2 pads, as shown in Figure 32. The chip has a wake-up power of −18 dBm (15.8 μW) and based on a previous work [Bjö12] we modelled it as a parallel connection with a resistance and capacitance of 2.85 kΩ and 0.91 pF, respectively. A cross-section schematic diagram of the IC is shown in Figure 33. The plastic film is 45 μm thick and the total thickness of the IC is 55 μm.

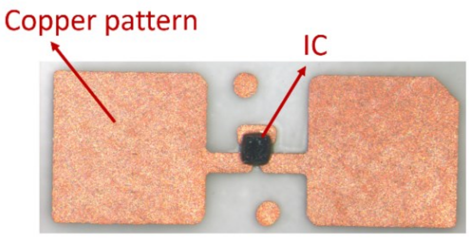


Figure 32. The IC used in this study.

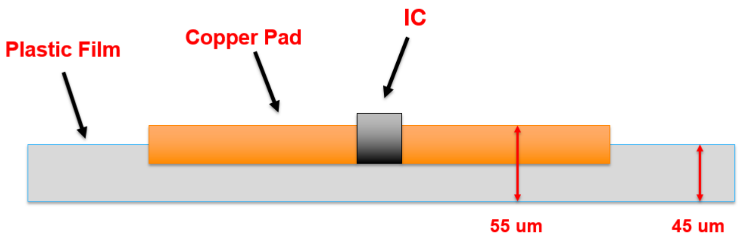


Figure 33. The structure of used IC.

The IC was usually attached to a textile antenna with conductive silver epoxy (Circuit Works CW2400). The IC can be embroidered directly onto an antenna body, and this method is discussed in [Publication II].

Some examples of IC attachments are shown in Figures 34-36. Figure 34 shows an IC stuck on with conductive glue; in this case it is glued to the antenna with conductive silver epoxy. Figure 35 shows a sewn-on IC attachment. The IC is sewn or embroidered onto the antenna with conductive yarn and without any glue. With the conductive paint antenna, the IC can be painted directly onto the antenna wire, as shown in Figure 36.

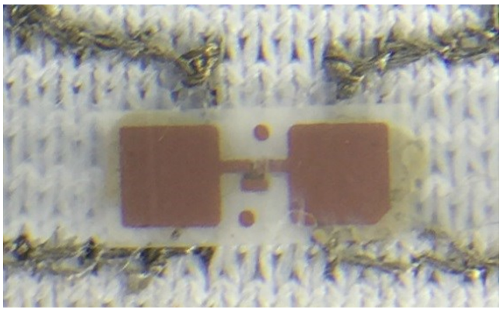


Figure 34. Magnified picture of glued IC by conductive glue.

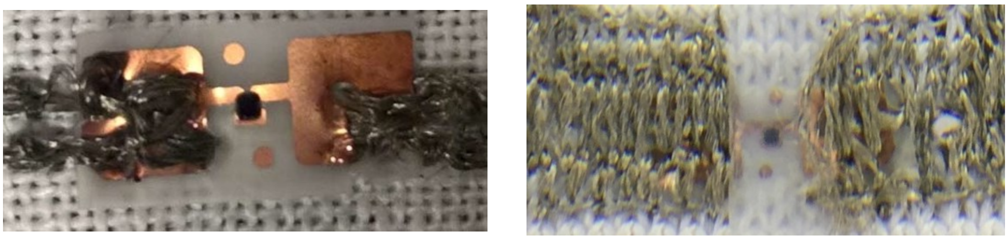


Figure 35. Magnified picture of embroidered IC with different embroidery methods.

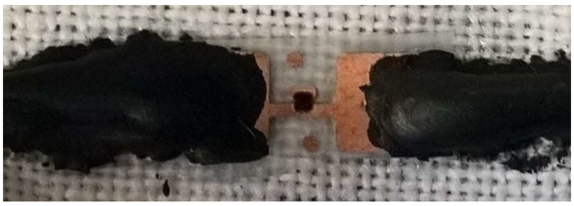


Figure 36. Magnified picture of IC covered by the paint directly.

In the both embroidery and direct paint structures, the IC was attached to the tag directly without conductive glue. For the conductive paint tag, the IC was located under the deposited conductive paint and then connected to the antenna body directly as shown in Figure 36. The embroidery tag embroidered the IC to the antenna body using conductive thread, as shown in Figure 35. Both these antenna fabrication methods were single-step and low-cost.

5 Measurements and Results

5.1 Measurements

The test measurements of the tags were carried out in a variety of environments to check their wireless performance under different conditions. In this study, all the tags were first measured in an anechoic chamber to obtain a standard for the wireless performance. The environment in the anechoic chamber can be considered as free space without interference, reflection, scatter or any multipath phenomena from the environment. This environment is similar to the simulation environment, so the measurements in the chamber could be used to test the fabricated tags' performance in comparison to the simulation results. Theoretically, these results should be very similar. Therefore, any mismatching results between the simulations and the chamber measurements should indicate any fabrication errors. However, the idea of this study is to test the tags in a real-world applications so after the chamber measurements our wearable tags were tested on-body in practical working environments, such as office. The backscattered signals of passive UHF RFID tags are noisy and unstable, and they are strongly affected by the environment and surrounding materials, which may affect the wireless performance of the developed tags. Thus, testing in an actual working environment is essential.

As the RFID standard frequency bands in different countries are usually within the 860 MHz to 960 MHz wavelengths, our tags were all measured on a frequency band which is included in the standard for most countries. In this study, the read range was usually the target parameter for assessing the performance of the antenna.

Normally, the read range of passive tags is limited by the forward link operation, i.e., the efficiency of the wireless power transfer from the reader to the tag IC. Assuming free-space conditions for site-independent comparison, the attainable tag read range (d_{tag}) at the spatial observation angles φ and θ of a spherical coordinate system centered at the tag in simulation is given by

$$d_{tag}(\phi,\theta) = \frac{\lambda}{4\pi}\sqrt{\left\{\frac{4\mathrm{Re}(Z_A)\mathrm{Re}(Z_{IC})}{|Z_A + Z_{IC}|^2}\right\}\frac{e_r D(\phi,\theta)EIRP}{P_{ic0}}}, \qquad (1)$$

where λ is the wavelength of the carrier tone emitted by the reader, EIRP is the regulated equivalent isotropic radiated power, P_{ic0} = -18 dBm is the wake-up power of the tag IC, e_r is the tag antenna radiation efficiency, *D* is the tag antenna directivity, and the factor in the curly brackets is the antenna-IC power transfer efficiency determined by the antenna and IC impedances Z_A and Z_{IC}, respectively. Equation (1) follows by combining Friis' transmission equation with basic circuit analysis where a generator (representing the tag antenna) with internal impedance of Z_A feeds the RFID IC. We present all the read range results corresponding to *EIRP* = 3.28 W (i.e. the emission limit in most European countries) in the direction normal to the antenna surface [Vir15].

In this study, all the tags and reader antennas are linearly polarized. During the test, we optimized that the polarization of the tags were parallel to the polarization of the reader antenna. Thus, the polarization loss will not be consider in the measurements. In the real life application, the human movement will affect the polarization direction of the tag. Thus, the linearly polarized reader antenna is not suitable in this condition. Instead, the circular polarized antenna with polarization loss factor could be used.

For the practical test, the manufactured tags were tested with a Voyantic Tagformance RFID measurement unit with the capability for power-frequency sweeps, as shown in Figure 37. It contains an RFID reader with an adjustable transmission frequency (0.8…1 GHz) and output power (up to 30 dBm) and provides a recording of the backscattered signal strength (down to - 80 dBm) from the tag under test. During the test, we recorded the lowest continuous-wave transmission power (threshold power: P_{th}). Here we defined P_{th} as the lowest power at which a valid 16-bit random number from the tag is received as a response to the query command in ISO 18000-6C communication standard. In addition, the wireless channel from the reader antenna to the location of the tag under test was characterized using a system reference tag with known properties. As has been described in [Vir15], this enabled us to estimate the attainable read range of the tag (d_{tag}) versus frequency from Equation (2)

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\Lambda}\frac{P_{th^*}}{P_{th}}}, \qquad (2)$$

where is the wavelength transmitted from the reader antenna, P_{th} is the measured threshold power of the tag, Λ is a known constant describing the sensitivity of the system reference tag, and P_{th^*} is the measured threshold power of the system reference tag. Here also, EIRP = 3.28 W [Vir14].

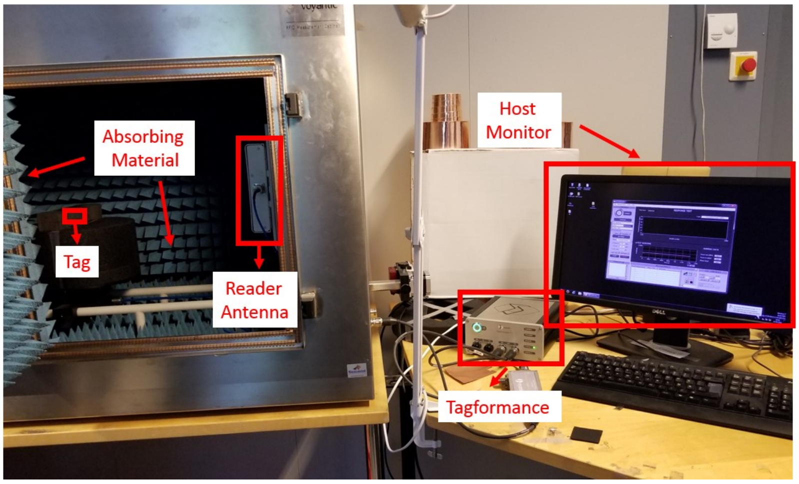


Figure 37. The Voyantic Tagformance RFID measurement system.

5.2 Sensor measurement results

All the sensors used for this study are self-sensing elements and do not need any extra sensor components. [Publication I] achieved novel referenced strain sensors for unambiguous readout. It presented two sensors, both based on a two-tag system, where one tag antenna is sensitive and one is insensitive toward strain. Both sensors were attested for strain sensing up 30 %. In the orthogonal configuration, the sensor featured a highly linear response, but in comparison with the linear configuration, it occupied a larger area. Further, [Publication VII] presented an embroidered moisture sensor tag made of dishcloth and conductive yarn. It was successfully tested with 10 drops of water. The performance of the sensor tag returned to the original status when the sensor structure was dry again. These kind of passive sensors have many advantages. They are lightweight, maintenance-free and their antennas can be fabricated from flexible conductive materials which makes them soft. Thus, they have great potential for the fabrication of wearable RFID devices.

5.3 Reliability testing and results

After the reliability tests, the wireless performance of the tags was analyzed in the anechoic chamber. This is because the focus of these studies was on the influence of stress conditions rather than the human body. In this thesis, mechanical, moisture and washing tests were performed on RFID made using different fabrication methods.

5.3.1 Mechanical testing

In [Publication II], the reliability of embroidery tags under stretching was studied. Five different embroidery methods were used on two different stretchable substrates. As shown in Figure 38, structures 1 and 2 had the fully-sewn antenna body. Structures 3 and 4 had higher-density embroidery near the feeding loop part since this part was known to have higher current density (in Figure 13). The contour sewing method was used to fabricate structure 5. The two embroidery methods with the best stretchability were selected to test the reliability of glued and sewn IC attachments, as shown in Figure 39.

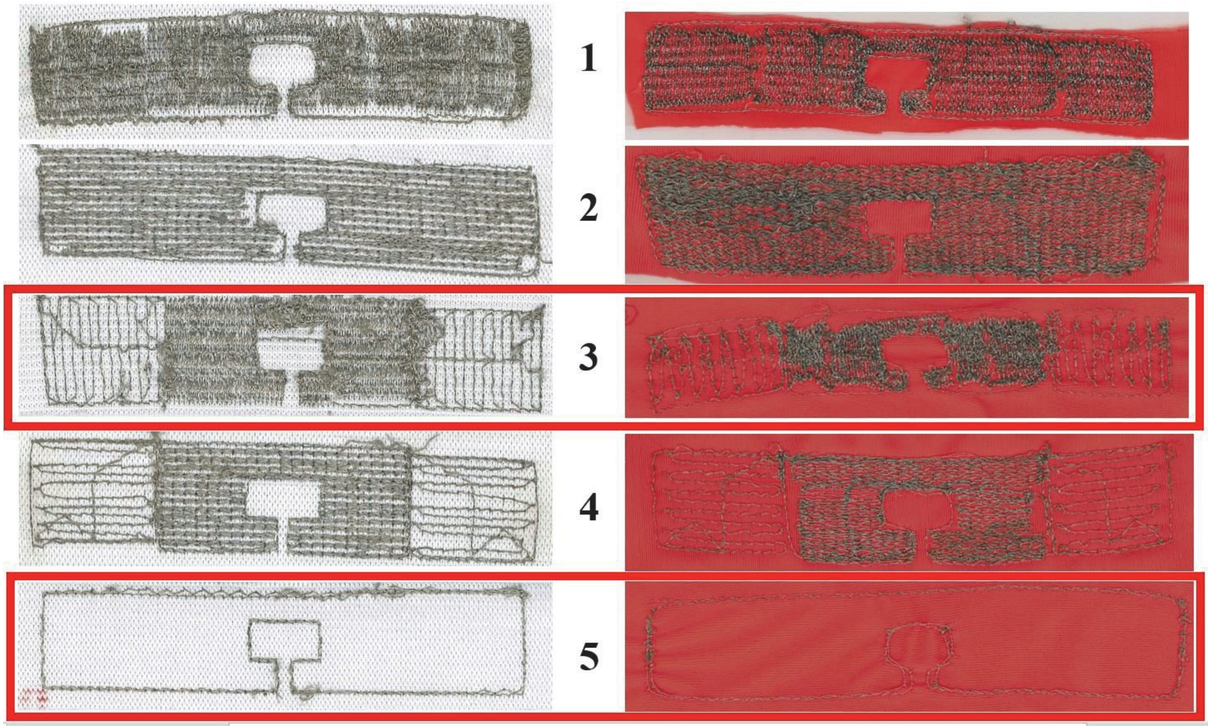


Figure 38. The 5 different antenna sewing patterns on both fabrics, as shown in [Publication II].

The results showed that the vertically stitched embroidered antenna was more stretchable in the horizon direction. Thus, tags 3 and 5, which can be stretched to 140% and 120% of their original length respectively in fabric 1 in Figure 38, were selected to test the stretchability of the antenna. Once the antenna body had been decided on, the IC was attached using two different methods, either sewn directly on to the textile or attached with conductive glue, as shown in Figure 39. Each tag was tested with 100 cycles of the strain test and both IC attachment methods had good stretch tolerance during the strain circles – they can still work after the stretching test. Although the glued IC seems to be more reliable according to the changes in the read range after 100 test cycles, there is more risk of it breaking during stretching, as can be seen in Figure 40.

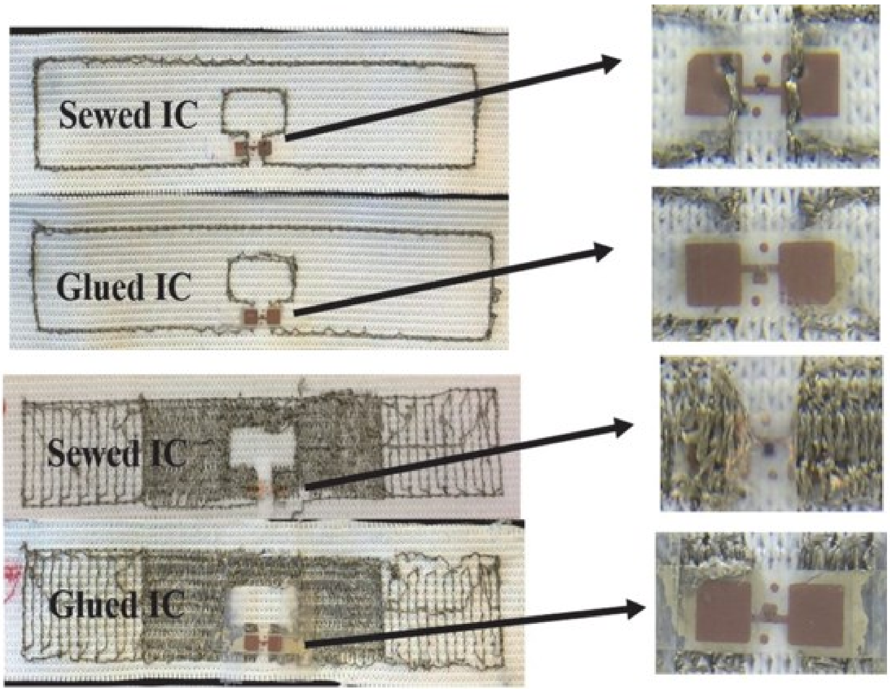


Figure 39. Different IC attachment methods: sewed and glued.

Figure 40. The broken IC interconnection [Publication II].

Another reliability study was presented in [Publication III] in which the two-part RFID tags were tested under mechanical stress to determine their reliability. All the tags were stretched 100 times to within 80% of their maximum strain and then allowed to contract. The wireless performance was measured after 1, 10, 20, 30, 40, 50, and 100 stretching cycles. The stretching was done by hand with each cycle lasting about 2 seconds. The tags were also tested several hours later after the last stretch circle, referred as “after rest” measurement. The E-textile and embroidery two-part tags, as shown in Figure 41, were fabricated for comparison with the one-part dipole tags. In the two-part tags, the radiation pattern was located separately from the feeding loop, so the IC was not affected by any environmental changes which occurred to the other part of the tag. For the E-textile antenna, the two seperated conductive parts were integrated in a EPDM foam substrate to hold them in the designed position. For the embroidered two-part antenna, the antenna body and matching loop were embroidered on different textile substrate materials, and then located on a EPDM foam for the measurements.

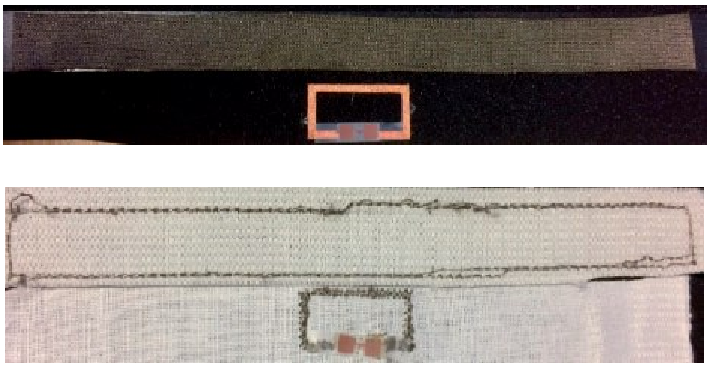


Figure 41. The E-textile two-part RFID tag (top) and embroidery two-part RFID tag (bottom) [Publication III].

In the stretching test, the one-part embroidered tags broke immediately when strained. For the E-textile one-part antenna, the stretching of the antenna also affected the read range significantly. The two-part antenna designs, however, can maintain high performance during continuous stretching as shown in Figure 42. The textile two-part tag underwent a slight change after the first stretch but then kept stable. As for the embroidery tag, the read range stayed totally the same throughout the strain test. In the future, we will also measure the wireless performance and read ranges of these tags when stretched to different lengths.

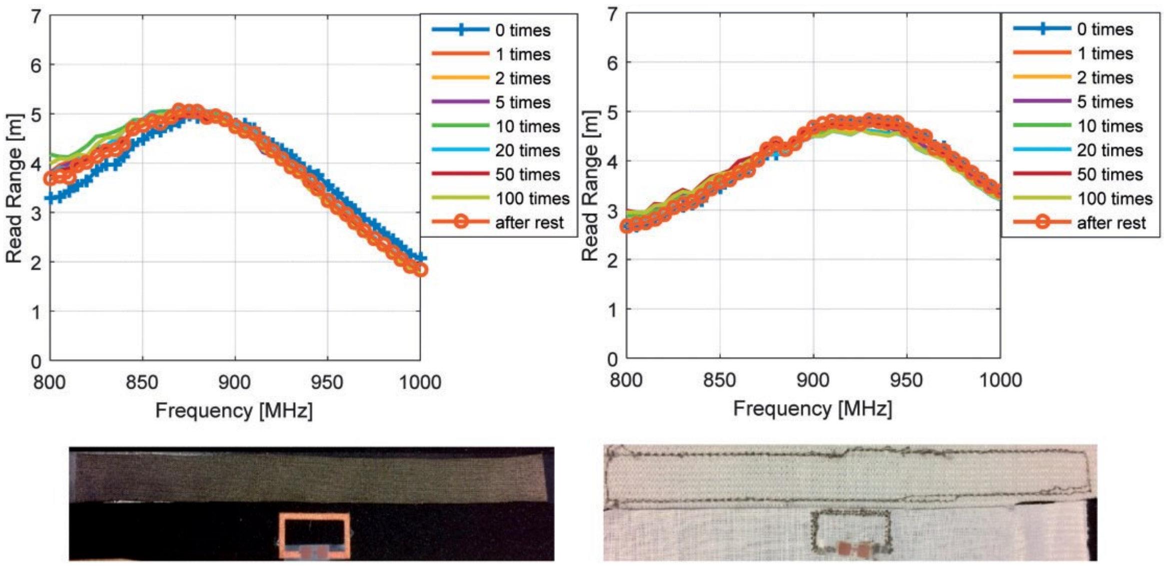


Figure 42. The measured results of two-part tags in stretching testing [Publication III].

5.3.2 Moisture testing

For the immersion test for the one-part and two-part tags, the read range of the tags was measured in their dry condition and then when they were wet. For the two-part antenna, the radiation part of the antenna, which is removable, was soaked into the water totally and then took out from the water. When they had dried again after being soaked, they were tested the third time. Based on our results, the high-humidity had a significant influence on the both E-textile and embroidered one-part tag and caused significant changes in the read range compared to the tag's performance in its initial condition. As the test results shown in Figure 43 illustrate, both types of two-part tags (E-textile and embroidered) showed stable wireless performance after soaking, and once they had dried their read ranges were almost back to the initial condition [Publication III].

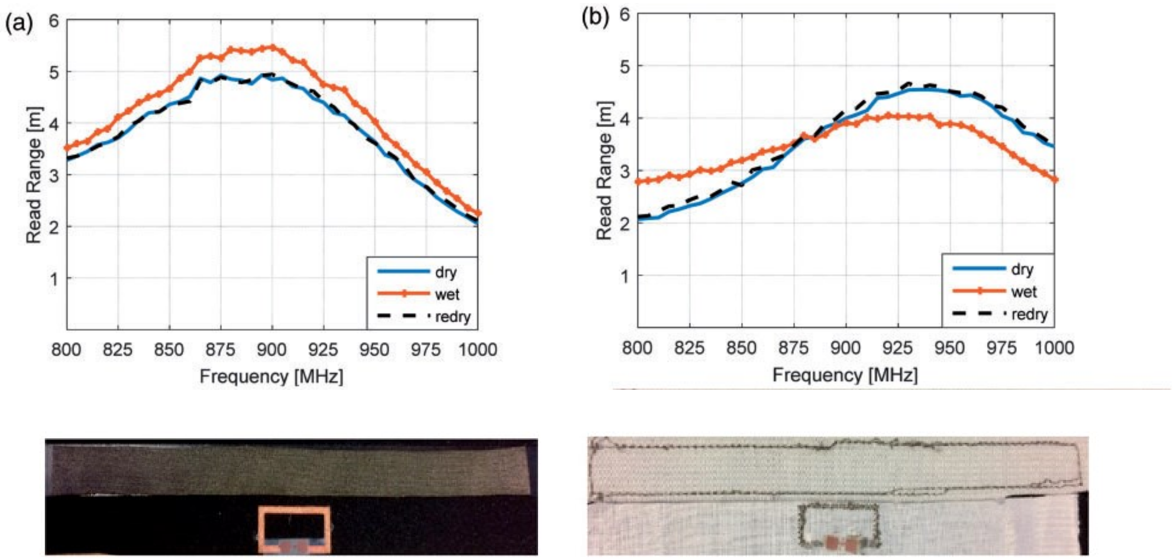


Figure 43. The measured results of two-part tags in moisture testing [Publication III].

Unlike the one-part tags, where the antenna-IC attachment is under stress, the two-part antenna designs can maintain high performance in a moist environment and during continuous stretching. They could be used in wearable applications, where textile-integrated RFID platforms need to be placed in a continuously strained or humid conditions, e.g. for monitoring movement or moisture.

5.3.3 Washing testing

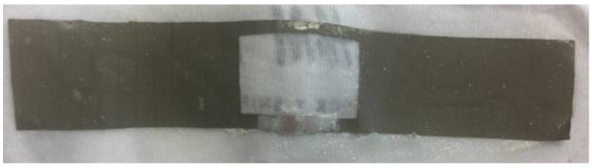
[Publication VI] took on-body measurements to test the antenna when worn by a human (on the back) and to test their washability. For the everyday garment-integrated wearable RFID device, its washbility is one of its most vital features. Three different antenna fabrication methods, 3D printing, E-textile and embroidery, were utilized in the study. Cotton cloth was used as the substrate for all the tags. The ready-made tags are shown in Figure 44. The tags were manufactured and then embedded into the back of an ordinary cotton T-shirt, as shown in Figure 45. Finally, to protect the fabricated RFID tags from the harsh environments produced in washing and drying machines, both sides of the tags were coated with a stretchable protective encapsulant (DuPont PE772). The coating was brush-painted to fully cover the tags and the coated tags were dried at 100 ºC for 60 minutes.

All the wireless test measurements were conducted with the same test subject wearing the target T-shirt at a distance of 1 meter from the RFID reader antenna. The read ranges of the tags were first tested in the anechoic chamber and then in an office on a human body to establish their initial condition, as shown in Figure 45. After one day's wear, the garment was washed at 40 ºC in a household washing machine. The tags were always attached on the T-shirt and washed in the washing machine together with the T-shirt. Each washing cycle lasted for 22 minutes without detergent. After washing, the T-shirts were dried at room temperature without any heat or draughts. The tags were measured after each washing cycle to test the wireless performance. The tag's reliability after machine-drying was also tested. After the 7 original washing cycles using drip-drying, the T-shirt was washed and then dried in an ordinary domestic tumble-drier for 1 hour and 30 minutes. A total of 9 washing + drying cycles were conducted on the tag, in addition to the 7 original washing cycles.

The initial read ranges of all the tags were around 3.5 meters when measured on-body in both an anechoic chamber and in an office environment. In the reliability tests, the electro-textile tags had a slightly better tolerance than the embroidery or 3D-printed tags in the washing and drying cycles. The read ranges of the electro-textile tags decreased by less than 0.5 meters after 7 washing cycles and 9 washing + drying cycles. The embroidered and 3D-printed tag antennas also fared quite well in the tests, although their read ranges had decreased by around 0.5-1 meters after the same number of washing and drying cycles. Nevertheless, all the tags showed good reliability during the tests as they all maintained read ranges of more than 2 meters, after being worn washed and dried multiple times. These results are very promising for the practical integration of passive RFID technology into garments.

The washability results for our tags are very promising when compared to earlier results. In [Fuy15], washing had a significant impact on the E-textile tags despite the use of different coating methods, non-coated, glue-coated, and textile moisture protection spray-coated. Comparing to their initial performance, the read ranges of these tags decreased by 3.5 meters, 2 meters, and 3 meters respectively, after 10 washing cycles in a washing machine. Moreover, in [Toi13], the non-coated embroidery tags were significantly influenced by the washing. Their read ranges decreased from 6 meters to 3 meters after 16 washing cycles. Although the coated tag studied in [Kaz16] using regular textile glue (Gutermann Creativ HT2) could withstand repeated washing, the coating materials were thick and not that flexible. The comparisons indicate that the protective coating utilized in this work could protect textile-integrated RFID tags during normal use.

(a)



(b)

(c)

Figure 44. The fabricated tags integrated into T-shirts: (a) 3D printed tag antenna, (b) Electro-textile tag antenna, (c) Embroidered tag antenna [Publication VI].

(a) (b)

Figure 45. Wireless measurements done in (a) Anechoic room, (b) Office conditions [Publication VI].

5.4 Body-centre testing and results

The on-body test is a vital parameter for measuring a tag's wireless performance. The tags, which were designed to be attached to different parts of the body, were tested in an anechoic chamber and/or in a practical working environment, such as an office. In [Publication IV], dipole antennas made with embroidery and conductive paint (Figure 46) were fabricated in order to compare the simulation results with the different sheet resistances of the conductive materials.

As the result, the read ranges of the embroidered and painted tags in air were 5-to-6 meters and 3.5-to-4 meters, respectively. For the on body measurements, the tag was attached vertically to the upper back, centered between the shoulder blades. The painted and embroidered tags achieved read ranges of 1 meter and 2 meters, respectively, which can meet the requirements for many wearable applications. In conclusion, the contour antenna design was shown to be more cost-effective and less time-consuming to fabricate than the full-printed antenna body design. Furthermore, this structure can be easily made with good wireless performance using different fabrication methods. The conductive paint does not require sintering, and can thus also be considered as an attractive alternative. Both methods enable the manufacture of textile RFID tags, including the antenna-microchip interconnection, in a single-step process.

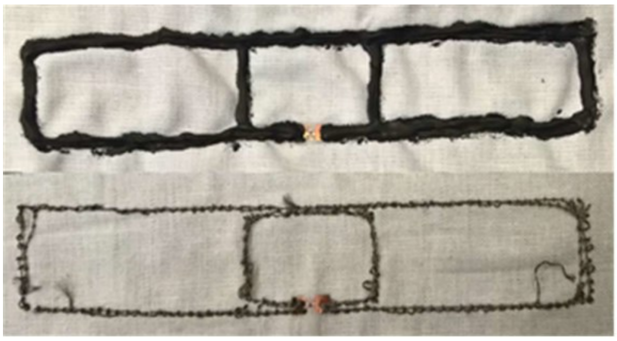


Figure 46. Ready-made tags of conductive paint (top) and conductive yarn (bottom) [Publication IV].

In addition to garments, RFID-based systems have been fitted on footwear, as well as on different types of gloves [Jun09] [Mug09] [Lee10] [Che17]. Another on-body measurement was carried out with an RFID tag integrated onto a normal working glove in [Publication VIII]. These "glove-tags" offer diverse possibilities for identification, access control, and possibly for antenna-based sensing. They could be especially useful in safety-critical working environments. In this case, the antenna was designed to the size shown in Figure 16. The long edge of the antenna was 76 mm, which could easily be integrated onto the back of a glove. The antennas were fabricated by three different methods: embroidery, E-textile material and copper tape, which was used as the reference tag. The ready-made tags are shown in Figure 47. It is especially of note that two different embroidery threads were used in the manufacture of the tags, one conductive and one non-conductive. At the upon side, the conductive thread was used to fabricate the antenna body on the upper face of the glove while the non-conductive thread was embroidered on the inside of the glove, where the embroidered figures are in direct contact with the skin on the back of the wearer's hand. This approach prevents the antenna from coming into direct contact the skin, which is conductive tissue. The measurements were performed by a test subject wearing the glove both in an anechoic chamber and in an office.

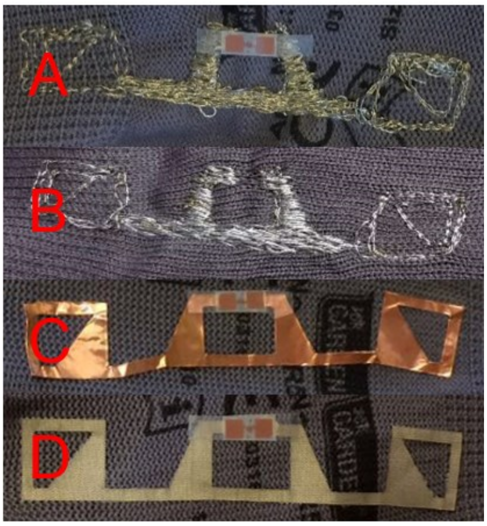


Figure 47. Ready-made glove tags. A: Embroidered antenna (top side of the glove, conductive thread), B: Embroidered antenna (inner side of the glove, non-conductive thread), C: Copper tape reference antenna (top side of the glove), D: Electro-textile reference antenna (top side of the glove) [Publication VIII].

As for the results, the read ranges of the embroidered glove-tags were around 1 meter, when the glove was worn and measured near the human body. Although these read ranges are shorter than those of the electro-textile and copper tape tags, which had read ranges of 2 to 2.5 meters under the same conditions, the embroidered glove tags do meet the requirements of many practical applications for glove-tags.

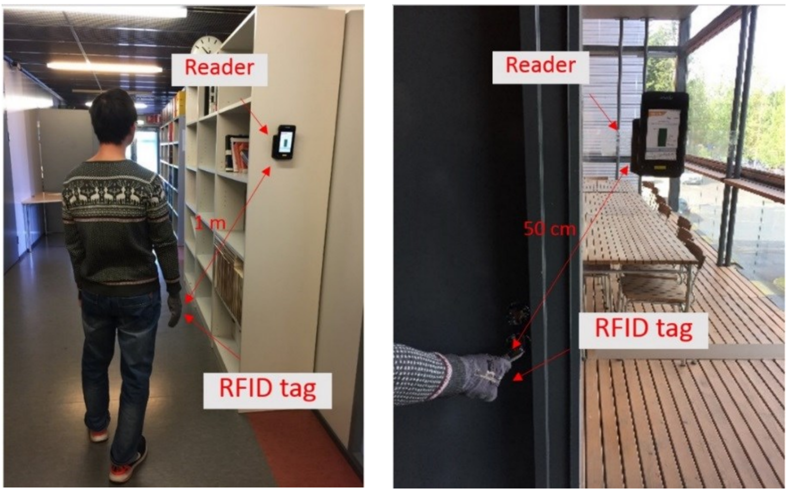


Figure 48. Practical evaluation of glove-tags: identification (left) and access control (right) [Publication VIII].

For the practical applications shown in Figure 48, a commercial mobile reader could be used to create a glove-based RFID tag system. In our tests the reader was located next to a shelf in a corridor and the male test subject walked past the reader. The distance from the glove-tag to the reader was about 1 meter and the reader was placed at a height at which the wearer was able to see the reader display with ease. The reader was able to recognize all the glove tags successively. By preinstalling the locations of the readers according to a suitable pattern, the system can identify a passing person wearing the glove-tag and map their walking path. This application could be used in a variety of working environments, for example in a factory or in a warehouse. Next, the reader was placed at a distance of 50 cm from a door handle, in order to test an automatic authentication system for access control. The reader was also able to read all the glove-tags in this configuration. Based on these preliminary results, the glove-tag developed here could be used for various applications aimed at promoting easier and safer working and living environments.

Figure 49. The test of different cloth layers. A: T-shirt, B: thin winter coat added, C: thick winter coat added [Publication IX].

This thesis has also investigated the influence of the clothes worn by the tagged subject. Such a test was conducted in [Publication IX], where the effects of different layers of clothing over the tag were tested. The tags were integrated onto T-shirt worn by a male test-subject under a thin jacket and a down jacket, as shown in Figure 49. The E-textile tag antennas were ironed on to the upper back of the cotton T-shirts and coated with the same stretchable coating material. The wireless performance of the tags was evaluated on-body in practical office conditions. Based on our measurement results, adding a thick coat on top of the T-shirt does not stop the tag from working, although it does reduce the peak read range from 7 meters to 5 meters. The fabricated electro-textile tags remained readable from distances of 2-5 meters, throughout the global UHF RFID frequency band, even when a thick winter coat was worn on top of the T-shirt.

6 Discussion and Conclusions

In the future, we will all be part of the Internet of Things (IoT) as sensing and computing devices embed themselves into everyday objects. These intelligent objects sense, interpret, and act on their environment. They communicate and exchange information with each other and with people. WBAN systems based on the human body will soon become established as commonplace ways to monitor human physical parameters, as well as path tracking, and for establishing the health and wellbeing of elderly and vulnerable citizens. As the features of passive UHF RFID tags include low-power and battery-free. Passive UHF RFID is one of the most promising candidates for this role technology. By utilizing passive UHF RFID wearable components, a low-cost long-range wireless system can be achieved unobtrusively. Furthermore, the RFID tag can also work as a self-sensing component to detect the changes to the attached object without needing to connect to a sensor device.

In this thesis, different structures for RFID antenna were fabricated, measured and evaluated in anechoic chamber, in a practical office environment and on the human body. The reliability of these RFID tags were also tested under strain, moisture and washing conditions.

6.1 Discussion

The passive UHF RFID tags presented in this thesis show promising read ranges of more than 1 meter when attached to different parts of the human body, which meets the requirements of many sensing applications, such as on-body strain and moisture sensing. RFID sensors with different functions were evaluated and tested. In [Publication I], the reference tag for the strain sensor tag is an innovative method for calculating the length of the stretch. Another stretchable sensor were introduced in [Lon16] but although the tag was stretchable and reliable after the stretch, the degree of elongation could not be determined. In [Lon15] [Mer11], the strain sensor tag was fabricated without a reference tag. Thus, the real-time environment cannot be determined and the stretching length of the sensor tag cannot be detected accurately. In [Publication I], the reference tag was introduced for the precious elongation measurement which had 2 mm resolution. Furthermore, a very low-cost moisture sensor was introduced in [Publication VII]. The RFID sensor tag was fabricated from conductive thread embroidered on to a dishcloth substrate. As the result, the sensor tag can detect any water dropped on to the sensor part of the structure.

Several challenges from previous studies of wearable devices have been resolved in this thesis, including RFID tags that can perform well under mechanical stresses, high-humidity environments and repeated washing.

The first challenge was the mechanical stress problem of wearable devices. A textile antenna was tested on a bending gauge (75-mm diameter) in [Loc06], but that does not replicate the daily on-body movements required for a wearable RFID tag. To make the tags more comfortable to wear, [Kio14] introduced a stretchable E-fiber antenna working at 915 MHz. However, this study only involved a flexible antenna design with a non-wearable signal source connected to the antenna by wire. A flexible graphene-based RFID textile tag, which remained readable even after 100 harsh bending cycles, was studied in [Akb16]. However, the tag failed after the first stretching cycle since cracks appeared in the printed antenna body after one stretch. The IC-antenna interconnection may also be broken during the stretching as the experiments in [Heh18] showed. In contrast, this work has introduced several antenna designs and fabrication methods, which provide the required flexibility and stretchability with lightweight materials [Publication II].

It is also challenging to produce tags which can operate in a high-humidity environment. Moisture usually affects the wireless performance of electronic components [Jia16] and sweat, for example, can affect the performance of an unprotected tag. Both electromagnetic parameters, relative permittivity and the loss tangent of the textile materials increased with increasing relative humidity of the environment in which the antennas operate [Her09]. For example, an E-textile patch antenna on a cotton fabric substrate suffered from a notable shift in its operation frequency due to moisture [Her10]. In addition, the IC-antenna attachment point had a slight gap (usually 2 mm in our antenna design) which was easy to cover by water drops when working in a high humidity environment. In such cases, the water may short-circuit the IC or even destroy it. In several antenna designs, such as the tag designs in [Man12] [Toi13], the tags were designed with the IC exposed to air. Those designs frequently suffer from broken ICs or interconnection problems when used in a practical working environment. The two-part tag introduced in [Publication III] provide a solution for IC protection in a high-humidity environment, as well as mechanical stresses. The IC is placed on a separate part of the tag, near the antenna radiation pattern, which needs to withstand under harsh conditions and sense changes in the environment. With a two-part tag, the IC can be protected without changing the physical features of the radiating antenna.

The final, and perhaps greatest challenge was to fabricate machine-washable wearable RFID tags. The mechanical stresses that occur in a washing machine may easily break the IC [Wan15]. In [Kel12] [Bjö14], the RFID tags were coated in plastic and tested in a washing machine. These studies showed that the read ranges of the tags were clearly attenuated by the washing circles. Another wash resistant coating material was studied in [Kaz16]. Although this material did protect the tag during repeated washing cycles, the coating layer was thick, rigid and non-stretchable. In [Publication VI], the T-shirt-integrated tags were made with a stretchable coating and then tested after 16 washing cycles and 9 drying circles. The tags were still highly reliable after all the experiments, which shows that our RFID tags can not only withstand the everyday stresses of human body movement but can also endure the extreme mechanical stresses of washing machines and driers.

This thesis provides several integrated solutions for wireless, wearable RFID devices and gives some promising solutions for improving their reliability. These wearable devices can be made at low cost and are robust enough for everyday use in a practical environment. This thesis shows that textile-integrated wearable sensors systems are already cheap and reliable enough to be put to increasing practical use in different environments, such as the hospital, the office or the home.

Future research will focus on building wearable RFID systems and designing antenna self-sense sensors. To establish the integrated wearable RFID sensing system in practical environment, off-the-shelf RFID readers can be utilized for practical measurements. The host computer of such a system can be connected to mobile devices, such as a tablet, for convenient daily use. These systems could be utilized to monitor human movements, but there are also many other possible applications, such as temperature, body fluid monitoring and monitoring vital signs which integrated sensor components. The accuracy of the sensing systems could be improved by optimizing the antenna design, utilizing multiple readers and trying out new fabrication methods.

6.2 Conclusions

The main conclusions of this thesis are listed below:

- Passive UHF RFID technology is one of the most promising candidates for future WBAN systems because of its low-cost, long-range and battery-free features. By utilizing E-textiles and conductive thread, the kind of flexible, reliable and lightweight RFID tag antenna required for wearable devices can easily be fabricated. This study has shown that such RFID tags can be integrated into different types of clothing, especially on gloves.
- Two lightweight and cost-effective passive RFID sensors, a moisture sensor and a strain sensor, were fabricated from textile materials. The reference tag was subjected to an RFID

stretching measurement system, and can sense the elongation of the attached object to within 2 mm.

- Different wireless performances can be achieved by using different embroidery methods (vertical, horizontal and contour sewing). Contour sewing, which does not require the full antenna body to be embroidered on the tag saves both material and time, and has a good read range. On a stretchable textile substrate, an embroidered antenna can be stretched to at least 120 % of its original length without any loss in performance when back to the original length.
- The IC attachment is a vital part of the RFID tag. For one-part dipole antenna design, a sewn IC interconnection by conductive yarn is more reliable than a glued one under stretching conditions. Furthermore, a two-part antenna has the feeding loop attached to the IC and the radiation body in two separate parts. Thus, the IC part can be protected from environmental changes which may happen to the radiation body part. For the one-part RFID tag, while environmental changes, such as mechanical stress and humidity, do affect the antenna body, the matching between the antenna and IC may change correspondingly, and thus influence the antenna's performance. In addition, the IC may also fail if the sensed environment is high-humidity or high-stress. The two-part structure design allows the antenna-IC attachment to be unaffected as long as the small feeding loop part is integrated into a rigid structure. In this case, the radiating antenna body can still be flexible, which it often needs to be in order to withstand mechanical stresses.
- Obviously, coating the antenna helps to improve the reliability of the wearable tags. The stretchable protective encapsulant coating material used in this study can protect the tag during daily machine washing and heating cycles when integrated onto an ordinary cotton T-shirt. To the best of our knowledge, this is the first time a stretchable coating material has been used in the manufacture of wearable RFID antennas.

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ORIGINAL PAPERS

Publication I

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Passive E-Textile UHF RFID based Wireless Strain Sensors with Integrated References

Xiaochen Chen, Leena Ukkonen, *Member IEEE*, and Toni Björninen, *Member IEEE*

***Abstract*—Highly stretchable e-textile antennas enable wireless strain sensing based on passive UHF RFID tags. We present two sensors both based on a two-tag system, where one tag antenna is sensitive and one is insensitive toward strain. This way, we achieve novel referenced strain sensors for unambiguous readout. We outline the antenna system development to achieve high EM isolation between the tags and present results from the wireless testing of the sensor.**

***Index Terms*—Wireless strain sensors, electro-textiles, conductive threads, dipole antennas, antenna coupling, RFID**

I. Introduction

The mechanism of modulated scattering utilized in passive radio-frequency identification (RFID) tags enables digital ultra-low-power radio communication over the distance of several meters. This makes the passive RFID-enabled sensor tags a compelling approach to the internet of things (IOT) [1].

Examples of sensor tags include gas [2–3], humidity [4], temperature [5], and strain sensors [6–7]. In all of these works, the sensing mechanism is based on antenna-sensor structures whose EM properties are altered by the monitored environmental parameter. This enables the very low-complexity devices desired in IOT applications. Still, the shortcomings in the current state-of-the-art are the lack of a reference readout and degradation in the sensor readout distance due to antenna detuning caused by alterations in the EM properties of the antenna. Recently, two approaches to remedy this have been investigated: the readout from the backscattered signal strength [7] and establishment of a stable reference state by using a reconfigurable antenna [3]. However, the sensor [7] lacked an embedded reference and in [3] the sensor readout was based on monitoring the detuning of the antenna and the implementation of the switch required for the referenced readout was reserved as future development.

In this work, we present two RFID-enabled strain sensors which provide referenced readouts. The sensors are based on the backscatter readout mechanism presented in [7]. The novel referenced readout is achieved through the EM optimization of a coupled two-tag system where one tag is made sensitive and one insensitive toward strain.

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Xioachen Chen, Leena Ukkonen and Toni Björninen are with Tampere University of Technology, Tampere, 33720 Finland (e-mail: toni.bjorninen@tut.fi).

II. Sensor Development

The sensor and reference tags are both based on dipole antennas with embedded inductive matching loops as shown in Fig. 1. This is a widely used antenna type in RFID tags [6–7]. The reference tag is made of non-stretchable Copper plated Polyester textile (Less EMF Cat. #A1212) whereas non-stretchable and stretchable (76% Nylon and 24% elastic fiber; Less EMF Cat. #A321) textiles were used in the sensor tag (Fig. 1). Elongation in the stretchable section modifies the EM properties of the tag and enables the sensing functionality. The stretchable and non-stretchable parts were connected using a sewing machine and metal plated sewing thread.

As in [7], the aim was to establish the sensor readout based on the backscatter strength. In an anechoic space, the backscattered power at the reader antenna at distance d from the tags is given by

$$P_{rx} = \frac{1}{4}|\rho_1 - \rho_2|^2 \left(\frac{\lambda}{4\pi d}\right)^4 G^2 G_{read}^2 P_{tx} \quad (1)$$

$$\rho_k = \frac{Z_{ic,k} - Z_a^*}{Z_{ic,k} + Z_a}; k = 1,2, \quad (2)$$

where P_{tx} is the continuous-wave output power of the reader, G and G_{read} are the gains of the tag antenna and reader antenna, respectively, and ρ_1 and ρ_2 denote the antenna-IC power reflection coefficient in the energy harvesting ($Z_{ic,1}$) and modulating ($Z_{ic,2}$) impedance states of the IC, respectively [7]. For simplicity, equations (1–2) assume tag antennas to be co-polarized with a monostatic RFID reader.

Based on (1–2), for effective operation, the sensitivity of the gain of the sensor tag antenna toward strain should be maximized and simultaneous the reference tag's gain should remain approximately constant. Also, both tags should maintain good complex-conjugate-matching with the RFID IC to maximize the sensor readout distance. A fundamental challenge in the sensor optimization is the EM coupling between the antennas in the sensor and the reference tags. This alters their input impedance and radiation properties as compared with isolated antennas. For this reason, a two-antenna system must be considered.

We used ANSYS HFSS (full-wave EM solver based on the finite element method) to model the antenna system. The two different configurations shown in Fig. 1 were found promising in minimizing the coupling. In the final optimization, the geometrical parameters of the antennas were adapted to yield high read range and maximal variation in G^2 of the sensor tag's antenna. The target frequency of the sensor's readout was 866.6

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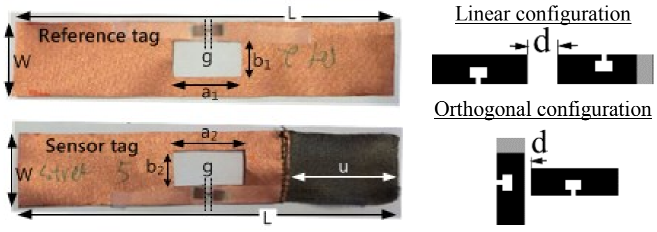


Unit mm	a_1	b_1	a_2	b_2	g	L	W	d	u
Linear	18.7	10	18.6	9.73	2	100	20	20	30
Orthogonal	17.3	10	17.3	10	2	100	20	5	30

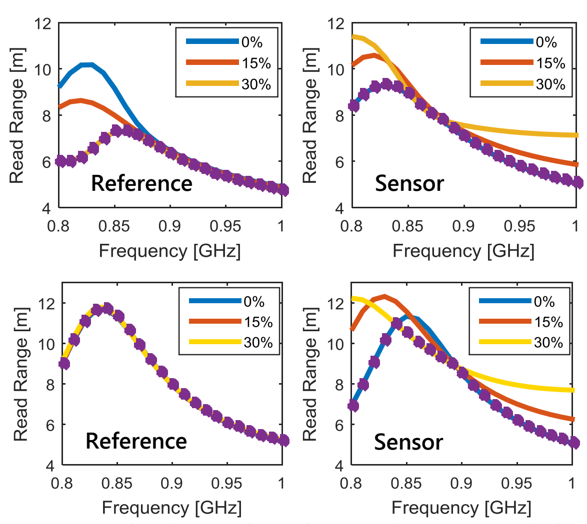
Fig 1. Samples of manufactured tags and studied sensor configurations.

MHz which is the center frequency of UHF RFID band in European countries.

Fig. 2 shows the read ranges of the sensor and reference tags obtained by varying the sensor tags physical length in the HFSS simulation. In contrast to [7], here the read range was obtained by considering the input impedances of coupled antennas instead of isolated ones. As the optimized antennas in Fig. 1 are slightly dissimilar, also the tag read ranges differ even in the absence of strain. In the linear configuration, the read ranges of the sensor and reference tags remained approximately constant at 866.6 MHz with the overall sensor readout distance of 7.2 meters, which is limited by the reference tag. In the orthogonal configuration, the antenna coupling effect is smaller and hence the read range of the reference tag is virtually unaffected by the strain at all frequencies. The antenna elongation changes the read range of the sensor tag, but overall the sensor maintains high read range of 10 meters at 866.6 MHz, which in this configuration is limited by the sensor tag. The G^2 parameter of the reference tag remained almost constant versus strain, as desired, and showed a linear increase for the sensor tag.

III. Results from Wireless Testing

In the real application environment, the reference tag enables the compensation of the possible contribution of multipath propagation from the strain readout since the signal from the reader to the closely spaced tags travels approximately through



Fig, 2. Simulated read range of the reference and sensor tags in the linear (top) and orthogonal (bottom) configurations. Markers highlight the minimum read range for all strains up to 30%.

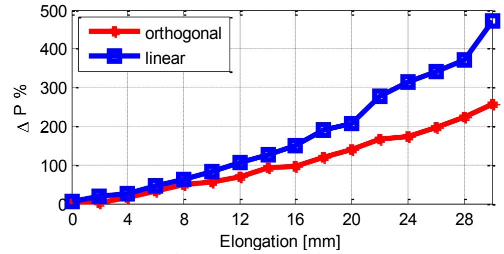


Fig 3. Sensors' measured response to strain.

the same channel. In this work we explore the sensor readout based on the percentage variation in the backscattered signal strength of the sensor tag with respect to the references defined as $\Delta P\% = (P_{sns}-P_{ref}) / P_{ref}$, where P_{sns} and P_{ref} are the received signal powers of sensor and the reference tags, respectively.

Measurement of the backscattered power was conducted with the Voyantic Tagformance measurement system. The measurement system and set-up are the same as described in detail in [7]. To avoid colliding responses from the two tags, we addressed the *query* command specifically to the sensor and reference tag IDs. As seen from Fig. 3, $\Delta P\%$ increased monotonically with the strain in both configurations and in the orthogonal configuration the response was highly linear. Thus, the elongation of the sensor tags can be unambiguously associated with $\Delta P\%$. Moreover, the strain increased P_{sns} for both sensors and it remained larger than P_{ref}. Therefore, the strain is not limiting the signal detection at the reader.

IV. Conclusion

Stretchable e-textile enables strain-sensitive antennas for passive UHF RFID tags. By including a non-stretchable reference tag and optimizing the two-antenna system we have demonstrated two wireless strain sensors with integrated references. They provide strain readout with regular unmodified RFID reader hardware. Both sensors were attested for strain sensing up 30%. In the orthogonal configuration, the sensor featured a highly linear response, but in comparison with the linear configuration, it occupied a larger area.

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Publication II

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Research Article

Experimental Study on Strain Reliability of Embroidered Passive UHF RFID Textile Tag Antennas and Interconnections

Xiaochen Chen,[1] Aruhan Liu,[2] Zhigang Wei,[2] Leena Ukkonen,[1] and Johanna Virkki[1]

[1]*Department of Electronics and Communications Engineering, Tampere University of Technology, P.O. Box 692, 33101 Tampere, Finland*
[2]*Department of Electronic Engineering, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon, Hong Kong*

Correspondence should be addressed to Xiaochen Chen; xiaochen.chen@tut.fi

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We present embroidered antennas and interconnections in passive UHF RFID textile tags and test their strain reliability. Firstly, we fabricate tag antennas on two different stretchable fabric substrates by five different embroidery patterns and choose the most stretchable ones for testing. Next, the tag ICs are attached by sewing and gluing, and the tag reliability during repeated stretching cycles is evaluated through wireless measurements. Initially, the chosen tags achieve read ranges of 6–8 meters and can strain up to 140–150% of their original length. After 100 stretching cycles to 80% of their maximum strain, the read ranges of the tags with glued interconnections are similar to the initial values. In addition, also the read ranges of the tags with sewed interconnections are still more than 70%–85% of their initial values. However, some challenges with the reproducibility need to be solved next.

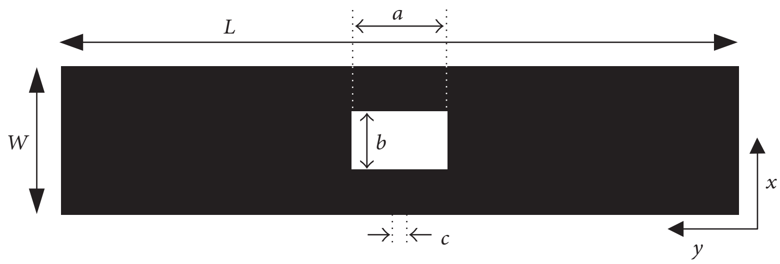
1. Introduction

Passive UHF (ultra-high frequency) RFID (radio frequency identification) inspired technology has been recognized as a compelling approach to achieve versatile energy efficient wireless technologies for future WBANs (wireless body area networks) [1–4]. The development of WBAN technologies has gained a lot of research attention during the recent years as they can offer remarkable benefits for healthcare and welfare sectors [1–5], as well as novel sports-related applications [5, 6].

Light-weight, flexible antennas and interconnections are needed for these versatile wireless systems and wearable applications also require the antennas and interconnections to be an integral part of clothing. In addition, antennas and interconnections in wearable applications need to endure different mechanical stresses, such as bending and stretching. Additive manufacturing methods have been found to provide the foundation for these novel applications, as they have the capacity to produce conductors on soft and stretchable materials, such as textiles [7–9]. One highly potential additive textile antenna fabrication method is embroidery with conductive yarn. Sewing is a simple manufacturing method with great possibilities due to its compatibility with various textile materials [9–13]. In embroidery, we have a full control of the conductive pattern: shape, stitch density, and stitch type [9]. In addition to conductor and antenna fabrication, sewing has also been found to be a highly potential method for embedding electrical interconnections into textile materials [9–13].

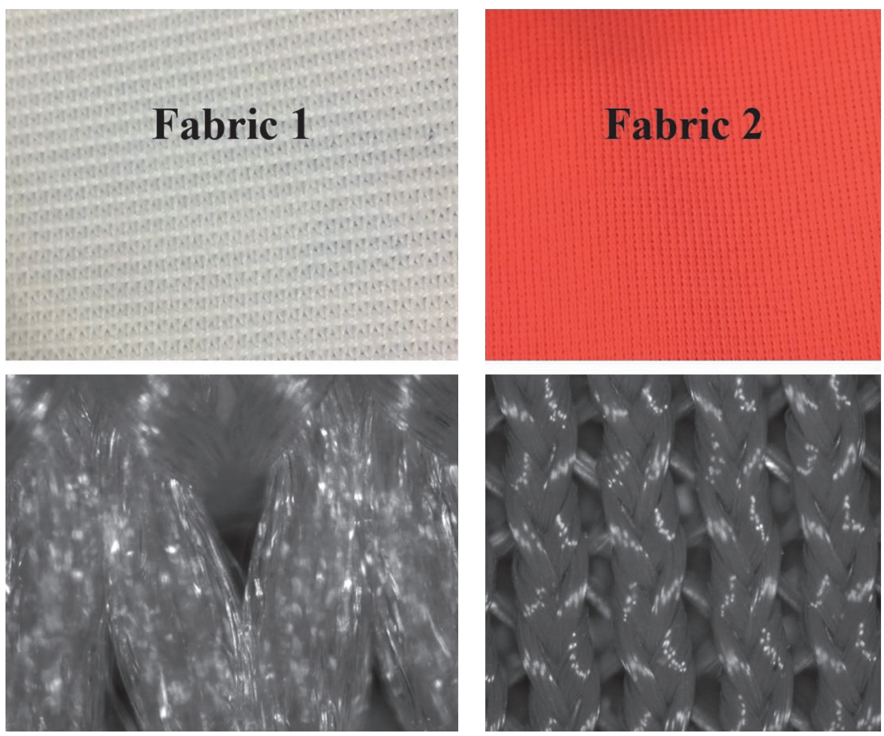
The effects of the antenna sewing pattern on the tag performance have been previously studied in [9, 14]. Also the strain reliability of sewed interconnections in general has been recently studied [15]. However, to the best of our knowledge, this is the first strain reliability study of embroidered RFID tag antennas and interconnections. During normal movement, the human skin may stretch up to 15%–20%, which means we need to implement antennas and interconnections that function well at least under such elongations [16].

In this study, dipole antennas for passive UHF RFID tags were embroidered on two different stretchable textile materials. After choosing the most suitable textile substrate and sewing patters, stretchable tag antennas were fabricated



Geometrical parameters in millimeters				
L	W	a	b	c
100	20	14.3	8.125	2

Figure 1: The tag antenna geometry.



(a) (b)

Figure 2: Photos and microscope pictures of Fabric 1 (a) and Fabric 2 (b), magnification ×5.

by embroidery, tag ICs were attached by sewing and by gluing, and the tag reliability was tested under cyclic strain. The performance of the tags before and after testing was evaluated by wireless measurements.

2. Tag Fabrication

The studied tag antenna (shown in Figure 1) is a straight dipole, which is a widely used antenna in UHF RFID tags. This antenna has been successfully used in several UHF RFID studies [7, 8] and it originated from a strain reliability study of stretchable electrotextile and screen-printed tags [17].

The tag antennas were fabricated on two different stretchable fabrics (Fabric 1 is an elastic band and Fabric 2 is a mixture of viscose and polyester), by using five different embroidery patterns. The two fabric materials are shown in Figure 2. The used thread was multifilament silver plated thread (Shieldex multifilament thread 110f34 dtex 2-ply HC). The DC linear resistivity of the thread is 500 ± 100 Ω/m, and the diameter is approximately 0.16 mm.

The simulated amplitude of the surface current [A/m] on the dipole antenna at 915 MHz is shown in Figure 3. In the simulation, 0.62 W was delivered to the antenna. As can be seen, the current density at 915 MHz was high around the embedded inductive matching loop and the nearby antenna edges. Two of the studied embroidery patterns were fully embroidered antennas (numbers 1 and 2 in Figure 4), sewed vertically (x-axis in Figure 1) and horizontally (y-axis in Figure 1). We also fabricated two dipoles with optimized patterns (numbers 2 and 3 in Figure 4), where full vertical and

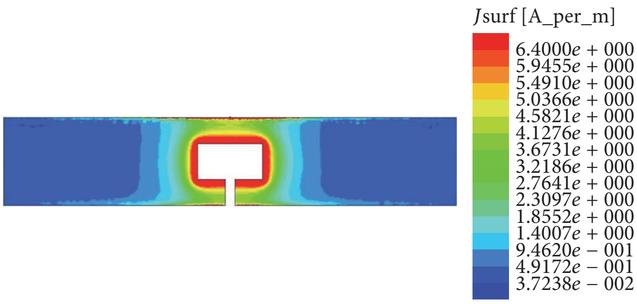


Figure 3: Current density on the dipole antenna.

horizontal patterns were used in places with highest surface current density and the rest of the antenna was only partially embroidered. In the fifth antenna, only the borders, that is, the contour of the antenna, were sewed (number 5 in Figure 4). It should be noted that the focus of this study was to test the strain reliability of the sewed antennas and interconnections, not to optimize the performance of the sewed antennas.

During sewing, it was noticed that embroidery on Fabric 2 is a major challenge because the cloth is soft, is thin, and has small tension. The ready-made tag antennas are shown in Figure 4, and for each tag type, we fabricated 5 antennas.

A vector network analyzer was used to measure the input impedance of the fabricated antennas. The port was glued with conductive silver epoxy on the position where the ICs were to be attached (the measurements were done without ICs to reduce the uncertainty). The input impedance of embroidered antennas with different patterns was measured at 915 MHz and the results are shown in Table 1. The reflection coefficient Γ and return loss RL can be calculated by

$$\Gamma = \frac{Z_A - Z_{ic}}{Z_A + Z_{ic}};$$
$$\mathrm{RL} = -20\log|\Gamma|, \tag{1}$$

where Z_A is the impedance of the antenna and Z_{ic} is the impedance of the IC, which is $12.76 - 190.28j$ at 915 MHz. Γ and RL of the embroidered antennas are shown in Table 1.

Next, the strain ability of the different antennas was tested (see Table 2). Based on the stretching results and the experience gathered during sewing, Fabric 2 was omitted from further research and two sewing ways of making the antenna on Fabric 1 were chosen: contour pattern (Pattern 5) and partial vertical pattern (Pattern 3), as shown in Figure 4, marked with the red rectangles.

The used tag IC (integrated circuit) is NXP UCODE G2iL series RFID IC, provided by the manufacturer in a fixture patterned from copper on a plastic film (see Figure 5, where the IC strap structure is presented).

We attached the fixture pads to the antennas by embroidering over them with the conductive yarn during antenna fabrication, as shown in Figure 6. Finally, for comparison, we created another set of identical tags where the IC was attached using conductive epoxy (Circuit Works CW2400). See Figure 6 for the ready tags with ICs attached.

3. Strain Testing and Wireless Measurements

The tags were stretched a 100 times to 80% of their maximum strain and back, and the wireless performance was measured after 1, 10, 20, 30, 40, 50, and 100 stretching cycles. The stretching was done by hand with each stretching cycle lasting about 2 seconds. The reason for the 2 second cycle time was that if the stretching cycle was any shorter, that is, the stretching was done any faster, the glued antenna-IC attachments were easily broken (see Figure 7). This kind of reliability problem was not found in case of the sewed antenna-IC interconnections.

The wireless performance of the tags was evaluated using Voyantic Tagformance RFID measurement system. It contains an RFID reader with an adjustable transmission frequency (800–1000 MHz) and output power (up to 30 dBm) and provides the recording of the backscattered signal strength (down to −80 dBm) from the tag under test.

We wanted to focus on the performance of the sewed tags in absence of environmental stress factors and the effects of the proximity of the human body, so that the source of any observed performance variation is limited to the antenna fabrication parameters and effects of cyclic strain. We conducted all the measurements with the tag suspended on a foam fixture in an anechoic chamber.

During the test, we recorded the lowest continuous-wave transmission power (threshold power: P_{th}) at which the tag remained responsive. The wireless channel from the reader antenna to the location of the tag under test was characterized using a system reference tag with known properties. As explained in [17], this enabled us to estimate the attainable read range of the tag (d_{tag}) versus frequency from

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{\mathrm{EIRP}}{\Lambda}\frac{P_{th^*}}{P_{th}}}, \tag{2}$$

where λ is the wavelength transmitted from the reader antenna, P_{th} is the measured threshold power of the sensor tag, Λ is a known constant describing the sensitivity of the system reference tag, P_{th^*} is the measured threshold power of the system reference tag, and EIRP is the emission limit of an RFID reader given as equivalent isotropic radiated power. We present all the results corresponding to EIRP = 3.28 W, which is the emission limit for instance in European countries.

4. Results and Discussion

In Figure 8, the read range results for two tags of each tag type are shown in a frequency range of 800–1000 MHz. As shown in Figure 8, the peak read ranges of the contour pattern tags with the sewed antenna-IC attachment are initially around 5.5–6.5 meters, whereas with the glued antenna-IC attachment, the read ranges can be slightly more than 7 meters. Thus, the glued antenna-IC interconnection seems to provide a better electrical connection. The peak read ranges of the Contour pattern tags are all around 900–920 MHz.

For the partial vertical pattern tags, the peak read ranges are around 7 meters with the glued IC and around 7-8 meters with the sewed IC. In this case the performance of both

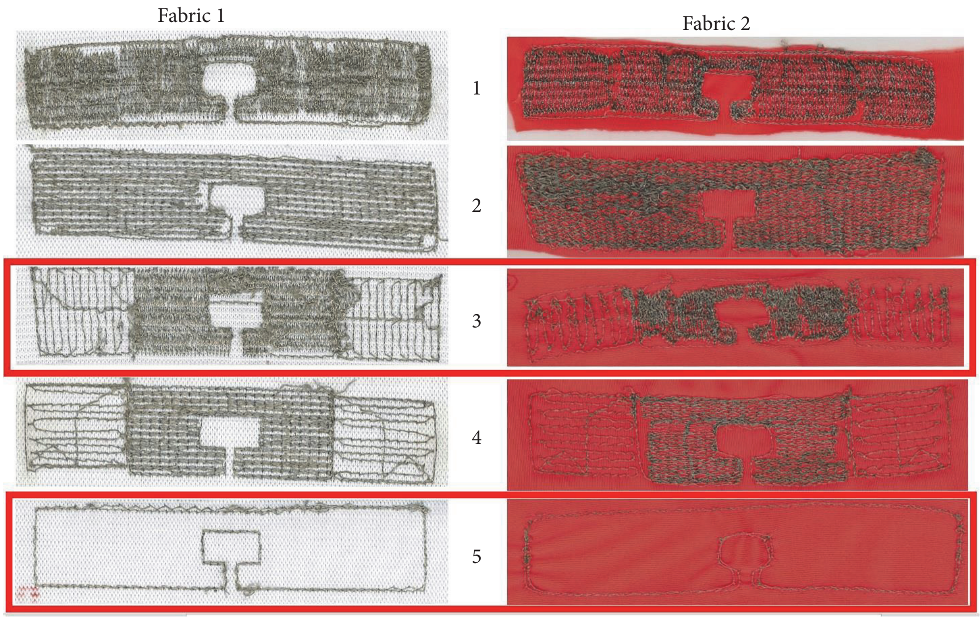


Figure 4: The 5 different antenna sewing patterns on both fabrics, the selected two sewing patters on Fabric 1 are marked with a red rectangular.

Table 1: Reflection coefficient and return loss of the antennas.

	Input impedance	Reflection coefficient (Γ)	Return loss (RL)
Contour pattern	$241.83 - 132.8j$	$0.05 + 0.3j$	10.34 dB
Partial vertical pattern	$152.35 - 9.99j$	$-0.19 - 0.88j$	1.1 dB

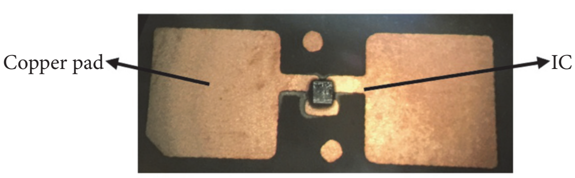


Figure 5: The used IC.

Figure 7: A broken glued antenna-IC interconnection.

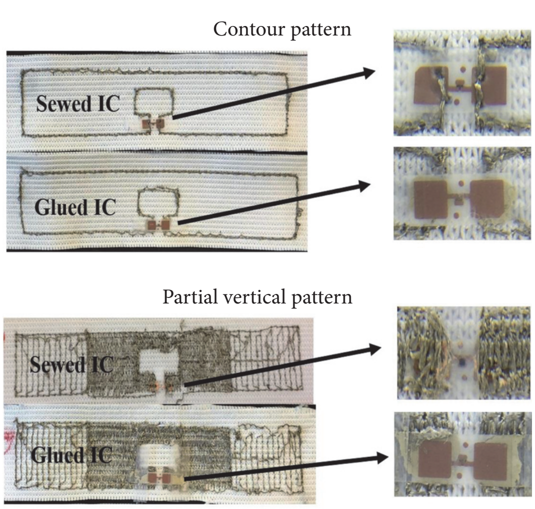


Figure 6: Ready-made tags and antenna-IC interconnections.

interconnection types is similar. This can be explained by the fact that, in the contour pattern antenna, the IC was only attached by sewing a single line over the pads. In the partial vertical pattern, there are several stiches of the conductive yarn over the IC pads (see Figure 6), which makes the embroidered interconnection more conductive than in the case of the contour pattern. The peak read ranges of the tags with glued ICs are around 950 MHz, whereas the peak read ranges of the tags with the sewed ICs are around 910–920 MHz.

It can be noticed from Figure 8 that the reproducibility of the tags with the sewed interconnections is a challenge, whereas the read range figures of the tags with the glued interconnections are very similar. Thus, optimizing the antenna-IC sewing patter for good reproducibility will definitely be the next step of this research.

Next, the tags were stretched 100 times to 80% of their maximum strain and the wireless performance was measured after 1, 10, 20, 30, 40, 50, and 100 stretching cycles. As can be seen from Figures 9 and 10, after 50 harsh stretching

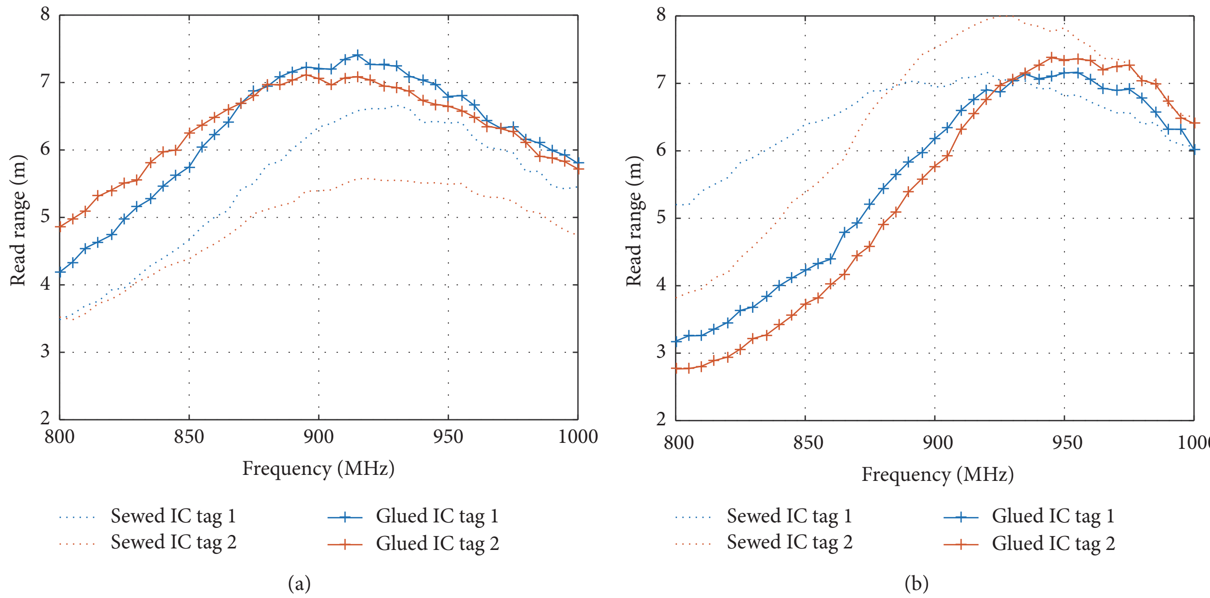


Figure 8: The initial attainable read ranges of the contour pattern (a) tag and partial vertical pattern (b) tag.

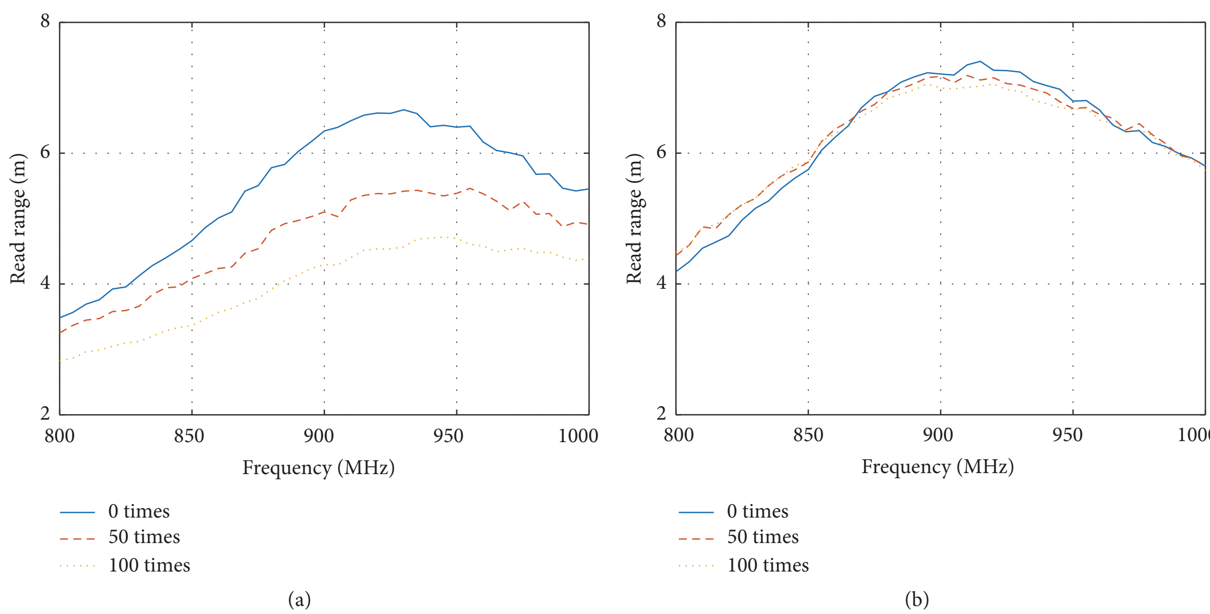


Figure 9: Repeated stretching test of contour pattern with sewed IC (a) and glued IC (b).

cycles, the peak read ranges of the tags with the sewed interconnections have decreased about 1 meter compared to the initial read ranges. After 100 stretching cycles, the read ranges of the contour pattern tags had still slightly decreased, to 4.7 meters, but the read ranges of the partial vertical pattern tags remained about the same as after 50 stretching cycles.

All the achieved read ranges are very promising. Based on our results, the sewed antenna-IC interconnections could be useful in future textile tag applications. However, the fabrication process needs to be further studied, for example, by trying different types of stiches around and through the IC pads. Also the challenges with the reproducibility need to be solved. As mentioned earlier, the tags with the glued antenna-IC interconnections were not able to endure any faster stretching cycles than the used 2 seconds/cycle. Thus, also their reliability in normal use conditions, that is, embedded into clothing, can introduce challenges and requires further studying. On the other hand, the used type of stretching did not seem to have an effect on the read ranges of the tags with the glued ICs.

It should be noted here that this cycled stretching test was relatively harsh in comparison with the commonly expected field conditions of wearable antennas, with the exception of the special scenario where the tag on textile would be

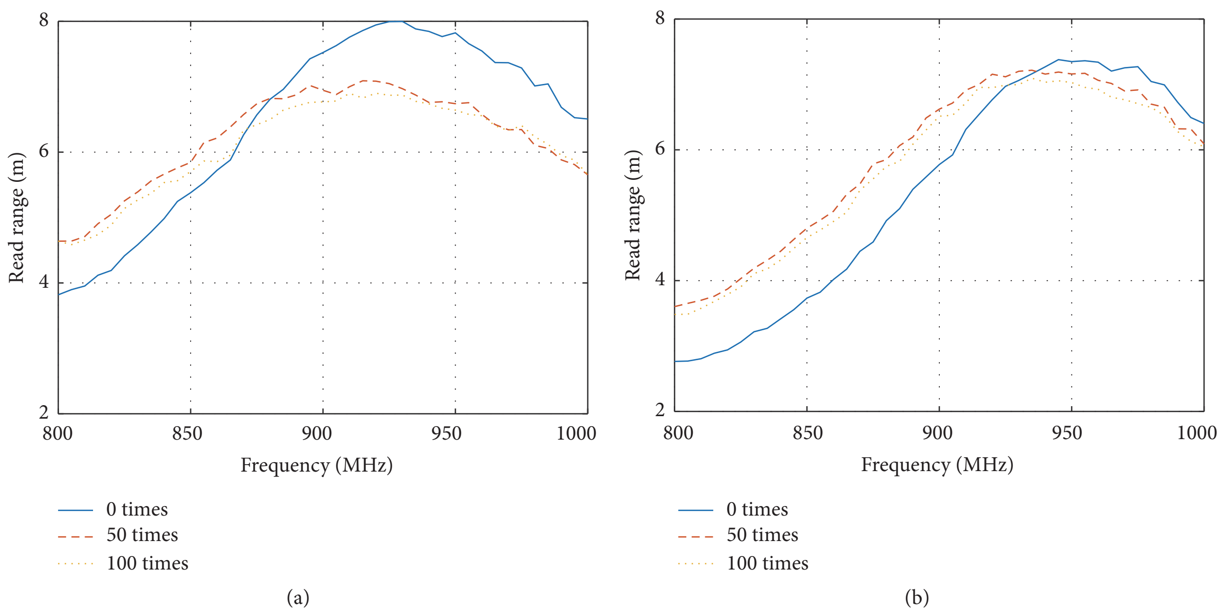


Figure 10: Repeated stretching test of partial vertical pattern with sewed IC (a) and glued IC (b).

Table 2: The maximum stretching lengths (% of the initial length) of tag patters on Fabric 1 and Fabric 2.

Tag pattern	Maximum length (%)	
	Fabric 1	Fabric 2
N/A	180%	180%
1	150%	125 %
2	125%	120 %
3	140%	120 %
4	110%	115 %
5	120%	120 %

placed at a continually strained location, for example, for the purpose of strain monitoring. In such harsh conditions, one possibility would be to use a suitable coating to protect the antenna-IC interconnection from any mechanical stress, as suggested in a recent washing reliability study of electrotextile RFID tags [18]. Next, we will also study the reliability of these tags in less severe strain conditions.

5. Conclusions

We studied the fabrication and impact of strain on the performance of passive UHF RFID textile tags with embroidered antennas on two structurally dissimilar substrates. Two fabrication methods, sewing and gluing, were also tested for the antenna-IC interconnections. According to our results, the characteristics of the fabric substrate have a huge effect on the fabrication of the tags. Our measurement results showed that a simple contour pattern and a partial vertically sewed pattern can be utilized to fabricate stretchable tag antennas on an elastic band-based substrate. However, both the sewed and glued interconnections showed some reliability/reproducibility issues that need to be solved. Also, the degree of stretching on different parts of clothing will be examined and further reliability testing will be done. Future work also includes electromagnetic optimization of the antennas and their measurements near the human body.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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Publication III

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Reliability evaluation of wearable radio frequency identification tags: Design and fabrication of a two-part textile antenna

Xiaochen Chen, Leena Ukkonen and Johanna Virkki

Abstract

Passive radio frequency identification-based technology is a convincing approach to the achievement of versatile energy- and cost-efficient wireless platforms for future wearable applications. By using two-part antenna structures, the antenna-electronics interconnections can remain non-stressed, which can significantly improve the reliability of the textile-embedded wireless components. In this article, we describe fabrication of two-part stretchable and non-stretchable passive ultra-high frequency radio frequency identification textile tags using electro-textile and embroidered antennas, and test their reliability when immersed as well as under cyclic strain. The results are compared to tags with traditional one-part dipole antennas fabricated from electro-textiles and by embroidery. Based on the results achieved, the initial read ranges of the two-part antenna tags, around 5 m, were only slightly shorter than those of the one-part antenna tags. In addition, the tag with two-part antennas can maintain high performance in a moist environment and during continuous stretching, unlike the one-part antenna tag where the antenna-integrated circuit attachment is under stress.

Keywords

radio frequency identification, E-textile antenna, embroidery antenna

Passive radio frequency identification (RFID)-based technology has been recognized as a compelling approach to utilize energy- and cost-efficient wireless platforms for future body-centric applications. With the help of wearable passive ultra high frequency (UHF) RFID equipment, identification and access control, as well as remote monitoring of movement and physiological parameters of a person, can be achieved unobtrusively. As the technology is passive, no onboard power sources or complex systems are needed. A passive tag is composed only of an antenna and an integrated circuit (IC), and it uses the power emitted from the reader to energize itself and backscatter its data. Wearable RFID technology could be utilized in healthcare applications in hospitals as well as in home environments. Further application areas include wearables for wellbeing and sports.[1–4] For further information on UHF RFID technology, a comprehensive introduction is available.[5]

Due to these great possibilities of textile-integrated passive wireless platforms, design and fabrication of wearable antennas and interconnections has been an active research area during recent years. Textile-integrated antennas, for example electro-textile antennas[6,7] and embroidered antennas,[8,9] enable the seamless integration of wireless components into wearable identification and sensing applications. Electro-textile antennas are cost-effective, lightweight, and easy to integrate with clothes.[6,7,10,11] Embroidery with conductive yarn is a simple manufacturing method with great possibilities due to its compatibility with various textile materials.[8,9,12,13] In embroidery, we have full control of the conductive pattern: shape, stitch density,

BioMediTech Institute and Faculty of Biomedical Sciences and Engineering, Tampere University of Technology, Finland

Corresponding author:
Xiaochen Chen, BioMediTech Institute and Faculty of Biomedical Sciences and Engineering, Tampere University of Technology, P.O.Box 692, Tampere FI-33101, Finland.
Email: xiaochen.chen@tut.fi

and stitch type.[9,14] In addition to conductor and antenna fabrication, sewing has also been found to be a highly useful method for embedding electrical interconnections into textile materials.[13,15–17]

There are still some challenges for wearable RFID tags that need to be resolved before wider field use. In wearable applications, where stretching and bending is common, the antenna-electronics interconnections are usually under strong stress, which may cause electrical and mechanical reliability challenges for the interconnections.[18] Furthermore, since the antenna's structure changes when stretched, it may cause the antenna-IC matching to change.[7,9,18] Another major challenge lies in the effect of moisture, which is commonly involved in wearable applications.[19–21] Washing the hands or face, staying outdoors when it is raining, or simply sweating, may cause clothing-integrated electronics to get wet. In the case of RFID components, the response from the passive tag is affected by the prevailing circumstances and surrounding materials, such as moisture and dry/wet textile. The increased moisture can alter the electromagnetic properties of textile materials, which contain many air cavities.[22] The changed permittivity of the textile material can thus create a mismatch between the tag antenna and the IC. The increased moisture can also increase losses in the textile substrate, degrading the overall tag performance.[23–25]

As previously presented,[26] the antenna-IC connection can be implemented by inductive coupling between two designed windings, connected to the IC and to the patch antenna ground. Thus, the galvanic connection between the IC and antenna can be avoided.[26] In this article, we optimized a two-part antenna structure in order to solve the reliability problems of wearable RFID tags caused by human activities – moisture and mechanical stresses. The separate antenna structures contain a radiating antenna and a feeding loop with the IC. These two parts of the antenna are connected by inductive coupling and thus the IC part can be placed at a small distance from the radiating antenna. Then, the small feeding loop part of the antenna, including the antenna-IC interconnection, can be protected from mechanical stresses and moisture, which can significantly improve the reliability of the RFID tag component. We fabricated two-part stretchable and non-stretchable passive UHF RFID textile tags using electro-textile and embroidered antennas, and tested their reliability in immersing conditions as well as under cyclic strain. In addition, traditional one-part dipole antennas were fabricated from the same materials as the two-part tags, in order to compare their performance in different conditions.

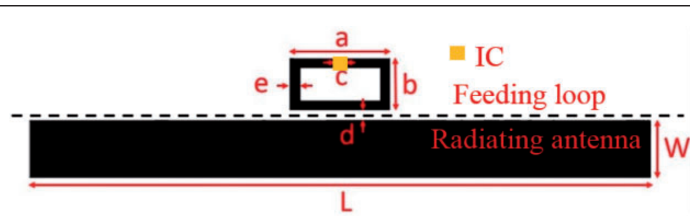
Tag fabrication

Two-part antennas

The structure and size of the two-part antennas is shown in Figure 1. The antenna design has two separate parts, the feeding loop and the radiating antenna, with a 2.5 mm gap between them. Thus, it is possible to attach the IC to a non-stretchable substrate, while the radiating antenna can be fully stretchable. We fabricated two-part electro-textile tags and two-part embroidered tags.

To fabricate the electro-textile two-part antennas, we cut the radiating antenna from Less EMF stretch conductive fabric, which is a commercial stretchable silver textile material, fabricated by plain knitting.[27] The feeding loop was cut from non-stretchable commercial, copper woven textile, Less EMF pure copper polyester taffeta fabric.[28] The electro-textile materials used are shown in Figure 2. The electro-textile antennas were cut using a laser cutter (Epilog Fusion Laser Model 13000).

For the embroidered two-part tag, the radiating antenna contour was embroidered on a plain knitting elastic band, using a Husqvarna Viking sewing machine and conductive multifilament silver-plated yarn (Shieldex multifilament thread 110f34 dtex two-ply



a	b	c	d	e	W	L
21.6 mm	11.3 mm	2 mm	2.5 mm	1.9 mm	12.6 mm	165.7 mm

Figure 1. The structure of the two-part antenna.

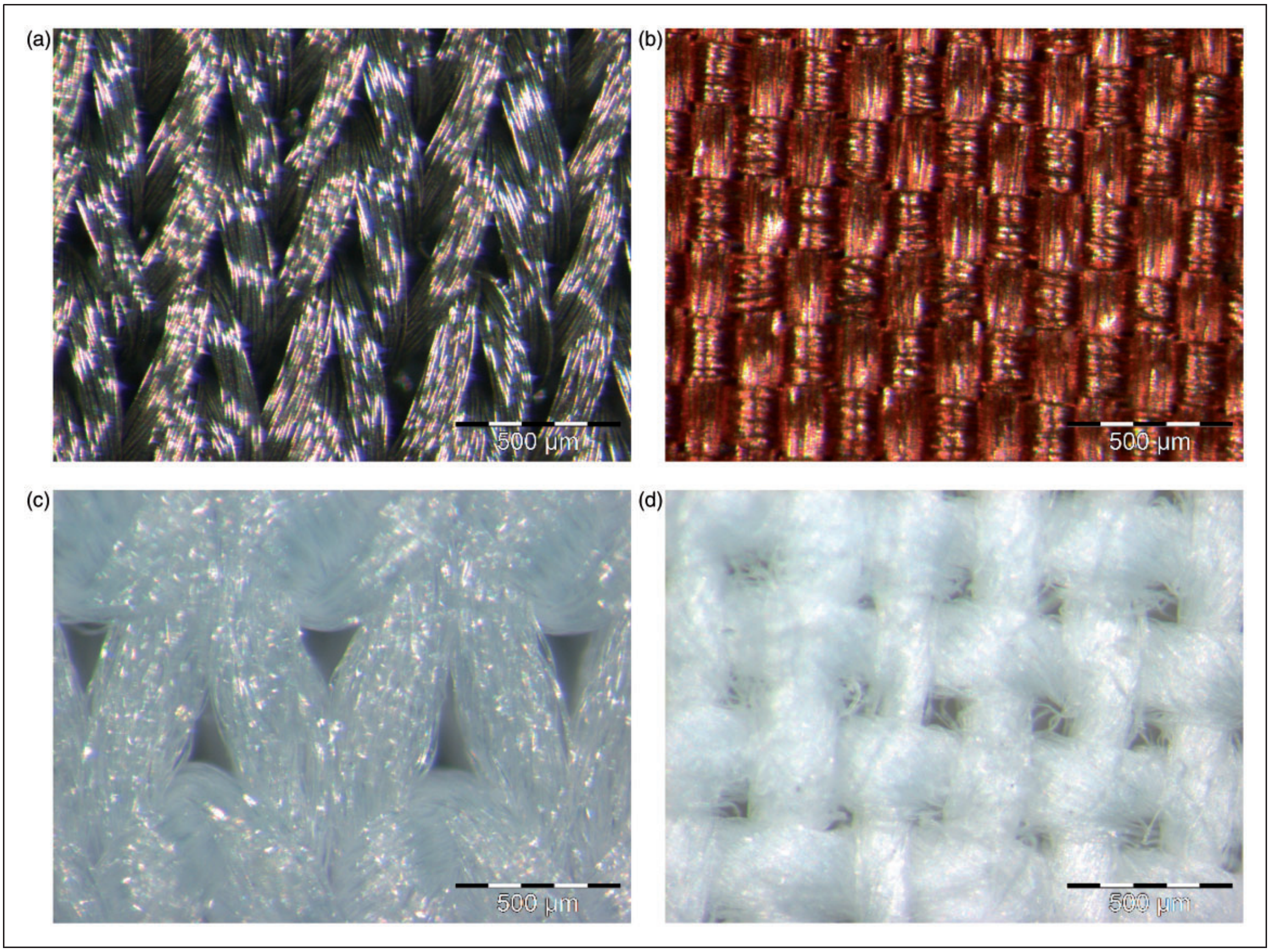


Figure 2. Microscope pictures of the used fabrics: (a) stretchable silver knitted fabric; (b) non-stretchable copper woven fabric; (c) knitted elastic band fabric; (d) 100% cotton woven fabric.

HC). The resistance of the yarn is $500 \pm 100\,\Omega/\mathrm{m}$, and the diameter is approximately 0.16 mm. The embroidery process is shown in Figure 3. The DC linear resistivity of the yarn is $500 \pm 100\,\Omega/\mathrm{m}$ and the diameter is approximately 0.16 mm. The feeding loop, on the other hand, was embroidered on a non-stretchable 100% cotton woven fabric. The substrate materials are shown in Figure 2.

The final substrate used for the two-part tags was 2 mm thick ethylene-propylene-diene-monomer (EPDM) with a dielectric constant and loss tangent of 1.26 and 0.007, respectively, at 915 MHz. The dielectric constant and loss tangent were measured by Agilent 85070E dielectric probe kit.[29] These two parts of the antenna design were integrated on this cell rubber foam substrate as shown in Figure 4. The feeding loop was glued with a textile glue and the radiation antenna body was attached with double-sided tape, which can be removed and attached several times.

One-part antennas

The structure and parameters of the one-part antenna are shown in Figure 5. It is a dipole antenna with a matching slot in the middle of the antenna body. We fabricated one-part electro-textile tag antennas from the stretchable silver fabric and from the non-stretchable copper fabric. Further, we fabricated embroidered one-part tag antennas on cotton and on elastic band. These tag antennas are shown in Figure 6.

IC attachment

After antenna fabrication, in order to establish fully functional RFID tags, NXP UCODE G2iL series RFID ICs, provided by the manufacturer in a strap with copper pads, as shown in Figure 7, were attached to the antennas with conductive silver epoxy (Circuit Works CW2400). For each tag type, four samples were fabricated to also evaluate the reproducibility.

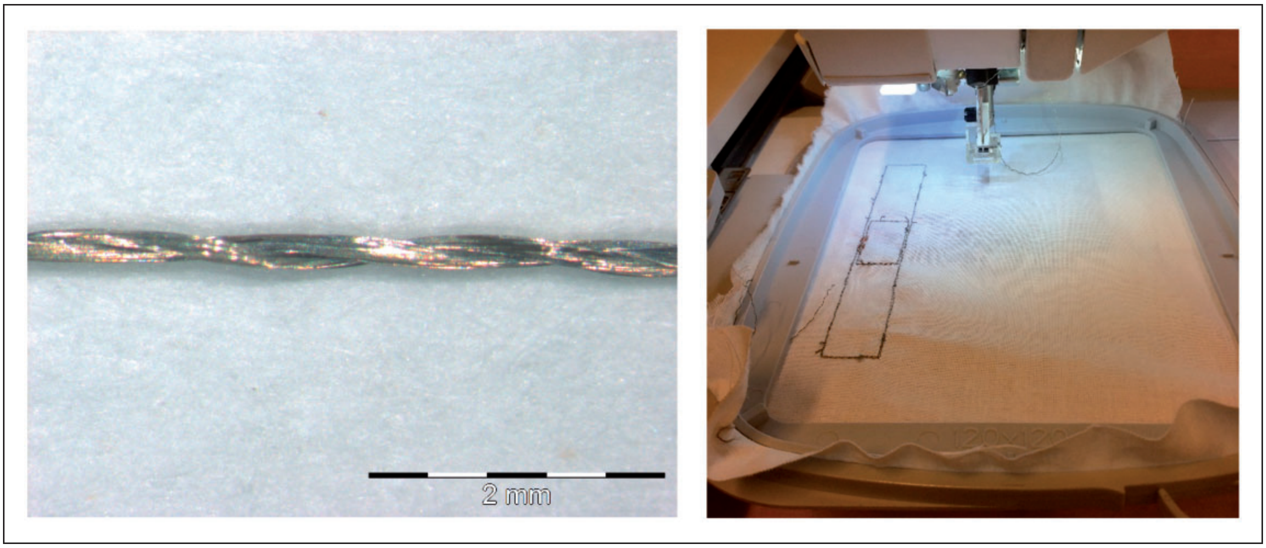


Figure 3. A microscope picture of the used conductive yarn (left) and the embroidery machine (right).

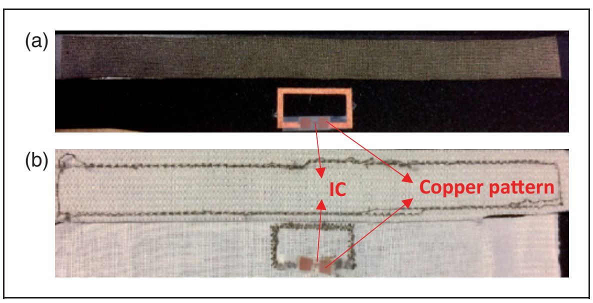
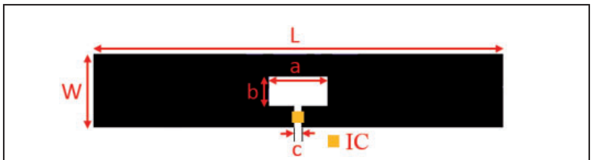


Figure 4. Electro-textile two-part tag (a) and embroidered two-part tag (b). IC: integrated circuit.



a	b	c	W	L
14.3 mm	8.125 mm	2 mm	20 mm	100 mm

Figure 5. The structure of the one-part antenna.

Ready-made two-part and one-part tags are shown in Figures 4 and 6, respectively.

Simulations and wireless measurements

The optimization of the antenna structure was based on electromagnetic modelling in an ANSYS High Frequency Structure Simulator (HFSS). In the simulation of the two-part antenna, 0.94 W was delivered to the antenna. As can be seen from Figure 8, the current density at 915 MHz was high around the feeding loop and the nearby antenna edges. For the one-part antenna, 0.57 W was delivered to the antenna, and also here the current density was high around the matching slot, as shown in Figure 8.

In simulation, we were searching for the optimized antenna dimensions. By adjusting the size of the feeding loop and the antenna body, we wanted to achieve the longest possible read ranges for the tags. Also, the current density in different parts of the tag antennas can be indicated by the simulation. According to current density, we can decide the needed density of conductive yarn at different antenna parts: significant amounts of time and conductive yarn can be saved in the embroidery of RFID tag antennas by only partially sewing them.[30] Especially, dipole tags where only the border lines of the antennas have been sewed, meaning sewing fully only the parts where the current density is the highest, have showed excellent wireless performance.[30] This was also the starting point in our work.

In this work, the ready-made tags were wirelessly measured in an anechoic chamber with the Voyantic Tagformance RFID measurement system, as shown in Figure 9. It contains an RFID reader with an adjustable transmission frequency (0.8–1 GHz) and output power (up to 30 dBm), and provides the recording of the backscattered signal strength (down to −80 dBm) from the tag under test. The tested tags were placed in an anechoic chamber to prevent any multi path effect.

Firstly, the wireless channel from the measurement system reader antenna to the location of the evaluated

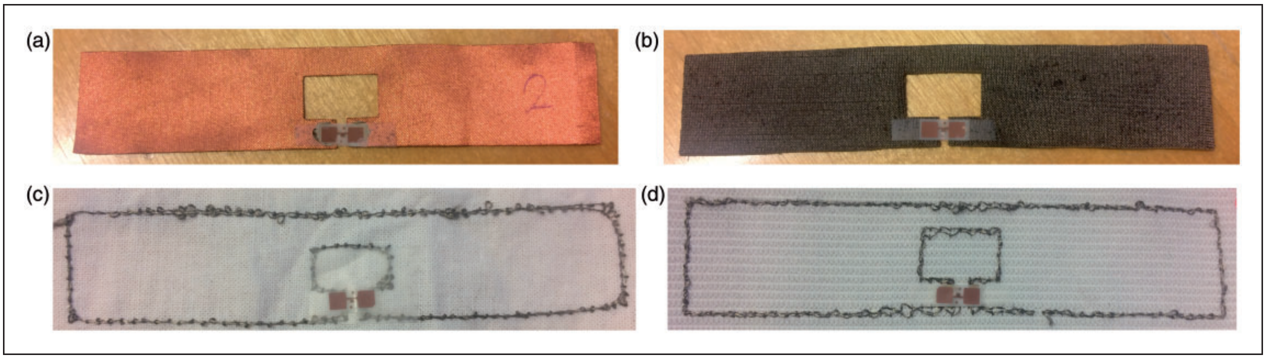


Figure 6. One-part antenna tags: (a) non-stretchable copper woven fabric tag; (b) stretchable silver knitted fabric tag; (c) embroidered tag on 100% cotton woven fabric; (d) embroidered tag on knitted elastic band fabric.

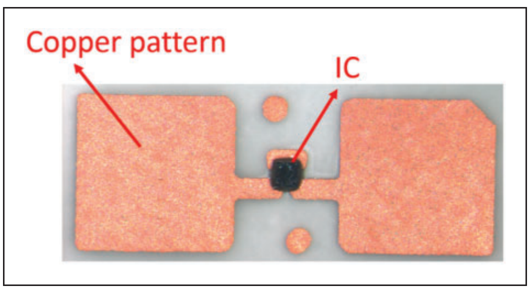


Figure 7. The used NXP UCODE G2iL series radio frequency identification (RFID) integrated circuit (IC).

tag under test was characterized using a system reference tag with known properties. During actual testing, we recorded the lowest continuous-wave transmission power (threshold power: P_{th}) of each tag, i.e. the lowest power at which a valid 16-bit random number from the tag was received as a response to the query command in ISO 18000-6 C communication standard. As has been detailed,[18] this enabled us to estimate the attainable read range of the measured tag (d_{tag}) versus frequency from

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\Lambda}\frac{P_{th*}}{P_{th}}}, \tag{1}$$

where λ is the wavelength transmitted from the reader antenna, P_{th} is the measured threshold power of the tag, Λ is a known constant describing the sensitivity of the system reference tag, P_{th*} is the measured threshold power of the system reference tag, and EIRP is the emission limit of an RFID reader, given as equivalent isotropic radiated power (EIRP). We present all the results corresponding to EIRP = 3.28 W, which is the emission limit in European countries.

Reliability testing and measurement results

The initial read ranges of different types of tags were measured to evaluate their wireless performance. The read range results of all fabricated tags are shown in Figure 10. As can be seen, the one-part non-stretchable copper textile tag had the highest read range, which was around 11 m. The embroidered one-part tag, both on an elastic band and on cotton, had a peak read range of 6.5 m. Further, the one-part stretchable silver textile tags achieved read range of 5–5.5 m. The electro-textile and embroidered two-part tags also showed read ranges of around five meters. Thus, the initial read ranges of the two-part antenna structure tags seem to be only slightly shorter than the one-part antenna structure tags. Further, all fabricated tags showed read ranges of a few meters throughout the global UHF RFID frequency band (860–960 MHz). Here we present only one measurement result for each tag type, as all same type of tags showed similar performance, except the one-part stretchable silver textile tags, which all worked with a variation of 0.5 m.

Immersing test

The purpose of the immersing test was to evaluate whether these textile tags could be used near the human body, where sweating and moist environment may cause them to get wet. We tested the tags in room temperature tap water, to simulate real daily life conditions. In the immersing test, the tags were dipped into tap water for two seconds and measured immediately after that. They were then dried for 24 h on an office table and measured again. In the case of the one-part antenna tags, the whole tag was placed into water. In case of the two-part antenna tags, only the radiating antenna (antenna without IC) was dipped into water. Again, we only present one measurement

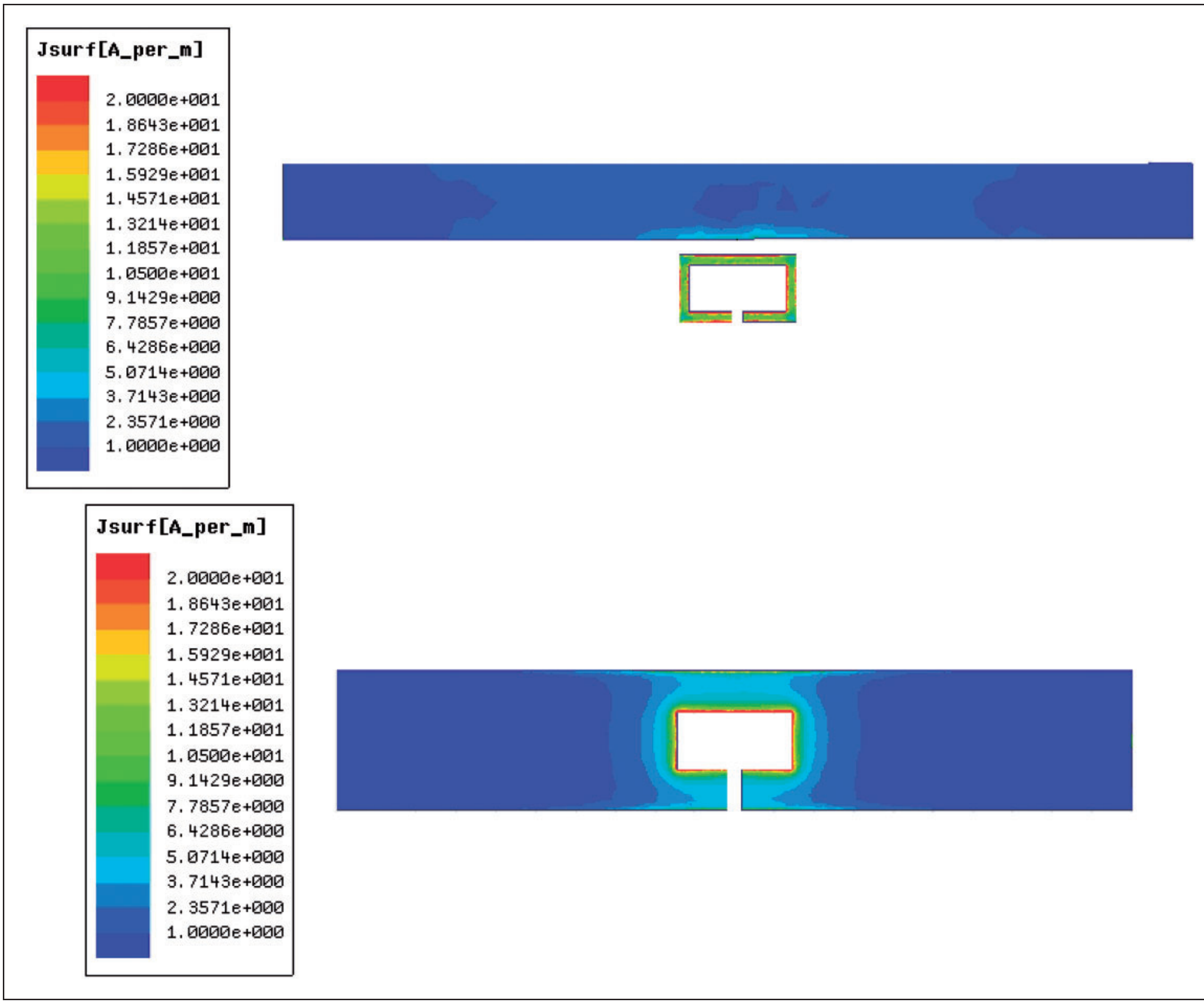


Figure 8. The simulated current distributions at 915 MHz for the two-part antenna (top) and one-part antenna (bottom).

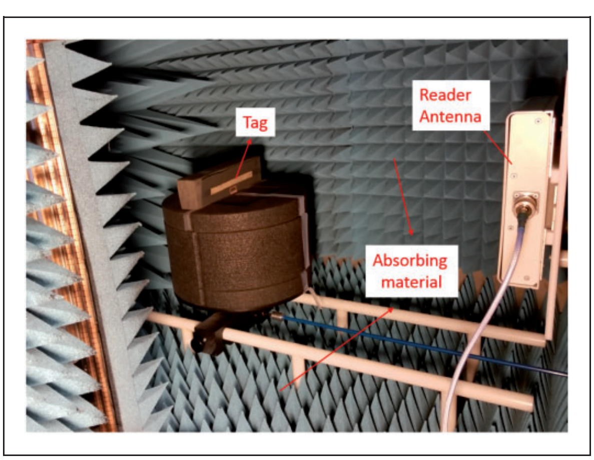


Figure 9. Tags measured in an anechoic chamber.

result for each tag type as the results of the same type of tags were similar.

As shown in Figure 11(a), for the one-part copper textile tags, after two seconds in water, the read ranges in the UHF RFID frequency band (860–960 MHz) decreased from 11 m to 3–4 m. Despite this significant change, the tag remains functional, and the read range returns to the original value, when the tag has dried for 24 h. The copper textile is not a water absorbing material; instead, the water drops stay on the surface of the textile, where they also easily transfer near the IC part. The moisture on the antenna surface creates a mismatch between the tag antenna and the IC, and thus shifts the peak read range from around 940 MHz to somewhere outside the shown UHF RFID frequency band. In addition, drops of water on the antenna

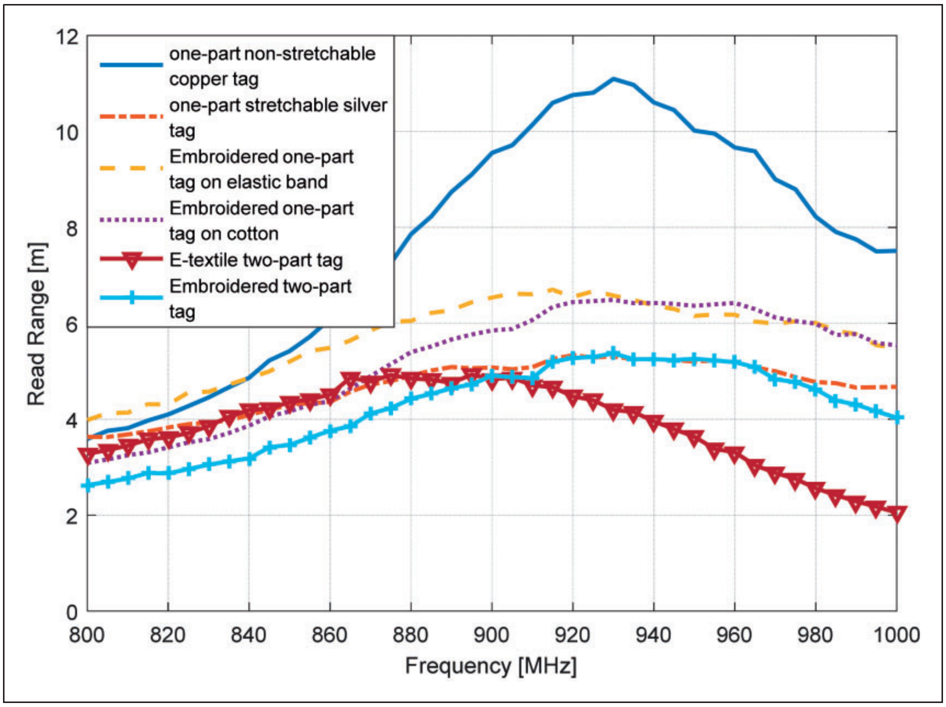


Figure 10. The initial read ranges of all fabricated tags.

surface seem to strongly degrade the overall tag performance.

The one-part stretchable silver textile tags achieved an initial read range of around five meters. As shown in Figure 11(b), the absorbed moisture actually increases the read range of the tag to six meters. This is most probably caused by the increased conductivity of the textile antenna, caused by the water absorbed into the antenna structure: the DC resistance of the antenna, measured from antenna corner to corner, decreased from 32 Ω to 20 Ω, when the antenna got wet. This is a phenomenon that needs to be studied further. After 24 h, the read ranges returned close to the initial value. Most probably there is still some moisture present in the antenna structure, which then slightly affects the tag read range.

For the embroidered tags on cotton, the absorbed moisture caused a significant read range decrease, as can be seen from Figure 11(c). The cotton fabric absorbs moisture very well, which then strongly affects the tag performance. During the 24 h of drying, the cotton substrate had completely dried, and the tag performance had returned to the initial level. The change in the read range was not as significant for the embroidered tag on the elastic band, which does not absorb moisture as well as the cotton material. Furthermore, the moisture seems to stay longer in the elastic band material, which shows in the tag performance also after 24 h of drying, as shown in Figure 11(d).

As shown in Figure 12, the read ranges of the electro-textile and embroidered two-part tags were initially around five meters. As shown earlier in Figure 10(b), the absorbed moisture increases the conductivity of the stretchable silver textile material, which also caused the read range of the two-part electro-textile tag to increase around 0.5 m, when it was wet. The read range of the wet embroidered two-part tag, on the other hand, decreased slightly, to four meters. In the case of the embroidered tag, the radiating antenna was embroidered on the knitted elastic band fabric, which is a water-absorbing substrate. When this part was dipped into water, the fabric substrate absorbed water, which decreased its sheet resistance to 0.5 M Ω/sq. Thus, the fabric substrate became slightly conductive, which also affected the shape of the radiating antenna embroidered on it. From simulations, we can see that increasing the length of the radiating antenna decreases the read range of the tag. The read ranges of both two-part tags returned to the initial values after drying for 24 h.

Based on these results, the two-part antenna structure can be considered more robust towards moisture than the one-part structure. As shown in Figure 8, the current density is high around the IC area, which means that any moisture near the IC area can affect the tag performance. In addition, the antenna material has a significant effect on how the tag performance changes

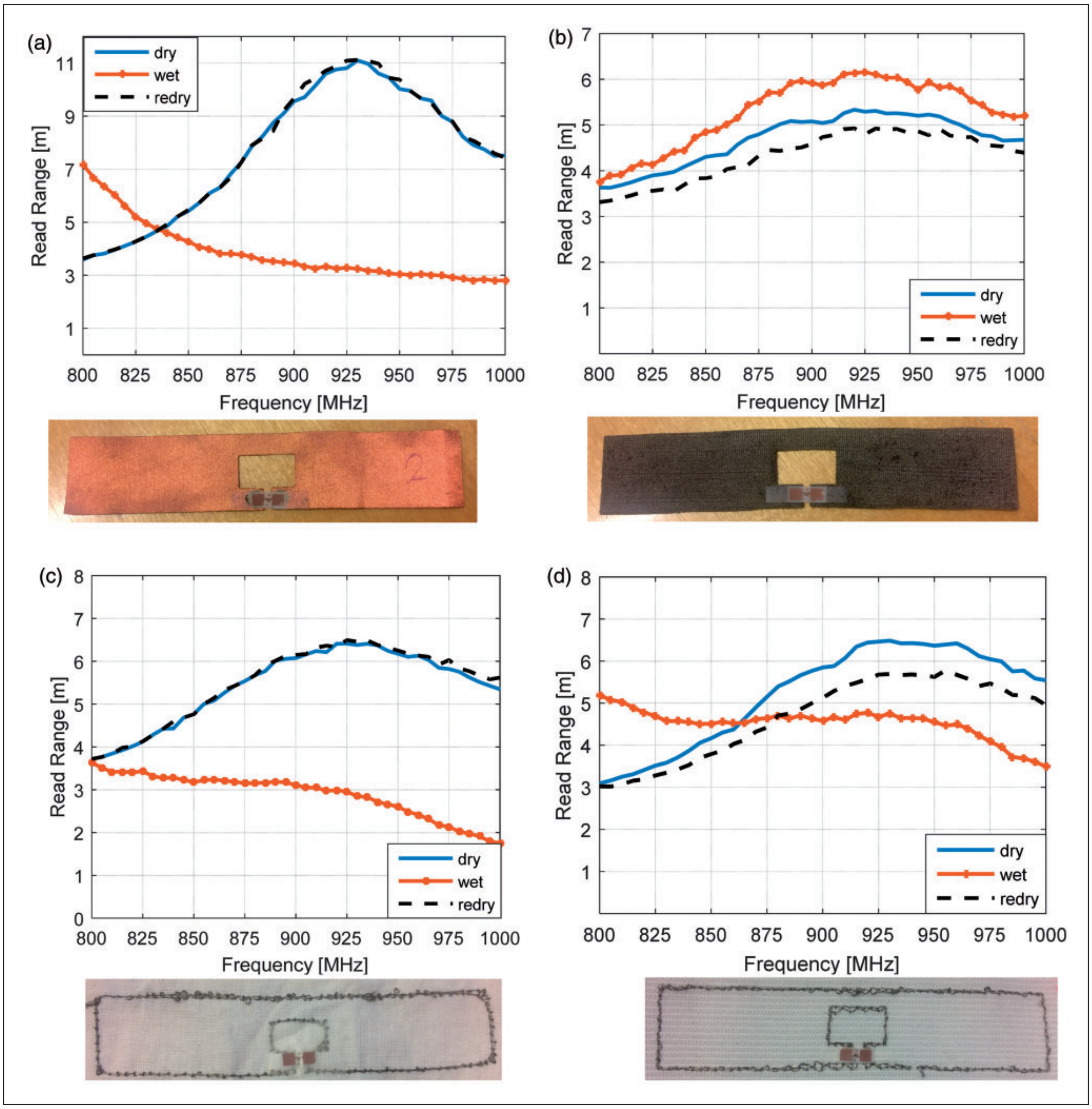


Figure 11. Moisture test results of one part tags: (a) non-stretchable copper textile tag; (b(stretchable silver textile tag; (c) embroidered tag on cotton; (d) embroidered tag on elastic band.

when the tag gets wet. The results are summarized in Table 1.

Continuous stretching test

In the stretching test, all four kinds of stretchable tags were tested: the embroidered one-part tag on the elastic band, the one-part stretchable silver textile tag, and the electro-textile and embroidered two-part tags. We strained the one-part tags from their initial length of 100 mm to 110 mm and the two-part tags were strained from 165.7 mm to 167.7 mm. The tags' wireless performance, i.e. read range, was measured initially and after 1, 2, 5, 10, 20, 50, and 100 stretching cycles. Each stretching cycle lasted about two seconds. Finally, the tags were measured again 30 min after the stretching test.

The one-part embroidered tags were broken immediately when strained. The broken antenna-IC interconnection is shown in Figure 13. However, all the one-part stretchable silver tags could be stretched 100 times. The measurement results are shown in Figure 14. As can be seen, the read range of the tag increased after each stretching cycle from the initial 5.5 m to around 6.5 m (after 100 cycles). Thus, the stretching of the antenna affected the read

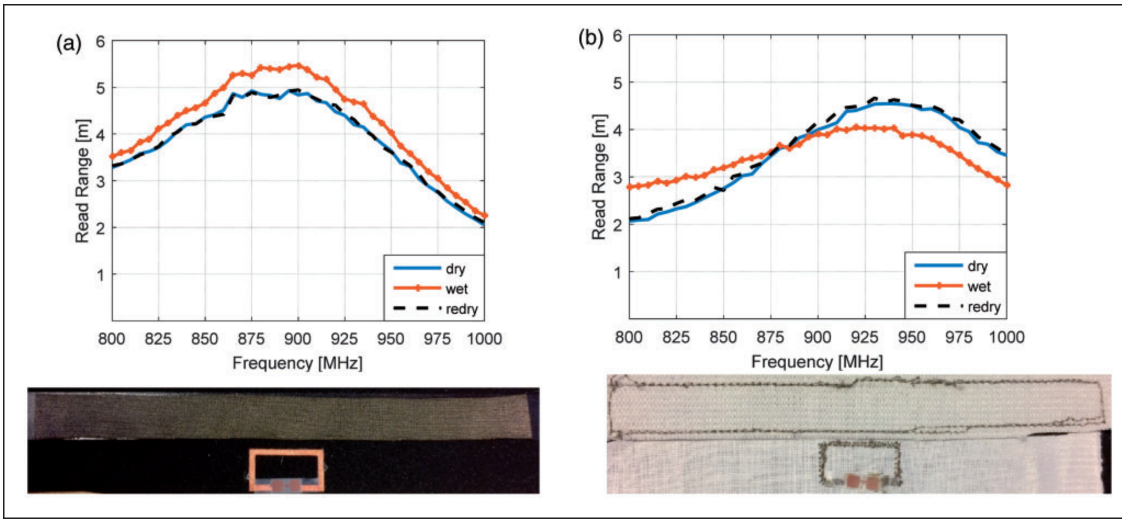


Figure 12. Moisture test results of electro-textile (left) and embroidered (right) two-part tags.

Table 1. Reliability testing results

	Immersing test			Stretching test			
	Initial	Wet	24 h	1 cycle	50 cycles	100 cycles	30 min
Electro-textile two-part tag	≥4 m	≥4 m	≥4 m	≥4 m	≥4 m	≥4 m	≥4 m
Embroidered two-part tag	≥4 m	≥4 m	≥4 m	≥4 m	≥4 m	≥4 m	≥4 m
One-part non-stretchable copper tag	≥4 m	<4 m	≥4 m	X	X	X	X
One-part stretchable silver tag	≥4 m	≥4 m	≥4 m	≥4 m	≥4 m	≥4 m	≥4 m
Embroidered one-part stretchable tag	≥4 m	≥4 m	≥4 m	Break	Break	Break	Break
Embroidered one-part non-stretchable tag	≥4 m	<4 m	≥4 m	X	X	X	X

Break: broke during testing; X: non-stretchable fabric.

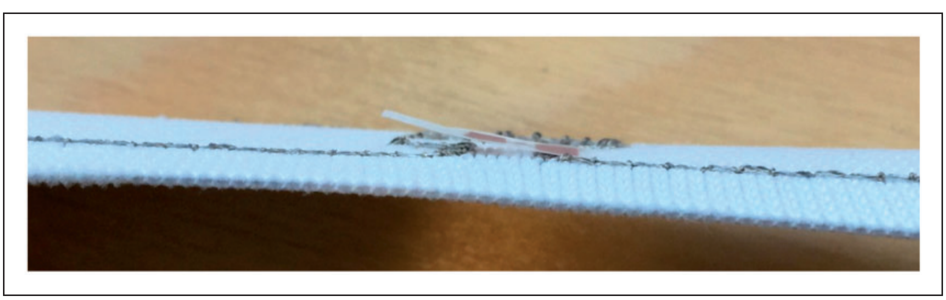


Figure 13. A broken antenna-integrated circuit (IC) interconnection in an embroidered one-part tag.

range significantly. After 30 min of rest, the read range had already returned to six meters. A similar performance has been found in an earlier study with the same type of electro-textile tags.[31] It was reported that the increment in the antenna length produces a slight positive impact on the read range. Furthermore, stretching may also temporarily influence the electromagnetic properties of the textile material, and thereby the impedance and radiation efficiency of the antenna.

For the embroidered two-part tags, the attainable read range before any strain was measured to be around five meters, as shown in Figure 15. After 100 times of stretching, the read ranges were still five meters. Thus, the stretching did not have any effect on the tag performance.

For the tags with electro-textile antennas, the initial read ranges were measured to be around five meters at 890 MHz, and the read ranges after the first stretching cycle had a 20 MHz frequency shift to a lower frequency. Thus, the peak read ranges of the electro-textile tags moved from 890 MHz to 870 MHz after the first stretching cycle. However, the wireless performance of these tags was then settled and further stretching did not have any effect on the tag's performance. After 30 min, the peak read ranges of the electro-textile tags were still at 870 MHz, which means that the first stretching cycle had an enduring minor effect on the tag performance. This fabric has a little shape change when strained, and it does not return to its original shape immediately. The antenna is little longer and thinner already after the first strain, which affects the antenna-IC impedance matching. Based on the equation:

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

where λ is the wavelength, c is the speed of the light, f is the frequency, the wavelength is inversely proportional to the frequency. When the length of the antenna increased, the matching point might shift to a lower frequency. Although this effect is not major, it should be taken into account when using this electro-textile material.

Based on these results, the two-part antenna design is a suitable antenna structure for stretchable tags, as the antenna-IC interconnections stays unharmed even during harsh strain. The results of the reliability test are summarized in Table 1.

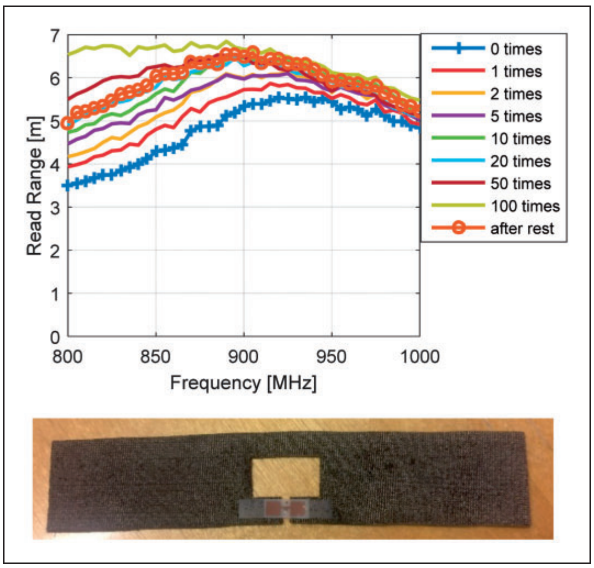


Figure 14. Strain test results of a one-part electro-textile tag fabricated from stretchable silver fabric.

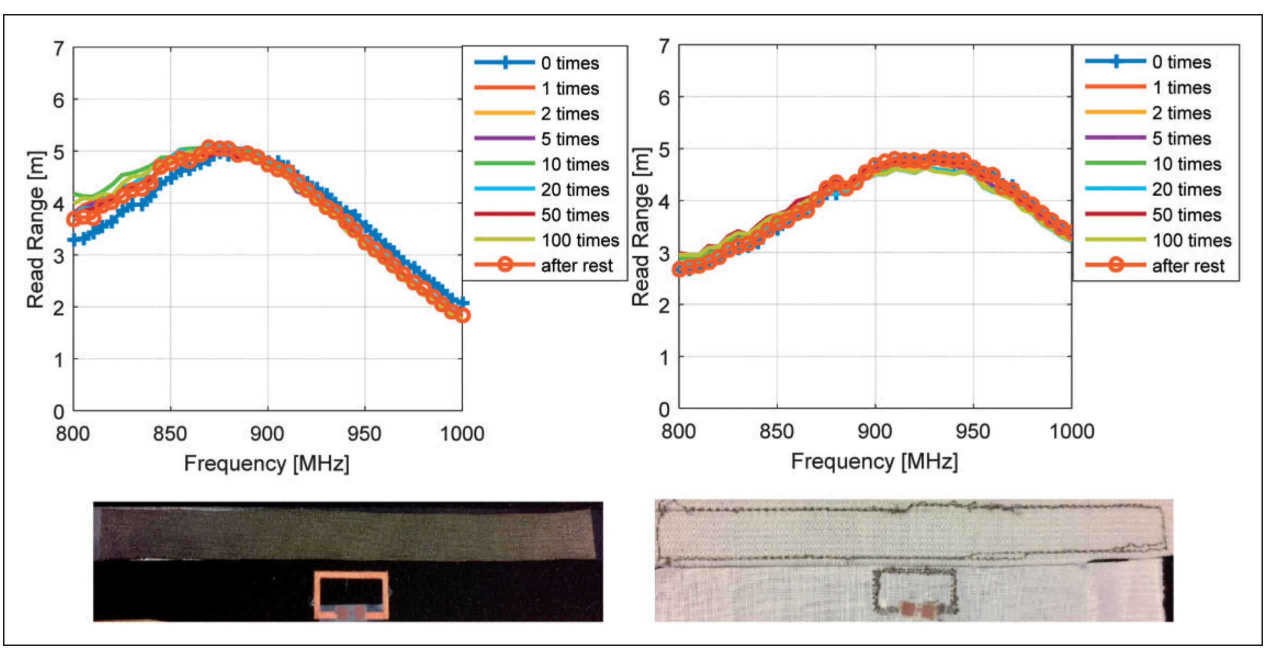


Figure 15. Stretching test results of electro-textile (left) and embroidered (right) two-part tags.

Conclusions

In this article, we presented one-part and two-part passive UHF RFID tags based on embroidered and electro-textile tag antennas. These two types of RFID tags were tested for immersing and continuous stretching, two common challenges of wearable wireless components. Initially, the one-part tags achieved peak read ranges from 5–11 m, which were longer than the read ranges of the two-part tags, which achieved peak read ranges of around five meters. However, according to the results achieved in this study, unlike the one-part tags, where the antenna-IC attachment is under a stress, the two-part antenna designs can maintain high performance in a moist environment and during continuous stretching. They could be used in wearable applications, where textile-integrated RFID platforms need to be placed in a continually strained or immersing condition, e.g. for the purpose of moisture or movement monitoring. Both fabrication methods, embroidery with conductive yarn, and cutting from conductive textile materials, were all found to be useful for the utilization of wearable wireless components. However, due to the slight reproducibility challenges and unexpected reliability testing results, the properties of the silver electro-textile material need to be carefully studied before it can be used in wireless platforms.

Declaration of conflicting interests

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Publication IV

X. Chen, S. Ma, L. Ukkonen, T. Björninen, and J. Virkki, Antennas and Antenna-Electronics Interfaces Made of Conductive Yarn and Paint for Cost-Effective Wearable RFIDs and Sensors, In Proceedings of IEEE International Microwave Symposium, 4-9 June 2017, Honolulu, HI, USA, 2017, pp. 827-830.

Antennas and Antenna-Electronics Interfaces Made of Conductive Yarn and Paint for Cost-Effective Wearable RFIDs and Sensors

Xiaochen Chen, Shubin Ma, Leena Ukkonen, Toni Björninen, Johanna Virkki
BioMediTech Institute and Faculty of Biomedical Sciences and Engineering, Tampere University of Technology, Tampere, Finland

***Abstract*—We characterize textile antennas and antenna-electronics interconnections created by depositing conductive paint and by embroidering with conductive yarn. Both approaches are based on affordable materials and enable single-step manufacturing of RFID tag on textiles. To achieve further material savings, our dipole antennas comprise of line-type structures instead of the commonly used metallized surfaces. To understand the electromagnetic properties of the antennas in and to assess the quality of the conductors, both wireless measurements and electromagnetic field simulations were used. Overall, the tags made of the conductive yarn by embroidering were detectable at the distances of 5-to-6 meters in air and at 2 meters on the human body. Conductive paint yielded the corresponding distances of 3.5-to-4 meters and 1 meter, respectively.**

***Index Terms*—antennas, conductive paint, embroidery, interconnections, passive UHF RFID, wearable electronics.**

I. Introduction

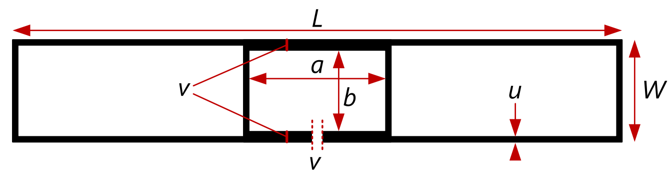
Textile-based radio frequency identification (RFID) tags offer endless opportunities in identification, monitoring, and sensing applications, especially in the healthcare and welfare sectors. These components need to be inconspicuous to the user, i.e., light-weight and conformal with the touch and feel of regular clothing. The increasing amount of these wearable wireless components has created a need for time- and cost-effective manufacturing of textile antennas and antenna-electronics interconnections.

Embroidery with conductive yarn has a high potential in wearable antenna fabrication due to its compatibility with non-electronic textile processing [1][2]. In addition, it has been found to be a particularly useful method when embedding interconnections into textiles [3][4][5]. In addition, the use of conductive paint, which does not need to be sintered, in fabrication of antennas has been found to be a potential new cost-effective approach [6][7].

In this study, to the best of our knowledge, we present the first comparison of wearable textile UHF (ultra-high frequency) RFID tags where we have realized the both antennas and antenna-electronics interconnections in a single-step process by depositing conductive paint and by embroidering with conductive yarn. The tags are characterized in air and body-worn in both simulations and measurements.

II. Fabrication of the Tags

The antenna we used in the studied tags is a folded dipole with an embedded inductive matching loop as shown in Fig. 1. The tags were fabricated on a thin 100 % cotton fabric with conductive yarn and conductive paint. The embroidery was done by using Husqvarna Viking embroidery machine and the used thread was multifilament silver plated thread (Shieldex multifilament thread 110f34 dtex 2-ply HC). The DC lineal resistivity of the thread is 500±100 Ω/m and the diameter is approximately 0.16 mm. The used conductive paint was Bare Conductive's nontoxic, solvent free, and water soluble Electric Paint [8] provided by the manufacturer in a 10-ml tube.



Parameter	L	W	a	b	u	v
Value [mm]	120	20	16	27	1	2

Fig. 1. Structural diagram of the studied antenna (top) and the studied UHF RFID tags made from conductive paint (middle) and conductive yarn (bottom).

To achieve fully functional textile RFID tags we equipped the antennas with NXP UCODE G2iL series RFID integrated circuits (IC). The IC was provided by the manufacturer attached on a thin fixture patterned from copper on a plastic film with 3 $\times$3 mm^2 pads for connection to the antenna (see Fig. 2). First, the IC was placed on the fabric substrate. Next, the antenna was embroidered with conductive yarn (two single-line tracks sewn immediately next to each other) or deposited by pressing the conductive paint directly from the tube. Figs. 1–2 show samples of the manufactured tags and antenna-IC interconnections. Finally, the tags were adhered to a 5-mm layer of ethylene propylene diene monomer (EPDM) cell rubber foam, which separates the antennas from the body so that adequate body-worn performance can be maintained. The dielectric constant and loss tangent of EPDM are 1.26 and 0.007, respectively, at 915 MHz.

Fig. 2. The antenna-IC interconnections fabricated with conductive paint (top) and with conductive yarn (bottom).

III. Simulations and Measurements

To assess the quality of the manufactured conductors, we simulated the antennas using ANSYS HFSS version 15. The simulated antenna geometry is given in Fig. 1. Here we used a one-millimeter-wide uniform conductor trace to model the painted and embroidered conductors. Structurally, the model was a two-dimensional sheet where we assigned various sheet resistance values to model the electrical conductivity. As opposed to a three dimensional conductor and conductivity, this approach was considered beneficial as defining a thickness for either of manufactured conductors would have been innate due to their non-uniform thickness profile. The layer of EPDM was modelled using the permittivity and loss tangent of 1.26 and 0.007, respectively.

Considering the test scenario, where the tag was attached vertically to the upper back, centered between the shoulder blades, we adopted a simplified rectangle model for the human body, which captures the approximate dimensions of the upper torso of the male test subject from the level of the lower end of the spine up to level of the neck. The rectangle measured 595 mm (height) by 480 mm (width) by 260 (thickness) and the center of the tag was located 200 mm from the top of the longest edge of the rectangle. Frequency dependent dielectric properties representing the human skin were assigned to the rectangle following the parametric dispersion model given in [10].

Normally, the read range of passive tags is limited by the forward link operation, i.e., the efficiency of the wireless power transfer from the reader to the tag IC. Assuming free-space conditions for site-independent comparison, the attainable tag read range (d_{tag}) at the spatial observation angles φ and θ of a spherical coordinate system centered at the tag is given by

$$d_{tag}(\phi,\theta)=\frac{\lambda}{4\pi}\sqrt{\left\{\frac{4\,\mathrm{Re}(Z_A)\mathrm{Re}(Z_{IC})}{|Z_A+Z_{IC}|^2}\right\}\frac{e_r D(\phi,\theta)EIRP}{P_{ic0}}}, \quad (1)$$

where λ is the wavelength of the carrier tone emitted by the reader, *EIRP* is the regulated equivalent isotropic radiated power, $P_{ic0} = -18$ dBm is the wake-up power of the tag IC, e_r is the tag antenna radiation efficiency, D is the tag antenna directivity, and the factor in the curly brackets is the antenna-IC power transfer efficiency determined by the antenna and IC impedances Z_A and Z_{IC}, respectively. Equation (1) follows by combining Friis' transmission equation with basic circuit analysis where a generator (representing the tag antenna) with internal impedance of Z_A is feeding the RFID IC. We present all the read range results corresponding to $EIRP$ = 3.28 W (emission limit e.g. in European countries) in the direction normal to the antenna surface. In the simulations, the tag IC impedance was obtained from a parallel connection of a resistance of 2.85 kΩ and capacitance of 0.91 pF [10].

The tags were tested wirelessly using Voyantic Tagformance measurement system. It contains an RFID reader with an adjustable transmission frequency (0.8…1 GHz) and output power (up to 30 dBm) and provides the recording of the backscattered signal strength (down to −80 dBm) from the tag under test. During the test, we recorded the lowest continuous-wave transmission power (threshold power: P_{th}). Here we defined P_{th} as the lowest power at which a valid 16-bit random number from the tag is received as a response to the query command in ISO 18000-6C communication standard. In addition, the wireless channel from the reader antenna to the location of the tag under test was characterized using a system reference tag with known properties. As has been detailed in [9], this enabled us to estimate the attainable read range of the tag (d_{tag}) versus frequency from

$$d_{tag}=\frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\Lambda}\frac{P_{th*}}{P_{th}}}, \quad (2)$$

where λ is the wavelength transmitted from the reader antenna, P_{th} is the measured threshold power of the tag, Λ is a known constant describing the sensitivity of the system reference tag, and P_{th*} is the measured threshold power of the system reference tag.

IV. Results and Discussion

Fig. 3 presents the simulated and measured read ranges in air through a frequency range of 0.8…1 GHz, which covers the global UHF RFID frequency bands. The read ranges of the embroidered and painted tags were 5-to-6 meters and 3.5-to-4 meters, respectively. From the comparison between the measured and simulated results, we can conclude that the embroidered and painted structures can be modeled with a sheet resistance of 0.04…0.36 Ω/sq and 2.3…2.6 Ω/sq, respectively, by considering a 1-mm wide track.

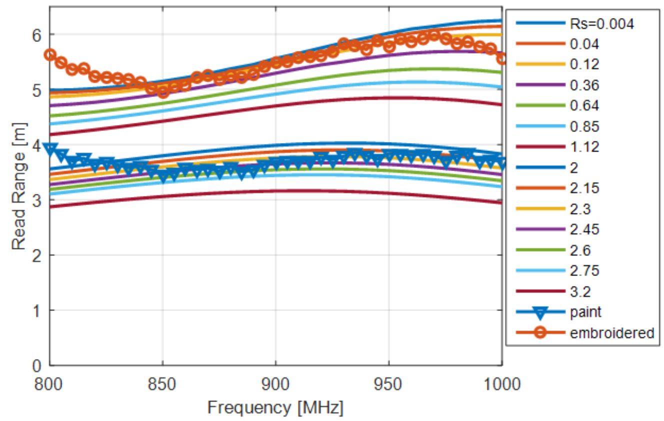


Fig. 3. Measured (markers) and simulated (solid lines) attainable read ranges of the studied tags in air.

The simulated read range of the body-worn tags using the above-mentioned sheet resistances is shown together with the measured results in Fig. 4. Overall, the simulated and measured results agree closely with a level-difference of less than 20 cm, which may have easily been caused by difference between the simplified simulation model and the actual anatomy. Here the painted and embroidered tags achieved read ranges of 1 meter and 2 meters, respectively.

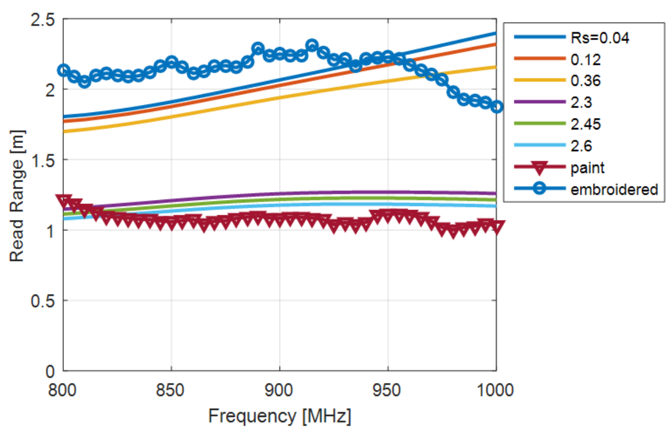


Fig. 4. Measured (markers) and simulated (solid lines) attainable read ranges of the body-worn tags.

The performance of the embroidered tag together with the other benefits related to the materials, manufacturing, and integration is compelling for versatile future electronics structures on textile substrates. As a future work, we will investigate the impact of the material and structure of the base textile on the performance of the painted conductor to gain insight on how to optimize the painting process on textiles. Further research will also include to study the effects of bending and wrinkling of the fabric on the tag performance.

V. Conclusion

To the best of our knowledge, we present the first comparison of textile antennas and antenna-electronics interconnections fabricated by depositing conductive paint and by embroidering with conductive yarn. Comparison of simulated and measured electromagnetic performance showed that the conductor created by embroidering just two adjacent tracks of the conductive yarn yielded highly conductive antennas. In comparison, the antenna composed of a painted track exhibited lower conductivity. However, in comparison with most printable conductive inks and pastes, it does not require sintering, and is thus considered an attractive alternative. Importantly, both methods enabled the manufacturing of a textile RFID tag, including the antenna-microchip interconnection, in a single process step.

Future research topics include reliability studies and analysis of the impact of the material and structure of the base textile on the performance of the painted conductor.

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Publication V

X. Chen, L. Ukkonen, T. Björninen, and J. Virkki, Comparison of E-textile Dipole and Folded Dipole Antennas for Wearable Passive UHF RFID Tags, In Proceedings of Electromagnetics Research Symposium, 19-22 November 2017, Singapore, 2017, pp. 812-817.

Comparison of E-textile Dipole and Folded Dipole Antennas for Wearable Passive UHF RFID Tags

Xiaochen Chen, Leena Ukkonen, Toni Björninen, Johanna Virkki
BioMediTech Institute and Faculty of Biomedical Sciences and Engineering
Tampere University of Technology
Tampere, Finland

Abstract

We present two wearable passive UHF RFID tags based on electro-textile folded dipole and slot antennas, which have the same footprint area. We simulated the antennas in a box model and optimized them to operate near the human body. The antennas were manufactured from commercial electro-textile material by a laser cutter and reference antennas were cut from copper tape. Based on the measurement results, the attainable read ranges of the copper and electro-textile dipole tags were nearly equal and reached 2 meters. The peak read ranges of the copper and electro-textile folded dipole tags reached 2.5 meters and 2.2 meters, respectively. The results show that both simple uniplanar antennas are suitable for body area applications, but we also found the folded dipole to permit better impedance matching in this application.

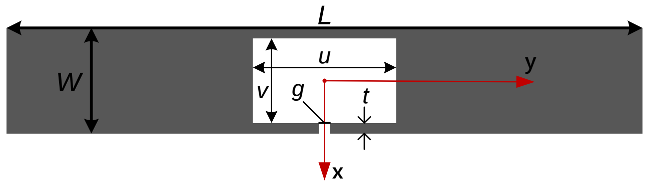
1. Introduction

The development of WBAN (wireless body area network) technologies has gained a lot of research attention during the recent years, as they can offer remarkable benefits for the healthcare and welfare sectors [1]-[5], as well as enable novel sports-related applications [5][6]. Passive UHF (ultra-high frequency) RFID (radio frequency identification) inspired technology has been recognized as a compelling approach to achieve versatile energy- and cost-efficient wireless technologies for future WBANs [1]-[4]. With the help of wearable UHF RFID equipment, the remote monitoring of movement and physiological parameters of a person can be achieved unobtrusively. The technology could be utilized in hospitals, for example in RFID-based automatic patient identification systems, and in the matching of a patient to an intended treatment. The technology can also be used for wearable wireless sensing, for example in passive moisture and strain sensors, which also have versatile possibilities in healthcare and well-being contexts [4], [7]-[11].

Electro-textile antennas have high potential in wearable RFID applications, as they are cost-effective, lightweight, and easy to integrate with clothes [12]. The main challenge of antenna development in body-centric systems comes from the proximity of the human body: the dielectric biological matter exhibits a notable electrical conductivity and polarizability. This leads to reduction in the antennas' radiation performance through the consumption of energy in the interaction between the antenna's electromagnetic fields and the human body. In this study, we modeled, implemented, and compared a dipole with an embedded inductive loop matching and a folded dipole having the same footprint area for wearable passive UHF RFID tags.

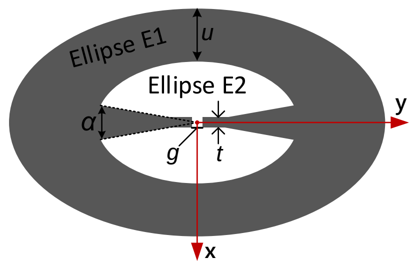
2. Fabrication of the tags

Fig. 1. shows the geometries and dimensions of the studied antennas, which both have a footprint area of $A = 2400$ mm^2. The electro-textile antennas were implemented by nickel and copper plated Less EMF Shieldit Super Fabric (Cat. #A1220) as the electro-textile conductor and 2 mm thick EPDM (Ethylene-Propylene-Diene-Monomer) cell rubber foam as the substrate. The electro-textile exhibits sheet resistance of approximately 0.16 Ω/□ and the dielectric constant and loss tangent of EPDM are 1.26 and 0.007, respectively, at 915 MHz. The electro-textile material has hot melt glue on the backside and can be easily



DIPOLE WITH INDUCTIVE LOOP MATCHING

t	g	L	W	u	v
2 mm	2 mm	120 mm	20 mm	27 mm	16 mm



FOLDED DIPOLE

t	g	α	u	q
2 mm	2 mm	20°	10 mm	1.65

Ellipse	Semi-minor axis	Semi-major axis
E1	$\sqrt{A/(q\pi)}$	$\sqrt{(q \cdot A)/\pi}$
E2	$\sqrt{A/q\pi} - u$	$\sqrt{(q \cdot A)/\pi} - qu$

Fig. 1. Structural diagrams of the antennas.

ironed on textile substrates. The electro-textile material is light-weight and conformal with the touch and feel of regular clothing. The performance of the electro-textile tags was compared with tags based on identical antennas patterned from copper tape.

The electro-textile antennas were cut by a laser cutter (Epilog Fusion Laser Model 13000). The electro-textile material can be accurately and quickly cut with a low laser power. In this case, 30 % of the maximum power of 75 W was used. Laser cutting of the copper tape, on the other hand, is not feasible with a low output power. Thus, as a more appropriate tool for this material, we used a vinyl cutter (Summa D60R), where an automated blade to cuts the outlines of the antennas on the copper tape.

The RFID IC (integrated circuit) used in this study was NXP UCODE G2iL RFID IC, provided in a fixture made of copper on a plastic film with 3×3 mm^2 pads. We attached the pads to the antennas using conductive epoxy (Circuit Works CW2400). The chip has a wake-up power of −18 dBm (15.8 µW) and based on a previous work [13] we modelled it as a parallel connection of the resistance and capacitance of 2.85 kΩ and 0.91 pF, respectively. Fig. 2 shows the ready-made tags.

Fig. 2. Ready-made copper dipole (left) and electro-textile folded dipole (right) RFID tags.

3. Simulations and Wireless Measurements

To account for the influence of the human body on the electromagnetic properties of the antennas, we simulated them affixed on a 26 cm × 50 cm × 59.5 cm rectangular block of dielectric material having the dielectric properties of the human skin (the relative permittivity is 76.11 and the conductivity is 0.48 S/m at 915 MHz). Fig. 3 presents the antenna structure and simulation model and indicates the tag placement in the skin block model. It corresponds to the center of the upper back in between the scapula. The software package we used in antenna modeling and optimization was ANSYS HFSS with the target of maximal tag read range at 915 MHz.

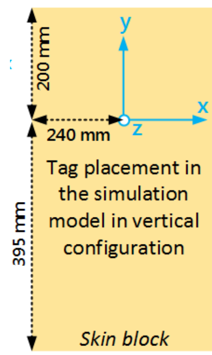


Fig. 3. The simplified model of the human torso used in the antenna modelling. The coordinate axes corrspond with Fig. 1.

Normally, the read range of the passive tags is limited by the forward link operation. In free space, the attainable read range of the tag at the spatial observation angles φ and θ of a spherical coordinate system centered at the tag is given by:

$$d_{tag}(\varphi,\theta) = \frac{\lambda}{4\pi}\sqrt{\frac{\tau e_r D(\varphi,\theta) EIRP}{P_{ic0}}}, \tag{1}$$

$$\tau = \frac{4\mathrm{Re}(Z_A)\mathrm{Re}(Z_{IC})}{|Z_A + Z_{IC}|^2}, \tag{2}$$

where λ is the wavelength of the reader' continuous-wave signal energizing the tag, *EIRP* is the regulated equivalent isotropic radiated power, P_{ic0} is the wake-up power of the tag IC, e_r is the tag antenna radiation efficiency, D is the directivity of the tag antenna, τ is the antenna-IC power transfer efficiency determined by the impedances of the antenna (Z_A) and IC (Z_{IC}).

To estimate d_{tag} of the manufactured tags, we tested them wirelessly with Voyantic Tagformance system. It is based on an RFID reader with an adjustable transmission frequency (0.8…1 GHz) and output power (up to 30 dBm) and provides the recording of the backscattered signal strength (down to −80 dBm) from the tag under test. Estimation of d_{tag} was done by characterizing the wireless channel from the reader antenna to the location of the tag under test and by recording the smallest output power of the reader (threshold power) at which a valid 16-bit random number from the tag is received as a response to the query command in ISO 18000-6C communication standard. First, the power loss factor (L_{iso}) between the reader and the tag was obtained as $L_{iso} = \Lambda / P_{th^*}$, where Λ is a constant provided by the system manufacturer to describe the sensitivity of the reference tag at each frequency, P_{th^*} is the measured threshold power of the reference tag. The incident threshold power density at the tag's location is given by:

$$S_{inc,th} = \frac{L_{iso} P_{th}}{\lambda^2/4\pi} = \frac{4\pi\Lambda}{\lambda^2 P_{th*}} P_{th}, \tag{3}$$

where λ is the wavelength and P_{th} is the measured threshold power of the tag under test. Thus, d_{tag} can be expressed as

$$d_{tag}(P_{th}, P_{th*}) = \sqrt{\frac{EIRP}{4\pi S_{inc,th}}} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\Lambda}\frac{P_{th*}}{P_{th}}}, \qquad (4)$$

where *EIRP* = 3.28 W, according to RFID emission limits in Europe.

In the wireless measurements, we attached each tag in the upper back of a male test subject. The tags were attached so that the substrate under the tag was affixed directly on skin and were worn underneath regular cotton shirt during the measurements. The measurements were conducted in an anechoic chamber at the distance of one meter.

4. Results and Discussion

The simulated impedance of the antenna in the box model is shown in Fig. 4. The reactances of the antennas are practically the same with different materials, but the electro-textile antennas exhibit slightly higher resistance compared with the copper ones. This correlates with the lower conductivity of the electro-textile material. As can be seen from Fig. 5, the main difference between the dipole and folded dipole antennas is that the folded dipole antenna achieves better impedance matching. According to our parametric studies, it was not possible to achieve better impedance matching for the dipole antenna in the body-worn configuration by using the embedded inductive loop matching, due to the inherently elevated antenna resistance. However, as shown by the further results discussed below, the radiation properties of the dipole were better than those of the folded dipole.

Table 1 compares the directivity, radiation efficiency, gain, and power transfer efficiency of each tag in the at different global UHF frequencies. In the table, the conductor material did not affect the radiation properties noticeably. The directivities of the dipole and folded dipole were also similar. However, the dipole antenna provided a much higher radiation efficiency and thereby higher gain. Conversely, we found the antenna-IC power transfer efficiency attainable with the embedded loop matching approach applied in the dipole limited, whereas we achieved a good complex conjugate impedance matching using the folded dipole.

TABLE I. SUMMARY OF THE ANTENNA RADIATION PROPERTIES.

	Freq. [MHz]	Cu dip.	E-text. dip.	Cu folded dip.	E-text. Folded dip.
D [dBi]	860	6.26	6.26	6.01	6.01
	915	6.47	6.49	6.21	6.21
	960	6.56	6.56	6.21	6.21
e_r [%]	860	1.81	1.70	1.09	0.78
	915	1.90	1.79	1.19	0.94
	960	2.00	1.88	1.32	1.09
G [dBi]	860	−11.2	−11.4	−13.8	−15.1
	915	−10.7	−11.0	−13.0	−14.1
	960	−10.4	−10.7	−12.6	−13.4
τ [%]	860	32	31	57	61
	915	32	31	86	78
	960	30	29	60	56

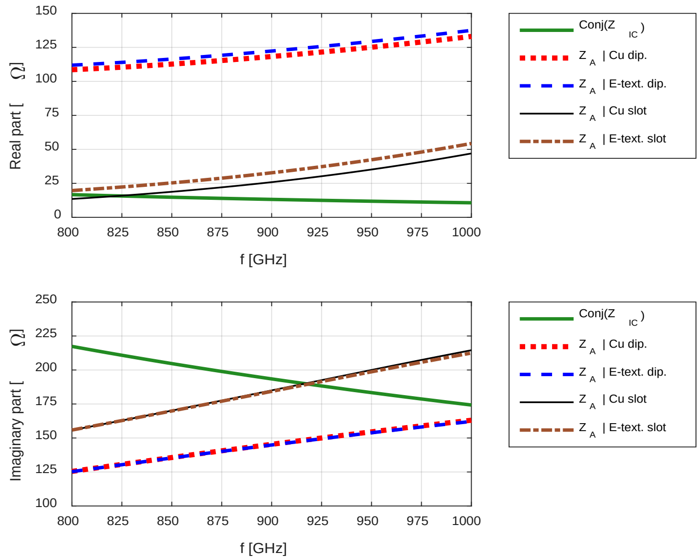


Fig. 4. Simulated antenna impedance in the box model and the conjugate of the microchip impedance from the parallel RC equivalent circuit model ($R = 2.85$ kΩ, $C = 0.91$ pF).

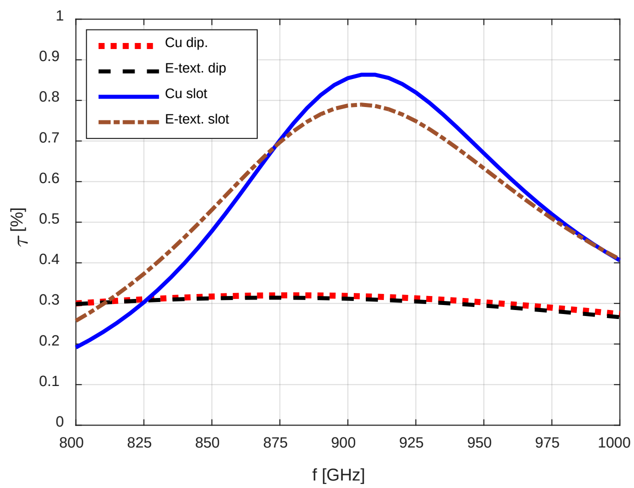


Fig. 5. Simulated antenna-microchip power transfer efficiency.

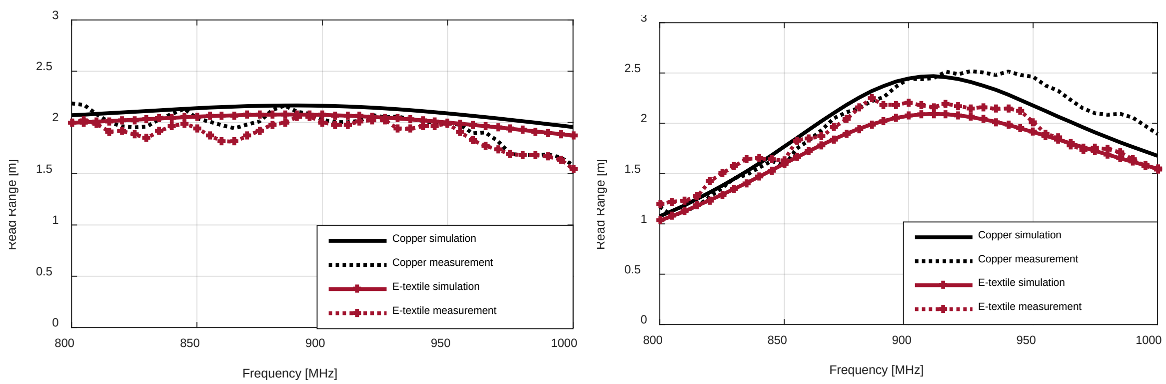


Fig. 6. Measured and simulated attainable read range of the dipole (left) and folded dipole (right) tags in the direction of the positive z-axis shown in Fig. 3

Fig. 6 presents the simulated and measured d_{tag} of all the studied tags. For the copper and electro-textile dipole tags, the measured read ranges were around 2 meters. In addition, the frequency trend of the read range was nearly flat in the whole frequency band, which corresponds with the same trend predicted for τ in Fig. 5. For the folded dipole tag, d_{tag} peaked at around 2.5 meters and 2 meters for the copper tape and electro-textile version, respectively. Overall, the simulations predicted the level and frequency trend of the measured d_{tag} extremely well for all studied tags. Notably, the performance of the electro-textile tags was highly comparable to the tags with copper antennas. This is promising for wearable applications where the tags must be seamlessly integrated with regular clothing. It should be noted, however, that the performance of the tag could significantly change when attached to other parts of the human body, as has been previously studied in the case of a slotted patch antenna [14], for instance.

5. Conclusions

We presented a comparison of wearable passive UHF RFID tags based on a dipole with embedded inductive loop matching and a folded dipole having equal footprint sizes. Antennas for both tag types were modelled and optimized using a simplified model where a homogenous dielectric block represented the human torso. The antennas were fabricated from copper tape and electro-textile material and the performance of each tag attached to the upper back of a test subject was assessed through wireless measurement. Our results showed that both of the studied uniplanar antennas are fit for wearable tags and provide similar performance in terms of the tag read range, but we also found the folded dipole to permit better impedance matching in this application.

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Publication VI

X. Chen, H. He, Y. Lu, H. Lam, L. Ukkonen and J. Virkki, Fabrication and Reliability Evaluation of Passive UHF RFID T-shirts, In Proceedings of International Workshop on Antenna Technology, 5-7 March 2018, Nanjing, China, 2018, 4p.

Fabrication and Reliability Evaluation of Passive UHF RFID T-shirts

X. Chen, H. He, L. Ukkonen, J. Virkki
BioMediTech Institute and Faculty of Biomedical Sciences and Engineering
Tampere University of Technology
Tampere, Finland

Y. Lu, H. Lam
Department of Electronic Engineering
City University of Hong Kong
Hong Kong

Abstract— **In this paper, we present textile antennas fabricated for T-shirt RFID applications by cutting from commercially available electro-textile, by sewing with conductive thread, and by 3D printing with stretchable silver ink on a 100 % cotton fabric. The ready tags with attached ICs are coated with a protective stretchable encapsulant. The wireless performance of the T-shirt tags is evaluated initially as well as after seven washing cycles, followed by nine washing-drying cycles in a household washing and drying machines. The initial read ranges of all kinds of tags, when measured on-body, are around 3.5 meters. Based on the reliability testing results, the coating effectively protects the components from cyclic washing and drying.**

Keywords— 3D Printing; electro-textiles; embroidery, passive UHF RFID; textiles; T-shirts; washing; wearable electronics

I. Introduction

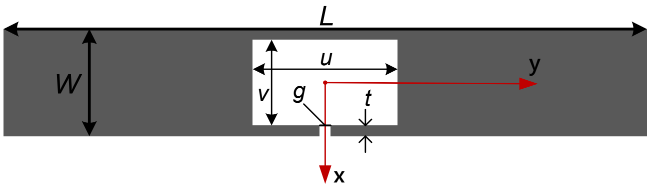
Wireless body area networks (WBAN) offer great potential for identification, monitoring, and communication in versatile application areas, e.g., in healthcare, welfare, and public safety [1][2]. One extremely potential wearable technology solution are passive ultra high frequency (UHF) radio-frequency identification (RFID) tags integrated into clothing [3][4], which will be the focus of this study. Wearable applications require the technology to be an integral part of clothing and to endure repeated mechanical stresses, moisture, and washing. This leads to the challenge of creating flexible and washable electronics structures, directly into clothing.

Antennas are critical enabling parts of all WBAN solutions. Conductive fabrics, i.e., electro-textiles, are a great example technology, which can be used to utilize cost-effective antennas for wearable solutions [5][6]. Electro-textile materials are easy to cut and can be unnoticeably embedded into traditional textiles. Further, sewing with conductive thread is a versatile manufacturing method, which has great possibilities in clothing-integrated antennas, due to its compatibility with various textile materials and easily modified conductive patterns [7]-[10]. In addition, 3D direct-write dispensing, a form of 3D printing, is an efficient additive manufacturing method, which enables the printing of complex antenna geometries with micron resolution accuracy. It is possible to 3D print versatile antenna materials on different types of fabric substrates [3]. These three techniques also provide the foundation for wearable identification and sensing applications by fabricating passive UHF RFID tags integrated into textiles.

In this paper, we present textile RFID tag antennas, fabricated by cutting from commercially available electro-textile, as well as by embroidering with conductive thread and by 3D printing with stretchable silver ink on cotton shirts. The ready tags equipped with ICs are coated with a protective encapsulant. All tags experience 7 washing cycles and 9 washing-drying cycles in a household washing and drying machines. The wireless performance of the tags integrated into shirts are evaluated, on body, before any reliability testing and after each testing cycle.

II. Fabrication of the Tags

Fig. 1 shows the geometry and dimension of the used wearable antenna. This dipole antenna design has been originally presented in [8] and has been optimized to work near the human body by using a human body model in ANSYS HFSS version 15. All the RFID tag antennas were fabricated on the upper back of a 100 % cotton T-shirt.



t	*g*	*L*	*W*	*u*	*v*
2 mm	2 mm	120 mm	20 mm	27 mm	16 mm

Fig. 1. The design and dimensions of the wearable UHF RFID tag antenna

The electro-textile antennas were utilized from nickel plated Less EMF Shieldit Super Fabric (Cat. #A1220), which has the hot-melt glue on the backside. The tag antennas were ironed directly on the cotton shirts. The electro-textile exhibits sheet resistance of approximately 0.16 Ω/□.

The embroidered antennas were utilized on the cotton fabric with Husqvarna Viking embroidery machine, using multifilament silver plated thread (Shieldex multifilament thread 110f34 dtex 2-ply HC). The resistance of the yarn is

500±100 Ω/m, and the diameter is approximately 0.16 mm. Based on the excellent results in [8], where only the antenna contour was sewed, we chose to only embroider the outline of the antenna. This method saves significant amounts of conductive thread and fabrication time, but does not significantly affect the antenna performance.

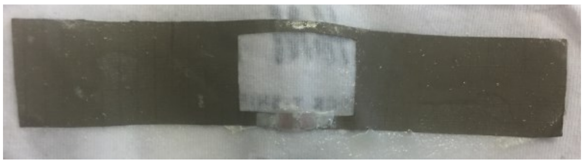
The 3D printing was completed directly on the cotton substrate by nScrypt tabletop series 3D direct-write dispensing system with a stretchable silver conductor (DuPont PE872). By adjusting the printing parameters, the printing system can produce a controllable ink flow, precise starts and stops, and the ability to utilize a wide range of material viscosities. The main printing parameters are defined in Table 1. Finally, the 3D-printed antennas were cured in 110 ºC for 15 minutes.

Table 1. 3D printing parameters

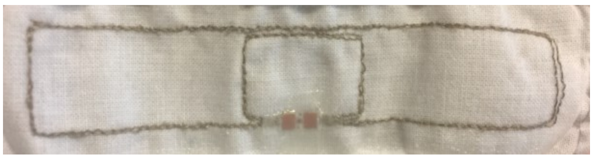
Parameter	
Material feed pressure	16.9 Psi
Printing spacing	125 microns
Printing angle	0°
Inner diameter of tip	125 microns

The RFID IC (integrated circuit) utilized in this study was NXP UCODE G2iL RFID IC, provided in a strap, which has copper pads on a plastic film. We attached the 3 × 3 mm^2 copper pads to the antennas using conductive epoxy (Circuit Works CW2400). The used IC has a wake-up power of −18 dBm (15.8 µW).

(a)



(b)



(c)

Fig. 2. The fabricated tags integrated into T-shirts: (a) 3D printed tag antenna, (b) Electro-textile tag antenna, (c) Embroidered tag antenna.

Finally, to protect the fabricated RFID tags from the harsh environment in washing and drying machines, both sides of the tags were coated with a stretchable protective encapsulant (DuPont PE772). The coating was brush-painted to fully cover the tags and the coated tags were dried in 100 ºC for 60 minutes. Fig. 2 shows the ready-made passive UHF RFID T-shirt tags.

III. Wireless Measurements

The wireless performance of the tags was evaluated using Voyantic Tagformance RFID measurement system. It contains an RFID reader with an adjustable transmission frequency (800-1000 MHz) and output power (up to 30 dBm) and provides the recording of the backscattered signal strength (down to −80 dBm) from the tag under test.

During the test, we recorded the lowest continuous-wave transmission power (threshold power: P_{th}) of the T-shirt tags. Here we defined P_{th} as the lowest power at which a valid 16-bit random number from the tag was received as a response to the query command in ISO 18000-6C communication standard. In addition, the wireless channel from the reader antenna to the location of the T-shirt tag under test was first characterized using a system reference tag with known properties. This enabled us to estimate the attainable read range of the tag (d_{tag}) versus frequency from

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\Lambda}\frac{P_{th*}}{P_{th}}} \quad (1)$$

where λ is the wavelength transmitted from the reader antenna, Pth is the measured threshold power of the measured T-shirt tag, Λ is a known constant describing the sensitivity of the system reference tag, $Pth*$ is the measured threshold power of the system reference tag, and EIRP is the emission limit of an RFID reader given as equivalent isotropic radiated power. We present all the results corresponding to EIRP = 3.28 W, which is the emission limit for instance in European countries.

All the T-shirt tag measurement were completed both in an anechoic room and in an office environment. Both measurement environments are shown in Fig. 3. During the wireless measurements, the female test subject wore the T-shirt and stood in a distance of 1 meter from the RFID reader antenna.

(a) (b)

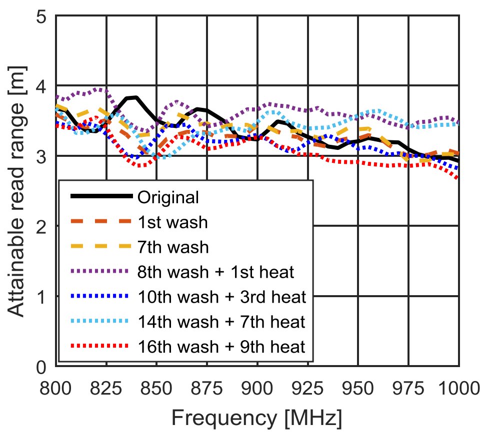
Fig. 3. Wireless measurements done in (a) Anechoic room, (b) Office conditions.

IV. Results and Discussion

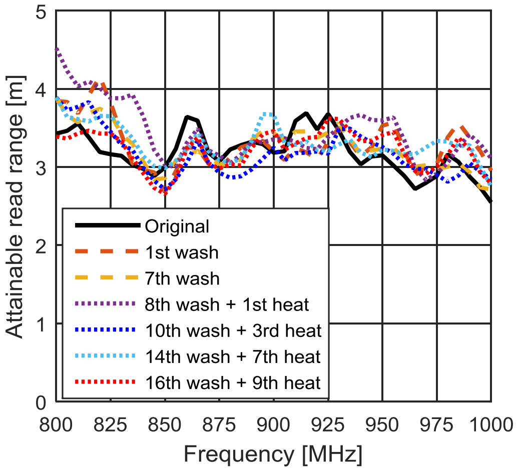
Firstly, the original on-body performance of the T-shirt-integrated RFID tags was evaluated in an anechoic room and in an office. The initial read ranges of all kinds of tags, when measured on-body, were around 3.5 meters**.** Next, the T-shirts were worn during the day and washed in a household washing machine in the evening. The washing was done in 40 °C without detergent and one washing cycle lasted for 22 minutes. The T-shirts were dried in room conditions. The tags were measured after each washing cycle and the results are shown in Figs. 4-6. After the eighth washing test, a normal household drying machine was started to use to dry the washed T-shirts. The drying cycle lasted for 1 hour and 30 minutes. Altogether 9 washing + drying cycles were done, after the original 7 washing cycles. The tags were measured on-body after each washing + drying cycle, in an anechoic room and in an office, and also these results are shown in Figs. 4-6.

As can be seen from Fig. 4, the washing and drying cycles did not have major effects on the electro-textile tags. The read ranges of the electro-textile tags decreased less than 0.5 meters after 7 washing cycles and 9 washing + drying cycles. However, as can be seen, human body causes significant variations to the measurement results. In case of the embroidered and 3D-printed tag antennas, the read ranges of the tags decreased around 0.5-1 meters, after all the washing and drying cycles. It should be noted that all types of tags maintained read ranges of more than 2 meters, after daily wearing and these harsh washing and drying tests.

These washing reliability results are very promising, when compared to earlier results. In [6], washing had a significant impact on non-coated, glue-coated, and textile moisture protection spray-coated electro-textile tags. The read ranges of the tags decreased 3.5 meters, 2 meters, and 3 meters respectively, from their initial values, after 10 washing cycles in a washing machine. Moreover, in [11], the read ranges of non-coated embroidered tags decreased from 6 meters to 3 meters after 16 washing cycles. The comparisons indicate that the protective coating utilized in this work could protect textile-integrated RFID tags during normal use.

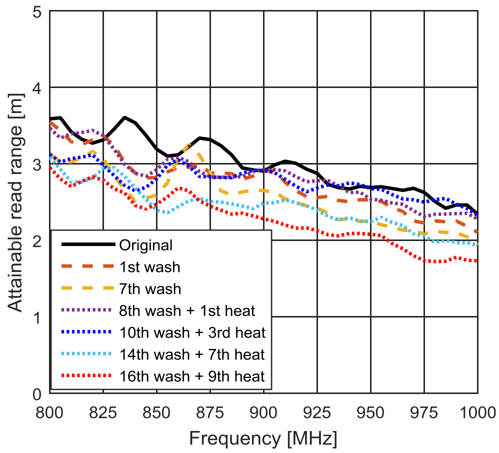


(a)

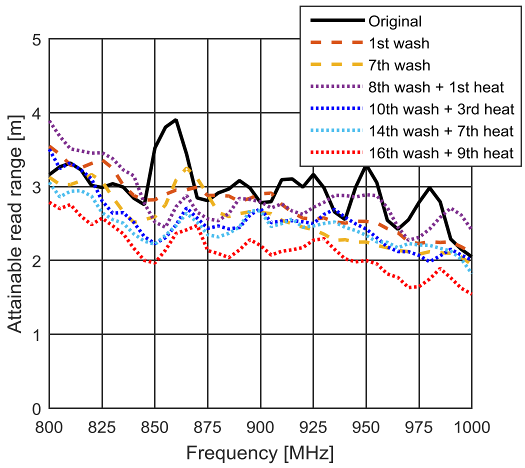


(b)

Fig. 4. Wireless performance of electro-textile tags after washing and drying testing in: (a) Anechoic room, (b) Office environment.

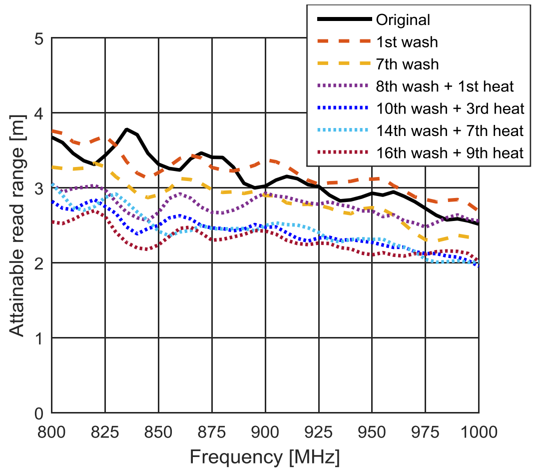


(a)

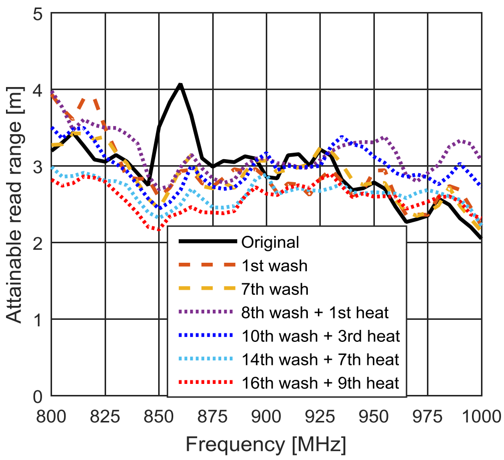


(b)

Fig. 5. Wireless performance of embroidered tags after washing and drying testing in: (a) Anechoic room, (b) Office environment



(a)



(b)

Fig. 6. Wireless performance of 3D-printed tags after washing and drying testing in: (a) Anechoic room, (b) Office environment

V. Conclusions

We fabricated and wirelessly evaluated three types of passive UHF RFID tags integrated into T-shirts. The tags with electro-textile, embroidered, and 3D-printed antennas were coated with a protective encapsulant and tested for daily on-body wearing, machine washing, and machine drying. The T-shirt tags were measured on human body both in an anechoic room and normal office environment. The initial read ranges of all kinds of tags, when measured on body, were around 3.5 meters. The tags showed similar performance in both measurements environments, which supports their practical use in different types of environments. After the washing and drying cycles, all tags still achieved read ranges of more than 2 meters, throughout the global UHF RFID frequency band. These results are very promising when considering practical integration of passive RFID technology into clothing. The next step is to carry out more washing and drying cycles and do tests with detergent. Further, we will test integration of these tags into different types of clothing, such as shirts made from thicker fabrics and stretchable sports clothing.

Acknowledgment

This work was supported by The Academy of Finland and City University of Hong Kong Overseas Internship Scheme.

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Publication VII

X. Chen, H. He, L. Ukkonen, and J. Virkki, Embroidered UHF RFID Moisture Sensor Tag on Dishcloth Substrate, In Proceedings of IEEE Antennas and Propagation Society Symposium on Antennas and Propagation, 8-13 July 2018, Boston, Massachusetts, USA, 2018, 2p.

Embroidered UHF RFID Moisture Sensor Tag on Dishcloth Substrate

Xiaochen Chen, Han He, Leena Ukkonen, Johanna Virkki
BioMediTech Institute and Faculty of Biomedical Sciences and Engineering
Tampere University of Technology
Tampere, Finland
xiaochen.chen@tut.fi

***Abstract*— In this paper, we present an embroidered passive UHF RFID moisture sensor tag made of dishcloth and conductive yarn. This extremely cost-effective and environmentally friendly wireless sensor can be easily embedded into versatile structures. The initial read range of the sensor tag was 4.7 meters at 915 MHz. In this preliminary study, 10 drops of water were applied on the sensor part of the structure and the performance of the sensor tag was measured in office conditions after 5, 10, and 15 minutes. After 5 minutes and 10 minutes, the read range increased to 5.0 and 5.2 meters, respectively, due to the conductivity improvement of the antenna pattern and increased backscattered power from the tag. After that, the sensor tag started to dry and the read range started to decrease. After 15 minutes, the read range was back to 4.7 meters at 915 MHz. Based on these initial results, these tags show potential for low-cost identification and sensing solutions.**

I. Introduction

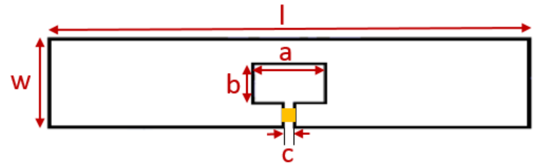
Passive UHF (ultra high frequency) RFID (radio frequency identification) -based technology has been recognized as a compelling approach to utilize energy-autonomous and cost-efficient wireless platforms for identification and sensing. These tags have showed great possibilities for example as strain, temperature, and humidity sensors [1]-[3]. As the technology is passive, no onboard power sources or maintenance are needed. For further information on UHF RFID technology, comprehensive introductions are provided in [4][5].

Fabrication of cost-effective and environmentally friendly antennas and interconnections has been an active research area during the recent years. One great example are embroidered structures fabricated from conductive yarn, which enable seamless integration of wireless components into versatile identification and sensing applications [6]-[8]. In this paper, we establish a truly low-cost and environmental-friendly identification and sensing platform. We fabricate and test an embroidered UHF RFID moisture sensor tag made of dishcloth and conductive thread.

II. Tag Fabrication

The structure of the antenna and antenna dimensions are shown in Fig 1. The substrate is normal thin single-use dishcloth. This material is environmentally friendly, and can be degraded by the nature in a short time. The antenna was embroidered by using a yarn coated with silver (Shieldex multifilament thread 110f34 dtex 2-ply HC). The resistance of the yarn is 500±100 Ω/m, and the diameter is approximately 0.16 mm.

After antenna fabrication, in order to establish fully functional RFID tags, NXP UCODE G2iL series RFID ICs were attached to the antennas. These chips are provided by the manufacturer in a strap with copper pads that were attached to the antenna with conductive silver epoxy (Circuit Works CW2400). A ready-made tag is shown in Fig. 2.



a	b	c	W	L
14.3 mm	8.125 mm	2 mm	20 mm	100 mm

Fig. 1. Sensor tag design.

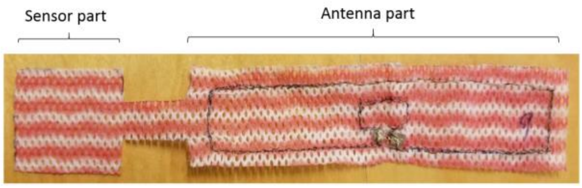


Fig. 2. Ready sensor tag.

III. Wireless Mesurements

In this work, the performance of the sensor tags was wirelessly evaluated in an anechoic chamber (to prevent any multi path effect in order to focus solely on sensor performance) with Voyantic Tagformance RFID measurement system. The system contains an RFID reader with an adjustable transmission frequency (0.8…1 GHz) and output power (up to 30 dBm), and provides the recording of the backscattered signal strength (down to −80 dBm) from the tag under test.

Firstly, the wireless channel from the measurement system reader antenna to the location of the evaluated sensor tag was characterized using a system reference tag with known properties. During actual testing, we recorded the lowest continuous-wave transmission power (threshold power: P_{th}) of the sensor tag. This enabled us to estimate the attainable read range of the measured tag (d_{tag}) versus frequency from

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\Lambda}\frac{P_{th^*}}{P_{th}}} \quad (1)$$

where λ is the wavelength transmitted from the reader antenna, P_{th} is the measured threshold power of the tag, Λ is a known constant describing the sensitivity of the system reference tag, P_{th^*} is the measured threshold power of the system reference tag, and *EIRP* is the emission limit of the RFID reader, given as equivalent isotropic radiated power. We present all the results corresponding to *EIRP* = 3.28 W, which is the emission limit in European countries.

The backscattered signal power is the time-average power detected from tag response at the receiver. It was measured by using the threshold power as the reader transmitted power. The backscattered power of the tag at the receiver $P_{backscattered}$ is:

$$P_{backscattered} = P_{th}G_{tag}^2 G_t^2 \left(\frac{\lambda}{4\pi d}\right)^4 \alpha|\rho_1 - \rho_2|^2 \quad (2)$$

where P_{th} and λ are as in (1), G_{tag} is the gain of the tag antenna, G_t is the gain of the reader (transmit/receive) antenna, d is distance from the tag, ρ_1 and ρ_2 are the power wave reflection coefficients of the tag in two different chip impedance states (used for modulating the backscattered signal) and α is a coefficient that depends on the specific modulation details.

IV. Measurement results

To evaluate the performance of the fabricated tag as a moisture sensor, 10 drops of water were applied on the sensor part of the structure. The sensor tag was measured after 5, 10, and 15 minutes, as well as afterseveral hours when the tag was totally dry again. The backscaterred power measurement results are presented in Fig. 3 between 900-930 MHz, as the peak frequency of the tag is at 915 MHz. As can be seen, the backscattered power increased when the sensor tag got wet, then started to return when the sensor structure started to dry, and returned back to the original condition after several hours, when the sensor tag got totally dry again.

In Fig. 4, the read range of the sensor tag is presented throughout the global UHF RFID frequency band. The initial read range of the tag was about 4.7 meters at 915 MHz. Next, 5 minutes after the water was applied on the sensor part, the read range increased to 5 meters. Then, after 10 minutes, the read range was around 5.2 meters. This phenomenon is caused by the conductivity change of the substrate material. Since the dishcloth is a non-conductive material, the conductivity increased when it absorbed water and the conductivity of the whole antenna pattern was increased accordingly. The read range of the tag decreased back to 4.7 meters after 15 minutes, whereas at lower frequencies the read range was still longer than originally. However, when the dishcloth dried again totally, the read range returned to the initial condition through the whole frequency band from 800 to 1000 MHz.

V. Conclusions

In this paper, we showed the design and measurement results of a low-cost wireless moisture sensor fabricated from dishcloth and conductive yarn. The initial read range of this RFID-based moisture sensor was about 4.7 meters at 915 MHz. When 10 drops of water were applied to the sensor, the read range increased to 5.2 meters, due to the conductivity improvement of the antenna pattern and increased backscattered power of the tag. The performance of the tag returned to the original status when the sensor structure was dry again. Based on these initial results, this type of cost-effective and environmental-friendly sensor structure could be useful in identification and moisture sensing applications in versatile fields.

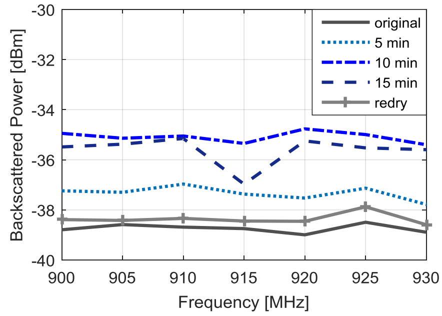


Fig. 3. Backscattered power of sensor tag between 900-930 MHz.

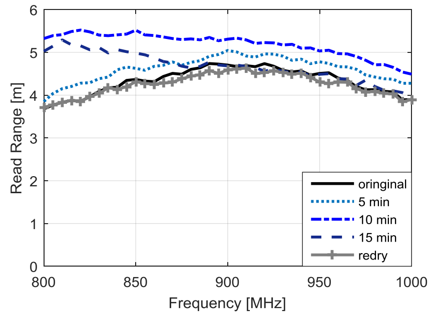


Fig. 4. Read range of sensor tag between 800-1000 MHz.

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Publication VIII

X. Chen, H. He, J. Xu, T. Wang, L. Cheng, L. Ukkonen, and J. Virkki, Fabrication and Practical Evaluation of Glove-integrated Passive UHF RFID Tags, Accepted to IEEE International Conference on RFID Technology and Applications 2018.

Fabrication and Practical Evaluation of Glove-integrated Passive UHF RFID Tags

X. Chen, H. He, L. Ukkonen, J. Virkki
BioMediTech Institute and Faculty of Biomedical Sciences and Engineering
Tampere University of Technology
Tampere, Finland

J. Xu[1], T. Wang[1], L. Cheng[2]
[1]School of Automation / [2]School of Computers
Guangdong University of Technology
Guangzhou, China

***Abstract*— Passive RFID-based technology is a convincing approach to achieve versatile energy- and cost-efficient wireless platforms for future wearable applications. In this paper, we present passive UHF RFID tags integrated into normal work gloves for wearable RFID applications. We introduce embroidery as a new efficient antenna fabrication method for glove-integrated tags as well as establish reference glove-tag antennas from electro-textiles and copper tape. The performance of the three types of glove-tags is evaluated on a male test subject in an anechoic room and in an office environment. Based on the wireless measurement results, the read ranges of the embroidered glove-tags were around 1 meter in an anechoic chamber and in an office, when measured near the human body. These results meet the requirements of many practical applications of glove-tags, although the read ranges are shorter than those of the electro-textile and copper tape tags that showed read ranges of 2-2.5 meters. Finally, the developed glove-tags were successfully tested in actual use situations for identification and access control. These results are very promising, especially considering the cost-effectiveness of embroidered tag antennas and the easiness of their integration into different types of gloves.**

Keywords—RFID, wearable antenna, glove-tag, embroidery electronics, electro-textile antenna

I. Introduction

Radio-frequency identification (RFID) technology can be used in versatile ways for efficient automatic identification [1][2]. By using cost-efficient RFID technology, identification, access control, as well as remote monitoring of movement and physiological parameters of a person or animal can be achieved unobtrusively [3]-[7]. Embedded RFID technology has also become essential for item tracking, supply chain management, and factory automation, just to name a few applications [8]-[10].

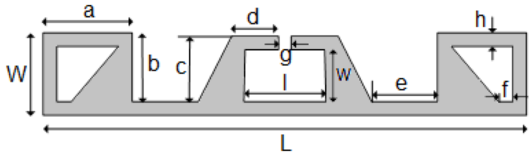
Further, in addition to clothes, RFID-based systems have been installed into footwear, as well as to different types of gloves [11]-[14]. Especially passive ultra high frequency (UHF) RFID technology is among the key technologies of future wearable wireless systems. As the technology is passive, no onboard power sources or complex systems are needed. Particularly gloves are an interesting choice to integrate simple passive RFID tags into. These “glove-tags” provide versatile possibilities for identification, access control, and possibly for antenna-based sensing. They could be especially useful in safety-critical working environments. This type of applications, however, require the antenna to be lightweight, cost-effective, easy to fabricate on different types of glove materials, as well as designed to be placed near the human body.

Embroidery with conductive yarn is an additive antenna fabrication method that can be used with a wide variety of substrates [15][16]. In embroidery, we have a full control of the conductive pattern: shape, stitch density, and stitch type [17]. Besides, embroidery is also a highly useful method for establishing textile-integrated interconnections [16][18]-[20].

In this work, we present passive UHF RFID tags integrated into normal working gloves. The tag antennas are embroidered into gloves using conductive yarn. Previously, electro-textile and copper tape have been used to establish prototype tag antennas attached into gloves [14]. Although electro-textiles can be useful for textile-integrated antenna fabrication, use conductive yarn provides significant advantages, such as extremely low cost, flexibility of embroidery, and suitability to mass production. The embroidered glove-tags together with reference glove-tags fabricated from electro-textile and copper tape, were tested on-body in the anechoic room and in an office environment. Part of the measurement results were published in [14], this paper is a review paper with some more results.

II. Antenna Design and Simulation

The used glove-tag antenna design in presented in Fig. 1. The optimization of the dipole antenna structure was based on electromagnetic modelling in ANSYS High Frequency Structure Simulator (HFSS).



W	L	w	l	a	b
13.1	76	8.3	12.9	14	10.9
c	**d**	**e**	**f**	**g**	**h**
12.3	7.4	10.4	2.3	2	2.1

Fig. 1. Glove-tag design with antenna dimensions [mm].

In the glove-tag antenna simulation model, two cubes (200 × 100 × 30 mm and 480 × 400 × 260 mm) were used to simulate human hand and body with a 120 mm gap between them. The hand part was set to bone model in HFSS, with a relative permittivity of 20.75 and conductivity of 0.34 S/m at 915 MHz. The body part was set to skin model in HFSS with a relative permittivity of 41.3 and conductivity of 0.87 S/m at 915 MHz. The top and bottom sides of the hand tissue were covered with a 2.5 mm thick sheet of polymide material (relative permittivity of 4.3 and conductivity of 0 S/m) to simulate the glove material, as shown in Fig. 2. For the tag antenna, a sheet resistance of 0.12 ohm/square was set, to simulate the copper tape.

In the glove-tag antenna simulation, we were searching for the optimized antenna dimensions. By adjusting the size of the antenna pattern, we wanted to achieve the longest possible read ranges for the tags with the limited antenna size. In addition, in the simulation we indicated the current density in different parts of the tag antenna. In the simulation, 0.15 W was delivered to the antenna. According to the current density presented in Fig 2, we can decide the needed density of conductive yarn at different antenna parts. Significant amounts of time and conductive yarn can be saved in the embroidery of RFID tag antennas by only partially sewing them from parts of low current density [10]. As can be seen from Fig. 2, the current density at 915 MHz was high around the feeding loop and the nearby antenna edges.

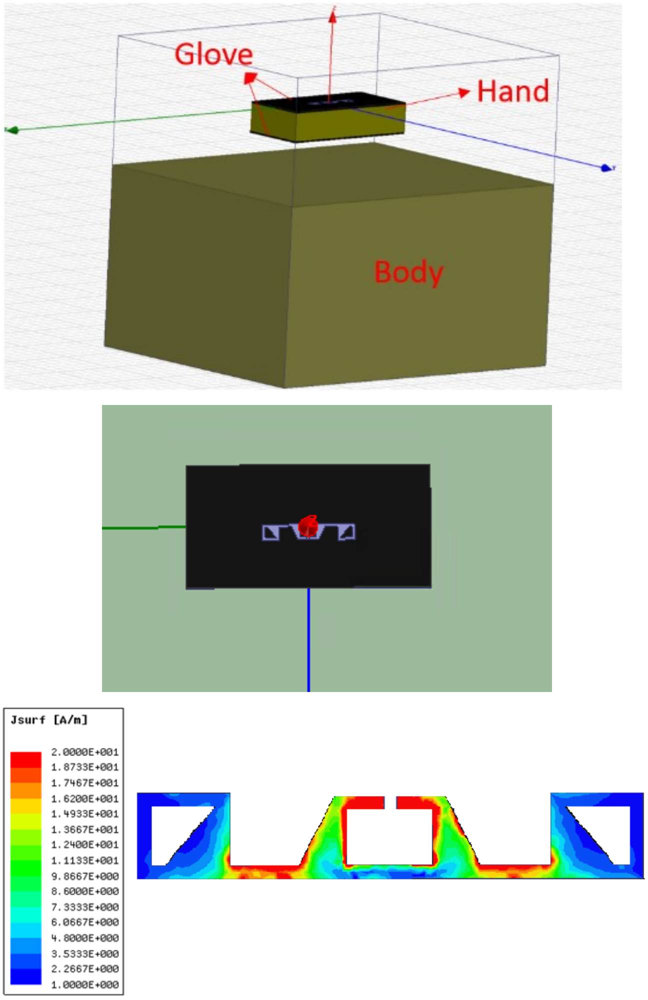


Fig 2. Glove-tag antenna simulation model (top) and simulated current density at 915 MHz (bottom)

III. TAG FABRICATION

The antenna was embroidered from multifilament silver plated thread (Shieldex multifilament thread 110f34 dtex 2-ply HC) by using a fully embroidered pattern at the antenna center with the feeding loop and by embroidering only the contours of the antenna side parts. This solution was chosen based on the simulated current density and was used to save conductive yarn material and time spent on embroidering.

The DC linear resistivity of the thread is 500±100 Ω/m, and the diameter is approximately 0.16 mm. The antenna was embroidered on the glove using Husqvarna Viking machine. We used conductive thread on the top and normal nylon thread as bobbin thread. Since the inner part of the glove will touch skin the hand, the bottom side of the antenna needs be non-conductive to maintain the performance of the tag.

For reference purposes, we fabricated similar tags from electro-textile and copper tape. The used electro-textile was nickel-plated Less EMF Shieldit Super Fabric (Cat. #A1220). This electro-textile exhibits sheet resistance of approximately 0.16 ohm/square and it has hot melt glue on the backside and can thus be easily ironed on versatile textile substrates, such as on gloves. The electro-textile antennas were cut by a laser cutter (Epilog Fusion Laser Model 13000), and then ironed to the top sides of the gloves. The copper tape antennas were cut with scissors from a copper tape with a conductivity of 58 MS/m and attached to the gloves. Both electro-textile and copper tape antennas were thus only attached on the top side of the glove and had no contact with the hand.

The RFID IC (integrated circuit) used in this study was NXP UCODE G2iL RFID IC, provided in a strap made of copper on a plastic film with 3 × 3 mm2 pads. We attached the pads to the antennas using conductive epoxy (Circuit Works CW2400). In the future, for the embroidered glove-tags, also the antenna-IC interconnection will be fabricated by embroidery, as embroidered interconnections have been found to be electrically excellent and mechanically reliable [15][21]. However, at this prototype stage, the focus is on the different antenna fabrication methods as well as on the future possibilities of glove-tags, and thus all the antenna-IC interconnections were done with the conductive glue. The ready glove-tags are all presented in Fig. 3 and Fig. 4 presents the used work glove.

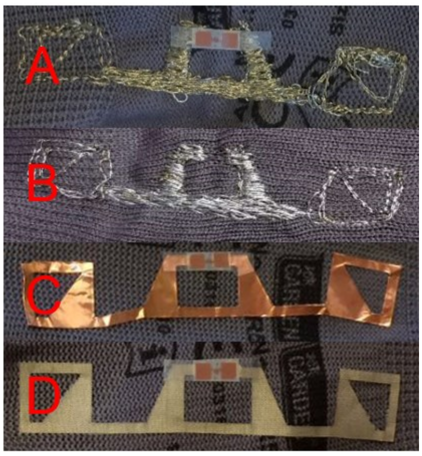


Fig. 3. Ready-made glove tags: A) Embroidered antenna (top side of the glove, conductive thread), B) Embroidered antenna (inner side of the glove, non-conductive thread), C) Copper tape reference antenna (top side of the glove), D) Electro-textile reference antenna (top side of the glove).

Fig. 4. Used working glove, top side.

IV. Wireless Measurements

The ready-made glove-tags were measured in an anechoic room (EMC room) and in a normal office environment, as shown in Fig. 5, from a distance of one meter. All the wireless measurements were conducted using Voyantic Tagformance RFID measurement system. It contains an RFID reader with an adjustable transmission frequency (0.8…1 GHz) and output power (up to 30 dBm), and provides the recording of the backscattered signal strength (down to −80 dBm) from the tag under test.

Firstly, the wireless channel from the measurement system reader antenna to the location of the evaluated tag under test was characterized in both measurement environments using a system reference tag with known properties. During actual testing, we recorded the lowest continuous-wave transmission power (threshold power: Pth) of each tag, i.e., the lowest power at which a valid 16-bit random number from the tag was received as a response to the query command in ISO 18000-6C communication standard. This enabled us to estimate the attainable read range of the measured tag (dtag) versus frequency from

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\Lambda}\frac{P_{th^*}}{P_{th}}}, \qquad (1)$$

where λ is the wavelength transmitted from the reader antenna, Pth is the measured threshold power of the tag, Λ is a known constant describing the sensitivity of the system reference tag, Pth* is the measured threshold power of the system reference tag, and EIRP is the emission limit of an RFID reader, given as equivalent isotropic radiated power. We present all the results corresponding to EIRP = 3.28 W, which is the emission limit in European countries.

Fig. 6 shows simulated and measured read ranges of a copper tape glove-tag near human body between 860-960 MHz. The simulated read range (around 4 meters) is about one meter longer than the measured read range (slightly less than 3 meters). This difference is caused by the effects of the human body, which in reality is larger and more complicated than the used simulation model, as well as by the crumpling and bending of the copper tape antenna on the glove surface. However, in both cases the read range is stable throughout the measured frequency range.

The measurement results in an anechoic room, in a frequency range of 860-960 MHz, are shown in Fig. 7. The read ranges of the embroidered glove-tags were around 1 meter, throughout the measured frequency range. For comparison, the electro-textile and copper tape tags showed read ranges of 2.4 meters and 2.6 meters. All the tags showed almost flat read ranges between 860-960 MHz.

Fig. 5. Measurement setups in an anechoic room (top) and in a normal office environment (bottom), the measurement distance was 1 meter.

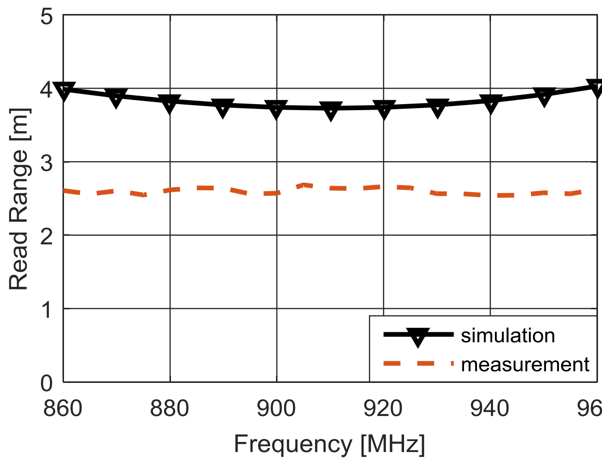


Fig. 6. Simulated and measured read ranges of copper tape glove-tags.

The measurement results in an anechoic room, in a frequency range of 860-960 MHz, are shown in Fig. 7. The read ranges of the embroidered glove-tags were around 1 meter, throughout the measured frequency range. For comparison, the electro-textile and copper tape tags showed read ranges of 2.4 meters and 2.6 meters. All the tags showed almost flat read ranges between 860-960 MHz.

Further, in the office measurements, the glove-tags were tested in a normal office environment with wooden and metallic furniture, people, and computers. The wireless environment in the office was also in a normal condition, meaning mobile phones were used and there was also an indoor WIFI signal. The office measurement results are shown in Fig. 7. Based on our measurements, the embroidered glove-tags showed similar performance in the office environment than in the anechoic room. On the other hand, the read ranges of the electro-textile and copper tape tags were slightly shorter in the office environment, as they both showed read ranges of around 2 meters there.

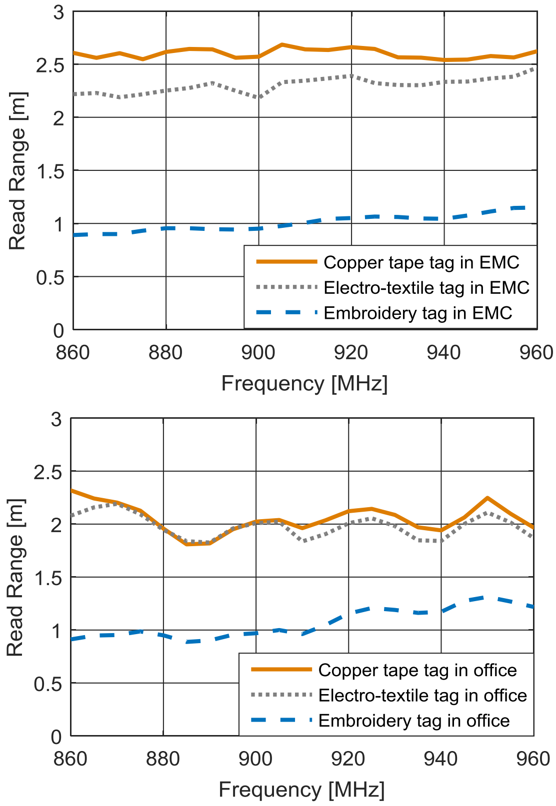


Fig. 7. The measurement results of different glove-tags in an anechoic room (top) and in an office environment (bottom).

Although the read ranges of the embroidered glove-tags are shorter than those of the copper tape and electro-textile ones, read ranges of one meter are already suitable for many practical applications of glove-tags, such as identification and access control. Further, the performance of the embroidered tag could be improved by fully embroidering the tag antenna pattern. However, this would increase material costs and fabrication time.

Next, a commercial mobile reader (Nordic ID Medea, which is designed for quick, accurate, and reliable data collection) was used to test our glove-tags in practical situations. This hand-held reader measures the tags at 866 MHz, which is the European center frequency for UHF RFID systems, and then communicates with any background system though WIFI.

As shown in Fig. 8, the reader was first located next to a shelf in a corridor and the male test subject walked past the reader. The distance from the glove-tag to the reader was about 1 meter and the reader was placed at a height where the person was able to read the reader display in a comfortable way. The reader was able to recognize all the glove tags successively. By preinstalling the locations of readers into a background system, the system will identify the person wearing the glove-tag and map the walking path of the person, for example in a factory or in a warehouse. Thus, also indoor tracing can be achieved with this system. Next, the reader was placed at a distance of 50 cm from a door handle, in order to test an automatic authentication system for access control. The reader was able to read all the glove-tags also in this configuration. Based on these preliminary results, the developed glove-tag could be used for versatile applications moving towards easier and safer working and living environments.

Fig. 8. Practical evaluation of glove-tags: identification (top) and access control (bottom).

V. Conclusions

We presented passive UHF RFID tags integrated into normal work gloves, introduced embroidery as a new efficient antenna fabrication method for glove-integrated tags, as well as established reference glove-tag antennas from electro-textiles and copper tape. The performance of the three types of glove-tags was evaluated on-body and the developed glove-tags were also tested in actual use situations for identification and access control. The read ranges of the embroidered glove-tags were around 1 meter, when measured near the human body. These results meet the requirements of many practical applications of glove-tags, although the read ranges are shorter than those of the electro-textile and copper tape tags that showed read ranges of 2-2.5 meters. The achieved results are very promising, particularly when considering the enormous amount of glove-tag applications, the cost-effectiveness of embroidered tag antennas and the easiness of their integration into different types of gloves. The next step is to improve the read ranges of the embroidered tags by modifying the embroidered pattern. The goal is also to integrate such tags into different types of gloves and test them in real world use environments, such as in a factory and in a warehouse.

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Publication IX

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2nd URSI AT-RASC, Gran Canaria, 28 May – 1 June 2018

The Effects of Added Clothing Layers on the Performance of Wearable Electro-Textile UHF RFID Tags

Xiaochen Chen, Han He, Leena Ukkonen, Johanna Virkki
BioMediTech Institute and Faculty of Biomedical Sciences and Engineering, Tampere University of Technology, Finland

Abstract

In this paper, we study the effects of added clothing layers on the performance of wearable electro-textile passive UHF RFID tags. The electro-textile tag antennas were ironed on the upper back of cotton T-shirts and coated with a stretchable protective encapsulant. The wireless performance of the tags was evaluated on-body in office conditions. We tested the effects of wearing two types of winter coats on top of the T-shirts. Based on our measurement results, adding a thick coat on top of the T-shirt does not stop the tag from working but reduces the peak read range from 7 meters to 5 meters. The fabricated electro-textile tags remained readable from distances of 2-5 meters, throughout the global UHF RFID frequency band, even when a thick winter coat was worn on top of the T-shirt.

1. Introduction

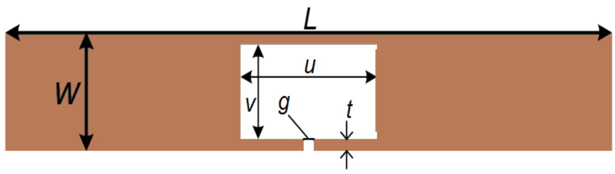
Antennas are critical enabling parts of wearable wireless solutions and thus an active research area. Conductive fabrics, i.e., electro-textiles, are a great example technology, which can be used to utilize cost-effective antennas for clothing-integrated solutions. Electro-textile materials are easy to cut and can be unnoticeably embedded into traditional textiles, for example by using hot-melt glue [1-2].

Passive ultra high frequency (UHF) radio-frequency identification (RFID) technology, which is the focus of this study, has gained a lot of interest as a versatile wearable wireless platform [3-6], mostly due to the simple structure and low cost of the passive UHF RFID tags. The battery-free and remotely addressable electronic tags, composed only of an antenna and an integrated circuit (IC), are readable from distances of several meters, which is extremely suitable for wearable applications. The simple structure also makes it easy to integrate these tags into clothing.

In this paper, we study the effects of added clothing layers on the performance of wearable electro-textile UHF RFID tags. We first introduce the simple fabrication method of the electro-textile tags integrated into T-shirts. Next, we evaluate their wireless performance on-body in an office environment. Finally, we test the effects of wearing two types of winter coats on top of the T-shirts, on the tags' wireless performance.

2. Fabricated Tags

Figure 1 presents the used antenna and antenna dimensions. This wearable dipole antenna design has been originally presented in [8]. It has been optimized to perform near the human body by using a human body model in ANSYS HFSS version 15.



t	*g*	*L*	*W*	*u*	*v*
2	2	120	20	27	16

Figure 1. The design and dimensions of the UHF RFID tag antenna in [mm].

The RFID tags were fabricated on the upper back of a 100 % cotton T-shirt. The electro-textile tag antennas were utilized from nickel plated Less EMF Shieldit Super Fabric (Cat. #A1220), which has a layer of hot-melt glue on the backside. These antennas were cut from the electro-textile material with scissors and then ironed directly on the cotton T-shirts. The electro-textile material has a sheet resistance of approximately 0.16 $\Omega/\square$.

The used IC is NXP UCODE G2iL RFID IC, provided in a strap that has copper pads on a plastic film, which we attached to the electro-textile antennas using conductive epoxy (Circuit Works CW2400). The used IC has a wake-up power of −18 dBm (15.8 µW) and the strap structure is presented in Figure 2.

Finally, to protect the fabricated RFID tags from their harsh use environment, especially considering the effects of moisture and the need for continuous washing cycles, both sides of the tags were coated with a stretchable protective encapsulant (DuPont PE772). This flexible coating has previously been found to be an effective way to protect copper-textile and embroidered RFID tags from the effects of moisture and machine washing [2]. As our goal is also to make these T-shirt tags reliable in normal use, the coating is essential. The coating was brush-painted to fully cover the tags and the coated tags were dried in 100 °C for 60 minutes. An example of a ready passive UHF RFID tag attached into a T-shirt is shown in Figure 2.

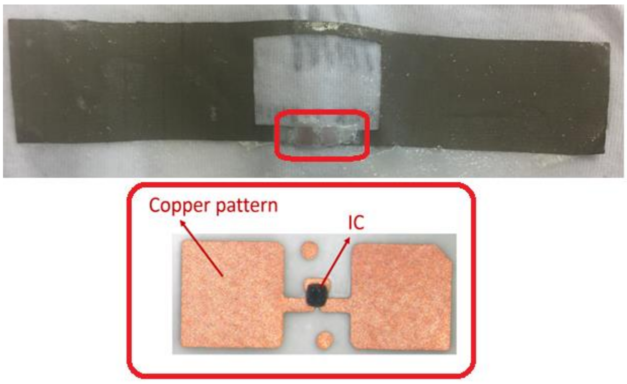


Figure 2. A ready electro-textile RFID tag attached into a T-shirt (top) and the used IC strap structure (bottom).

3. Wireless Measurements

The wireless performance of the tags was evaluated using Voyantic Tagformance RFID measurement system. This system contains an RFID reader with adjustable transmission frequency (800-1000 MHz) and output power (up to 30 dBm) and provides the recording of the backscattered signal strength (down to −80 dBm) from the tag under test.

During the test, we recorded the lowest continuous-wave transmission power (threshold power: P_{th}) of the fabricated T-shirt tags. Here we defined P_{th} as the lowest power at which a valid 16-bit random number from the tag was received as a response to the query command in ISO 18000-6C communication standard. In addition, the wireless channel from the reader antenna to the location of the T-shirt tag under test was first characterized using a system reference tag with known properties. This enabled us to estimate the attainable read range of the tag (d_{tag}) versus frequency from

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\Lambda}\frac{P_{th*}}{P_{th}}} \qquad (1)$$

where λ is the wavelength transmitted from the reader antenna, Pth is the measured threshold power of the T-shirt tag, Λ is a known constant describing the sensitivity of the system reference tag, $Pth*$ is the measured threshold power of the system reference tag, and EIRP is the emission limit of an RFID reader given as equivalent isotropic radiated power. We present all the results corresponding to EIRP = 3.28 W, which is the emission limit for instance in European countries.

The backscattered signal power is the time-average power detected from T-shirt tag's response at the receiver. It was measured by using the threshold power as the reader transmitted power. The backscattered power of the tag at the receiver $P_{backscattered}$ is:

$$P_{backscattered} = P_{th} G_{tag}^2 G_t^2 \left(\frac{\lambda}{4\pi d}\right)^4 \alpha|\rho_1 - \rho_2|^2 \qquad (2)$$

where P_{th} and λ are as in (1), G_{tag} is the gain of the tested tag antenna, G_t is the gain of the reader (transmit/receive) antenna, d is distance from the tag, ρ_1 and ρ_2 are the power wave reflection coefficients of the tag in two different chip impedance states (used for modulating the backscattered signal) and α is a coefficient that depends on the specific modulation details.

For the wireless measurements, a male test subject wore the T-shirt and stood in a distance of 1 meter from the RFID reader antenna. Initially, the subject wore the T-shirt with the attached RFID tag on top of a thin long sleeve shirt, as presented in Figure 3.

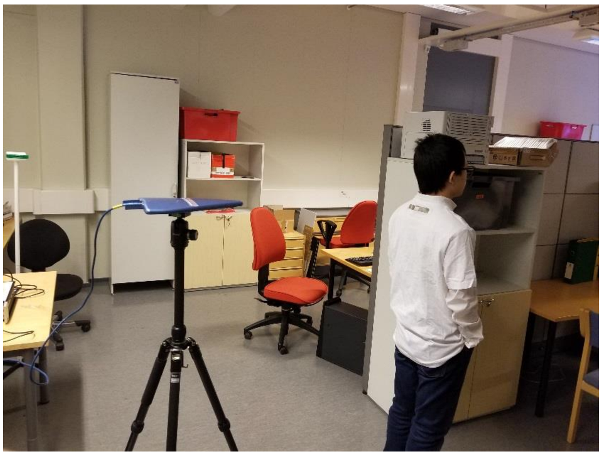


Figure 3. The initial measurement setup: T-shirt on top of a thin long sleeve shirt.

Figure 4. The second measurement setup, where a thin winter coat is worn on top of the T-shirt.

Next, a thin coat, which was a 3 mm thick down jacket, was added on top of the T-shirt, as shown in Figure 4, and the performance of the tag was measured again. Finally, a thick coat, which was a 10 mm thick down jacket, was added on top of the T-shirt and the tag was measured. All the on-body measurements were completed in a normal office environment, including office furniture, as shown in Figures 3-5.

Figure 5. The last measurement setup, where a thick winter coat is worn on top of the T-shirt.

4. Measurement Results

The wireless measurements results of an example T-shirt tag in the frequency range of 800-1000 MHz are presented in Figures 5 and 6. Firstly, Figure 5 shows the measured backscattered signal power from the tested tag. Next, Figure 6 presents the attainable read range results of the tag.

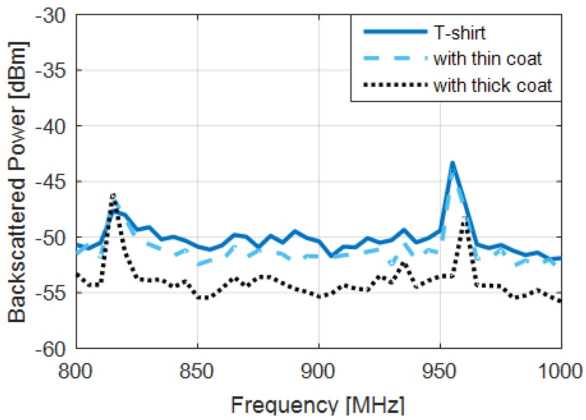


Figure 6. Wireless measurement results: backscattered signal power.

As can be seen, the peak read range and the best wireless performance of the tag is originally placed between 860-870 MHz, which is around the European center frequency. The initial peak read range of the tag, when measured on-body in normal office conditions, is around 7 meters. Further, the tag is readable from a distance of around 4 meters in the frequency range of 800-1000 MHz. Thus, the tag works in a suitable way all over the global UHF RFID frequency band.

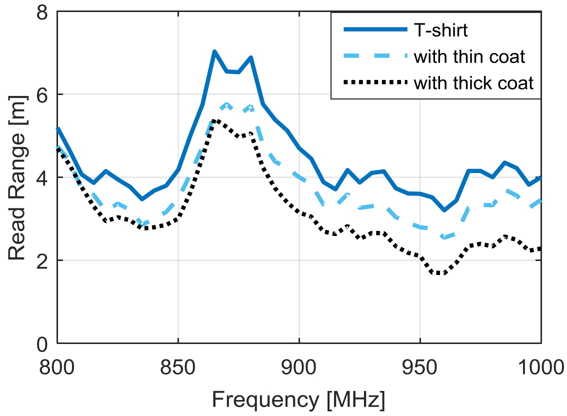


Figure 7. Wireless measurement results: read range.

Based on these measurement results, the winter coats have an effect on the tag read range: Adding the thin coat on top of the T-shirt drops the read range to slightly below 6 meters, to around 5.8 meters. Further, adding the thick coat over the T-shirt drops the read range further, to slightly over 5 meters. However, the tags remain readable from distances of 2-5 meters, throughout the global UHF RFID frequency band. These read ranges are more that suitable for many practical applications and thus using these passive UHF electro-textile RFID tags under thick clothing layers should not be a problem. However, for further conclusions, measurements need to be carried out from different directions and with different materials worn on top of the T-shirts.

5. Conclusions

We fabricated electro-textile passive UHF RFID tags integrated into T-shirts. The ready tags were coated with a protective encapsulant and their on-body wireless performance was evaluated initially as well as under two types of winder coats. The initial read ranges of the tags, when measured on-body, were around 4-6 meters, throughout the global UHF RFID frequency band, while the peak read range was 7 meters. In our next paper, we will present the washing reliability results of these T-shirt tags. Following, we will test integration of these electro-textile tags into different types of clothing and evaluate the tag performance under different types of clothing layers. Further, the plan is to evaluate the wireless performance of several wearable tags in one T-shirt at the same time.

6. Acknowledgements

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