



TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

Masoumeh Hasani

Wearable Passive RFID Tags in Advanced Applications

Detection Methods for RFID-Enabled Sensor Tags and RFID-based Localization



Julkaisu 1560 • Publication 1560

Tampereen teknillinen yliopisto. Julkaisu 1560
Tampere University of Technology. Publication 1560

Masoumeh Hasani

Wearable Passive RFID Tags in Advanced Applications
Detection Methods for RFID-Enabled Sensor Tags and RFID-based
Localization

Thesis for the degree of Doctor of Science in Technology to be presented with due permission for public examination and criticism in Rakennustalo Building, Auditorium RG202, at Tampere University of Technology, on the 21st of September 2018, at 12 noon.

Doctoral candidate: Masoumeh Hasani
Wireless Identification and Sensing System
Faculty of Biomedical Sciences and Engineering
Tampere University of Technology
Finland

Supervisor: Leena Ukkonen, Prof., Dr. Tech.
Wireless Identification and Sensing System
Faculty of Biomedical Sciences and Engineering
Tampere University of Technology
Finland

Instructor: Lauri Sydänheimo, Prof., Dr. Tech.
Wireless Identification and Sensing System
Faculty of Biomedical Sciences and Engineering
Tampere University of Technology
Finland

Pre-examiners: Gaetano Marrocco, Prof.
Electromagnetics Lab
University of Roma Tor Vergata
Italy

Atif Shamim. Assoc Prof.
Computer, Electrical and Mathematical Science and
Engineering Division
King Abdullah University
Saudi-Arabia

Opponent: Pasi Liljeberg, Prof., Dr. Tech.
Department of Future Technologies
University of Turku
Finland

Abstract

The radio frequency identification (RFID) is one of the many Automatic Identification and Data Capture (AIDC) methods which use propagation of electromagnetic waves for sending and receiving information. RFID has become increasingly popular over recent years from simple items labeling to more complicated applications such as sensing and positioning. One of the most exciting research trends of today in the field of RFID is the sensing capabilities offered by passive RFID technology. The massive use of wireless sensors in ubiquitous sensing and Internet of things (IoT) increases the demand for low-power, low-cost and sensing-friendly wireless communication devices. The well-known features of passive RFID system such as power efficient nature, the tiny size and easy implementation can overcome some major issues of the remote sensor systems. In addition, introducing new materials and advanced manufacturing technique for fabrication of RFID sensor tags, as well as introducing less complex detection techniques for collecting the data from the sensor nodes, can add more values to RFID to be prominent and promising technology for sensing application. In this thesis, first, we concentrate on using the passive ultra-high frequency (UHF) RFID tag in wireless sensing applications. As results of the research work presented in this thesis, the novel and low-cost manufacturing techniques, as well as innovative detection methods for RFID sensor tags, were introduced. For the first time, taking advantage of the nonlinear behavior of the RFID chip impedance as a function of the incident power, a novel sensing method has been presented. The method presented in this work relies upon the detection of the backscattered response for two distinct transmitting power levels and then calculating the difference between these two responses. The nonlinearity of the chip causes a large variation of its impedance value and thus a large difference of RCS value enabling a reliable operability over different measurement ranges. The detection methodologies presented in this work are suitable to be implemented in any kind of industrial environment that utilizes the RFID-enable wireless platform for sensing. Second, this thesis deals with a novel hybrid configuration for indoor positioning, utilizing the RFID and wireless local area network (WLAN). It is shown that combination of power efficient, cost-effective and easy to be implemented RFID system with WLAN technology, improve the localization accuracy compared to pure RFID and pure WLAN location solutions. The presented configuration based on the hybrid model can be expanded for the larger indoor area, as it has been presented in the results of research work. Overall, this thesis thus provides insights into the benefit of using passive UHF RFID tags and sensors in a wide range of application from inventory control and intelligent packaging to health care and human positioning.

Preface

This thesis is based on research work carried out during the years 2013-2015 in Wireless Identification and Sensing Systems (WISE) research group, at the Department of Biomedical Sciences and Engineering, in Tampere University of Technology, Tampere, Finland.

First, I would like to thank my supervisor Prof. Leena Ukkonen and my advisor prof. Lauri Sydänheimo for providing me the opportunity to work in WISE team and for their help and advice during these 2 years. My gratitude extends to Prof. Manos M. Tentzeris, for his extensive knowledge and experience in this field and research in general. I would also like to thank Prof. Simona Lohan for her beneficial collaboration with our team.

Foremost, I would like to express my deepest gratitude to Adj. Prof. Arnaud Vena for his hard-working nature, incredible support and all valuable knowledge that he shared with me during one year visit of WISE team. Further, I am very fortunate that I had the opportunity to work in a great research environment and with so many nice people. I would like to thank all my roommates Toni Björninen, Karoliina Koski, Elham Moradi, Mitra Akbari, Ali Babar, for all countless discussions, lunches, dinners, coffees, trips and laughs shared.

For the financial support, I would like to thank the following organizations and funds: The Finnish Funding Agency for Technology and Innovation (TEKES), the Academy of Finland and the Nokia Foundation.

I am also grateful to Prof. Gaetano Marrocco and Assoc Prof. Atif Shamim for acting as pre-examiners of this thesis work. Moreover, I am grateful to prof. Pasi Liljeberg for accepting to act as the opponent at my defense.

I would like to thank Toni for all his support and kindness. Last but not least, I would like to express my deepest gratitude to my dear family. My education would not have been possible without them. I am very grateful to all of them, in particular to my lovely mother and father for their unconditional love and support.

Tampere, Finland

September 2018

Masoumeh Hasani

Contents

Abstract	i
Preface	iii
Abbreviations	vii
List of Publications	ix
1 Introduction	1
1.1 Background and Research Motivation	1
1.2 Thesis Scope and Objectives	2
1.3 Thesis Structure and Outlines	3
1.4 Author's Contributions to the Publications	3
2 Fundamentals of RFID Technologies	5
2.1 Overview of the Technology	5
2.2 Operation Principle of Passive UHF RFID	8
2.3 Performance Indicators of Passive UHF RFID	12
3 RFID-Enabled Sensor Tags and Detection Methods	13
3.1 RFID-Enabled Sensor Tags	14
3.2 Wireless Detection of RFID Sensors	18
3.3 Double Power Detection Technique	25
4 Passive Wearable RFID Tag for Localization Applications	31
4.1 Positioning- Underlying Principles	31
4.2 RFID Propagation Channel Model	33
4.3 Hybrid Positioning Solution: WLAN-RFID	38
5 Conclusion	41
Bibliography	43
Publications	51

Abbreviations

AIDC	Automatic Identification and Data Capture
AOA	Angle of Arrival
ASK	Amplitude Shift Keying
CW	Continuous Wave
EIRP	Equivalent Isotropic Radiated Power
EM	Electromagnetic
FCC	Federal Communications Commission
HF	High Frequency
IC	Integrated Circuit
IoT	Internet of Things
LF	Low Frequency
PET	Polyethylene Terephthalate
PSK	Phase Shift Keying
RFID	Radio Frequency Identification
RCS	Radar Cross Section
RSS	Received Signal Strength
SHF	Supra High Frequency
TOA	Time of Arrival
UHF	Ultra High Frequency
UWB	Ultra Wide Band
VNA	Vector Network Analyzer
WLAN	wireless Local Area Network
WSN	Wireless Sensor Networks

List of Publications

- I M. Hasani, A. Vena, L. Sydänheimo, L. Ukkonen and M. M. Tentzeris, "Implementation of a Dual-Interrogation-Mode Embroidered RFID-Enabled Strain Sensor," *IEEE Antennas and Wireless Propagation Letters*, Vol. 12, pp. 1272–1275, December 2013.
- II M. Hasani, A. Vena, L. Sydänheimo, L. Ukkonen and M. M. Tentzeris, "A Novel RFID-Enabled Strain Sensor Using the Double Power Measurement Technique," in *Proc IEEE International Microwave Symposium*, pp. 1–4, June 2014.
- III M. Hasani, A. Vena, L. Sydänheimo, L. Ukkonen and M. M. Tentzeris, "A Novel Enhanced-Performance Flexible RFID-Enabled Embroidered Wireless Integrated Module for Sensing Applications," *IEEE Transaction on Components, Packaging and Manufacturing Technology*, Vol. 5, pp. 1244 - 1252, August 2015.
- IV M. Hasani, L. Sydänheimo, L. Ukkonen, "Design and Implementation of Fully 3D Miniaturized Passive RFID Tag for Sensing Applications," in *Proc Loughborough Antennas and Propagation Conference*, pp. 1–4, November 2015.
- V M. Hasani, E. S. Lohan, L. Sydänheimo, L. Ukkonen, "Path-Loss Model of Embroidered Passive RFID Tag on Human Body for Indoor Positioning Applications," in *Proc IEEE RFID-TA*, pp. 170–174, September 2014.
- VI M. Hasani, J. Talvitie, L. Sydänheimo, E. S. Lohan, L. Ukkonen, "Hybrid WLAN-RFID Indoor Localization Solution Utilizing Textile Tag," *IEEE Antennas and Wireless Propagation Letters*, Vol. 14, pp. 1358 - 1361, February 2015.
- VII M. Hasani, L. Sydänheimo, L. Ukkonen, "Performance Evaluation of Wearable Passive RFID Tag for Human Indoor Positioning," *Proc IEEE International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting*, pp. 1750 - 1751, July 2015.

1 Introduction

1.1 Background and Research Motivation

Automatic identification (Auto-ID) is involved in modern lives on a daily basis. There are several technologies and techniques that can be used to identify objects or people, such as barcodes, magnetic strip cards, smart cards, and holographs. Increasing demand for automatic identification in various applications, and the limitations of the old identification methods alongside of the rapid transition towards wireless technologies are a few of the major reasons for developing a more advanced identification technique, known as radio frequency identification (RFID). Compared to other identification methods, RFID has several advantages: it is more reliable due to less human involvement, it is sustainable in harsh environments, it is power and cost efficient, there is no need for line-of-sight communication, it can handle more information and update it real-time, and it can be read from a long distance, for example. These facts make RFID attractive for different industries and increase its popularity in various areas where identification and tracking can add significant value to core services, from logistics and supply chain to health care and smart housing [1].

On the other hand, in everyday life we are surrounded by billions of intelligent physical objects and devices with Internet embedded in them. Therefore, the term Internet of things (IoT) can be considered as one of the key concepts for the realization of ambient intelligence. A futuristic vision that is coming closer to reality every day is an environment containing a vast number of smart objects and devices with computing and sensing ability. These devices are connected to each other wirelessly and they can sense and collect data and share it [2]. One simple example of this is a smart home where all intelligent items, such as security devices, air conditioning system, computers, laptops, appliances, and lighting are connected to the Internet and can be controlled and managed remotely [3]. This is an easy way to provide flexibility and convenience for the owner of the house and enables a highly secure and energy-efficient lifestyle. Wireless sensor network (WSN) is one of the potential technologies for enabling IoT. A WSN includes a set of sensor nodes which can collect information by sensing and measuring environmental parameters, such as temperature, humidity, vibration, and pressure [4]. The sensor nodes typically are equipped with computing units (such as micro-controllers) and batteries. They can communicate with each other using short-range wireless systems [4].

Integration of the RFID technology into WSN attracted considerable attention in recent years, due to the important advantages and broad applicability of both technologies [4]. RFID was first introduced for identifying and tracking items with no knowledge or information about their actual physical or environmental conditions. On the other hand, there are various applications where identification and location information are not enough, and where getting further information by sensing the environmental conditions

is very important. Therefore, for these kinds of applications, merging the RFID and wireless sensor networks is considered an optimal solution, since they complement each other. One simple architecture for such an integration would be implementing the sensing ability into RFID tags and using those as sensor nodes. This way the sensor-tags are able to communicate with the reader and provide not only the tag's ID but also the collected sensed data [5].

The sensing functionality can be implemented to RFID-enabled sensor tags using different techniques. A tag contains an antenna which acts as a wireless interface for transferring and receiving data between the sensor nodes and the environment. The antenna itself can be used as a sensor element, or a circuit with sensing ability can be integrated in the tag [6]. Utilizing RFID-enabled wireless sensors are rapidly growing in many different industrial areas and therefore, the advanced development of the idea has been one of the hottest topics in both academic and commercial research work in the field of RFID [6].

1.2 Thesis Scope and Objectives

The main focus of this thesis is on two highlighted research topics of recent years in the field of RFID technology: passive wireless sensing and localization.

Regarding the RFID-enabled wireless sensors, this thesis provides a general view on the development and implementation of the wireless passive sensing platform utilizing the RFID technology, from tag design and advanced fabrication methods to detection and realizing the performance. The studies in this thesis cover the entire process for developing a passive tag with sensory functionality and defines novel methods for the realization of sensed parameters. More specifically in the passive sensing topic, this thesis concentrates on analyzing and developing a detection method to best enhance the performance of the system. Developing the idea for commercializing the solution for industrial use is outside of the scope of this thesis. Therefore, the objectives of this thesis in regards to the sensing topic are as follows:

- Development of the passive tag utilizing additive manufacturing methods for sensing applications
- Development of the flexible passive strain sensor tag
- Comparison of the different interrogation methods for the strain sensor tag
- Introducing an advanced and novel detection method for sensor tags
- Validation of the sensor sensitivity and accuracy

The second focus of the thesis is on the benefits of using passive RFID technology in positioning applications. Utilizing wearable passive RFID technology for human localization in indoor environment has been studied empirically. The results of the study were compared with conventional indoor positioning methods such as WLAN. Taking into account the advantages and drawbacks of different methods, a novel hybrid solution for indoor positioning was introduced. The main objectives can be listed as follows.

- Development of wearable passive RFID tags

- Implementation of real-field measurement environment
- Communication channel modeling of passive RFID system
- Studies on hybrid RFID-WLAN configuration based on received signal strengths

1.3 Thesis Structure and Outlines

This thesis is based on seven publications, defined I to VII. The introductory remarks and outlines of these publications form the chapters 1 to 5 of this thesis book. The contributions of each publication and the chapter reviews are presented as follows.

Chapter 1 starts with the motivations and goals of the research work and continues by discussing the objectives and scope of the thesis. Finally, the author's contribution in the publications is presented.

Chapter 2 is about the overview of the RFID technology and background of the research work. The principles of the passive UHF RFID system, the operation and performance indicators are described. In addition, a closer look at the structure of the passive UHF tag antenna, matching, and scattering structure is presented.

Chapter 3 talks about the passive UHF system in sensing applications. Firstly, the details of passive sensor tags including the sensing mechanism and fabrication methods are presented. Then, different wireless detection methods for the realization of the sensed parameter are covered. In the next step, the process of the implementation and interrogation of a passive strain sensor is described. Finally, an enhanced detection method for wireless readout of sensor tags is introduced. The outcomes of the **Publications I, II, III and IV** contribute to the contents of this chapter.

Chapter 4 is related to the use of a passive wearable UHF tag in localization application. First, the feasibility of the use of a fully wearable passive tag for indoor localization is discussed.(V). When the outcomes of the study show that the results are comparable with some conventional positioning method such as WLAN, a hybrid positioning solution utilizing both RFID and WLAN is demonstrated (**VI, VII**).

Chapter 5 as the final chapter of the thesis, is summarizes the study work and draw the final conclusions and future trends.

1.4 Author's Contributions to the Publications

The scientific research outlines presented in **Publications I to VII** were achieved in collaboration. The contribution of the author in each publication is listed below.

Publication I: The author and co-author Dr. Arnaud Vena are the main contributors of the work. The author conducted the simulations, design and fabrication of the tag. The author also performed the measurements in section III. The post-processing of the measurement results presented in section III part B was conducted with the help of Dr. Arnaud Vena.

Publication II: The author has contributed to the publication contents and is the main contributor to the publication text. The theoretical model discussed in section III part B, has been introduced by the co-author of the article Dr. Arnaud Vena.

Publication III: The author and co-author Dr. Arnaud Vena are the main contributors of the work. The author conducted the simulations, design, and fabrication of the tag.

The author also performed all the measurements. The analysis of some measurement results was done with the help of Dr. Arnaud Vena.

Publication IV: The author has contributed to the publication contents and is the main contributor of the publication text.

Publication V: The design, fabrication and implementation of the RFID related hardware and conducting the measurement and data collection was done by the author. The WLAN data collection and post-processing of the collected data using positioning algorithm were conducted by Prof. Simona Lohan.

Publication VI : The author and co-author Prof.Simona Lohan are the main contributors of the publication text. The author has designed the tag and implemented the measurement set up and conducted the measurement related to RFID data collection. Co-author Prof. Simona Lohan and her team have introduced and conducted the topic presented in section III of the publication.

Publication VII : The author was responsible for the design and fabrication of the prototype sample, as well as data collection. In addition, she is the main contributor of the publication text. The post-processing of the collected data was conducted by Prof. Simona Lohan.

2 Fundamentals of RFID Technologies

In this chapter, some principles and parameters of the RFID technology and mainly the passive UHF (Ultra High Frequency) system will be discussed. It starts with a general review of the RFID technology and then goes into more detail in analyzing the passive UHF system. Finally, the measure and metrics for the performance evaluation of the system are discussed.

2.1 Overview of the Technology

Radio frequency identification (RFID) is an umbrella term covering different technologies with various communication protocols, operating frequencies, identification ranges and device types. In fact, the similarity between all these different technologies is the RFID system configuration and components which includes the tag, the reader unit and an application host for directing the communication between the tag and the reader. The information about the items that need to be identified is stored into the tag, and it backscatters to the reader using RF signals.

An RFID tag typically includes a microchip and an antenna. However, there are types of RFID tags without a microchip, known as chipless tags. The chipless RFID tag which is printed with conductive ink on a certain substrate material has no IC to store the information. Therefore, the tag does not have much capacity for data handling. Furthermore, no conventional communication protocol such as amplitude or phase modulation is possible with the chipless tag. However, the simple structure and low production cost are the main reasons why chipless tags are developed for certain identification applications. They have advantages over the barcode system since they can be read remotely like a chipped RFID tag and do not need certain reading positioning like an optical barcode. The operational principle of the chip-less tag, as well as the realization and reading system are discussed in detail in [7].

In a typical tag, the chip or IC is used for storing data and is the main responsible for the tag functionality. The communication protocol between the tag and the reader, the coding, decoding and modulation of the backscattered data from the tag is handled by the IC. Normally items that are labeled with an RFID tag have a unique ID which comes from the RFID chip. In fact, the unique identification number of the IC is defined by the manufacturer and it is stored in the memory of the IC. This way it is easy to identify the target item while transferring its information to the reader. [8]

The antenna is the key element that enables the RF communication of the tag with the reader. Depending on the application, there is a variety of antenna structures for the

RFID tags. Usually, the antenna size, shape, and the material are selected based on the operation frequency and the environment where the tag is going to be used. Moreover, the antenna should be properly designed to transfer the maximum energy to the IC and also to provide strong enough backscattered signal to the reader. To form an RFID tag, the antenna is normally fabricated on top of certain dielectric substrate material and the IC is connected to the antenna. Depending on the antenna fabrication technique, the substrate materials can vary from a very thin and flexible layer of PET or paper to thicker and hard material such as FR4. The conventional technique for fabrication of the antenna is the etching method which will be described in the next chapter. Aluminum is the conductive material which is widely used in the manufacturing of commercial RFID tag due to the good conductivity and reasonable price. Since electromagnetic properties of the IC, such as impedance or power sensitivity are dictated by the IC manufacturer, the performance of the RFID tags is mostly defined by the antenna design and choosing the correct substrate material. There are a few parameters that must be taken into account when designing the tag antenna to ensure the tag meets the application requirements. The important parameters are normally the antenna gain, matching, and the radiation pattern as discussed in detail in [1][9][10][11][12].

The tag antenna is designed to operate on a certain frequency band [8]. In terms of operating frequencies, the different RFID system families operate from low frequency up to microwave band: *The low frequency (LF) RFID* 125 kHz and 134 kHz, *the high frequency (HF) RFID* 13.56 MHz, *the Ultra high frequency (UHF) RFID* 860 MHz to 960 MHz, also 433 MHz, and finally *Supra high frequency (SHF)* 2.4 GHz and 5.8 GHz. The RFID tags have different performance capabilities depending on their frequency classification. This is discussed in more detail in the following sections.

There are 3 types of RFID tags based on how a tag can power up itself: *passive, semi-passive and active*. The simple structure of a tag including the antenna and IC usually refers to a passive tag, in which there is no battery or any other source of energy. In fact, a passive tag harvests the energy from the reader to operate and also to transmit data to the reader. Therefore, the reader always initiates the communication and the tag's antenna captures the energy to energize the IC and communicate back to the reader. The passive tags are the most widely used type of RFID tags because of their simple structure that led to low production cost. In addition, having no battery makes them a perfect candidate for applications that need a wireless solution with a long operating lifetime. [8]

The drawbacks of the passive tag are mainly the short read range and demand for high power from the reader. The semi-passive or battery-assisted passive tag addresses these issues by adding a battery to the structure of the tag. The semi-passive tag uses the battery to set the IC in operation mode and it does not need the reader signal for activating the IC. This will increase the forward link (reader to tag) read range compared to the passive tags. However, the tag to reader communication is not still active transmission, and the tag modulates and backscatters the reader signal and generates the response using reader's energy [8]. The active tag has more complex hardware compared to the other two types and typically has a higher price. It utilizes the battery for both IC operation and data transmission, which enables an active transmission from the tag to the reader as well. The active tags offer the longest read range among the three types. [7][8]

Another classification for RFID tags is based on their operation region as shown in figure 2.1. An RFID tag can operate in near field or far field, depending on its antenna structure. As addressed in [12], the surrounding space of an antenna can be separated into three regions. The structure and operational principle of the electromagnetic field is different

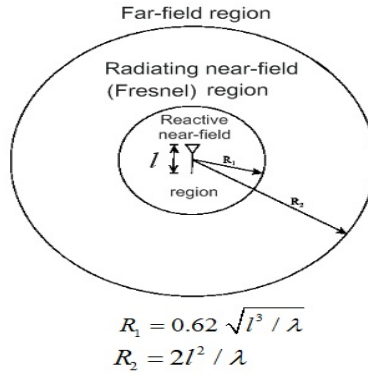


Figure 2.1: Operation area (near-field and far-field) of RFID technology. [12]

in each region as it is explained in detail in [12]. In a simplified way, closest to the antenna is the reactive near-field region where the reactive part of the field is dominant and the radiation is poor. In most cases, any distance from the antenna surface up to $0.62\sqrt{\frac{l^3}{\lambda}}$, belongs to the reactive near-field region. Here, λ refers to the wavelength and l is the maximum antenna dimension. The region bigger than $0.62\sqrt{\frac{l^3}{\lambda}}$ and smaller than $\frac{2l^2}{\lambda}$, where the reactive part of the field is no more dominant and the field has some propagation properties is known as the radiating near-field. This area does not exist for an antenna if $l < \lambda$. The region outermost to the antenna is called far-field. In far-field the radiated wave can be considered as a plane wave and the distribution of the field is no longer dependent on the distance from the antenna. Far-field exists at a distance bigger than $\frac{2l^2}{\lambda}$. [12]

The LF and HF RFID tags operate in the near-field. The energy transfer between the reader and tag is achieved by inductive coupling. The form of the antenna for both the reader and the tag is a kind of loop antenna or coil (planar or wire-wound). The reader generates a strong magnetic field which produces a voltage in the tag side. This voltage will power up the IC connected to the tag antenna and enables the IC to demodulate and execute the reader commands. Overall, the read range of the LF and HF tags does not exceed one meter. In many cases, they are mainly used in applications with a high demand for confidentiality in data handling. For instance, payment cards, passports, tickets and mobile payments are handled utilizing HF or LF RFID technology. To guarantee security, the IC used in this type of tag must be equipped with certain cryptography features and also enough memory. [1][13]

The RFID tags operating in the UHF or UWB (Ultra Wide Band) frequency band mostly follow the far-field communication rules. As mentioned before, the electromagnetic wave propagated by the reader antenna will be captured by the tag to enable the communication. And part of the reader energy will be reflected back to the reader by the tag. In the following sections, the communication principles between the tag and the reader in far-field is discussed in more detail. For the UHF tags, depending on the passive or active type, the read range can vary from one to tens of meters. The retails, supply chain management, access control, and smart packaging are a few application areas in which UHF tags are popularly used. A brief review of the RFID technology family is presented in table 2.1.

Table 2.1: A brief classification of RFID technology. [7]

Family	Read Range	Capacity of Coding	Cost of the Tag
LF, HF	Less than 1 m	Some Kbits	> 0.4 euros
UHF, SHF	1-100 m	Some Kbits	> 0.1 euros
UWB	Less than 60 m	Some bits	> 0.3 euros

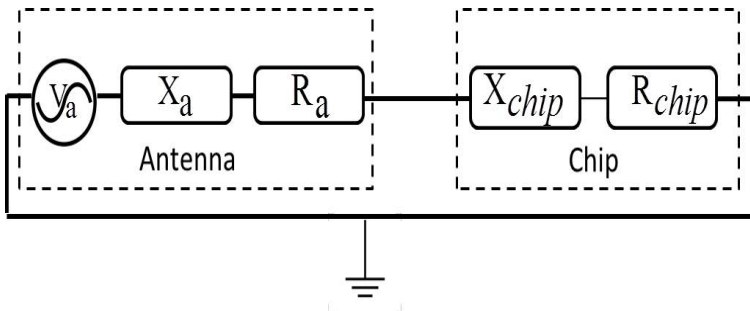
2.2 Operation Principle of Passive UHF RFID

The passive UHF RFID tags are commercially the most used in the market, due to the cheap price and power efficient features. Therefore, the main subjects of the studies in this book are focused on the far-field operation of the passive tag on the UHF frequency band. In this section, an overview of the operation principle of the passive UHF system is discussed.

2.2.1 The Structure of the Passive Tag and Matching

A passive UHF system consists of three main components: the tag, the reader unit, and the application host. A passive UHF tag includes an antenna and a microchip which is known as the RFID IC (chip), and it is connected to the antenna as a load. The interaction between the antenna and the IC is significant when evaluating the performance of a tag. Considering the antenna as the generator of voltage and power for the load (IC), the power exchange should be optimized to achieve the desired performance from a tag.

As the equivalent circuit model shows in figure 2.2, the antenna input impedance can be presented by $Z_a = R_a + jX_a$ and the input impedance of the RFID chip is $Z_{chip} = R_{chip} + jX_{chip}$. The R_a , R_{chip} represent the resistance part and X_a , X_{chip} refer to the reactance part of the impedance for the antenna and the IC, respectively, at their input terminal. To maximize the performance of the tag, the maximum power transfer between the antenna and load should be considered [14]. This will be achieved only if the impedance of the chip, as a load, be the complex conjugate of the antenna impedance or $Z_{chip} = Z_a^*$ [15].

**Figure 2.2:** The passive RFID Tag: equivalent circuit model

Otherwise, it causes additional waste of power. The mismatch level between the tag antenna and IC can be defined using the term power reflection coefficient (Γ) given as [14]

$$\Gamma = \frac{Z_{chip} - Z_a^*}{Z_{chip} + Z_a}. \quad (2.1)$$

Assuming the tag collects the power P_{r-tag} , the fraction of the power which is delivered to the chip is defined as

$$P_{chip} = \tau P_{r-tag} \quad (2.2)$$

where the $\tau = 1 - |\Gamma|^2$ is the power transmission factor and it is a value between zero and one. For the maximum power transmission, where $Z_{chip} = Z_a^*$, the τ factor is simplified as follows

$$\tau = \frac{4R_a^2}{|Z_{chip} + Z_a|^2}. \quad (2.3)$$

Later in section 2.3, the importance of the matching and transferring enough power to the chip for the performance evaluation of the RFID tags will be discussed more. In general, the RFID chips are commercially available components with the defined impedance. Therefore, designing an antenna with proper matching and acceptable performance has always been one of concerns of antenna designers. There are several kinds of matching techniques and other considerations for antenna design which have been addressed in many research works, such as [10], [16] and [17].

2.2.2 The Power Transmission in Forward and Reverse Link

To be able to communicate with the reader, a passive tag must power up itself by harvesting the energy transmitted by the reader. The communication between the tag and the reader can be divided into three main phases: in the start, the reader sends continuous wave (CW) to wake up the tag. When the tag receives power level above the IC's threshold power ($P_{th-chip}$), the tag is activated and the second phase of communication, in which the reader sends the commands, starts. Finally, in the third phase, the reader sends another CW which the tag modulates and backscatters to the reader. [18]

The details of the communication protocols in the signal processing level is out of the scope of this work. However, overall, the UHF RFID system follows the standards defined by EPCglobal UHF Class-1 Gen-2, for data handling. As addressed in details in [8] and [20], the tag and the reader can use different modulation, coding and decoding techniques, such as amplitude shift keying (ASK) or phase shift keying (PSK) for communicating with each other. The FM0 baseband or Miller modulation of sub-carrier are typical methods which the tag uses for encoding the backscatter data. These techniques are implemented into the firmware of the reader measurement units provided by the measurement device manufacturers (such as Voyantiv) for easy measurement and performance analysis of the system.

Since the tag is passive with no source for generating power, it utilizes the tag's antenna as scatterer element for reflecting the power back toward the reader. Based on this fact, the reverse communication link (tag to reader) can be defined as purely scattering and overall, the RFID system can be considered as a radar system [21]. Details about the tag antenna as a scattering element, and also different indicators for explaining the scattering mechanism are provided in [22] and [23]. Similar to radar systems, when the reader antenna (as source) transmits power toward the tag (as the target), the capability of

the tag antenna to scatter the incident power can be evaluated using the term radar-cross-section (RCS). The general definition for radar-cross section according to the radar system equations presented in [22] as

$$RCS = \sigma = \lim_{R \rightarrow \infty} (4\pi R^2) \frac{S_r}{S_i} \quad (Wm^2). \quad (2.4)$$

Here, S_i is the power density of the incident plane wave (coming from the source) when it is illuminating the area of the target, and S_r is the power density of the reflected (scattered) wave at the receiver. Since the principle of the communication between the tag and the reader is based on changing the RCS of the tag antenna, a more specific equation about the RCS of the tag is given later in this section.

Looking into the details of the tag and reader communication mechanism, the tag modulates the backscattered signal utilizing the change of input impedance of the IC, when it switches between two different states, as shown in figure 2.3. In one state (i.e. Z_{chip0}) the antenna and IC are matched and the power collected by the tag is fully absorbed, in which the tag presents a certain RCS level, for example, the RCS_0 . The power reflection coefficient for this impedance state can be presented as Γ_1 . For the other impedance state (i.e. Z_{chip1}), where the antenna and IC are mismatched and most of the power reflected back, the tag presents another RCS level such as RCS_1 and power reflection coefficient Γ_2 can be defined as well. The $\Delta RCS = RCS_1 - RCS_0$ defines the difference between two impedance backscattered signal. This type of communication in which the tag IC modulates the antenna RCS by load modulation is called modulated backscattering. [19][24]

As mentioned earlier in this section, the communication starts by the reader transmitting the power toward the tag. Starting from forward link (reader to tag), and assuming that the reader unit sends an output power of P_t watts and it is connected to a transmitter antenna with a gain of G_t , the power density (S) at a distance R from the reader, where the tag is located is given by

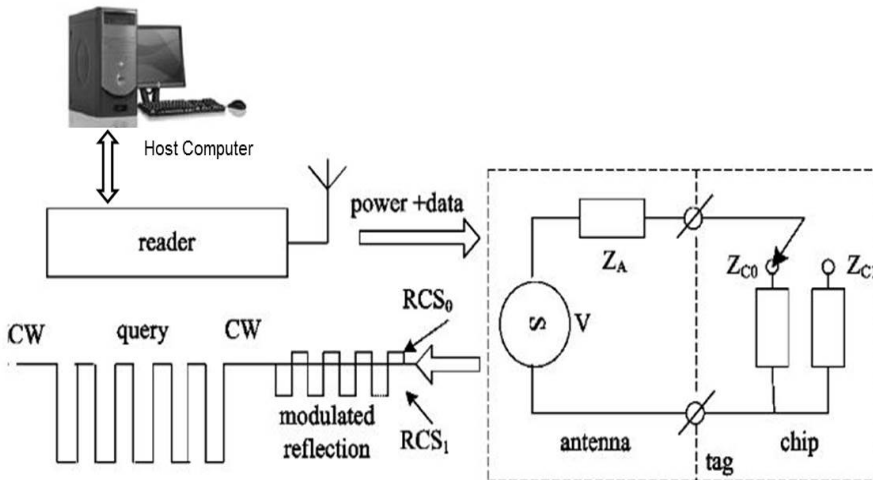


Figure 2.3: Principle of operation for a passive UHF system. [19]

$$S_{@tag} = \frac{P_t G_t}{4\pi R^2} \quad (W/m^2). \quad (2.5)$$

Thus, the received power in the tag side where the tag's antenna has an effective aperture A_{e-tag} , given as

$$P_{r-tag} = S_{@tag} A_{e-tag} \quad (W) \quad (2.6)$$

and

$$A_{e-tag} = \frac{\lambda^2 G_{tag}}{4\pi} \quad (m^2) \quad (2.7)$$

λ is the wavelength and G_{tag} stands for the tag's antenna gain. [12][25]

Similarly, for the reverse link (tag to reader), the power density at the reader location defines as

$$S_{@reader} = \frac{P_{t-tag} G_{tag}}{4\pi R^2} \quad (W/m^2), \quad (2.8)$$

where P_{t-tag} is the transmitted power by the tag toward the reader. Thus, the backscattered power or the power collected by the reader antenna is

$$P_{r-reader} = S_{@reader} A_{e-reader} = S_{@reader} \frac{\lambda^2 G_t}{4\pi} \quad (W), \quad (2.9)$$

and, $A_{e-reader}$ is the effective aperture of the reader antenna [25].

Based on the fact that the reverse communication link (tag to reader) can be described according to the radar equations, and as presented in 2.2, depending on the matching between the antenna and the IC, the total or only portion of P_{r-tag} will be reflected back toward the reader. Therefore, the relationship between the power received by the tag (P_{r-tag}) and the power transmitted from the tag (P_{t-tag}) depends on the matching states. In addition, for different matching states the tag presents different RCS values. Utilizing 2.4 and taking into account the matching coefficient between the IC and antenna (2.1), the RCS of the tag is given as [12][25]

$$\sigma = \frac{\lambda^2 G_{tag}}{4\pi} |1 - \Gamma|^2 \quad (Wm^2). \quad (2.10)$$

Considering the tag as an object with a radar cross-section σ , the 2.9, total backscattered power received at the reader can also be presented as follows [12]

$$P_{r-reader} = P_t \frac{\lambda^2 G_{tag} G_t}{(4\pi)^3 R^4} \sigma \quad (W). \quad (2.11)$$

2.3 Performance Indicators of Passive UHF RFID

As explained in the previous section, transmitting enough power for activating the RFID chip is significant in analyzing the performance of the passive RFID system. Therefore, in the specification of commercially available RFID chips, the sensitivity level of the chip ($P_{th-chip}$) is usually defined by the manufacturers. This means that the IC should receive at least the power level equal to or above the $P_{th-chip}$ to operate in the active mode. On the other hand, the minimum required transmitted power for activating the tag is known as threshold power (P_{th}) which is one of the performance indicators of UHF passive tags.

The threshold power (P_{th}) can be defined by substituting 2.6 with 2.2 as follows [26]

$$P_{chip} = \tau P_t \frac{\lambda^2 G_{tag} G_t}{(4\pi R)^2} \quad (W), \quad (2.12)$$

and replacing the P_t with P_{th} , and P_{chip} with $P_{th-chip}$, the power required to activate the tag from distance R is known as the tag threshold power and is given by

$$P_{th} = \frac{P_{th-chip}}{(\lambda/4\pi R)^2 G_{tag} G_t \tau} \quad (W). \quad (2.13)$$

The typical sensitivity level ($P_{th-chip}$) of RFID chips is between -16 dBm to -18 dBm, however the chip manufacturers such as NXP or Impinj introduced new ICs with sensitivity of about -20 dBm, which leads to lower threshold power for activating the tag [27][28].

Another important performance indicator of the UHF passive tag is the read distance of the forward communication link. The read distance R for the forward link can be calculated from 2.12 and changing the P_{chip} to $P_{th-chip}$ [8]

$$R_{fwr} = \frac{\lambda}{4\pi} \left(\frac{P_t G_t G_{tag} \tau}{P_{th-chip}} \right)^{\frac{1}{2}} \quad (m). \quad (2.14)$$

Assuming that the output power of the reader plus the gain of the transmitter antenna provide the maximum transmitted power toward the tag and with respect to the defined value for IC sensitivity by the IC supplier, the parameters which can maximize the read range of the tag are the gain of the tag antenna and matching condition. Therefore, designing the tag antenna with the maximum possible gain and optimum matching can significantly improve the performance of the passive tag.

3 RFID-Enabled Sensor Tags and Detection Methods

Utilizing the RFID technology in a wireless sensing system can vary according to different possible functionalities and costs. For instance, active RFID tags which are equipped with a battery and actual microcontrollers are very suitable for a sensing application that requires a higher data rate exchange and a long operating range. However, the big size together with the high implementation cost and limited lifetime are the main drawbacks for this type of sensor. Regarding the size and cost of tags, the chipless RFID is known to be cost-effective and tiny. Especially when considering the ongoing development in printing technology with conductive ink, which makes direct printing on paper or packages possible, the chipless tag could be transformed into a cheap sensor, but again they are very limited in terms of data storage. Conversely, the passive RFID tags with their very tiny microchips ensure good data rates and a longer lifetime since they are a fully battery-free system. Although in comparison to the active RFID sensor, the passive tag sensors are limited in terms of the reading range but their cost-efficient and power-efficient nature makes them attractive for many wireless sensing applications available in the market.

The implementation and measurement methods are important aspects in RFID-based sensor technology, due to the direct impact on the performance of the whole system. The materials and methods used for the fabrication and implementation of the RFID tags affect the performance and price of the tag, which are essential elements in the commercial RFID technology market. In addition, the measurement techniques utilized in the RFID system, and in particular the detection methods for the sensor tags, have a significant impact on the rapid growth in the use of RFID sensors in more complex applications.

There are high demands in the commercial market for passive tag sensors, since the fabrication technology can be environmentally friendly, reliable, robust and cost efficient. Furthermore, the measurement techniques that can be simply implemented and provide accurate information and also guarantee the confidentiality of the data exchanged has been interesting for the commercial applications that use passive sensor tags. All these were enough reasons that in the past few years, some of the key topics in several remarkable research and development work in the field of RFID focused on introducing novel technologies for the fabrication of sensor tags as well as a simple and new technique for measuring them. [29][30][31][32][33]

Taking advantage of the UHF passive RFID system in the development of wireless sensing technology, this chapter discusses the most recent manufacturing techniques of the passive RFID sensor tags. The focus is also on how RFID-enabled sensors can be detected and what are the advantages and disadvantages of the different detection methods. Finally, we will introduce and discuss a simple method for the detection of the RFID-enabled

sensor tag that can be useful and practical for the detection of the passive sensor tags which are placed outside of the shielded chamber in the free environment, similar to many actual use-cases of RFID sensor tags.

3.1 RFID-Enabled Sensor Tags

The passive UHF RFID technology with its unique features plays a significant role in wireless pervasive sensing. The demand for low-cost, power-efficient sensors which have a long life-time and can be easily integrated in the target application, makes the passive UHF RFID tags one of the capable candidates in the implementation of ubiquitous sensing [3][4]. The RFID-enabled sensor has the potential to bring different benefits to several applications.

Everywhere where real-time monitoring is important, such as health care, cold chain monitoring, and food tracking or smart house, the RFID-enabled sensor could be used [3]. For instance, one use-case of the passive RFID-enabled sensor in the automotive industry is to recognize water leakage in any part of the car body during the final quality control check in the production line. By using a passive RFID humidity sensor as a water leakage tag it is possible to sense and measure moisture condition changes within a car body and detect any water ingress into the vehicle during the final quality control checks [34]. The commercial version of this product was introduced to the market for the first time by SMARTRAC Technology Group [34].

Health care is another industry where demands for RFID-enabled sensors rise every day. It has already been proved that the RFID technology is capable of improving the performance and responsiveness of health care systems [3][35][36]. From reducing the risk of misidentifying the patients (by using a very simple RFID tag) to bringing a health care system to the homes of the elderly to monitor their medication, there are several examples showing why adopting RFID technology is improving the efficiency and management of patient care inside and outside of hospitals [3][37]. One useful and practical example is a proposal for pervasive-sensing hospitals reported in [38], where utilizing the RFID and sensor networks technology has improved the management of the available equipment, assets, drugs, and the personnel and patients information .

3.1.1 Implementation and Manufacturing Techniques

A passive UHF RFID tag can be easily transformed to a sensor due to its simple but smart structure which consists of an antenna and an RFID chip. Using the antenna as a sensing element has been introduced years before the existence of RFID technology [39]. An antenna's characteristics are sensitive to the surrounding environment which means that any change in a parameter in the environment can be sensed by observing a change in the antenna characteristics [40][41]. Moreover, the use of modern technologies for the fabrication of an antenna and utilizing different materials (such as conductive ink), help expanding the variety of parameters that can be detected. In addition, the RFID chip, being a tiny computer, can be manufactured to have advanced sensing features in addition to the radio (RF) features. Nowadays, there are commercially available RFID chips with sensing features that are used for the fabrication of passive sensor tags in many different applications [42]. In this section, a few different methods of manufacturing the RFID antenna, which also can be used for implementation of the antenna-based sensor tags are introduced.

Fabrication of the tag by using the embroidered technique for wearable RFID applications has been studied widely in past few years [43][44][45]. Such a tag can be implemented using conductive textiles which are commercially available or sewing the antenna pattern using conductive threads directly on a fabric. One of the benefits of the embroidered tags is their flexible structure. For instance, an antenna pattern which has been sewed onto a stretchable fabric can simply work as a strain sensor to detect the applied strain [43]. In addition, the wearable RFID tags can be easily integrated into clothes to be utilized for human identification and many sensing applications. More details of this technique will be discussed later in this chapter.

Manufacturing the antenna for ordinary RFID tags is most popularly done using subtractive methods, such as etching. In this method, the entire substrate area is covered with the conductive material and during the process, the antenna layout remains on substrate and the rest of the conducting material will be removed from the area. The main disadvantage of this method is waste of the conductive material, a complex process, and using chemical materials that are not environmentally friendly [46]. The RFID tags manufactured with subtractive methods are widely used in the commercial market of RFID. These tags can occasionally be used for sensing purposes and they are known as self-sensing tags [47].

Due to the complexity and cost of the subtractive method for manufacturing the RFID antenna, introducing the additive manufacturing technology shows a promising future in the fabrication of the antenna for the sensor tag, especially the antenna-integrated sensors. Contrary to the subtractive method, in the additive manufacturing process the conductive material is added to that part of the substrate where the antenna layout is meant to be. This way the waste of the conductive material is minimum, and the manufacturing process is simpler. The screen printing, brush-painting, Gravure printing, Flexography, Inkjet printing and 3D direct write dispensing are a few examples of additive methods that can be used for the fabrication of the RFID antenna.

Inkjet printing is one of the famous additive manufacturing methods for manufacturing the RFID antenna. During the recent years, many research studies have focused on the use of Inkjet printing techniques for the fabrication of the RFID antenna and antenna-integrated sensors [48][49][50]. Utilizing the inkjet printing and nanoparticle inks it is possible to print the antenna pattern directly on the substrate material. Printing the antenna pattern partially with nanoparticle inks such as graphene, whose properties change by changing the environment parameters (such as humidity, temperatures), is one way of fabricating the antenna-integrated sensors [51][52]. The drawbacks of inkjet printing techniques are maybe the slow printing process and the risk of nanoparticle inks for health which are not known well so far.

3D direct write dispensing is another additive manufacturing technique that can be used for the fabrication of the RFID antenna. In contrary to inkjet printing where the ink material does not flow continuously and works as a drop-on-demand method, in 3D direct write the material flows continuously between the nozzle tip and the substrate. This will make the printing process much faster compared to inkjet printing. In addition, the printing nozzle can freely move in X, Y and Z directions and this will make it easy to print of the antenna over any 3D surfaces. [53]

The figure 3.1 shows the 3D direct write dispensing machine from nScript [53] (the tabletop series) which has been used in the study in **Publication IV**. The machine includes two dispensing pumps which are controlled by a computer and print the designed antenna pattern precisely on almost any kind of substrate material surface. In the

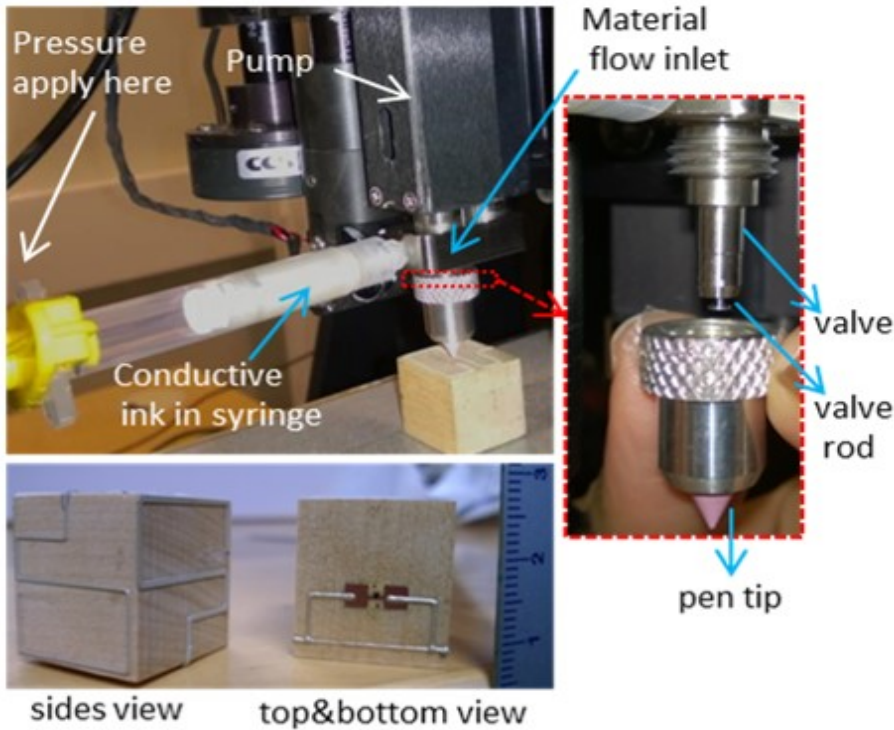


Figure 3.1: nScript 3D direct write machine: used here for printing on wood. IV

following study case, it briefly is explained how a miniaturized RFID tag was fabricated using this machine.

Study case 1: 3D miniaturized passive UHF tag for sensing applications

Utilizing 3D direct write dispensing, a fully 3D passive UHF tag was developed in **Publication IV**. The purpose of the study was to show how using the novel additive manufacturing methods can promise an efficient and low-cost fabrication method for high-frequency components and devices such as the antenna.

There have been studies on the fabrication methods for antennas such as Inkjet printing, but the printing of the antenna's layouts was limited to 2D planar circuit [54][55]. Concerning the use of the antenna as the propagation element for a sensor device in a WSN node, the direction of the maximum directivity is limited to one dimension if the antenna structure is a planar patch or a monopole/dipole antenna. Thus, the design and fabrication of the antenna with a 3D structure which can offer an omnidirectional radiation pattern has been the subject of many interesting research works, like [56][57][58][59][60]. However, in those studies, the fabrication was performed by designing a planar antenna and folding it to a 3D form. The folding can help achieving an omnidirectional radiation pattern but limitation in the size and shape of the antenna as well as used materials are the main drawbacks of the method. While, with help of the modern 3D technique for manufacturing of the antenna, the tag antenna can be printed directly on any 3D structure (i.e. cube, cone, sphere) using a variety of conductive materials (such as silver ink or copper ink). Therefore, the passive RFID tag as the final product can have full

visibility from all orientations. One of the main advantage of this method is the easy transformation of a simple tag to a sensor tag.

The structure of the passive UHF tag presented in **Publication IV** is simple and efficient and it has been designed to operate on the FCC frequency band (900 MHz). The dispensing technique described above is used for the fabrication of this dual-antenna tag. The antenna design, simulation, and optimization were performed using the HFSS simulator tools. The narrow-line dipole structure was selected for the antenna, due to easy and low-cost fabrication. The RFID IC chosen for this design was NXP UCODE G2iL [61] and T-match structure was used to achieve the best matching between the antenna and the IC. Since the length of the antenna for operating at 900 MHz was much bigger than the size of the substrate, meanderlines were used for minimizing the design.

The narrow line dipole antenna was dispensed on a 8 cm³ wooden cube (2 cm × 2cm × 2 cm) utilizing the nScript dispensing machine (figure 3.1). Wood was selected as the substrate to present the capability of the utilized technique and to show that it is not limited by the rough surface or shape and size of the substrate material. In addition, the narrow-line dipole structure enables low cost, is quick to fabricate, and provides good performance for the tag. The dipole pattern was printed directly on the wooden cube using conductive silver ink. The figure 3.1 shows the fabrication process of the tag and from the top view picture we can see how direct printing on the conductive strap of the IC eliminates the use of any conductive epoxy for connecting the IC and the antenna.

The performance of this tag has been measured using Voyantic's Tagformance setup. The measurement result presented in figure 3.2 shows the radiation pattern of the tag in the form of the read range. The tag has approximately a 2-meter read range which is very good performance compared to the size of the tag. In addition, the result illustrates that the tag has full visibility from all directions.

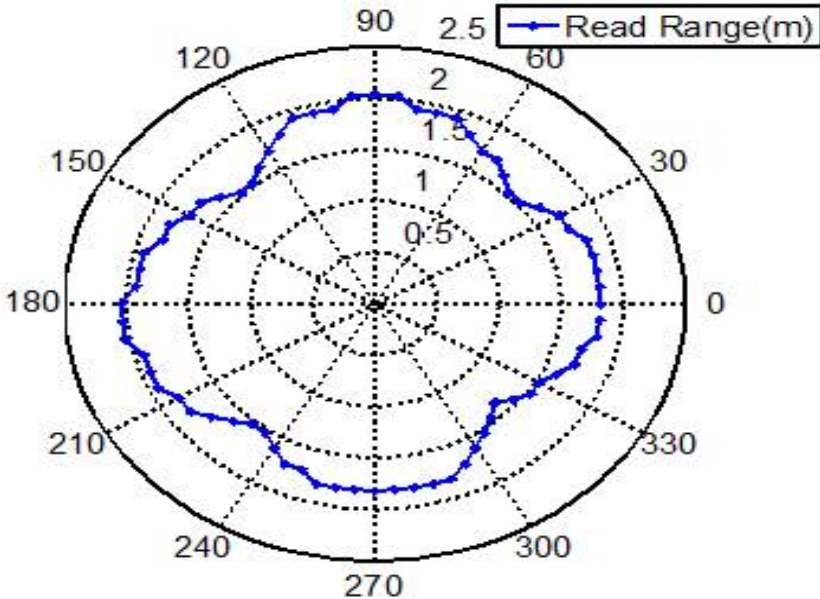


Figure 3.2: Radiation pattern of the tags in term of read range at 900 MHz, ZY-plane. IV

3.1.2 Antenna-Based Sensing Mechanism

Considering the components of a passive RFID tag, both the antenna and the IC can be used as sensing elements. Obviously, antenna-based sensing is a low-cost and easy approach for the implementation of the passive RFID sensor tags [47]. As mentioned previously, an ordinary passive RFID tag can be used as a sensor, which is known as a self-sensing tags, and some examples are reported in [62] and [63]. These kinds of tags do not include any sensor components, but they detect the change in the electrical properties of the object that they have been attached to. This is because the antenna is sensitive to changes in the background material properties.

Here are a few different mechanisms that explain how the self-sensing tags operate. A very basic way is the intrinsic sensing capability of RFID tags which sometimes can be considered as a limitation also. In principle, the tag antenna is extremely sensitive to a change in electromagnetic properties (i.e. relative permittivity and loss tangent) of the background material. This easily can tune the antenna to a different frequency [64]. However, it is a limitation when the electromagnetic characteristics (relative permittivity and/or loss tangent) of the background objects should be known while optimizing the tag performance. The sensor tag reported in [47] and [62] is an example of a self-sensing tag used to detect the filling level in a bottle of liquid. Basically changing the permittivity of the background material will change the backscatter power level that is sent out by the tag. The sensing process is performed by analyzing the variation in the received signal strength.

Detecting the deformation is another way that a self-sensing tag can work. Such a tag is used for detecting geometrical changes. When the tag is attached to the target object, any change that can affect the geometrical size and shape of the antenna can be detected by analyzing the tag response. The sensor tags presented in [43], [65] and [66] are a few examples of these kinds of a sensor tags.

Despite the simple structure of self-sensing tags, some certain physical parameters (i.e. temperature or gas) cannot be detected using this kind of sensor tags. For the detection of such parameters, the antenna-integrated sensor tag has been introduced. One method for implementing this kind of sensor is to load the tag with chemicals. Typically, part of the antenna pattern is made using certain chemical materials which have sensing capability. There have been several researches related to the use of nanoparticle materials such as carbon nanotube (CNT) or graphene for the implementation of sensor tags, due to the change of their chemical properties with respect to the environmental changes [52][67][68][69]. The nanomaterial-based inks can be printed as part of the antenna layout and be used, for instance, as a gas or humidity sensor.

3.2 Wireless Detection of RFID Sensors

Beside the implementation methods and sensing mechanism of a UHF passive RFID sensor tag, the wireless readout or detection technique is another important topic for monitoring the sensed parameter. Regardless of the mechanism with which a change is applied to a sensor tag, the applied changes are visible in the performance indicators such as the backscattered power level, operating frequency, and the read distance. Here we discuss the practical methods with which the sensed parameters can be extracted from the tag's responses and present two methods for wireless readout of sensed data.

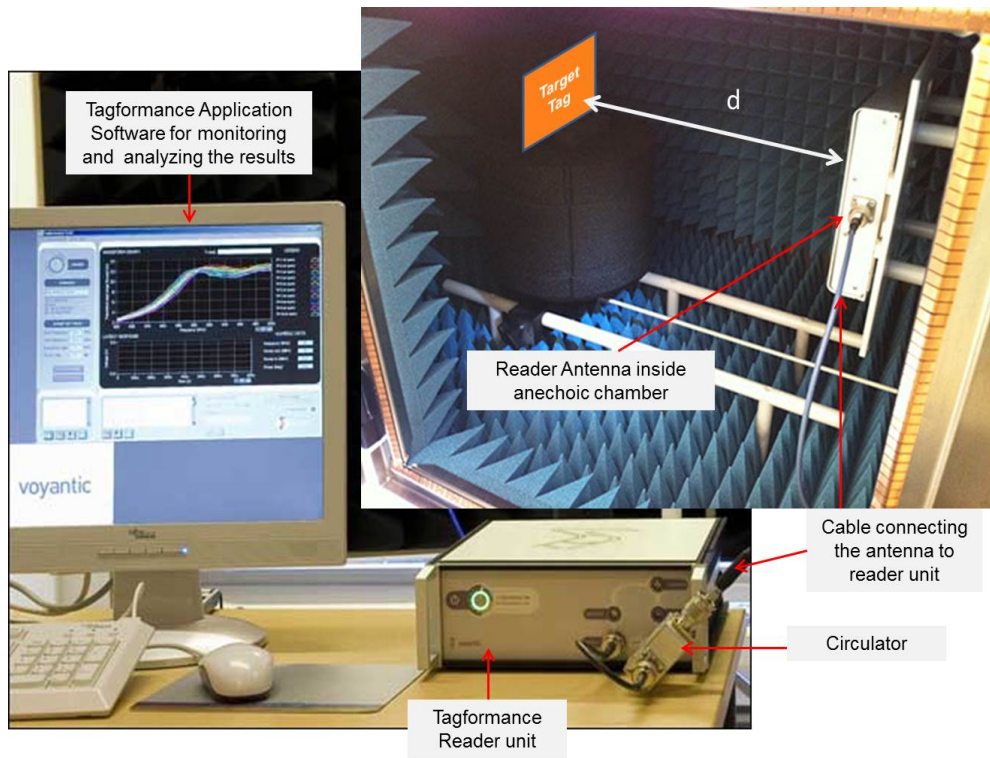


Figure 3.3: The Tagformance measurement unit from Voyantic.

Protocol-based testing units

For the passive UHF sensor tags which are equipped with an IC (*chip-equipped* sensor tag), the commercially available transceiver units can be used for wireless readout of the data from the tag. These measurement units which are popularly used in companies, universities and research centers, follow a common conventional method for measuring the tag's responses. The method is based on a certain communication protocol defined by ISO 18000-6C ("Gen2") [70], that was briefly mentioned in 2.2. A standard Gen2 measurement device typically includes a reader unit, a reader antenna, cables, connectors, a circulator, and also a host computer for installing the application and monitoring the data. The reader unit consists of the main processor which can support the protocol command exchange with the tag and also of other necessary components such as RF generator and RF receiver.

In this method of measurement, the tag is placed in a fixed distance from the reader and the power transmitted by the reader varies from the minimum level to the maximum value that reader unit can provide. The transmitted power varies until the tag starts responding to the reader. The measurement is typically conducted inside a controlled environment, such as an anechoic chamber to have repeatable benchmark measurement [18].

Portable test systems, such as Tagformance Lite from Voyantic [71], RFID Xplorer test system from CISC [72] and TC-2600A RFID test system from TESCOM [73] can be mentioned as examples of commercially available protocol-based testing solutions. Figure

3.3 shows the UHF testing solution from Voyantic. This measurement unit is discussed later in more detail in study case 2.

Radar-based measurement technique

Another technique for measuring an RFID sensor tag does not need any specific communication protocol. The radar-based method is mostly used to measure chipless RFID tags and to extract the electromagnetic signature of the tag, since the conventional method cannot be used due to the chipless nature of the tag. However, in coming sections of this chapter we discuss that how radar-based method also can be used for measuring the performance of sensor tags that are equipped with an RFID chip.

As addressed before, the reverse communication link in the RFID system is fully scattering, and the system can be treated as a radar system. The radar target scattering data can be collected by using the RCS measurement, and here, the RFID tag can be seen as a radar target. Thus, the analysis of the radar cross section (RCS) as a function of the frequency is one the methods for the interrogation of the passive UHF tags.

The RCS measurement can be conducted both inside an anechoic chamber or an open environment. Based on [22], one type of an RCS measurement is the frequency-domain type that allows measuring the amplitude and phase of the reflected response of the tag as a function of frequency. There are two different configurations for conducting the measurement, bistatic and monostatic. The bistatic setup includes an RF source, a transmitter and a receiver antenna, which are separated by distance and sometimes at a maximum angle of 180 degrees. The set up is similar for the monostatic configuration, but the transmitter and receiver antennas are collocated.

The figure 3.4 shows the main elements of a bistatic RCS measurement setup. The VNA (vector network analyzer) can be used as the RF source to generate the CW (continues wave) for performing the frequency scanning. The port 1 of the VNA is connected to the

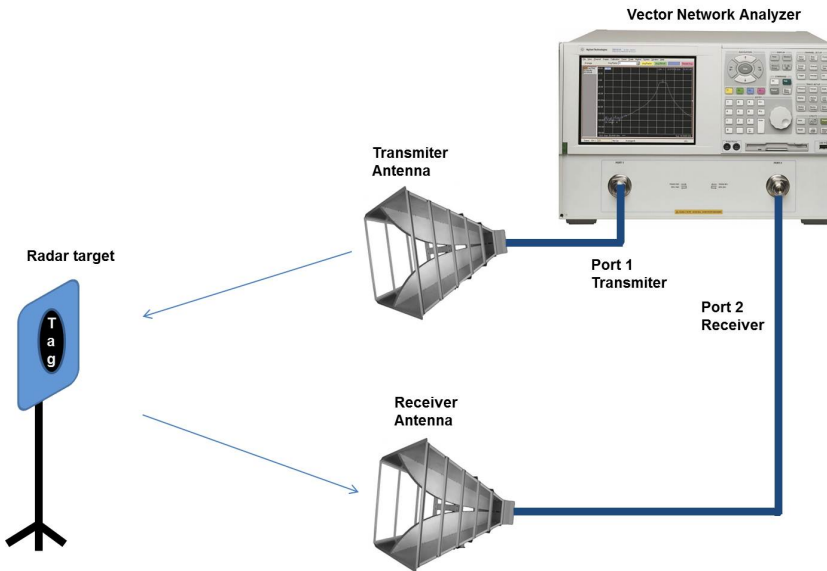


Figure 3.4: A bistatic frequency measuring radar bench.

transmitter antenna and the port 2 is connected to the receiver antenna. The ratio between the reflected and the transmitted power as well as the phase difference is calculated for each frequency point. This refers to the complex S_{21} parameters of the target (here RFID sensor tag). In fact, the measured reflected signal includes responses from both the tag and the environment. According to 2.4, and in the far-field approximation, the RCS (σ) of the tag can be defined as follows [7]

$$\sigma = 4\pi R^2 |S_{21}|^2 \quad (3.1)$$

Using 3.1 to calculate the RCS of the tag in an open environment where the measurement setup is surrounded with disturbing objects, will not provide the pure tag response. Thus, a calibration process is required to distinguish the tag response from the background response. The calibration procedure for a radar-based measurement system has been described in detail in [74] and also in the section 5.3.1.1 of [7]. Based on the simpler model described in section 5.3.1.1 of [7], in addition to the target tag measurement (S_{21tag}), two extra measurements are required for calibration. One is the empty environment (no-tag) measurement in which the results are known as $S_{21notag}$. This will remove all static reflections from the environment. Other measurement is the reference sample measurement and the results are named as $S_{21reference}$. The reference sample can be for example a simple metallic rectangular plate whose RCS (σ_{ref}) is known based on simulation or analytical equations. Conducting these three measurements, the value of the RCS of the tag under test can be calculated as follows [74]

$$\sigma_{tag} = \left[\frac{S_{21tag} - S_{21notag}}{S_{21ref} - S_{21notag}} \right]^2 \sigma_{ref}. \quad (3.2)$$

Measurement of the RCS as a performance identifier for the detection of the sensed parameter in a passive RFID sensor tag has been studied in detail in **Publication I**.

Study case 2: dual-interrogation-mode sensor

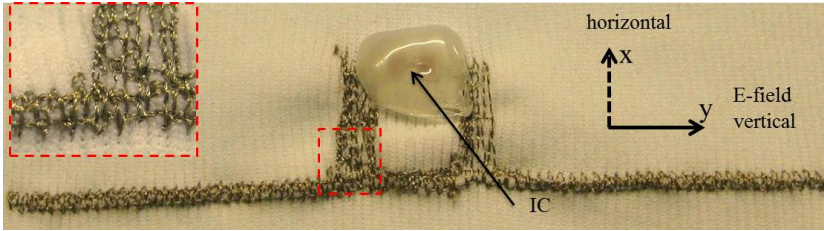


Figure 3.5: The embroidered strain sensor tag. I

The performance of a strain sensor has been measured using two different techniques, in **Publication I**. An embroidered passive UHF RFID tag for sensing the strain and monitoring deformation has been fabricated and the applied strain is realized and interrogated using two different techniques. The first technique is read-range extraction which relies upon the detection of the threshold power, and the second technique is protocol-free RCS-based technique I.

Utilizing stretchable fabric and conductive thread together with the embroidered technique, a simple and practical sensor tag for detection of the strain was implemented (figure 3.5). The antenna is a dipole and the famous T-match structure is used to achieve the proper matching with the RFID chip. The antenna layout has been sewed on a *polyester-based stretchable fabric* as a substrate. The sewing pattern for the antenna was selected based on the study results published in [75], [44] to achieve the best conductivity for the antenna. For the fabrication of this sensor, the same conductive thread and embroidered machine as [75] is used, for the best agreement in results. The sensor tag is equipped with NXP G2iL chip with the impedance of $Z_{IC} = 23-j224 \Omega$ at 915 MHz [61]. The manufacturer provided the IC with a strap fixture which has large conductive pads and can be easily glued to the antenna pattern using conductive glue as shown in figure 3.5.

To measure the performance of the strain sensor based on the *chipped-enabled* technique, the Voyabtic Tagformance RFID measurement system was used [71]. Tagformance, as a bistatic reader unit, includes an RF generator and an RF receiver. The reader output power varies from 3 dBm up to 27.8 dBm over the frequency range of 800 MHz - 1GHz, and the receiver sensitivity is -80 dBm. The Tagformance software offers many advanced features to obtain the read range of the tag. One feature is calculating the minimum power level ($P_{t,th}$) for activating the tag, using the threshold sweep [71]. In practice, the software does a frequency sweep over the entire frequency band with adjustable steps (i.e. 5MHz). For each frequency point the transmit power is changing in 0.1-dB steps to find the minimum power level at the reader port which enables the tag to reply to *query command* [70].

In addition to $P_{t,th}$, the forward link path loss (L_{iso}) is also required for calculating the maximum forward link read range. The system obtains L_{iso} by performing a calibration process done by the user. The user places a reference tag on the location where the tag-under-test would be placed and reference tag is aligned to match the polarization of the reader antenna. The software performs a threshold sweep on the reference tag to obtain all the losses in the measurement channel. Basically, software stores the information about the exact amount of power required at the reference tag to activate it if it would be connected directly to the transmit port, any deviation from these values are considered as path loss. The path loss includes the reader antenna gain and losses, the losses of

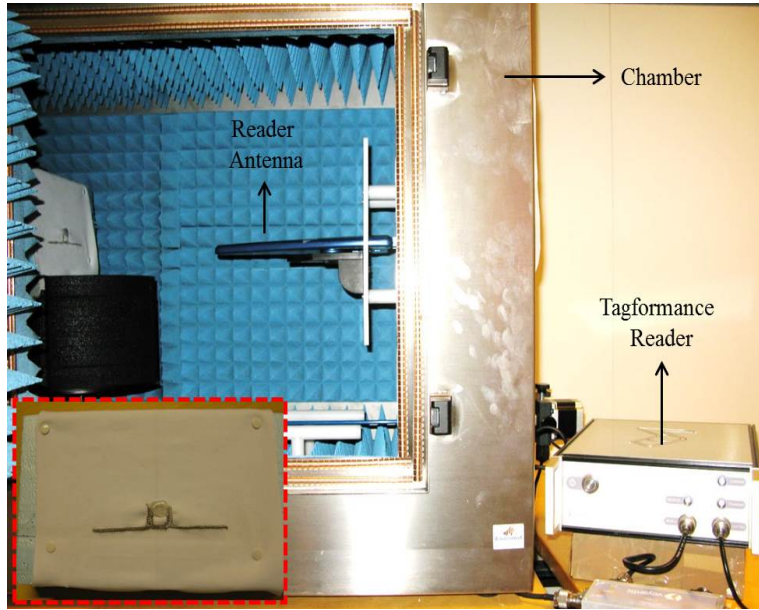


Figure 3.6: Read range measurement of strain sensor tag using Tagformance set-up. I

the cables and polarization losses. Having information of L_{iso} and $P_{t,th}$, the maximum forward link read range is given as,

$$R_{max} = \frac{\lambda}{4\pi} \sqrt{\frac{EIRP}{L_{iso} P_{t,th}}} \quad (3.3)$$

where EIRP is the maximum allowed equivalent isotropically radiated power. As shown in figure 3.6, strain is applied to the sensor by stretching the fabric using 4 pins, and the read range of the sensor for each certain length of the antenna was measured inside an anechoic chamber. The results of the measurements are presented in figure 3.8b and obviously the read range of the tag has been increased by increasing the length of the sensor.

Another applied method studied in **Publication I** for measuring the performance of the strain sensor was the *chipless* technique which is based on a monostatic radar-based measurement using a VNA. This technique was introduced in detail in the previous section, and the only difference here is utilizing a monostatic setup instead of bistatic, for simplification purposes. As shown in figure 3.7, measurement was conducted in a room environment and the strain sensor tag was placed in front of the reader antenna in the same polarization. The reader antenna is connected to port 1 of the VNA.

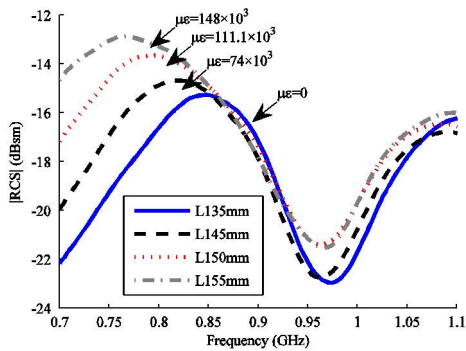
By applying tensile force to the fabric and stretching the sensor, the antenna length increases. The S_{11} parameter of the tag has been measured for the different lengths of the sensor and the RCS value has been extracted from the measured data based on the equation 3.2. Figure 3.8a shows the RCS change of the tag by increasing the length of the sensor.

Comparing figures 3.8a and 3.8b shows that applied strain on the sensor tag can be sensed accurately utilizing both protocol-based and chipless techniques. Basically, this proves

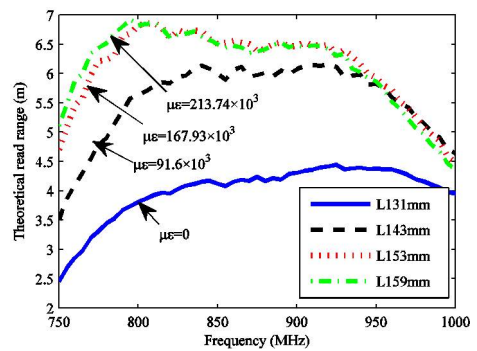


Figure 3.7: The strain sensor tag in front of reader antenna in room environment. I

that the combination of these two techniques can provide a passive sensor with a large identification coding capacity which still can be detected with no specific protocol.



(a) Change of the RCS value when strain is applied.



(b) The read range of the tag increases by applying the strain.

Figure 3.8: Detection of the strain by read range and RCS measurements of the sensor tag. I

3.3 Double Power Detection Technique

As discussed in the **Publication I** and also in the previous section, the two main techniques for the detection of the sensor tag have their own advantages and disadvantages. Detection of the sensed parameter based on the measurement of the tag RCS, which is mostly used for the detection of the chipless tag, is a simple and protocol-free method. However, using this technique outside the anechoic chamber needs very accurate calibration measurements for removing the static reflections of ambient scatterers, which is a time-consuming process [74]. Moreover, the extraction of the RCS value from measured return loss (S_{11}) requires complicated post-processing calculations. On the other hand, in many real-life applications, the detection process is done in a free space environment where there are background reflections included in sensor tag responses.

In **Publication II** a novel detection method for chipped RFID-enabled sensors was introduced. This approach still uses the radar cross-section measurement method but to cancel the effect of environmental reflections takes the benefit of the nonlinear properties of the RFID chip, and this eliminates the whole calibration process and makes the detection process more simple and fast.

In practice, the idea of this method comes from the fact that the impedance of the RFID chip is a nonlinear function of the incident power while the ambient scatterers feature a linear behavior by changing the transmitted power. Based on this idea, by transmitting two distinct power levels toward the sensor tag, two very different electromagnetic responses (RCS) are expected. This will happen if two different power levels can cause a significant variation of the chip impedance. Thus, measuring the sensor tag using two different incident power levels in a highly-cluttered indoor environment and by subtracting the two different EM responses, it is only pure tag's response which remains and not background reflection. Because the normalized response of the background reflection does not change by changing the power.

For a better clarification of the concept, a simplified model of the whole measurement channel is presented in figure 3.9 [7][76]. Based on this model the block M is recording the total system response. The response includes the effect of direct coupling between the transmitter and receiver antennas when there is no tag or any other object in front of the

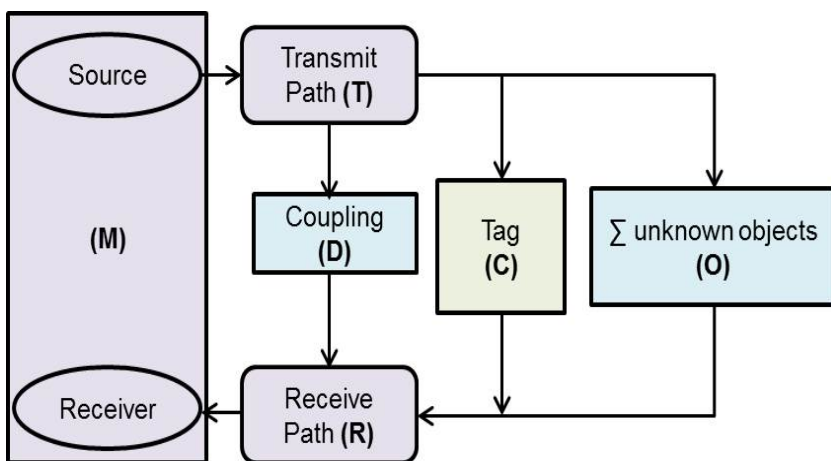


Figure 3.9: A simplified channel model of sensor tag detection system. [7]

antennas. The direct coupling is represented by $I=T.D.R$ where T and R are modeling the effect of cables and antennas in the transmitter and receiver paths respectively. The system response also includes the measurement channel and the ambient scatterers effect. The sensor tag under test is modeled using block C and the unknown objects in the surrounding environment are modeled by block O [76]. According to this model, the total system response could be presented as follows [76]

$$M_{total} = I + T.C.R + T.O.R. \quad (3.4)$$

The response of this system can be considered as a function of transmitted power. Thus, the system's response for two different transmitted power is represented below

$$M_{total}(P_{tx1}) = I(P_{tx1}) + T(P_{tx1}).C(P_{tx1}).R(P_{tx1}) + T(P_{tx1}).O(P_{tx1}).R(P_{tx1}), \quad (3.5)$$

$$M_{total}(P_{tx2}) = I(P_{tx2}) + T(P_{tx2}).C(P_{tx2}).R(P_{tx2}) + T(P_{tx2}).O(P_{tx2}).R(P_{tx2}). \quad (3.6)$$

The subtraction of the system responses for two different powers is equal to

$$M_{total}(P_{tx1}) - M_{total}(P_{tx2}) = [T(P_{tx1}).C(P_{tx1}).R(P_{tx1}) - T(P_{tx2}).C(P_{tx2}).R(P_{tx2})]. \quad (3.7)$$

In 3.7, the total measurement results are only dependent on the tag's response for two different power levels, because the terms "O" and "I" do not change by changing the transmitted power. This way the effect of unknown objects can be easily removed. Later in this section, it will be discussed how this model can be used for the detection of a strain sensor.

As mentioned before, the nonlinearity properties of the RFID chip is an advantage for implementing the double power detection method. In fact, when the chip receives different power levels its impedance changes significantly and this impedance variation causes the tag to present certain RCS values. The difference between the tag's backscattered signals in high and low impedance levels of the chip is noted $\Delta RCS = |\sigma_{max} - \sigma_{min}|$.

In **Publication III**, an estimated model of the chip impedance as a function of the transmitted power has been introduced. Utilizing this estimated model the up-most read distance of the proposed detection method has been predicted and verified experimentally by the detection of a strain sensor.

Extraction of the chip impedance for different transmitted power

To extract the chip impedance as a function of the transmitted power, two steps were taken. In the first step, utilizing a frequency domain measurement setup, the RCS of a simple dipole tag for different transmitted power was measured. The tag composed of an NXP UCODE G2iL chip with the sensitivity of -18 dBm was attached to a dipole antenna made from pure copper tape on a thin polyimide as substrate. This tag was placed at the distance of 20 cm from the reader horn antenna which was connected to the port 1 of the VNA. The power delivered by the VNA was varying from -14 dBm to +14 dBm and the tag response (S_{11}) was measured for different power levels. The RCS values were calculated using 3.2.

In the second step, the RCS value of the same tag was simulated and calculated using CST Microwave studio tools. In the simulation, the chip was modeled using lumped

element circuit (RC parallel circuit) and the RCS value was achieved by changing the values of R_{chip} and C_{chip} . The value of R_{chip} varies from 300 Ω to 2800 Ω and C_{chip} evolves from 0.9 pF to 1 pF.

The impedance of the equivalent circuit model of the chip is defined as

$$Z_{chip} = \frac{R_{chip} \cdot X_{chip}}{R_{chip} + X_{chip}} \quad (3.8)$$

where $X_{chip} = \frac{1}{j \cdot \omega \cdot C_{chip}}$.

Finally, comparing the simulation with the measurement results and finding the most similar simulated RCS curves to the measured RCS curves, it was possible to derive a relationship between the power levels transmitted toward the tag (P_{tx}) and the value of its chip impedance (Z_{chip}). This relationship is illustrated in figure 3.10. As one can see, by increasing the transmitted power, the absolute value of the impedance decreases while for the power values of less than -10 dBm, the chip impedance is constant. This explains that with respect to the certain measurement distance of 20 cm and chip's sensitivity of -18dbm, the transmitted power of -10 dbm is not enough for activating the chip.

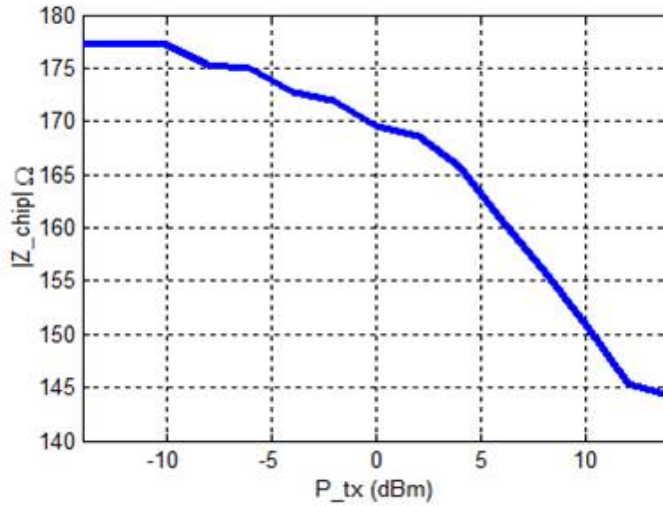


Figure 3.10: The impedance of RFID chip as a nonlinear function of transmitted power. III

Generalizing of impedance model for different measurement distances

The chip impedance model presented in figure 3.10 depends on two parameters: the measurement distance and the level of transmitted power. In the experimented setup, the upper power level (14 dBm) was limited due to the VNA model. Due to this limitation, it was not possible to monitor the behavior of the impedance for higher power levels. Thus, to expand the estimated impedance model for other measurement distances and power levels, the impedance of the chip also was measured using a VNA at a single frequency (915 MHz). The details of the measurement have been explained in section 3 part A of **Publication III**. As the measurement results in fig.4b of the same section show, despite of the slight disagreement between the results, both measurement techniques prove the nonlinear behavior of the chip impedance as a function of the transmitted power.

Utilizing the impedance model attained by the VNA measurement, which is only a function of the transmitted power, and using the link budget calculations as explained in detail in section 3 part B of **Publication III**, the chip impedance behavior has been estimated when both parameters of distance and transmitted power change. The estimated impedance behavior as a function of (P_{tx}) for different measurement distances is illustrated in figure 3.11.

As addressed in detail in III, changing the RCS between a minimum and maximum value is an important principle for a reliable detection using the double-power measurement technique. On the other hand, it is obvious in figure 3.11 that for a larger measurement distance the transmitted power level should increase to keep the variation of the chip impedance in the levels that it can ensure a sufficient RCS change. The outcomes of the study in **Publication III** indicate that the Δ RCS of about 5 is sufficient for having a reliable detection.

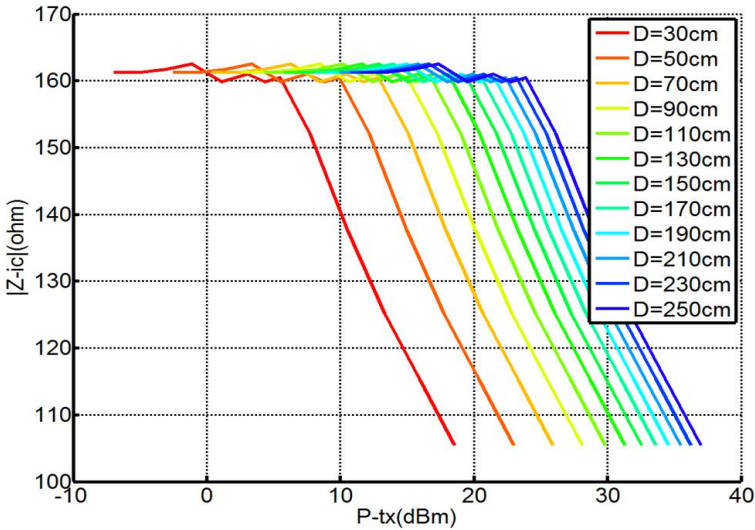


Figure 3.11: The estimated behavior of impedance of RFID chip as a nonlinear function of transmitted power for different measurement distance. III

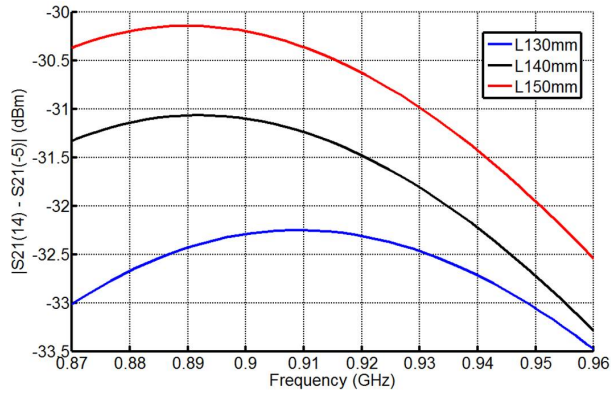
Verifying the proposed detection method

Now, knowing more details of the nonlinear behavior of the chip impedance, it is easier to understand how the proposed double-power measurement technique works. In principle, and according to figure 3.10, transmitting two different power levels toward the sensor can cause a large variation of the chip impedance. This leads to different EM responses of the sensor tag (different RCS value). Therefore, the subtraction of two different responses contains only the tag response and no environment scatterers since the background reflections do not change by varying the transmitted power.

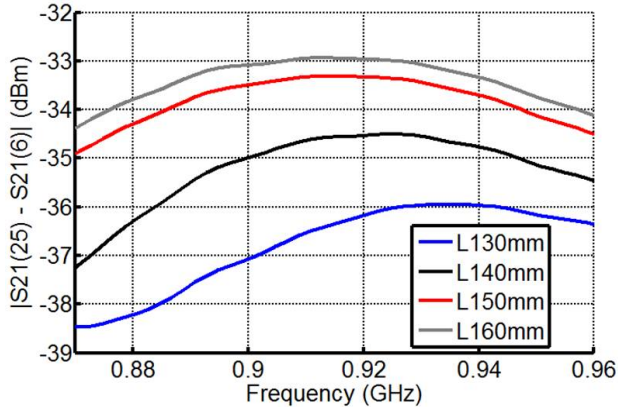
This technique has been proved by applying the measurement to detect the strain sensor. The detailed studies in **Publications II** and **III** show the use of the double-power measurement technique for the detection of an RFID-enabled strain sensor when the sensor tag is pulled by an external force and the magnitude of the response changes significantly.

In the **Publication III**, it has been discussed how the impedance model proposed in figure 3.11 can help to choose the right power levels for the detection of the strain when the measuring distance increases. The same strain sensor has been detected using a bistatic measurement setup first at a distance of 30 cm from the reader antennas and then at a distance of 150 cm. According to the estimation in figure 3.11, when the measuring distance is 30 cm the power levels of -5 dBm and +14 dBm will change the impedance of the chip from 163 Ω to 120 Ω and this can guarantee the sufficient RCS change for observing the large variation of the magnitude of response. The figure 3.12a shows the response of the sensor for different applied strain.

Similarly, when the measuring distance increases to 150 cm, based on 3.11, the minimum and maximum power levels of 6 dBm and 25 dBm should be selected for the detection since those values can guarantee a sufficient Δ RCS. Figure 3.12b illustrates the response of the sensor for the applied strain when the measuring distance increases to 150 cm.



(a) Sensor is placed at distance of 30 cm from reader.



(b) Sensor is placed at distance of 150 cm from reader.

Figure 3.12: Detection of the strain sensor at different distances. III

4 Passive Wearable RFID Tag for Localization Applications

4.1 Positioning- Underlying Principles

The positioning or the task to derive the location of a moving object is one of the areas of science in which utilizing radio signals has a significant influence on the development of the technology. The radio-based positioning systems have been an interesting field of research for years now, and radio technologies such as satellite systems, cellular networks, Wireless Local Area Networks (WLAN) are among the most popular used in positioning systems. Positioning in both open spaces and indoor environments are highly demanded due to the wide range of applications. Different techniques in each environment should be implemented to fulfill the requirements. [77][78]

Estimating the location in outdoor environments is typically done using satellites signals [77]. The signals are strong enough to be received at a high power level, and there is a line of sight between the transmitter and the receiver and no obstacles to attenuate the signals. However, using satellite signals for localization in indoor environments is challenging, since signals are weak due to the attenuations by windows or walls, and they also suffer interference from other available signals [77]. Overall, there are not many challenges left to be solved regarding outdoor positioning but for many different applications, the indoor location solutions are not developed enough yet. Finding an accurate, reliable and cost-efficient method with low complexity for indoor localization gained more attention in the industry, also among the researchers to study and compare and combine the different methods to offer an advanced solution [79][80][81]. The technologies such as Ultra Wide-Band (UWB), WLAN, infra-red light, Bluetooth and cellular have been proposed and used for indoor localization.

Using wireless signals in indoor positioning, the location can be estimated in two steps. In the first step, some of the environment's parameters are measured. For instance, it can be the estimation of TOA (the time of arrival of the signal) or AOA (angle of arrival) or measurement of the power of the signal (received signal strength). Then, in the second step, the actual location estimation is done utilizing techniques, such as trilateration or fingerprinting. [77][82]

In particular, using the Received Signal Strength (RSS) has a advantage over other parameters since it is available as part of an existing structure and does not add extra cost to the deployment of the system [82]. In an RSS-based localization technique that is used by cellular, WLAN and some other wireless systems, location is found by measuring the received signal power and analyzing it by software-based solutions in the receiver [82][83]. The relationship between the measured RSS and the distance is calculated using a path

loss model [77]. In fact, the path loss indicates the attenuation of the signal strength with respect to the distance. The path loss models often have the information regarding both shadowing and path losses [83][84]. Shadowing refers to the fluctuation in the RSS caused by random obstacles in wireless communication channels [77].

RFID-based localization

RFID technology is already famous for identification, tracking, and logistics. Increasing the use of this technology in indoor environments such as shops, schools, hospitals is leading to taking advantage of its available signals for positioning applications as well. RFID is a contactless communication system with the ability to handle high data rate, non-line-of-sight availability, and components that can be easily integrated into any objects. All these advantages plus the cost and power efficient communication features make the RFID a promising technology to be used in a positioning system. The communication between the tag and the reader is based on the backscattered modulated signal. In a similar way as the WLAN system, in which the measurement of the received signal strength (RSS) is used as a positioning approach, the modulated backscattered signal from the tag to the reader is carrying the identification information of the tagged item, and at the same time provides the required information for positioning [82][83]. The RSS is a measure of the power and readily available to be used for location estimation.

Depending on the application requirements, both RFID system components (tag and reader) can be used for localization purpose. Localization based on the tag is when the target item carrying the tag and RFID readers are fixed. The practical implementation of the tag-based localization has been the topic of several studies, such as [81][85][86]. For instance, in [86], the target items have been labeled with tracking tags but some reference tags with a known location have been used in the desired area, as well. The reader recognizes the location of the tracked item by receiving the RSS from both the tracking and reference tags and comparing the responses. The location calculation is performed based on the reference tags that have the closest response to the tracking tag. In the reader-based localization, a portable RFID reader needs to be attached to the target item to collect the information of the fixed tags in the environment. Therefore, the location of the tags is known and the target item location is determined based on the detected tag by the reader [86].

One of the application areas which has gained popularity in the domain of indoor localization is human positioning. Finding the location of people in an indoor environment such as hospitals, factories, offices, and shops is important due to the added value to the security and safety, and also facilitating the services. The positioning solution for this kind of applications needs to be cost-effective, reliable, accurate and easily integrated. The wearable RFID is a key enabler technology, and its involvement in applications fulfills many of the requirements [44][87][88]. An RFID tag which is attachable to the human body can be implemented and it operates using different techniques. Depending on the structure of the tag, it can only be used for identification and localization purpose or for sensing the human vitals as well [44]. The wearable tag can be fabricated in a hard format including also additional components such as sensors or batteries (active tags) to offer more advanced functionality and higher performance, or it can be implemented in a simple and flexible form for easier on-body attachment. The passive RFID tags made of electro-textile or embroidered tags are excellent examples of wearable intelligence. They have a very simple structure with great RF performance, and also good flexibility to be integrated to clothes and long durability to be repeatedly used. In the following sections of this chapter, the investigation on the use of passive wearable tags in the context of

indoor localization is presented. The goal is to evaluate using a tag-based localization approach to estimate the location of people in the indoor environment.

4.2 RFID Propagation Channel Model

As mentioned before, utilizing passive RFID technology and implementing a tag using electro-textile or embroidered technique provide a very cheap and simple solution for human localization in the indoor environment. To understand the feasibility of exploiting a fully wearable RFID tag for indoor positioning, the indoor channel model for the RFID system needs to be studied. In fact, modeling of the channel including path loss and shadowing effects for RFID signals based on experimental measurement can provide valuable information regarding the capability of using RFID for indoor positioning, compared to other conventional technologies (such as WLAN). For this purpose, in **Publication V** the channel model for a passive embroidered RFID system is studied and the results are compared to a similar study utilizing WLAN technology reported in [84].

Fully wearable passive UHF tag solution

An embroidered passive tag that could provide sufficient performance for on-body application has been fabricated for the study work in **Publication V**. In the beginning, the tag was designed and modeled using a simulation tool, CST Microwave Studio. The antenna structure is a simple dipole and NXP Ucode G2iL is used as the RFID IC [61]. The T-match structure was used to match the antenna with the RFID IC (at 866 MHz) for achieving the best tag performance.

To model and simulate an embroidered structure tag in CST, the electromagnetic characteristic of a cotton fabric as the substrate material, was measured using the method reported in [44]. The measured relative permittivity (ϵ_r) and loss tangent (δ) for the cotton fabric was 2.2 and 0.088 respectively. The antenna pattern that was going to be fabricated with the conductive silver thread, was modeled as an ohmic-sheet type of a material in the simulation. Basically, no thickness was defined for the antenna layout in the simulation model, but the surface impedance of $1.2 + j 0.08$ ohm/sq could represent the sewn conductive thread structure properly as also reported in [87].

The parallel RC equivalent circuit was created in simulation to model the RFID chip impedance (20-j175 ohm at 860 MHz [61]). The length of the designed antenna, and the size of the T-matched structure to achieve the desired frequency and read range were presented in figure 4.1. For a reasonably short antenna length, the simulation results show a read range about 6 meters (figure 4.2). Generally, the simulation model has been created carefully to achieve a good agreement with the measurement results. Later, it is shown that this design provides about 7-meter read distance in free air measurement.

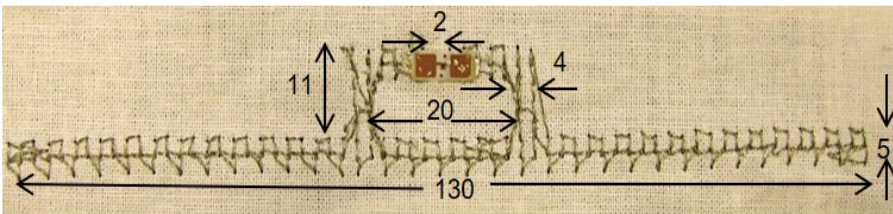


Figure 4.1: Embroidered passive UHF tag. The chip is glued on the antenna. (unit:mm). V

In **Publication V**, the human as a moving object is carrying this passive UHF tag. Since the tag should be attached to the human body and the body's tissue is a high permittivity environment, some performance (read range) drop is expected due to the detuning of the antenna in lossy environment [44]. Due to the limitation of simulation tool and also for the sake of simplicity, in **Publication V**, the author did not investigate much on optimizing the tag performance in the human body environment, however, it is possible to improve the performance of the passive wearable tag by adding the human body model into the simulation tool and tuning the antenna for the on-body scenario. In addition, selecting another type of antenna such as a patch antenna can help to have a better on-body performing tag, since the patch has a more directive radiation pattern than a dipole antenna. Here using the patch antenna could lead to a larger size tag due to the embroidered technique for fabrication, therefore it was not very suitable choice due to the application.

After finalizing the simulation, the antenna pattern was extracted from the simulation tool in the format which was readable by a computer-aided sewing machine. Then, the layout was sewn on the cotton fabric using silver thread. Based on the results reported in [75], the sewing pattern and density of the thread were adjusted to attain the best performance of the tag. After sewing the antenna, the IC was attached using conductive glue as shown in figure 4.1.

The performance of the tag was measured initially in free-space condition inside an anechoic chamber utilizing the Tagformance setup. Figure 4.2 illustrates a good agreement between the simulation and the measurement result. To verify the actual on-body tag performance, the sample was measured in office space afterwards. Figure 4.3 presents the measurement set-up where the tag is installed on a human arm standing in front of the reader antenna. The tag and the reader antenna were aligned in the same polarization and the read range was measured utilizing the Tagformance reader set-up [71]. The read range of the tag dropped by half (about 3.5 meters) while measuring it on the body which was expected due to the tuning of the antenna. Thus, the experimental area for studying the channel model has been made based on the maximum on-body read range of the tag which means an area smaller than 3.5 by 3.5 meters.

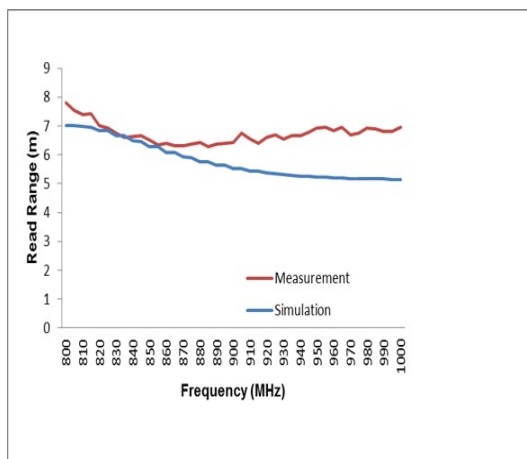


Figure 4.2: Simulation and measurement results for designed tag. V

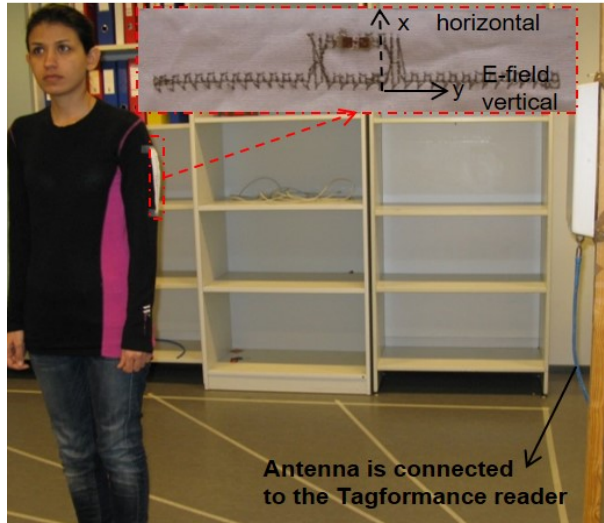


Figure 4.3: Performance measurement of the embroidered wearable tag on human body. V

Data collection experiment

As mentioned before, in the RSS-based location estimation system, the relation between the measured RSS values and the location is defined based on the indoor channel model [82]. Therefore, the response of the designed wearable tag was collected in an indoor office environment, to model the channel. The data collection experiment was deployed in a university room, a 3 m by 3 m rectangular area. The figure 4.4 represents 11 measurement lines in the 9 square meter area where the measurements were conducted. The angle between every 2 adjacent lines is about 18 degrees. The blue stars on each line indicate the positions where the tag response was measured. The distance between 2 measurement points in the same line is 30 cm.

As shown in figure 4.4, the reader antenna is placed at the center line and is connected to the Tagformance reader unit. The reader antenna is a vertical polarized planar antenna which covers the UHF frequency band (850 MHz - 960 MHz) with the gain of 9.5 dBi. The tag is attached to the human arm in same polarization as the reader antenna and the tag's response was measured in all the marked spots (blue stars). The measured response of the tag is backscattered signal power, where the transmitted power is set to be 23-27 dBm at frequency 866 MHz. The measurement for each spot was repeated 3 times to understand the fluctuation between the scans, and also to increase the veracity of the measurements. By this experiment, the power map for further study of the channel was created. The figure 4.5 shows the power map for one of the scans. The red circle marks the position of the reader antenna. The stronger backscatter response belongs to the measurement spots closer to the reader antenna. Obviously, the signal gets weaker in the measurement areas farther from the reader antenna.

The detailed explanations provided in **Publication V** describe well how the channel parameters have been calculated using data collected from the RSS measurement of the tag. In fact, the path loss coefficient and the shadowing standard as two important parameters of the communication channel have been calculated based on the measured data. The experiment-based modeling of the indoor channel for RFID signals which

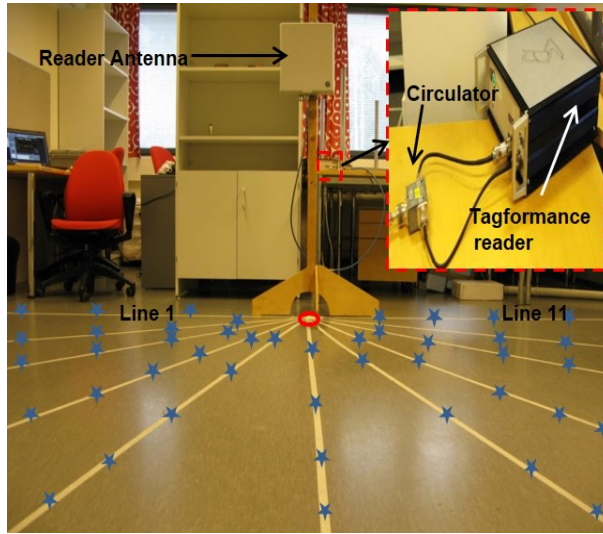


Figure 4.4: Measurement area for channel model study. V

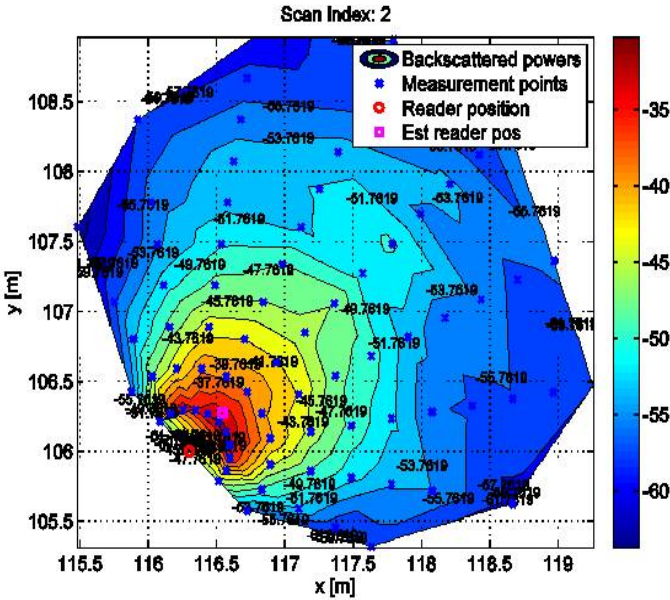


Figure 4.5: The backscattered power map of wearable tag. V

includes the path loss and shadowing effects was studied for the first time in **Publication V**. Knowing these two parameters of the channel, it is possible now to compare the behavior of the RFID channel with other wireless methods that have been previously studied for indoor localization application [84].

Comparison with WLAN

Finally, in **Publication V**, the RFID-based channel parameters were compared with a similar experiment using the WLAN technology. The WLAN-based study had been

conducted before in the same room in the university by students of positioning team of TUT. The details of the study work have been published in [84]. Basically, in [84], the data collection was handled utilizing a Windows tablet with WLAN connectivity. The WLAN access points were installed in different locations in the corridors of the university. The moving object (human) was carrying the tablet in the same experimental area and collecting the RSS value of the WLAN signals in the same measurement points. The post-processing calculations of the collected data were done similarly to RFID. The results of the study work including the channel parameters are reported in [84].

To have a comparison, the highlighted position-related features of the both systems (RFID and WLAN) are listed in Table 4.1. The main conclusions are that the typical path loss coefficients are almost the same for both techniques and they are close to free space propagation coefficients, and that RFID RSS fluctuations are slightly more stable than WLAN RSS fluctuations. The positioning range of RFID system which is maximum about 3 meter is likely to give a better accuracy of positioning than the WLAN, because the positioning error would be bounded by the maximum read range. In addition, the apparent power value comparison in the table shows that the total transmitted power should be much larger in RFID system and the reason is the passive nature of this system.

Table 4.1: Comparison of the positioning-related parameters based on RFID and WLAN results. V[82][84]

Features	RFID	WLAN
Typical path-loss coefficient	2.15 : 2.35	2.2 : 2.3
Shadowing standard deviation [dB]	4.2 : 4.5	6 : 9
Typical apparent power [dB]	-7 : -3	-12 : -8
Positioning ranges [m]	1-3 m	Few tens of m
Accuracy as RMSE [m]	less than 3 m	6 : 10

4.3 Hybrid Positioning Solution: WLAN-RFID

The outcomes of the study in **Publication V** imply that the RFID-based channel model is promising, and also the stability of the results is comparable with the WLAN measurements. Therefore, in **Publications VI, VII** authors investigated a new approach utilizing both WLAN and RFID technology to enhance the accuracy and robustness of indoor positioning. The joint exploitation of WLAN and RFID for positioning has been addressed in publications such as [79]. However, for instance in [79], still the RFID signal was used mainly to indicate the area where the mobile target was located and the actual estimation of the position was determined using WLAN signals.

The architecture proposed in **Publication VI** is novel from this perspective in that the RSS data is collected from both WLAN and RFID. Thus, in the data analysis phase, there is a possibility of choosing between either of the technologies, based on the measured signal strengths. Figure 4.6 shows a simple implementation of the proposed hybrid architecture where the human is labeled with a passive wearable tag and at the same time carrying a mobile device. The mobile device needs to be equipped with a hybrid location engine. This way the location of the person can be estimated accurately utilizing both WLAN and RFID signals. It is worth emphasizing here that the recommended solution in figure 4.6 is not a fully commercial solution, and the main focus here is presenting the proof of concept for joint WLAN-RFID positioning.

The flowcharts in figure 4.7 represent the algorithm of the proposed hybrid model in comparison to a pure WLAN or pure RFID location estimation. The process consists of two phases. The first phase which is a *training stage (off-line phase)* is similar for both block 1 and 2. The actual hybridization happens in the second phase which is called *estimation phase (on-line phase)* and it is presented in block2.

One advantage of the solution proposed with WLAN-RFID is the use of a textile passive UHF tag for the RFID experiment. A textile tag can be easily integrated to clothes, and provides an efficient communication link to monitor the human movement, especially in

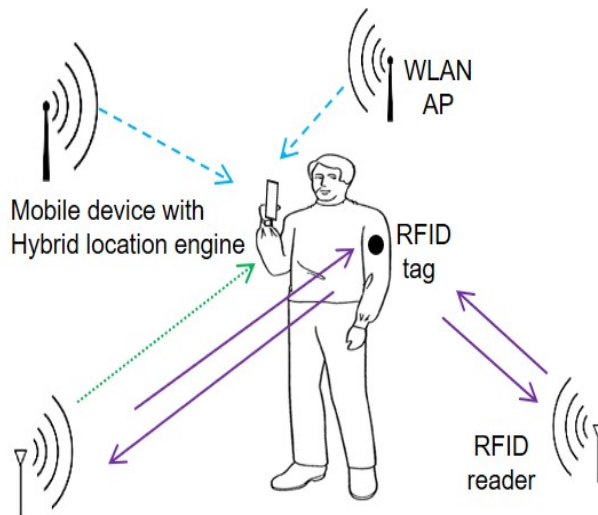


Figure 4.6: The hybrid RFID–WLAN architecture with wearable passive RFID tags. VI

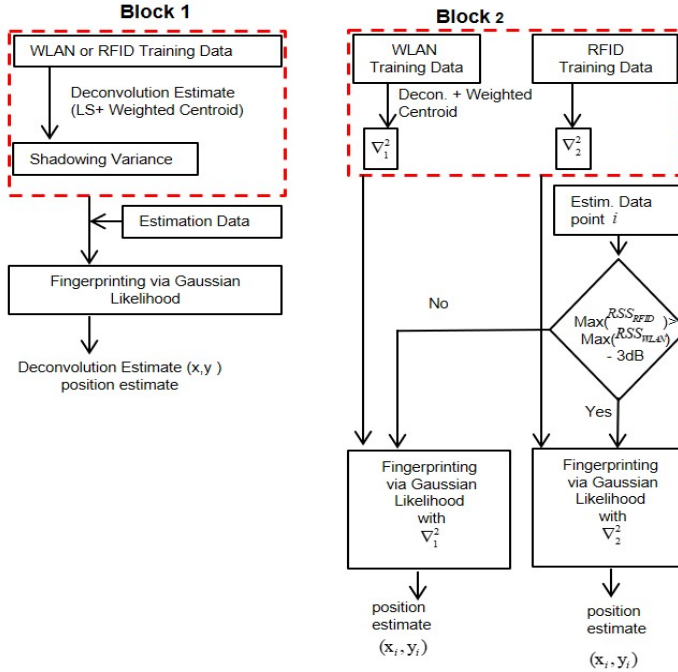


Figure 4.7: Block 1: Pure RFID/pure WLAN location. Block 2: Proposed Hybrid RFID-WLAN positioning algorithm. VI

the office environment. The utilized sample tag for this study is a passive dipole UHF tag and it is designed to be fabricated using electro-textile, as addressed in detail in **Publication VI**. Overall, the electro-textile tag made for this study has better on-body performance (around 8 m) compared to the embroidered sample which was used for study in **Publication V**, despite same antenna length. The reasons can be the uniform structure and higher conductivity of the antenna layout made by electro-textile compared to the silver thread. Therefore, a bigger experimental area for conducting the localization measurement was selected.

As mentioned in **Publication VI**, the same university room was used in collecting data for the database used in the training and estimation phase for both RFID and WLAN. The 6 meters by 6 meters area in the room was split into 144 smaller regions (of the same size), and the whole measurement area included 169 positions for measurements. For the RFID experiment, four reader antennas were used for the RSS measurement. The wearable passive tag was installed on a human body, and the RSS measurement was performed in all 169 points. Gathering of the data for the estimation phase was done in the same region but in 42 random coordinates. The training and estimation data for WLAN were collected in similar coordinates as RFID utilizing a tablet.

To obtain the positioning-related information, the collected data was analyzed based on the algorithm presented in figure 4.7 and also using the Gaussian probabilities computational models, as **Publication VI** is discussing in detail. Based on the calculations, an optimization value for selecting between the WLAN-based or RFID-based positioning was estimated. This value appraised to be 2 dB which means if the RSS gathered from the RFID system is higher than WLAN with a margin of 2 dB, then the RFID is selected

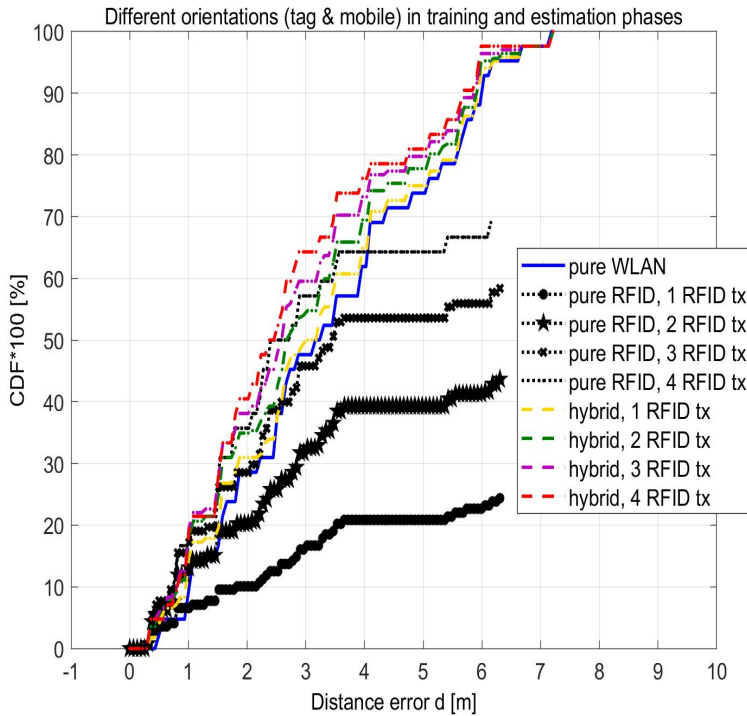


Figure 4.8: Percentage of points where we attain an error smaller than the threshold, via pure WLAN, pure RFID and hybrid estimates.

as a trustworthy positioning method, otherwise, WLAN is selected.

The result of the hybrid algorithm, as well as the pure WLAN and pure RFID, is presented in figure 4.8. The pure RFID results prove that increasing the number of RFID readers has a significant effect on the accuracy of the estimated location, due to better coverage of all the measured points. However, even using four readers, only 38% of the time a pure RFID solution is able to offer a distance error below 2 meters and this value drops to 28.5% when using pure WLAN. On the other hand, the proposed hybrid (WLAN-RFID) solution clearly shows a benefit here, when in 78% of the cases the distance positioning is less than 4 meters.

On basis of the outcomes achieved in **Publications VI** and **VII**, it is very well proved that for the indoor environment where RFID and WLAN signals both are available, the joint hybridization architecture offers a better positioning solution, since the system has good coverage because of the WLAN and higher accuracy because of the RFID.

5 Conclusion

This thesis work includes a comprehensive study on two of the advanced applications of the passive RFID technology, the RFID-enabled sensor tags, and RFID-based localization. The unique features of the passive UHF RFID technology offer a low-cost wireless sensing solution that can be easily integrated into devices and provides long-range identification and sensing information. On the other hand, increasing the use of the RFID system and availability of the RFID's signals in many indoor environments provide an excellent opportunity to take advantage of such freely available signals in indoor positioning systems.

The first part of the study started with an extensive look into the fabrication of a passive antenna-based sensor tag utilizing different technologies. The novel additive manufacturing technologies for the fabrication of the antenna provide the possibility for direct printing on varieties of substrate materials and this could add significant features to the passive RFID tags. In **Publication IV**, using direct printing of conductive ink on 3D structure substrate, a passive UHF tag was fabricated easily and it has almost full visibility from all orientations. A miniaturized but still well performing passive tag which can be further developed as a sensor easily and be used as a power-efficient and cost-effective solution for system-in-package technology and WSN node, in which omnidirectional readability is the key.

The study on antenna-based passive sensor tags continued with more focus on the detection and realization methods of the sensors, in **Publications I, II and III**. Taking advantages of the nonlinearity properties of the RFID's IC and using the radar measurement technique a novel method for detection of the sensed parameter, by a passive sensor tag, was introduced. This novel technique relies on double-power measurement and does not require performing any calibration processes while measuring the tag parameters. Therefore, it speeds up the detection process and eliminates the use of any protocols for discovering the sensed parameters.

Considering the future trends for RFID-enabled sensor tags, there are still several important topics that should be addressed. One can be the further development of novel materials which can add excellent sensing features to the antenna layout. For instance, nano-based ink materials such as graphene have extraordinary properties that can add unique sensing features to an RFID tag easily. The research and development on RFID-enabled sensor tags utilizing advanced and novel materials with selective and repeatable sensing features that can be used in industry are definitely one of the hottest topics in the world of RFID. Another topic is that, the proposed detection methodologies presented in this work can move from a laboratory experimentation to real-life applications by developing a more simplified measurement unit including required hardware and firmware, to be used in any kind of industrial environment that utilizes the RFID-enable wireless platform for sensing.

In the second part of the thesis, it is shown that passive RFID is a promising technology for localization application in the indoor environment, where technologies such as GNSS is suffering from signal attenuation and non-line-of-sight.

The feasibility study in **Publication V** showed that the achieved channel model for an embroidered passive RFID tag is comparable with a wireless system, and the RFID RSS fluctuations are slightly more stable than the WLAN RSS fluctuations. In addition, it was discussed that the small ranges of RFID may lead to smaller errors in a location solution compared to those in WLAN positioning.

The determination of the RFID path loss modeling in **Publication V** was performed by only using the training phase of the fingerprinting method. To obtain the exact location of the labeled object, the positioning phase of the fingerprinting method were performed in other study work reported in **Publication VI**. In this study work, the available signals of both the RFID and WLAN systems in an indoor environment were used for location estimation. The experimental results showed that the hybrid solution can enhance the probability to get errors below 2 m with several percents even if only one RFID reader is available and that RSS coming from two different systems can be successfully combined towards a joint hybridization solution.

Overall, the results of the studies reported in **Publications V, VI and VII** proved that the wearable passive RFID tag can be considered as a cost-effective, easily implemented, and efficient configuration for human tracking in harsh environments, and it can be deployed for another purposes such as access control or patient tracking in health care applications VI. In addition, using empirical study and a positioning algorithm, a novel hybrid WLAN-RFID solution for indoor positioning was introduced. The proposed architecture utilizes the passive wearable RFID tags and a mobile device equipped with WLAN technology. The estimation of the position is done by analyzing both the RFID and WLAN signals, and the outcomes of the study showed that the hybrid solution provides better performance in comparison to each individual technology.

All in all, the innovative use of materials, and novel implementation and manufacturing techniques for the fabrication of the RFID tag, plus the ingenious methods of realization can provide numerous opportunities and applications where the RFID technology is capable of offering accurate and cost-efficient solutions.

Bibliography

- [1] K. Finkenzeller, *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards, Radio Frequency Identification and Near-Field Communication*. New York, USA: Wiley, 2010.
- [2] D. Saha and A. Mukherjee, "Pervasive computing: a paradigm for the 21st century," *Computer*, vol. 36, no. 3, pp. 25–31, Mar 2003.
- [3] A. Rida, L. Yang, and M. M. Tentzeris, *RFID-Enabled Sensor Design and Applications*. MA. USA: Norwood, 2010.
- [4] Y.Zhang, L.T.Yang, and J.Chen, *RFID and Sensor Networks*. Oxford, UK: Taylor and Francis Group, LLC, 2010.
- [5] L.Zhang and Z.Wang, "Integration of rfid into wireless sensor networks: Architectures, oppurtunities and challenging problems," in *5th International conference on Grid and Cooperative Computing Workshops*, 2006, pp. 463–469.
- [6] C. Occhiuzzi, S. Caizzone, and G. Marrocco, "Passive uhf rfid antennas for sensing applications: Principles, methods, and classifications," *IEEE Antennas and Propagation Magazine*, vol. 55, no. 6, pp. 14–34, Dec 2013.
- [7] A.Vena, E.Perret, and S.Tedjini, *Chipless RFID based on RF Encoding Particle*. Oxford, UK: Elsevier Ltd, 2016.
- [8] D.Dobkin, *The RF in RFID: Passive UHF RFID in Practice*. Burlington, MA: Elsevier Inc., 2008.
- [9] J.D.Kraus and R.J.Marhefka, *Antennas for All Applications*. NY, USA: McGRAW-Hill, 2003.
- [10] T.Koskelainen, *UHF Antenna Design and Design Validation Measurements*. Tampere University of Technology, 2007.
- [11] NXP, *Application note: AN 1629 UHF RFID Label, Antenna Design, UHF Antenna Design*. NXP Semiconductors, Rev.1.0-2008.
- [12] C.A.Balanis, *Antenna Theory, Analysis and design*. USA: John Wiley and Sons Inc., 2005.
- [13] A. Vena and P. Roux, "Near field coupling with small rfid objects," in *Proceedings of the PIERS*, Moscow-Russia, 2009, pp. 535–539.

- [14] P. V. Nikitin, K. V. S. Rao, S. F. Lam, V. Pillai, R. Martinez, and H. Heinrich, "Power reflection coefficient analysis for complex impedances in rfid tag design," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 9, pp. 2721–2725, Sept 2005.
- [15] P. V. Nikitin, K. V. S. Rao, R. Martinez, and S. F. Lam, "Sensitivity and impedance measurements of uhf rfid chips," *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, no. 5, pp. 1297–1302, May 2009.
- [16] G. Marrocco, "The art of uhf rfid antenna design: impedance-matching and size-reduction techniques," *IEEE Antennas and Propagation Magazine*, vol. 50, no. 1, pp. 66–79, Feb 2008.
- [17] K. V. S. Rao, P. V. Nikitin, and S. F. Lam, "Antenna design for uhf rfid tags: a review and a practical application," *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 12, pp. 3870–3876, Dec 2005.
- [18] P. Nikitin, K. Rao, E. Lam, and P. Pinc, "Uhf rfid tag characterization: Overview and state-of-the-art."
- [19] A. Pouzin, T. P. Vuong, S. Tedjini, J. Perdereau, and L. Dreux, "Measurement of radar cross section for passive uhf rfid tags," in *The Second European Conference on Antennas and Propagation, EuCAP 2007*, Nov 2007, pp. 1–6.
- [20] GS1, "Epc™ radio-frequency identity protocols generation-2 uhf rfid."
- [21] R. C. Hansen, "Relationships between antennas as scatterers and as radiators," *Proceedings of the IEEE*, vol. 77, no. 5, pp. 659–662, May 1989.
- [22] E.F.Knott, J.F.Shaeffer, and M.T.Tuley, *Radar Cross Section*. USA: SciTech, 2004.
- [23] K. Penttila, M. Keskilammi, L. Sydanheimo, and M. Kivikoski, "Radar cross-section analysis for passive rfid systems," *IEE Proceedings - Microwaves, Antennas and Propagation*, vol. 153, no. 1, pp. 103–109, Feb 2006.
- [24] P. V. Nikitin, K. V. S. Rao, and R. D. Martinez, "Differential rcs of rfid tag," *Electronics Letters*, vol. 43, no. 8, pp. 431–432, April 2007.
- [25] P. Pursula, M. Hirvonen, K. Jaakkola, and T. Varpula, "Antenna effective aperture measurement with backscattering modulation," *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 10, pp. 2836–2843, Oct 2007.
- [26] P. V. Nikitin and K. V. S. Rao, "Antennas and propagation in uhf rfid systems," in *2008 IEEE International Conference on RFID*, April 2008, pp. 277–288.
- [27] Impinj, "Monza r6 product brief / datasheet. available: <https://support.impinj.com/hc/en-us/articles/202765328-monza-r6-product-brief-datasheet>."
- [28] NXP, "Ucode8/8m product datasheet. available: <https://www.nxp.com/docs/en/data-sheet/sl3s1205-15-ds.pdf>."
- [29] G. Marrocco, "Pervasive electromagnetics: sensing paradigms by passive rfid technology," *IEEE Wireless Communications*, vol. 17, no. 6, pp. 10–17, December 2010.

- [30] A. A. Kutty, T. Björninen, L. Sydänheimo, and L. Ukkonen, “A novel carbon nanotube loaded passive uhf rfid sensor tag with built-in reference for wireless gas sensing,” in *2016 IEEE MTT-S International Microwave Symposium (IMS)*, May 2016, pp. 1–4.
- [31] M. Zgaren, S. Mohamad, A. Amira, and M. Sawan, “Epc gen-2 uhf rfid tags with low-power cmos temperature sensor suitable for gas applications,” in *2016 14th IEEE International New Circuits and Systems Conference (NEWCAS)*, June 2016, pp. 1–4.
- [32] F. Long, X. D. Zhang, T. Björninen, J. Virkki, L. Sydänheimo, Y.-C. Chan, and L. Ukkonen, “Implementation and wireless readout of passive uhf rfid strain sensor tags based on electro-textile antennas,” in *2015 9th European Conference on Antennas and Propagation (EuCAP)*, May 2015, pp. 1–5.
- [33] 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, pp. 7835–7836, Nov 2016.
- [34] Smartrac, “Water leaks sensor. available: <https://www.smartrac-group.com/pr/new-passive-sensor-tag-identifies-water-leaks-in-vehicles-ships-and-planes.html>.”
- [35] C. Occhiuzzi and G. Marrocco, “Pervasive body sensing: Implanted rfid tags for vascular monitoring,” in *2010 IEEE Antennas and Propagation Society International Symposium*, July 2010, pp. 1–4.
- [36] E. Jones, M. Henry, D. Cochran, and T. Frailey, “Rfid pharmaceutical tracking: From manufacturer through in vivo drug delivery,” *Journal of Medical Devices*, vol. 4, no. 1, 2009.
- [37] B. Bacheldor, “Belgium hospital combines rfid, sensors to monitor heart patients. available: <http://www.rfidjournal.com/articles/view?3120/2>,” 2007.
- [38] B. Wu, Z. Liu, R. George, and K. A. Shujaee, “ewellness: Building a smart hospital by leveraging rfid networks,” in *2005 IEEE Engineering in Medicine and Biology 27th Annual Conference*, Jan 2005, pp. 3826–3829.
- [39] L. Theremin, “Signaling apparatus,” February 1928.
- [40] R. Bhattacharyya, C. Floerkemeier, and S. Sarma, “Towards tag antenna based sensing - an rfid displacement sensor,” in *2009 IEEE International Conference on RFID*, April 2009, pp. 95–102.
- [41] P. Kalansuriya, R. Bhattacharyya, and S. Sarma, “Rfid tag antenna-based sensing for pervasive surface crack detection,” *IEEE Sensors Journal*, vol. 13, no. 5, pp. 1564–1570, May 2013.
- [42] RFmicron, “Technology overview. available: <http://rfmicron.com/overview/>.”
- [43] A. Vena, K. Koski, E. Moradi, A. A. Babar, L. Sydänheimo, L. Ukkonen, and M. M. Tentzeris, “An embroidered two-dimensional chipless strain sensor for wireless structural deformation monitoring,” *IEEE Sensors Journal*, vol. 13, no. 12, pp. 4627–4637, Dec 2013.

- [44] E. Moradi, T. Björninen, L. Ukkonen, and Y. Rahmat-Samii, "Characterization of embroidered dipole-type rfid tag antennas," in *2012 IEEE International Conference on RFID-Technologies and Applications (RFID-TA)*, Nov 2012, pp. 248–253.
- [45] J. Choi, Y. Kim, K. Lee, and Y. C. Chung, "Various wearable embroidery rfid tag antenna using electro-thread," in *2008 IEEE Antennas and Propagation Society International Symposium*, July 2008, pp. 1–4.
- [46] S. L. Merilampi, T. Bjorninen, A. Vuorimaki, L. Ukkonen, P. Ruuskanen, and L. Sydanheimo, "The effect of conductive ink layer thickness on the functioning of printed uhf rfid antennas," *Proceedings of the IEEE*, vol. 98, no. 9, pp. 1610–1619, Sept 2010.
- [47] G. Marrocco and F. Amato, "Self-sensing passive rfid: From theory to tag design and experimentation," in *2009 European Microwave Conference (EuMC)*, Sept 2009, pp. 001–004.
- [48] J. Virtanen, L. Ukkonen, T. Bjorninen, A. Z. Elsherbeni, and L. Sydänheimo, "Inkjet-printed humidity sensor for passive uhf rfid systems," *IEEE Transactions on Instrumentation and Measurement*, vol. 60, no. 8, pp. 2768–2777, Aug 2011.
- [49] E. Koski, K. Koski, L. Ukkonen, L. Sydänheimo, J. Virtanen, T. Björninen, and A. Z. Elsherbeni, "Performance of inkjet-printed narrow-line passive uhf rfid tags on different objects," in *2011 IEEE International Symposium on Antennas and Propagation (APSURSI)*, July 2011, pp. 537–540.
- [50] A. A. Babar, J. Virtanen, V. A. Bhagavati, L. Ukkonen, A. Z. Elsherbeni, P. Kallio, and L. Sydänheimo, "Inkjet-printable uhf rfid tag antenna on a flexible ceramic-polymer composite substrate," in *2012 IEEE/MTT-S International Microwave Symposium Digest*, June 2012, pp. 1–3.
- [51] M. Akbari, L. Sydänheimo, J. Juuti, J. Vuorinen, and L. Ukkonen, "Characterization of graphene-based inkjet printed samples on flexible substrate for wireless sensing applications," in *2014 IEEE RFID Technology and Applications Conference (RFID-TA)*, Sept 2014, pp. 135–139.
- [52] M. Akbari, M. W. A. Khan, M. Hasani, T. Björninen, L. Sydänheimo, and L. Ukkonen, "Fabrication and characterization of graphene antenna for low-cost and environmentally friendly rfid tags," *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 1569–1572, 2016.
- [53] nScript, "nscript 3dn series datasheet. available:<https://www.nscript.com/wp-content/uploads/2017/02/2016-3dn-brochure.pdf>."
- [54] M. M. Tentzeris, A. Rida, A. Traille, H. Lee, V. Lakafosis, and R. Vyas, "Inkjet-printed paper/polymer-based rfid and wireless sensor nodes: The final step to bridge cognitive intelligence, nanotechnology and rf?" in *2011 URSI General Assembly and Scientific Symposium*, Aug 2011, pp. 1–4.
- [55] J. Virtanen, T. Bjorninen, L. Ukkonen, and L. Sydanheimo, "Passive uhf inkjet-printed narrow-line rfid tags," *IEEE Antennas and Wireless Propagation Letters*, vol. 9, pp. 440–443, 2010.

- [56] P. Deffenbaugh, K. Church, J. Goldfarb, and X.Chen, "Fully 3d printed 2.4 ghz bluetooth/wi-fi antenna," in *IMAPS, International Symposium on Microelectronics*, 2013.
- [57] S. Shamsinejad and P. Mousavi, "3d folded cubical slot antenna," in *2014 IEEE Antennas and Propagation Society International Symposium (APSURSI)*, July 2014, pp. 860–861.
- [58] A. Galehdar, D. V. Thiel, and S. G. O’Keefe, "Design methods for 3d rfid antennas located on a conducting ground plane," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 2, pp. 339–346, Feb 2009.
- [59] S. Yao, S. V. Georgakopoulos, B. Cook, and M. Tentzeris, "A novel reconfigurable origami accordion antenna," in *2014 IEEE MTT-S International Microwave Symposium (IMS2014)*, June 2014, pp. 1–4.
- [60] C. M. Kruesi, R. J. Vyas, and M. M. Tentzeris, "Design and development of a novel 3-d cubic antenna for wireless sensor networks (wsns) and rfid applications," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 10, pp. 3293–3299, Oct 2009.
- [61] NXP, "Ucode g2il product datasheet. available: <https://www.nxp.com/docs/en/datasheet/sl3s1203.pdf>."
- [62] R. Bhattacharyya, C. Floerkemeier, and S. Sarma, "Rfid tag antenna based sensing: Does your beverage glass need a refill?" in *2010 IEEE International Conference on RFID (IEEE RFID 2010)*, April 2010, pp. 126–133.
- [63] S. Capdevila, L. Jofre, J. Romeu, and J. C. Bolomey, "Passive rfid based sensing," in *2011 IEEE International Conference on RFID-Technologies and Applications*, Sept 2011, pp. 507–512.
- [64] G. Deschamps, "Impedance of an antenna in a conducting medium," *IRE Transactions on Antennas and Propagation*, vol. 10, no. 5, pp. 648–650, September 1962.
- [65] S. Merilampi, P. Ruuskanen, T. Björninen, L. Ukkonen, and L. Sydänheimo, "Printed passive uhf rfid tags as wearable strain sensors," in *2010 3rd International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL 2010)*, Nov 2010, pp. 1–5.
- [66] C. Occhiuzzi, C. Paggi, and G. Marrocco, "Passive rfid strain-sensor based on meander-line antennas," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 12, pp. 4836–4840, Dec 2011.
- [67] A. Vena, L. Sydänheimo, M. M. Tentzeris, and L. Ukkonen, "A fully inkjet-printed wireless and chipless sensor for co2 and temperature detection," *IEEE Sensors Journal*, vol. 15, no. 1, pp. 89–99, Jan 2015.
- [68] A. Vena, L. Sydänheimo, M. M. Tentzeris, and L. Ukkonen, "A novel inkjet printed carbon nanotube-based chipless rfid sensor for gas detection," in *2013 European Microwave Conference*, Oct 2013, pp. 9–12.
- [69] C. Occhiuzzi, A. Rida, G. Marrocco, and M. Tentzeris, "Rfid passive gas sensor integrating carbon nanotubes," *IEEE Transactions on Microwave Theory and Techniques*, vol. 59, no. 10, pp. 2674–2684, Oct 2011.

- [70] GS1, “Class 1 generation 2 uhf protocol standard. available: <https://www.gs1.org/gsm/kc/epcglobal/uhfc1g2>.”
- [71] Voyantic, “Product data sheet, tagformance-lite. available: <http://voyantic.com/products/tagformance-lite>.”
- [72] CISC, “Cisc rfid xplorer. available: <http://www.cisc.at/xplorer.html>.”
- [73] Tescom, “Tescom rfid tester: <http://www.tescom-lab.com>.”
- [74] W. Wiesbeck and D. Kahny, “Single reference, three target calibration and error correction for monostatic, polarimetric free space measurements,” *Proceedings of the IEEE*, vol. 79, no. 10, pp. 1551–1558, Oct 1991.
- [75] E. Moradi, T. Bjorninen, L. Ukkonen, and Y. Rahmat-Samii, “Effects of sewing pattern on the performance of embroidered dipole-type rfid tag antennas,” *IEEE Antennas and Wireless Propagation Letters*, vol. 11, pp. 1482–1485, 2012.
- [76] A. Vena, E. Perret, and S. Tedjni, “A depolarizing chipless rfid tag for robust detection and its fcc compliant uwb reading system,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 8, pp. 2982–2994, Aug 2013.
- [77] E. S. Lohan, “Radio signal based positioning techniques,” *Tampere University of Technology, Department of Communications Engineering*, www.cs.tut.fi/tlt/pos.
- [78] E. S. Lohan, “Wlans and cellular positioning principles,” *Tampere University of Technology, Department of Communications Engineering*, www.cs.tut.fi/tlt/pos.
- [79] A. I. S. C. Spinella and A. Molinaro, “On potentials and limitations of a hybrid wlan-rfid indoor positioning technique,” *Int. J. Navigat. Observat*, Mar. 2010.
- [80] J. Wu, “Three-dimensional indoor rfid localization system,” Ph.D. dissertation, University of Nebraska – Lincoln, 2012.
- [81] Z. Kai, L. Binghao, and A. Dempster, “Ignss symposium,” july 2013.
- [82] S. Shrestha, E. Laitinen, J. Talvitie, and E. S. Lohan, “Rssi channel effects in cellular and wlan positioning,” in *2012 9th Workshop on Positioning, Navigation and Communication*, March 2012, pp. 187–192.
- [83] H. Nurminen, J. Talvitie, S. Ali-Löytty, P. Müller, E. S. Lohan, R. Piché, and M. Renfors, “Statistical path loss parameter estimation and positioning using rssi measurements in indoor wireless networks,” in *2012 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, Nov 2012, pp. 1–9.
- [84] S. Shrestha, J. Talvitie, and E. S. Lohan, “On the fingerprints dynamics in wlan indoor localization,” in *2013 13th International Conference on ITS Telecommunications (ITST)*, Nov 2013, pp. 122–126.
- [85] S. L. Ting, S. K. Kwok, A. H. Tsang, and G. T. Ho, “The study on using passive rfid tags for indoor positioning,” *International Journal of Engineering Business Management*, vol. 1, no. 1, 2011.
- [86] L. M. Ni, D. Zhang, and M. R. Souryal, “Rfid-based localization and tracking technologies,” *IEEE Wireless Communications*, vol. 18, no. 2, pp. 45–51, April 2011.

-
- [87] K. Koski, A. Vena, L. Sydänheimo, L. Ukkonen, and Y. Rahmat-Samii, “Design and implementation of electro-textile ground planes for wearable uhf rfid patch tag antennas,” *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 964–967, 2013.
- [88] E. Moradi, K. Koski, L. Ukkonen, Y. Rahmat-Samii, T. Björninen, and L. Sydänheimo, “Embroidered rfid tags in body-centric communication,” in *2013 International Workshop on Antenna Technology (iWAT)*, March 2013, pp. 367–370.

Publications

Publication I

M. Hasani, A. Vena, L. Sydänheimo, L. Ukkonen and M. M. Tentzeris. "Implementation of a dual-interrogation-mode embroidered RFID-enabled strain sensor", *IEEE Antennas and Wireless Propagation Letters* Vol. 12, pp. 1272–1275.

© 2013 IEEE

Publication II

M. Hasani, A. Vena, L. Sydänheimo, L. Ukkonen and M. M. Tentzeris, "A Novel RFID-Enabled Strain Sensor Using the Double Power Measurement Technique," in *Proc IEEE International Microwave Symposium*, pp. 1–4, June 2014.

© 2014 IEEE

Publication III

M. Hasani, A. Vena, L. Sydänheimo, L. Ukkonen and M. M. Tentzeris, "A Novel Enhanced-Performance Flexible RFID-Enabled Embroidered Wireless Integrated Module for Sensing Applications," *IEEE Transaction on Components, Packaging and Manufacturing Technology*, Vol. 5, pp. 1244 - 1252, August 2015.

© 2015 IEEE

Publication IV

M. Hasani, E. S. Lohan, L. Sydänheimo, L. Ukkonen, “Path-Loss Model of Embroidered Passive RFID Tag on Human Body for Indoor Positioning Applications,” in *Proc IEEE RFID-TA*, pp. 170–174, September 2014.

Publication V

M. Hasani, E. S. Lohan, L. Sydänheimo, L. Ukkonen, “Path-Loss Model of Embroidered Passive RFID Tag on Human Body for Indoor Positioning Applications,” in *Proc IEEE RFID-TA*, pp. 170–174, September 2014.

© 2014 IEEE

Publication VI

M. Hasani, J. Talvitie, L. Sydänheimo, E. S. Lohan, L. Ukkonen, “Hybrid WLAN-RFID Indoor Localization Solution Utilizing Textile Tag,” *IEEE Antennas and Wireless Propagation Letters*, Vol. 14, pp. 1358 - 1361, February 2015.

© 2015 IEEE

Publication VII

M. Hasani, L. Sydänheimo, L. Ukkonen, “Performance Evaluation of Wearable Passive RFID Tag for Human Indoor Positioning,” *Proc IEEE International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting*, pp. 1750 - 1751, July 2015.

© 2015 IEEE

Tampereen teknillinen yliopisto
PL 527
33101 Tampere

Tampere University of Technology
P.O.B. 527
FI-33101 Tampere, Finland

ISBN 978-952-15-4178-0

ISSN 1459-2045