Experimental Assessment of Orientation Sensing and Constructive Interference in Passive RFID Systems

Krigslund, Rasmus

Publication date:
2012

Document Version
Accepteret manuscript, peer-review version

Link to publication from Aalborg University

Citation for published version (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

Take down policy
If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.
Experimental Assessment of Orientation Sensing and Constructive Interference in Passive RFID Systems
~ PhD Thesis ~

Rasmus Krigslund, rkr@es.aau.dk
Aalborg University

July 6, 2012
Abstract

English Abstract

This thesis focus on passive Radio Frequency IDentification (RFID), a technology designed for automated identification of tagged objects. The tags are small passive devices powered by the wireless signal from the reader. Their simple operation thus solely allows them to reply with their unique ID when requested by the reader, which is a high power handheld or stationary transceiver. The RFID technology has matured over the past two decades, but still there exist ambiguities regarding the reading, or interrogation, of tags. Due to the passive nature of the tags, they are severely affected by the environment and the object they are attached to. Hence they may be rendered unable to reply to the readers request, in spite of being within the expected read range of the reader. This is referred to as False Negative Detections (FNDs). Similarly, constructive effects in the environment can enable a tag outside the expected read range to reply. This is denoted a False Positive Detection (FPD). It is desired to reduce the occurrence of these false positive and negative detections hence in this thesis it is proposed to impose interference on the communication between reader and tag. Interference has a well-known blocking effect, and the experimental investigations show how tag replies outside the expected read range are blocked, as expected. Moreover, tuned and detuned tags alike are affected by the decreased Signal to Interference and Noise Ratio (SINR) due to the imposed interference, hence their read ranges are thus effectively equalized. From the investigations it can therefore be concluded that the imposed interference has a constructive effect as it enables design of well defined and sharply bounded interrogation
zones, where tags are read with high probability regardless of the level of detuning they might experience.

Moreover, this thesis proposes to use passive RFID tags as orientation sensors. This is an innovative application for RFID technology in itself, but orientation sensing can also help existing RFID applications that relies on the Received Signal Strength (RSS) in the tag reply. Many Ultra High Frequency (UHF) RFID tags utilize a dipole antenna, and the RSS metric of the tag reply is thus prone to polarization and gain mismatches between tag and reader antennas. Being able to estimate the orientation can help mitigate this effect. It is proposed to let a reader antenna collect information about the polarization of the received tag reply by decomposing the RSS into the horizontal and vertical dimensions using a dual linearly polarized reader antenna. The method is evaluated experimentally, and when the movement of the tag is limited to two dimensions, i.e. a plane, the results for tracking the tag orientation are promising. Tag movements in three dimensions complicates however the orientation estimate. Multiple reader antenna are therefore utilized in order to collect samples of the tag reply from multiple directions, and their data are fused using Kalman filtering. The final results show good potential, as even simple data processing enables recognition of gestures, i.e. predefined motions with the tag. However, the estimate of the three dimensional orientation vector offers relatively low precision, and does therefore not allow dedicated motion capture of the tag. But it has been shown through experimental investigations that the orientation information is available in the tag reply, and using more advanced methods for data processing, a reliable orientation estimate can be obtained.
Dansk resume


Ydermere foreslår denne afhandling at anvende passive RFID tags som orienteringssensorer. Dette er en innovativ anvendelse af RFID teknologien i sig selv, men orienteringssensorer kan også være en hjælp til eksisterende RFID applikationer, der afhænger af signalstyrken modtaget fra taggen. Mange UHF RFID tags benytter en dipol antenne, og signalstyrken i taggens svar er derfor modtagelig overfor misforhold i polarisering og forstærkning mellem taggens og læserens antenne. At være i stand til at estimere taggens orientering vil derfor være med til at afhjælpe disse effekter. Det foreslås at lade læserens antenne opsamle information om polariseringen af det modtagne tagsvar ved at opdele den modtagne signalstyrke i horisontale og vertikale komposanter ved at benytte en bi-lineær polariseret læser antenne. Denne metode er evalueret eksperimentelt, og når taggens bevægelse er begrænset til to dimensioner, dvs. et plan, er resultaterne lovende med hensyn til at estimere og følge taggens orientering. Bevægelse af taggen i tre dimensioner komplicerer derimod estimeringen af orienteringen. Derfor benyttes
flere læser antenner, for dermed at opsamle data fra tagsvaret fra flere retninger. Dataene fra læser antennerne er herefter kombineret via Kalman filtrering. De endelige resultater viser et godt potentiale, da selv de simple databehandlingsmetoder der anvendes tillader genkendelse af gestikulationer, dvs. prædefinerede bevægelser med taggen. Estimatet af den tredimensionelle orienteringsvektor har derimod relativ lav præcision, og tillader derfor ikke detaljeret estimering af taggens bevægelse. Men det er blevet vist gennem eksperimentelle undersøgelser at orienteringsinformationen er til stede i taggens svar, og ved at benytte mere avancerede metoder til at behandle dataene vil det være muligt at opnå et robust og pålideligt estimat af taggens orientering.
This Ph.D. thesis focuses on passive RFID systems and logical localization of passive tags by enabling the design of well defined, and sharply bounded, interrogation zones by using interference constructively. Moreover, this thesis proposes a novel application of passive tags using them as orientation sensors.

The thesis was prepared under the supervision of Professor Gert F. Pedersen and Professor Petar Popovski, and funded by Aalborg University and a scholarship from the Danish Agency for Science Technology and Innovations (Forsknings- og Innovationssstyrelsens) program for education of researchers. The thesis is comprised by six publications in total, where two are on constructive interference, and four are on orientation sensing with passive RFID tags. Two additional publications are enclosed as well, written in parallel with the papers included in the thesis. They are related to the thesis in the sense that they also consider the RFID technology as more than just a mean to identification, but in a different context than orientation sensing and constructive interference.

All publications are enclosed as the latest version, i.e., the final version of the accepted paper. One enclosure however (Paper 6), is enclosed as the latest submitted version, as it is currently in the review process. Hence the page layout varies between contributions depending on the publication channel.

References are listed with numbers in the order they are used in the text, and each enclosed publication has its individual list of references.
Acknowledgements

During this Ph.D. I have had many discussions with, and received many advises from, colleagues and friends from Aalborg University and from industry. This sparring and support has been a great help in the progress and finalization of the work presented in this thesis.

First of all I would like to thank my supervisors Gert and Petar, who figuratively speaking have guided me over the hills and through the valleys of the Ph.D. project. Gert for his insights into practical measurements and his never-failing optimism regarding me, my project and the Antennas, Propagation and Radio Networking (APNet) section in general. A special acknowledgement goes to Petar, with whom I have had the day-to-day contact and discussions, for his innovative ideas and continuous intellectual challenges. Petar has supervised several of my student projects during my master studies at Aalborg University as well, the first time in 2006, and over the years we have gotten to know each other very well both collegial and personally.

I would also like to thank Kim Olesen and Kristian Bank for their support and discussions on practical RFID measurements. Also Jørgen B. Andersen, Ondrej Franek and Patrick Eggers for their support and discussions on the physical and propagational aspects of the RFID technology.

Also the fellow Ph.D.s at Aalborg University, Mads Lauridsen, Niels L. Pedersen, Jesper H. Sørensen, German C. Madueno, Anders R. Jensen, Jesper Kjær, Jesper Rindom, Rasmus M. Jacobsen, Karsten Fyhn, Morten L. Jakobsen, Samantha C. del Barrio and Alexia Jacobsen, all with whom I have shared the joys, successes and the inevitable frustrations during a Ph.D. project.

Also Associate Professor Christian Floerkemeier and Professor Sanjay Sarma for welcoming me into their research group at Massachusetts Institute
of Technology (MIT), and to PhD Fellows (at the time) Rahul Bhattacharyya, Isaac Ehrenberg and Dominique Guinard for helping me get settled in Cambridge, MA, and feel welcome.

Also the companies and engineers I have been in contact with and discussed the practical use of, and challenges with, the RFID technology. Especially Christian Klock, Finn Zoega and Morten Pedersen, all from Teknologisk Institut, Nikki Grigoriou, Intelligent Systems, Karsten Bang and Niels Have, both from Logimatic, Rita Westergaard, RFID Specialisten. A special thank goes to Jørgen Albøge, Claus B. Christensen, Mogens Beltoft, Jesper Egebjerg, Kim L. Rasmussen, Richard Christensen and Michael Malmgaard, all from Lyngsoe Systems A/S, for providing me with up-to-date RFID equipment and welcoming me into the company to gain practical experience with the challenges of RFID installations.
# Contents

1 Introduction ........................................ 1
  1.1 RFID Context ........................................ 1
  1.2 State of Art .......................................... 2
  1.3 Thesis Objectives .................................... 4
  1.4 Structure of the Thesis ............................... 6

2 Contributions In This Thesis ....................... 7
  2.1 Constructive Interference .......................... 7
     2.1.1 Paper 1 .......................................... 7
     2.1.2 Paper 2 .......................................... 9
  2.2 Orientation Sensing ................................. 11
     2.2.1 Paper 3 .......................................... 11
     2.2.2 Paper 4 .......................................... 13
     2.2.3 Paper 5 .......................................... 15
     2.2.4 Paper 6 .......................................... 17

3 Discussion ............................................ 19
  3.1 Constructive Interference .......................... 19
  3.2 Orientation Sensing .................................. 20

4 Conclusion ............................................ 23

References .............................................. 25

List of Abbreviations .................................... 29

xiii
CONTENTS

Contributions Included In This Thesis  
  Paper 1: Measuring the Interference at an RFID Tag: Where Does It Have an Impact? 33  
  Paper 2: Interference Helps to Equalize the Read Range and Reduce False Positives of Passive RFID Tags 43  
  Paper 3: Potential of RFID Systems to Detect Object Orientation 55  
  Paper 4: Orientation Sensing Using Multiple Passive RFID Tags 61  
  Paper 5: A Novel Technology for Motion Capture Using Passive UHF RFID Tags 67  
  Paper 6: Experimental Assessment of 3D Gesture Recognition Using Passive RFID Tags 73

Related Contributions Not Part of The Thesis 83  
  Paper 7: Green Communication: Where Can It Really Help and How It is Related to RFID 85  
  Paper 8: Using ICT in Greening: The Role of RFID 91

Complete List of Publications 113
CHAPTER 1

Introduction

1.1 RFID Context

The concept of Radio Frequency IDentification (RFID) technology dates back more than half a century, and is designed for automatic identification of objects. An RFID system is comprised by two key components: The tag and reader. An RFID tag is a small wireless radio transceiver that can be attached to, or embedded in, the object to be identified. It holds an ID large enough to identify unique objects, where a barcode of practical reasons often is limited to identify groups of objects. Readers are wireless transceivers responsible for identifying tags in their proximity and collect their information. In this way readers act as interface between the physical world, i.e. the tagged objects, and the digital world, e.g. a warehouse management system processing the collected tag IDs. Readers can be handheld devices or stationary devices deployed at strategic locations in order to efficiently collect the information from the tags. Due to the wireless communication between reader and tag, Line Of Sight (LOS) is not required between the two devices and the interrogation of a tag can be done seamlessly without interfering with normal operation.

In general there are three types of RFID tags: 1) Active tags, that comes with an internal power supply in form of a small battery. This enables autonomous operation as well as the option of using a high transmission power and/or advanced modulation and coding schemes for the data. The lifetime of the tag is therefore dependent on the capacity of the battery. 2)
Passive tags, which have no internal power supply. These tags are solely energized by the power in the wireless signal from the reader, i.e. the power “in the air”, and the available processing on the tag is therefore limited to only returning its ID. However, the lifetime of a passive tag is thus only limited by the durability of the microchip silicon and tag antenna conductor.

3) Semi-passive tags, which holds a small battery like the active tags. But for these tags the battery only enables data processing, not data transmission, which makes the semi-passive tag a hybrid between passive and active tags.

In spite of having been a research area with immense activity for more than two decades, RFID is today still mainly used for identification purposes in supply chain applications, with the limiting factor being production costs and profitability of the technology. [1] It is therefore no surprise that RFID often is described as the successor of the barcode, albeit this is not a fair description as the RFID technology has the potential of being much more than that. This postulate is supported by recent years attention towards using RFID tags as for example sensors, i.e. enable collection of data about the object and/or the environment around it via the tag. This combination of the unique ID and whatever additional side-information that can be obtained from the tag holds a great potential. As an example consider a warehouse. Using RFID all objects arriving to, and leaving, the warehouse can be identified automatically which provides a complete overview, in real-time, of the objects inside. In this way the RFID system is providing valuable information. But the value increases if the RFID system is able to provide the location of the tagged object inside the warehouse, in addition to its ID.

1.2 State of Art

The problem of localizing RFID tags has received great attention in recent years. This is probably due to the direct applicability of such functionality in various supply chain applications, but also since it is a natural extension to the problem of localizing nodes in Wireless Local Area Networks (WLANs) and cellular networks. The localization of RFID tags is generally referring to Ultra High Frequency (UHF) RFID tags, due to their relatively long range. For RFID tags operating on lower frequencies, e.g. the High Frequency (HF) band, their location is usually associated with the readers location due to the short read range.

The limited capabilities of passive tags introduces certain constraints on the localization methods, and for sparse reader deployment the location of a tag is usually associated with that of the reader, as it is the case for HF tags. Albeit, for dense reader environments more complex localization me-
methods can be utilized, and [2] presents an overview of the existing methods for localization in indoor wireless networks and how concepts from localization methods designed for indoor WLANs are reused for localization of RFID tags. The methods for localizing RFID tags are usually categorized into two families: Lateration and Angulation methods and Scene Analysis methods, where the former localize a tag based on metrics like Received Signal Strength (RSS), Time Of Arrival (TOA), Direction Of Arrival (DOA) or Angle Of Arrival (AOA). Using RSS for the location estimate poses several complications, as the RSS metric is sensitive to environmental conditions, e.g. multi path reflections and interference, and the properties of the tagged object. In [3] it is suggested to combine multiple propagation models in order to compensate for these drawbacks of the RSS metric. The phase of the tag reply does not suffer from the same drawbacks, and [4] presents a method for localizing a tag moving in one dimension, e.g. through a portal in a warehouse. The method is based on the phase of the received tag reply, obtained by either multiple reader antennas or multiple samples by the same reader antenna. In the same line [5] proposes a method that enables a handheld reader to estimate the DOA of a tag reply based on phase information from multiple samples combined with knowledge of its own movement. Common for the metrics for lateration or angulation based localization is that they are sensitive to not having LOS to the tag. Based on measurements in a common RFID application, [6] shows that the RFID channels are usually not dominated by the LOS path. In effect this leads to significant errors when localizing tags using the normal metrics. Instead the same authors suggests, in [7], to use Ultra Wide Band (UWB) ranging of the passive UHF tags, as the improved time resolution in UWB signaling allows for extraction of the LOS component in the tag reply, or the first arriving reflection in case of Non Line Of Sight (NLOS).

The localization methods based on scene analysis are collecting fingerprints of the environment, which compared to the characteristics of the received tag reply, helps localizing the tag. An example is the well-known LANDMARC scheme, presented in [8], where reference tags (landmarks) are distributed in the environment. A tag is then localized by comparing its reply with those from the reference tags. Similarly, [9] seeks to construct a simple map of the Radio Frequency (RF) environment based on the expected RSS from various reference points. When using RSS as metric, the scene analysis methods suffers from the same drawbacks as described above. Usually UHF tag antennas are some variant of meander dipole antennas, and the polarization mismatch between tag and reader antennas is therefore dependent of the orientation of the tag. A polarization mismatch reduces the RSS received at the reader, and thus contributes to the errors in the location estimate. In [10]
methods for estimating the loss from polarization mismatch are presented in order to improve the location estimate. But in general the precision of the localization methods is orientation dependent.

Moreover, in order to localize a tag, its presence needs to be identified by the reader. However, if the tag is heavily detuned by the object it is attached to, the reader may not be able to activate the tag, even though the tag is located within the expected read range of the reader. This phenomenon is referred to as a False Negative Detection (FND) and is described in detail in [11, 12, 13] along with its counterpart, the False Positive Detection (FPD). FPDs refer to the case where constructive effects in the environment enables a tag located outside the expected range of a reader to be read. Together, FPDs and FNDs represent the ambiguity associated with a (missing) tag observation. It is desired to minimize this ambiguity, and seeking to reduce the probability of FNDs [14] presents a method for estimating the size of the tag population and from that determine if all tags have been identified. A different approach is taken in [15] where the probability of having experienced a FND is estimated based on a set of proposed statistical estimators. In order to filter out FPDs, [16, 17] presents probabilistic models for filtering the collected RFID data.

1.3 Thesis Objectives

Investigating the current state of art methods for localization of passive RFID tags reveals underlying issues and ambiguities that are severely affecting the performance of these methods. It is currently an active field of research finding solutions to mitigate these effects, and a general solution for reducing these ambiguities can potentially benefit several existing localization methods. Hence the objective of this thesis is twofold: Firstly, this thesis seeks to remove the occurrence of false negative and false positive detections. This can be regarded as logical localization, as it will increase certainty that a tag located within the interrogation zone is identified, and that identified tags are in fact located within the zone. A common characteristic for the current methods for reducing these false detections is that they accept the presence of this ambiguity, and implements measures to cope with it. As an alternative it is desired to investigate methods for reducing the occurrence of FNDs and FPDs. This can potentially enable the design of well defined interrogation zones covering a confined and sharply bounded area, which in turn may improve the applicability of RFID systems and aid their market penetration. However, methods for reducing one tends to increase the occurrence for the other. As an example consider FNDs. It may be argued that
increasing the transmission power of the reader increases the probability of identifying all tags within the desired interrogation zone. But the total read range of the reader is increased as well, increasing the probability of falsely detecting tags outside the desired zone. In this thesis it is therefore suggested to introduce interference sources in the environment and impose interference onto the RFID system. Close to the reader the Signal to Interference and NoiseRatio (SINR) is high and the interference has little impact on the communication between reader and tag, whereas outside the desired interrogation zone the interference blocks tags from replying. The combination of the interrogation power level and the interference power level then allows for designing interrogation zones in which a tag is read with high probability regardless of how it is affected by the object, while tags outside the zone are blocked from responding.

The second objective of this thesis is to enable detection of the orientation of a passive tag from the reader side. This means detecting the tag orientation based on the signal content in the tag reply alone, and supplements therefore the current activity within RFID sensors. Moreover, orientation sensing may aid current localization methods, which is affected by the polarization mismatch between tag and reader. In this thesis the fact that the RSS changes with the orientation of the tag, due to the polarization mismatch, is utilized constructively as orientation information to be processed by the reader directly or by the middleware of the RFID system. Using passive tags as orientation sensors is a novel idea in itself, and represents an innovative application of passive RFID, applicable in areas as diverse as health care technology and the entertainment industry. No prior work has considered estimating the orientation of a passive RFID tag, to the best of the authors knowledge, and continuously tracking the orientation, and thereby the motion, of the tag has the potential to enable motion capture using a passive RFID system. Previously, passive UHF RFID tags have been utilized as binary motion sensors (i.e. is there movement or not), e.g. in [18] where passive RFID tags attached to body segments are used to monitor movements during common sleep disorders. Capturing motion, e.g. of human body segments, can be achieved by several existing technologies [19]. The current state of art is based on optoelectronic systems using infrared cameras for tracking the positions of markers placed on the human body. From this information the three dimensional pose of the body is reconstructed. The high precision of an optoelectronic system comes at the price of expensive and calibration intensive laboratory equipment. Alternatively Inertial Measurering Units (IMUs), i.e. combined accelerometer and gyroscopes, can be used to capture the motion of an object or a body segment. These sensors offer reduced precision compared to an optoelectronic system, but at a
competitive price. [20] However, the motion estimated from noisy velocity and acceleration samples is affected by several sources of error, e.g. internal drift in the sensor hardware and collision accelerations.

1.4 Structure of the Thesis

The thesis is divided into three parts. The first part seeks to design a confined interrogation zone by imposing constructive interference. The impact on the interference at tag level is investigated followed by experimental evaluation of the confinement of the resulting interrogation zone. The second part investigates the potential of estimating a tags orientation and presents the proposed method to extract orientation information from the tag reply and evaluates this method experimentally in various scenarios of increasing complexity. The final part of this thesis discusses the combined outcome and results, and draw the final conclusions.
Contributions In This Thesis

The contributions included in this thesis are briefly summarized in this chapter. The motivation for each individual contribution is described along with their main results and how they are linked to the other contributions.

2.1 Constructive Interference

2.1.1 Paper 1

Measuring the Interference at an RFID Tag: Where Does It Have an Impact?

Rasmus Krigslund, Petar Popovski, Gert F. Pedersen, and Kim Olesen

Motivation

The term interrogation zone for an RFID system is ambiguous, due to the probabilistic nature of the communication channel between reader and tag. Hence a tag located outside the desired zone may reply to queries from the reader. Inside the zone, a tags antenna performance can be severely degraded due to various objects rendering the tag unable to reply. It is desired to minimize the effect of these phenomena, denoted FNDs and FPDs as described in Section 1.2. In this thesis it is proposed to utilize interference constructively in order to block tag replies from outside the interrogation zone, and ensure
tags inside the zone are powered up and able to reply. This paper documents the initial steps towards reducing the occurrence of these false detections using constructive interference. The paper presents an experimental evaluation of the impact of interference, when imposed on the communication from reader to tag, from tag to reader or both, respectively.

**Paper Content**

It is assumed that the interference is generated by the existing RFID infrastructure. The frequency spectrum available to RFID communication is divided into channels, in Europe four channels in total, where an RFID reader utilizes one channel at the time. The interference can thus occur in the same channel, denoted Co-Channel Interference (CCI), or one of the other channels, i.e. Adjacent-Channel Interference (ACI). It is expected that the impact of interference depends on the frequency distance between interrogation signal and interference signal. This paper therefore investigates three different interference signals, one CCI and two ACIs, one separated by a single channel width and one separated two channel widths from the interrogation signal. Moreover the difference between using modulated and unmodulated interference is investigated. In order to have a controlled environment and reduce the effects of multi path fading, this paper confines the interrogation zone to be inside a shielded box.

**Main Results**

The tested interference types have a significant impact on the performance of the RFID system, especially the modulated interference, as expected. In general modulated CCI is the most harmful interference, and the Signal to Interference Ratio (SIR) required to get a high read rate decrease as the frequency distance increases. It is worth noting that the unmodulated CCI appeared to have little impact on the tags ability to interpret the interrogation signal, even though the interrogation and interference signals were unsynchronized. This is initially believed to indicate the option for using interference as an additional power source aiding in powering up the tag. However, in the utilized setup interferer and reader are co-located, due to the limitations using the shielded box, and it is therefore not suited to test this idea. Hence no reliable results are achieved to confirm whether the concept of an additional power source is an option, and this part of the paper therefore remains inconclusive.
2.1 Constructive Interference

2.1.2 Paper 2

Interference Helps to Equalize the Read Range and Reduce False Positives of Passive RFID Tags

Rasmus Krigslund, Petar Popovski, Gert F. Pedersen, and Kim Olesen
Published in IEEE Transactions of Industrial Electronics.

Motivation

The investigation from Paper 1 is continued in this paper. Paper 1 focused on the blocking ability of imposed interference, and thus mitigating FPDs, but the paper was inconclusive regarding whether interference could help reduce FNDs. This paper focuses on FNDs and how interference can help improve read reliability in close range of the reader and thus enable well-defined and sharply bounded interrogation zones. The read range of tags depends on how the environment affects the matching of the tag antenna, i.e., the level of detuning of the antenna. This means that an interrogation zone becomes a diffuse concept and its coverage will thus depend on the tagged objects. This effect is undesired and sought to be minimized in this paper. Moreover, the limitations of the experimental setup from Paper 1 are in this paper removed by moving the measurements from the shielded box to the multi-path fading environment in the lab.

Paper Content

The utilized setup in this paper contains a reader and an interference source placed on opposite sides of the desired interrogation zone. This allows for more detailed investigation of the tag performance when near the edge of the desired interrogation zone. Hence it is investigated which interference type creates the sharpest edge of the zone and how the read range is affected of both tuned and detuned tags.

Main Results

In Paper 1 it was shown how the blocking ability of CCI was superior over ACI. This is confirmed in this paper. But for CCI the read rate decays gradually with the distance to the reader, whereas for ACI the read range may be longer, but the read rate decays very abruptly. Hence ACI yields the sharpest edge for the interrogation zone and is thus used in all subsequent measurements. The resulting read range can be adjusted by changing the interference power level, and thus the SIR.
Moreover, the measurements show how the interference helps equalizing the read range of tuned and detuned tags, since they are both equally affected by the decreased SIR. In this way the interference constructively helps reducing the probability of tags inside the desired zone being unable to reply to the reader. Hence, this enable the design of well defined interrogation zones, where the resulting range can be adjusted by the interference power level.
2.2 Orientation Sensing

2.2.1 Paper 3

Potential of RFID Systems to Detect Object Orientation
Rasmus Krigslund, Petar Popovski, Gert F. Pedersen and Kristian Bank
Presented at the IEEE International Conference on Communications (ICC). Kyoto, Japan, 2011.

Motivation

The passive RFID tag is a simple wireless device designed just to return its unique ID when interrogated by a reader. Often are the ID, the RSS and the phase of the tag response signal the only information a reader collects from the communication with the tag. This puts certain constraints on applications trying to locate the tag, as described in Section 1.2. Especially methods relying on the RSS metric, as the RSS is sensitive to changes in the environment, how the tag is affected by the objects it is attached to and how the tag is oriented with respect to the reader, due to the polarization mismatch. The environment and objects are application specific, but the problem of the orientation affecting the RSS is general to many RFID applications. Being able to estimate the orientation of an RFID tag and the associated object, in order to predict the polarization mismatch, therefore has a wide applicability. The orientation may aid existing localization methods, but like the location the orientation is a valuable side-information by itself, and increases the value of the existing RFID setup in e.g. a supply chain application.

Paper Content

The paper represents the initial steps towards sensing the orientation of a passive RFID tag, based on the characteristics of the tag reply. The orientation of a tag can be decomposed into the inclination (or elevation) angle and the azimuth angle, and this paper focuses on the elevation angle. It is proposed to exploit the fact that often UHF tag antennas are a variant of meander dipole with linear polarization, and information of the tag inclination can thus be extracted by estimating the polarization angle. Even though focus in this paper is the inclination angle, a rotation around the azimuth still introduces an polarization mismatch to be accounted for, hence three reader antennas are distributed around the desired interrogation zone to provide a better statistical certainty of the estimated inclination. To extract the polarization angle the paper utilizes dual linearly polarized antennas, which
Contributions In This Thesis

basically refers to two co-located linearly polarized antenna elements, oriented orthogonally with respect to each other. In this way the RSS in the tag response is decomposed into two orthogonal polarizations, i.e. an RSS vector from which the polarization angle seen from a given antenna can be reconstructed. The RSS samples collected from all three antennas are fused into a single estimate of the inclination angle using a Bayesian estimator. The proposed method is evaluated experimentally in a lab environment using artificial tags, i.e. small transmitters with a dipole antenna, and objects of different materials.

Main Results

The proposed method shows robust in estimating the inclination of the tag, regardless of its azimuth angle. The certainty of the estimate vary with the material of the object, and this is expected as it affects the performance of the tag antenna. However, the utilized Bayesian estimator has some undesired constraints. Basically it is comprised of the likelihood and prior probability distributions of the RSS metric, and the most suited likelihood distribution depends highly on the given environment. The prior knowledge of the RSS is collected experimentally, introducing a significant requirement for calibration with respect to the surrounding environment and object material.
2.2 Orientation Sensing

2.2.2 Paper 4

Orientation Sensing Using Multiple Passive RFID Tags

Rasmus Krigslund, Petar Popovski and Gert F. Pedersen
Published in IEEE Antennas and Wireless Propagation Letters.

Motivation

The main drawback of the method proposed in Paper 3 was the requirement for calibration of the prior knowledge in order to estimate the inclination. In this paper it is desired to estimate the inclination directly from the tag reply, without taking prior knowledge about the object and the environment into account.

Paper Content

The paper suggests to estimate the inclination directly from the tag reply decomposed into the horizontal and vertical dimensions by the same dual linearly polarized antenna as utilized in Paper 3. It is expected that removing the requirement for calibration comes at the price of precision. Hence this paper proposes to utilize multiple tags per object in order to have multiple samples in space and time from the tagged object, in this case two orthogonal tags are utilized. The inclination is then estimated using a simple statistical estimator combining the multiple RSS samples from the two tags. The estimation is complicated by the RSS being positive per definition. This means that all inclination angles obtained from the two dimensional RSS vectors are mapped to the first quadrant. To maintain the angular relationship between the two tags, the samples from the second tag are artificially mapped to the second quadrant. This effectively reduces the possible range for the inclination to 90°, and inclinations outside this range are estimated with a large error.

Main Results

The measurements shows that with a single tag the proposed method is able to estimate the inclination with a precision of ±25°. This precision improves to ±7° when information from two tags are combined, which confirms the applicability of fusing multiple RSS samples into the inclination estimate. The experimental evaluation showed however, that in order to achieve this precision certain requirements had to be met: First of all, the range of the inclination is limited to span only 90°, due to the mapping to the first quadrant. Moreover, the direction from which the reader antenna observes the
tags should be perpendicular to the plane spanned by the two orthogonal RFID tags. This is expected, since, if this is not the case, the angle of the individual tags and the angle between them will appear different seen from the perspective of the reader antenna.
2.2.3 Paper 5

A Novel Technology for Motion Capture Using Passive UHF RFID Tags
Rasmus Krigslund, Strahinja Dosen, Petar Popovski, Jakob L. Dideriksen, Gert F. Pedersen and Dario Farina
Accepted in June 2012 for publication in IEEE Transactions on Biomedical Engineering.

Motivation
The concepts from Paper 3 and Paper 4 are continued in this paper, taking into account the experiences obtained so far. Where the previous papers have considered a static setup this paper utilizes the proposed method for estimating the tag inclination in a dynamic setup. As described in Section 1.3, orientation sensing is very related to motion capture, and in this paper the dynamics are provided by human body motion as the proposed method is utilized to estimate, and track, the angle of the leg segments, thigh and shank, each fitted with a standard UHF passive RFID tag.

Paper Content
The proposed methods ability to track the angle of the thigh and shank is tested while the test subject is walking on a treadmill. The current state of the art for motion capture, an optoelectronic system with infrared cameras, is used as reference. The motion of the two tags is confined to two dimensions, referred to as the sagittal plane.

Main Results
Due to the known issue of all RSS vectors being mapped to the first quadrant, the results requires some post-processing before they are comparable with the reference system. Since the true angles of both thigh and shank are varying around the vertical axis, the mapping to the first quadrant is accounted for by introducing a simple angular offset. The resulting trace of the angles showed a crude approximation of the angles obtained by the reference system. This was mainly due to the 1 dBm resolution of the RSS metric returned by the reader. This truncation of the RSS can be regarded as high frequency noise and filtered out by interpolating the RSS samples and passing the estimated angles through a simple low-pass filter. Comparing the filtered angles with the reference system shows a mean absolute error of $7^\circ$. This precision is
Contributions In This Thesis

clearly much lower than the optoelectronic system, but sufficient for some applications in the medical field, e.g. electrical stimulation.
2.2 Orientation Sensing

2.2.4 Paper 6

Experimental Assessment of 3D Gesture Recognition Using Passive RFID Tags

Rasmus Krigslund, Petar Popovski and Gert F. Pedersen
Submitted in June 2012 to IEEE Transactions on Industrial Electronics.

Motivation

After the positive results in Paper 5, where the proposed method is successfully capturing the motion of two tags in two dimensions, it is interesting to investigate the potential for capturing motion in three dimensions (3D). In this paper this is investigated in the context of gesture recognition, i.e. recognizing predefined motions performed with a tag or object in 3D. The mapping of all RSS vectors to the first quadrant of the antenna coordinate space is expected to affect the precision. Hence, it is proposed to use multiple reader antennas, and it is desired to investigate whether the fusion of these data can aid the estimation and to some extent compensate for the ambiguity introduced by the mapping of the RSS vectors.

Paper Content

The proposed method is extended to comprise three dual linearly polarized antennas distributed around the interrogation zone, in order to interrogate the tag from multiple directions. Their samples are then fused via a Kalman filter into an estimate of the tags three dimensional orientation vector, i.e. the method for fusing data differs significantly from the one utilized in Paper 3. The measurements investigates the ability to recognize and distinguish between simple gestures, by estimating, and tracking, the three dimensional orientation of the tag.

Main Results

The results are positive, as the proposed method, based on relatively simple data processing and metrics, enables differentiation of certain gestures performed with the RFID tag. The precision of the estimated orientation is too low to do motion capture in 3D. But from the results it appears that the proposed method is applicable for doing relative motion capture, i.e. determining whether a tags orientation has changed since last time the tag was interrogated. The results thus show that the orientation information is available and can be extracted from the physical characteristic of the tag reply, given a more suited method for data processing.
Contributions In This Thesis
The results obtained throughout the contributions for the two objectives in this thesis, i.e. using interference constructively and enable orientation sensing, are discussed in this chapter. The link between the results are described, along with their perspective and consequences.

3.1 Constructive Interference

Using interference constructively has been investigated experimentally in order to reduce False Negative Detections (FNDs) and False Positive Detections (FPDs), and thereby obtain sharply bounded interrogation zones. In Paper 1 the blocking capabilities of interference are investigated, and the difference between using Co-Channel Interference (CCI) and Adjacent-Channel Interference (ACI) is exposed. In general these initial measurements shows good potential, but even though the utilized setup provides a controlled environment, it has certain limitations and drawbacks. Hence the more detailed investigation in Paper 2 is required in order to determine whether interference can be used constructively to design well defined interrogation zones.

As expected Papers 1 and 2 show how CCI is the most harmful interference type, but investigations show how the sharpest bound is achieved with ACI. For an Radio Frequency IDentification (RFID) tag to be able to reply to the reader it must receive sufficient power from the readers interrogation signal and the Signal to Interference and Noise Ratio (SINR) must be high enough for the tag to decode the reader commands. A detuned tag con-
Discussion

tributes to the probability of FND, as the mismatched antenna has reduced capabilities in harvesting power from the reader signal. This is the case for both the interrogation signal and the interference signal, hence the Signal to Interference Ratio (SIR) is the same regardless of the level of detuning a tag is experiencing. In Paper 2 it is shown how the power harvested by the tag is the primary limitation of the read range in the absence of interference. But when imposing interference the SINR, or SIR, becomes the limiting factor, and since tuned and detuned tags experience approximately the same SIR their read ranges are equalized. It should be noted that the investigations in Paper 2 show no indication that the interference is acting as an additional power source and helps powering up detuned tags. On the contrary, the interference reduces the read range of both tuned and detuned tags. This range can then be controlled by adjusting the level of interference power, and with the SINR as the limiting factor the power and SINR requirements are fulfilled for both tuned and detuned tags within the resulting read range. Hence the combination of interrogation and interference power levels allows for the design of well defined interrogation zones bounded with a sharp edge, inside which a tag is identified with high probability regardless of the level of detuning it is experiencing.

3.2 Orientation Sensing

The ability to sense the orientation of passive Ultra High Frequency (UHF) RFID tags using only the received Received Signal Strength (RSS) has been investigated experimentally in this thesis. Initially it is investigated whether anything can be inferred about the orientation, form the polarization mismatch of the tag reply, hence Paper 3 considers only the inclination angle estimated with a Bayesian estimator, and relies on artificial RFID equipment. During the autumn 2010, the idea is successfully extended to consider both inclination and azimuth, and ported to commercial RFID equipment, as a part of a student project [21]. However, the main limitation with this initial idea remains the requirement for calibration, due to the required knowledge of the channel and the assumed channel model of the RSS distribution. In this way the initial idea is subject to the same issues regarding the changing environment and objects as the localization methods that originally was the motivation for considering orientation sensing. By relying directly on the RSS components, the dependency on channel models and the requirement for calibration are removed, but at the price of precision as the environmental effects remain present. In Paper 4 it is shown how precision can be improved by combining the collected RSS vectors from multiple tags. But the paper
also reveals the greatest challenge when estimating the orientation based on polarization information, namely that all RSS samples are positive and all RSS vectors are thus mapped to the first quadrant. This mapping introduces an ambiguity about the tag inclination observed from a given direction. The absolute ratio between the vertical and horizontal RSS components match, and due to the symmetric radiation of the tag dipole antenna it is not possible to distinguish between a ±180° rotation, hence the ambiguity is whether the inclination angle is positive or negative. This means that the span in which the tag inclination can be estimated reliably is effectively reduced to a single quadrant, i.e. 90°, and inclinations outside this range are estimated with a large error. Being aware of these limitations of the proposed method, Paper 5 presents measurements in a real life application where the method is utilized for capturing the motion of the thigh and shank during walking, i.e. capturing two dimensional motions in the sagittal plane. The obtained precision is sufficiently high for specific applications within the medical field, e.g. rehabilitation and electronic stimulation, albeit lower than what can be achieved with the current state of the art equipment.

The ambiguity and limitations introduced by the mapping to the first quadrant has a significant effect on the final orientation estimate. Hence in Paper 6 it is desired to cope with this effect in order to enable recognition of gestures and orientation sensing in three dimensions, and thus allow for an angular change of more than 90°. It should be noted that a gesture refers to a predefined motion performed with the RFID tag or object. The experimental investigations utilize multiple reader antennas and fuse the collected data with a Kalman filter. This is a relative simple method for data processing, albeit the proposed method shows able to recognize and differentiate between simple gestures. However, when estimating the actual orientation of the tag, the simple data processing affects the precision significantly, and it is not feasible to do motion capture in 3D. Alternatively, the proposed method can be used for detecting relative motion, i.e. determine whether the orientation of an object has changed since last time the tag was interrogated.

Moreover, the proposed method, based on the polarization of the received signal, is not confined to the RFID technology. It can basically be ported to any technology where linearly polarized antennas can be applied, e.g. Bluetooth or WiFi. Such devices do not support passive operation though, and with an internal power source it can be argued that sensors like accelerometers and Inertial Measuring Units (IMUs) are more suited. However, the proposed method can then act as a supplement, as accelerometers are prone to errors from e.g. integration drift and collision accelerations.
Discussion
The objective in this thesis was twofold: 1) To improve logical localization of Radio Frequency IDentification (RFID) systems by removing the ambiguity of tag readings. This was achieved by reducing the occurrence of False Negative Detections (FNDs), where tags inside the desired interrogation zone are unable to reply to the requests from the reader, and False Positive Detections (FPDs), where tags outside the desired zone are able to reply to the reader. 2) To enable the use of passive RFID tags as orientation sensors, which is considered a novel application of passive tags which can potentially improve the precision of localization methods relying on the Received Signal Strength (RSS) in the tag reply. These objectives have been investigated experimentally, and in this chapter the final conclusions are drawn and interesting areas for future work are identified.

To reduce the occurrence of FNDs and FPDs it was proposed to impose interference on the communication between reader and tag. This is a novel idea that utilizes interference constructively, and works to decrease both these effects simultaneously. The idea was evaluated with respect to read range, rather than a two dimensional interrogation zone, and functioned as expected. By imposing interference onto the communication between reader and tag, the Signal to Interference and Noise Ratio (SINR) became the limiting factor of the read range. Hence by adjusting the interrogation and interference power levels the probability of FNDs and FPDs was decreased. It can therefore be concluded that the proposed method helps improving the logical localization of tags.

The main topic in this thesis have been to enable orientation sensing in
Conclusion

passive RFID systems. The proposed method extracted orientation information from the polarization of the signal in the received tag reply. This was achieved using multiple dual linearly polarized reader antennas which decomposed the RSS from the tag into two dimensional RSS vectors. In this way the method could be utilized together with standard passive RFID tags. The simplicity however, of the proposed method introduced certain limitations to the orientation estimate. The non-linearity of the polarization mismatch between the orthogonal elements of the reader antennas and the tag antenna contributed to the error in the resulting orientation estimate. However, the most significant limitation was the mapping of all RSS vectors to the first quadrant of the coordinate spaces of the reader antennas. The utilized data processing was unable to properly cope with this mapping, at the price of an imprecise orientation estimate. Albeit, the proposed method showed able to recognize, and differentiate between, simple gestures, and identify in which plane the gesture was being performed. However the precision of the orientation estimate was too low to offer motion capture and tracking of the tag. The main conclusion is therefore, that the orientation information is available in the physical signals in the tag reply, but from the experimental investigations conducted in this thesis, it can be concluded that more advanced methods for signal and data processing is required in order to unlock the true potential of orientation sensing with passive RFID tags. Moreover, the proposed method is not specific to the RFID technology, and can thus be ported to other wireless technologies like for example Bluetooth or WiFi devices.

In this thesis there has been an emphasis on experimental investigations and practical evaluation of the proposed methods. It will therefore be interesting for future work to develop the analytical aspects of the proposed method and incorporate more sophisticated methods for processing the data collected by the RFID system. Most importantly a method for resolving the problem of all RSS vectors being mapped to the first quadrant of the reader antennas coordinate systems, as this is considered the most significant source of error in the proposed method. It may be possible to make inferences about the correct quadrant of the RSS vector by utilizing algorithms from the field of machine learning and the combined information collected from the tag from diverse directions using multiple reader antennas. Solving the mapping issue would bring the orientation sensing capabilities using passive RFID tags much closer to real motion capture in three dimensions.
References


REFERENCES


REFERENCES


List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACI</td>
<td>Adjacent-Channel Interference</td>
<td>19</td>
</tr>
<tr>
<td>APNet</td>
<td>Antennas, Propagation and Radio Networking</td>
<td>xi</td>
</tr>
<tr>
<td>AOA</td>
<td>Angle Of Arrival</td>
<td>3</td>
</tr>
<tr>
<td>CCI</td>
<td>Co-Channel Interference</td>
<td>19</td>
</tr>
<tr>
<td>DOA</td>
<td>Direction Of Arrival</td>
<td>3</td>
</tr>
<tr>
<td>FND</td>
<td>False Negative Detection</td>
<td>23</td>
</tr>
<tr>
<td>FPD</td>
<td>False Positive Detection</td>
<td>23</td>
</tr>
<tr>
<td>HF</td>
<td>High Frequency</td>
<td>2</td>
</tr>
<tr>
<td>IMU</td>
<td>Inertial Measuring Unit</td>
<td>21</td>
</tr>
<tr>
<td>LOS</td>
<td>Line Of Sight</td>
<td>1</td>
</tr>
<tr>
<td>NLOS</td>
<td>Non Line Of Sight</td>
<td>3</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
<td>3</td>
</tr>
<tr>
<td>RFID</td>
<td>Radio Frequency IDentification</td>
<td>23</td>
</tr>
<tr>
<td>RSS</td>
<td>Received Signal Strength</td>
<td>23</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal to Interference and Noise Ratio</td>
<td>23</td>
</tr>
<tr>
<td>SIR</td>
<td>Signal to Interference Ratio</td>
<td>20</td>
</tr>
<tr>
<td>TOA</td>
<td>Time Of Arrival</td>
<td>3</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra High Frequency</td>
<td>20</td>
</tr>
<tr>
<td>UWB</td>
<td>Ultra Wide Band</td>
<td>3</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
<td>2</td>
</tr>
</tbody>
</table>
List of Abbreviations
## Contributions Included In This Thesis

### Contents

<table>
<thead>
<tr>
<th>Paper</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Measuring the Interference at an RFID Tag: Where Does It Have an Impact?</td>
<td>33</td>
</tr>
<tr>
<td>2</td>
<td>Interference Helps to Equalize the Read Range and Reduce False Positives of Passive RFID Tags</td>
<td>43</td>
</tr>
<tr>
<td>3</td>
<td>Potential of RFID Systems to Detect Object Orientation</td>
<td>55</td>
</tr>
<tr>
<td>4</td>
<td>Orientation Sensing Using Multiple Passive RFID Tags</td>
<td>61</td>
</tr>
<tr>
<td>5</td>
<td>A Novel Technology for Motion Capture Using Passive UHF RFID Tags</td>
<td>67</td>
</tr>
<tr>
<td>6</td>
<td>Experimental Assessment of 3D Gesture Recognition Using Passive RFID Tags</td>
<td>73</td>
</tr>
</tbody>
</table>
Paper 1

Measuring the Interference at an RFID Tag: Where Does It Have an Impact?

Rasmus Krigslund, Petar Popovski, Gert F. Pedersen, and Kim Olesen

Measuring the Interference at an RFID Tag: Where Does It Have an Impact?

Rasmus Krigslund, Petar Popovski, Gert F. Pedersen and Kim Olesen
Aalborg University, Department of Electronic Systems, E-mail: {rkr, petarp, gfp, ko}@es.aau.dk

Abstract—In this paper we consider reader collisions in an Radio Frequency IDentification (RFID) system, especially how interference impacts the ability of a passive UHF tag to respond. We propose two innovative applications for using interference: 1) Blocking a tag response, and 2) cooperative reading of a tag. In order to investigate their applicability we focus on the experimental evaluation, where we impose interference on the download and uplink, respectively, and on both links simultaneously. The results are positive with respect to blocking the tag, where modulated Co-Channel Interference (CCI) shows most effective. Based on the measurements it is however not possible to read a tag cooperatively, i.e. the tag is unable to utilize the interference as an additional energy source.

I. INTRODUCTION

Today’s Radio Frequency IDentification (RFID) is primarily utilized as a tool for identification in supply chain management services. But in recent years the RFID technology has received great attention, [1], as RFID has the potential of becoming ubiquitous, and it is therefore considered a key technology for pervasive networks and services [2]. Such widespread use of RFID systems to provide accurate identification of all tagged objects, requires a dense deployment of RFID readers, introducing collisions as the readers interfere with each other.

The read range of a reader is significantly shorter than the interference range. Hence, when considering reader collisions they cover two different collisions: 1) Reader-tag collision, where a tag is located within the read range of multiple readers. The reader signals interfere with each other, making it challenging for the tag to decode as much as just a single reader request, not impossible though. 2) Reader-reader collision, where a reader signal interferes with the reception of a tag response at an adjacent reader. This can occur when readers are sufficiently spaced so their interrogation zones do not overlap, but their interference range reach into interrogation zones of adjacent readers. The EPC Global C1 Gen 2 standard [3] implements a dense-reader-mode, allowing densely deployed readers to operate simultaneously in separate frequency bands. Modern readers then implements filters that can separate frequency bands and thereby filter out the main part of the interference. However, tags do not have this option, and are thus forced to cope with the interfered signal.

In this paper we investigate the impact of reader collisions under different types of interference in order to map in which conditions a tag can be read. Basically the communication between reader and tag can be interfered in the following transmission periods:

a) The reader-to-tag commands

b) The tag-to-reader reply

c) During both periods

The reader and tag represents two different levels of complexity, and is therefore expected to have different susceptibility to interference. Hence, in this paper we consider each of the periods above separately, and investigate the impact of interference on the tags readability.

As an example consider Fig. 1, a scenario with two readers, \( R_1 \) and \( R_2 \), and two tags, \( T_1 \) and \( T_2 \), with the transmissions a) and b) illustrated by arrows. The probability of reading a tag decreases with the distance between reader and tag. In Fig. 1 the tags are located on the edge of the interrogation zones, and will therefore be read with decreased probability. Outside the zones a tag may still be read, but with low probability. The readers operation causes mutual interference, hence they are deployed with a certain separation, often referred to as the buffer zone. By clarifying the impact of a), b) and c) we enable a constructive utilization, in contrast to the normal destructive perception, of interference. We thus propose two innovative applications for using interference constructively in an RFID system:

1) Blocking a tag response, i.e. preventing tags from sending replies. This can be used to block tags for security purposes, or mitigate the problem of false positives. In Fig. 1, this means that by letting \( R_2 \) interfere the operation of \( R_1 \), we can prevent \( T_2 \) in responding to \( R_1 \) and cause a false positive reading, which again enables a closer deployment of readers and their interrogation zones.

2) Foster cooperative reading of tags. While interference is harmful for reception, it can be seen as an additional RF power available to be harvested by the tag and thus help the tag to get its response through. This means that the interference from \( R_2 \) helps energizing \( T_1 \), so it with high probability can respond to \( R_1 \), i.e. the range of \( R_1 \) is effectively increased due to the interference from \( R_2 \).
Fig. 2. Signal flow diagram of the setup used in this work.

Immense work have been published in the area of reader collision already, proposing different methods to utilize the dense-reader-mode and optimize for low probability of reader collision. In [4], [5] the problem of reader collision is thoroughly described and existing methods to cope with this problem are surveyed. An example is [6], where reader collisions are described as a graph coloring problem, in order to derive a suited reuse distance between the frequency channels in RFID dense-reader-mode. Alternatively [7] suggests using an algorithm similar to the Q-algorithm, from the Gen 2 standard, as MAC protocol for the network of readers. Most recently [8], [9] presents schemes to dynamically adapt modulation depth and transmission power, respectively, to avoid reader collisions. Moreover, in [10], [11] it has been investigated what level of interference will cause a tag not be identified by the reader.

The approaches above presents intelligent methods to avoid reader collision in general, not differing between reader-reader collision and reader-tag collision. This paper considers both collision types separately. Moreover, we present the experimental investigation of the applicability of using interference to enable blocking of passive tags and cooperatively power up and read the tags.

The remainder of this paper is structured as follows; In section II the system model and the experimental setup are described. The obtained results are presented in section III and in section IV the results are discussed and final conclusions are drawn.

II. SYSTEM MODEL AND EXPERIMENTAL SETUP

In this work we are considering a scenario where multiple readers are deployed to cover the entire space. Note that the term reader refers to the apparatus that can read tags in its proximity, i.e. in practice, this can refer to an RFID reader including an antenna, or just an antenna attached to a reader located elsewhere. We define an interrogation zone as the area around the reader where a tag is read with high probability (> 99 %).

To investigate the impact of interference in this scenario we have constructed a setup, where distances are introduced artificially using signal attenuators. In Fig. 2 this setup is illustrated with a signal flowchart.

The reader and interference signals are denoted \( s_r \) and \( s_i \) respectively, and the blocks labeled \( A \) and \( B \) are adjustable attenuators. It should be noted, experiments have shown that due to a lossy wireless coupling to the tag, the reader is unable to read the tag if \( A \) attenuates the signal more than 12 dB. Using \( A \) and \( B \) the signal range, or the theoretical distance, can be adjusted from the interrogating and interfering reader to the tag, respectively. The utilized interrogation power is 30 dBm, which is the maximum power allowed in Europe. But due to connectors and cables in the signal path, we have a fixed attenuation of 2.5 dBm, and the combining element has an internal attenuation of 6 dB. This means that the maximum power delivered by either the interrogating or the interfering reader is 21.5 dBm. The resulting Signal to Interference Ratio (SIR) is then given by the difference between \( A \) and \( B \):

\[
SIR = B - A \quad \text{[dB]}
\]

Basically the interferer could represent any nearby source using the Ultra High Frequency (UHF) band, but in this work we focus on densely deployed RFID systems, where the interference will come from an adjacent reader. An interfering reader shifts between transmitting commands, using an amplitude modulated carrier wave, and listening for tag responses while continuously transmitting the unmodulated carrier wave to energize tags. To investigate both situations \( s_i \), then needs to be modeled with and without amplitude modulation.

The dense-reader-mode specified in the EPC Global Gen2 standard [3], enable readers to use four different frequency bands, in order to decrease the interference between them. Moreover, the tags uses two sub-carriers, so their response lies in the side bands to the readers carrier frequency, as this helps the reader to filter out adjacent and co-channel interference. Hence to represent an RFID system in dense-reader-mode, \( s_i \) should have center frequencies corresponding to the different channels in the available frequency band.

The reader available in this work, an Intermec IF5, does not support the dense-reader-mode. Tags will therefore respond using the same carrier frequency as the interrogating reader, making Co-Channel Interference (CCI) particularly harmful in this setup. However, this does not mean that the experimental results obtained in this work cannot be compared to RFID systems operating in dense-reader-mode. Imposing Adjacent-Channel Interference (ACI), whether dense or single reader mode is utilized, will have similar effect on both a tags ability to correctly receive the reader commands and a readers ability to receive the tag response. Only CCI is different, as in this work the interrogating reader will share the band with both interference and the tag.

A. Notation

To ease descriptions and explanations we introduce the following notation when addressing events:

<table>
<thead>
<tr>
<th>Event</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T )</td>
<td>Tag received Query from reader</td>
</tr>
<tr>
<td>( R )</td>
<td>Reader received tag response successfully</td>
</tr>
<tr>
<td>( I_{R} )</td>
<td>Interference imposed during Query from the reader</td>
</tr>
<tr>
<td>( I_{T} )</td>
<td>Interference imposed during tag response</td>
</tr>
<tr>
<td>( Z )</td>
<td>The tag is located inside the interrogation round</td>
</tr>
</tbody>
</table>

TABLE I

SPECIFICATION OF EVENTS IN THE EXPERIMENTS.
A. Reader-Tag Collision

When investigating collisions at the tag, we are interested in the ability to receive and interpret the reader commands under interference. It is complex in practice to sniff the reception directly on the tag, since a connected probe would change the reception parameters of the tag significantly. Instead we utilize that a tag requires to successfully receive the Preamble + Select + Query commands [3] in order to respond. In this experimental setup it is therefore only required to switch on the interferer during the initiation of the interrogation round, leaving the tag response undistorted. Given that the uplink channel from tag to reader is error less, any failed readings can be ascribed to the tags ability to receive the reader commands. This requires the tag to be located inside the interrogation zone, in a distance where a good read rate, > 99%, can be maintained. The events from Table I can be used to summarize the setup:

\[ I_B: \] Interference imposed during Query from the reader
\[ T_T: \] Interference switched off during tag response
\[ Z: \] The tag is located inside the interrogation round

Given that \( P(R|T, T_T, Z) \approx 1 \), the probability that the tag successfully receives the reader commands can be written as \( P(R|I_B, T_T, Z) \).

For ACI a frequency distance of one and two channel widths have been utilized. In this way the importance of frequency separation to the tag and to the reader, respectively, will be evident from the measurements. To have the tag located inside the interrogation zone we use the attenuation \( A = 4 \, \text{dB} \). This attenuation has been experimentally identified, and is relatively low due to a loss in the coupling element in the shielded box, see Fig. 3(c), of approximately 20 dB.

The interference power is then stepwise increased by decreasing the attenuation \( B \). For each SIR value, the reader initiates \( n \) interrogation rounds with a frame size of 1, and based on the number of successful responses the response probability, \( P(R|I_B, T_T, Z) \), is calculated. The required size of \( n \), for the response probability to be statistically significant is investigated in appendix A. Table II summarizes the parameters used in this setup, and in Fig. 4 the resulting \( P(R|I_B, T_T, Z) \) is plotted as a function of SIR. From the plots we see that in general a high SIR is required to maintain a good response rate, and that CCI provides both the best and the worst tag performance. The former is surprising since CCI was expected to be the most harmful type of interference. The

III. Results

To investigate the susceptibility of an RFID system to interference, we have constructed an experimental setup based on the flow chart from Fig. 2. An elaborate flow chart is described in appendix B. Pictures of the resulting setup is shown in Fig. 3, where the tag is placed inside a shielded box, see Fig. 3(c), to shield the tag from multi-path effects in the lab.

We will investigate both the reader-tag and the reader-reader collisions respectively, and the measurement procedures are presented in the following along with the results for each collision type.

### Table II

| Samples (n) | 500 |
| Reader: | Intermec IF5 |
| Reader carrier wave (f_c): | 866.5 MHz |
| ACI #1 (f_c1): | 867 MHz |
| ACI #2 (f_c2): | 867.5 MHz |
| Tag: | Alien, ALN9640 (Passive, UHF) |
| Tag cardinality: | 1 |

© 2011 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works. DOI: 10.1109/RFID-TA.2011.6068648
The response probability of a tag when reader commands are subject to interference, both Co-Channel Interference (CCI) and Adjacent-Channel Interference (ACI).

An example of a 866.5 MHz carrier wave modulated with a square wave plus interference, where amplitude is plotted as function of bit times. The interference has a small difference in phase and a frequency difference of 0 Hz in Fig. 5(a), 1 Hz in Fig. 5(b) and 8 kHz in Fig. 5(c).

An explanation to why unmodulated CCI is less harmful may be that it mainly contribute with a decrease in modulation index, hence unmodulated CCI might help energize the tag.

During the measurements for CCI, with \( f_c = 866.5 \text{ MHz} \), we experienced an unmotivated dip in response probability at an SIR of \( 8 - 20 \text{ dB} \). It was observed that increasing \( f_c \) to 866.508 MHz did not give the same dip in performance. This is due to the unsynchronized operation of the reader and interferer, where a small difference in carrier frequency, \( \Delta f_c \), can occur. This difference causes the resulting amplitude of the interfered signal to vary according to \( \Delta f_c \), as illustrated in Fig. 5. In Fig. 5(a) where \( \Delta f_c = 0 \text{ Hz} \), the AM modulation is relatively simple to deduce from the resulting signal. The same is the case when \( \Delta f_c \) is high, see Fig. 5(c), as the interference just causes a fast ripple on the levels in the AM modulated reader signal. However, if \( \Delta f_c \) is only a few Hz, Fig. 5(b), the periods in amplitude variation are similar to the length of a symbol transmitted from the reader. In this case it becomes difficult to determine the high and low levels of the AM modulation, which significantly decreases the probability of decoding the reader commands at the tag.

It was expected that a modulated interferer would have a greater impact on the tag than an unmodulated. However, if we consider a response rate of 99 \%, we see a difference of \( \approx 10 \text{ dB} \) between modulated CCI and modulated ACI #1. Since the tag does not come with any internal frequency filtering this is a quite unexpected result. The utilized tag is targeted for global use, and operational in the frequency band from 860 – 960 MHz covering both the American, European and Asian bands for UHF RFID. Hence, the tag is expected to have constant performance in the relative small frequency band utilized in these experiments. Instead the explanation to the 10 dB difference is considered to be the frequency difference, \( \Delta f_c \). Modulated interference has, as expected, the most significant impact on the tags ability to respond, but as the frequency distance between the reader and interferer signals increase, the interference has less impact. In this way interference from adjacent channels introduces a fast ripple of the reader signal, as illustrated in Fig. 5(c), where the modulation introduces a small, but constant, impairment of the tags ability to respond.

From this measurement, the main result that can be concluded is that by imposing interference, it is possible to keep a tag, that otherwise would respond, from responding.

B. Reader-Reader Collision

The collisions at the reader are investigated by repeating the experiment for reader-tag collision, but where the interference is absent in the initiation of the interrogation round, and instead present while the tag responds. The tag is assumed to remain inside the interrogation zone, \( A = 4 \text{ dB} \). In this way the tag will successfully receive the reader commands, and the interference made to the incoming tag response can be isolated as the only source for rendering the reader unable to receive the tag response. This setup can be summarized by the following events:

\[
\begin{align*}
T_{IR} & : \text{Interference switched off during Query from the reader} \\
I_T & : \text{Interference imposed during tag response} \\
Z & : \text{The tag is located inside the interrogation round}
\end{align*}
\]

The probability of the tag successfully receives the reader commands is then denoted \( P(R|T_{IR}, I_T, Z) \), and is plotted in Fig. 6 with solid lines, as a function of the SIR. Note that the dashed lines in Fig. 6 are the probability of the tag responding under interference, \( P(R|I_{IR}, T_{IR}, Z) \), repeated from Fig. 4 for comparison. Considering only the plots for reader-reader collision, we see that the ACI leaves the system in much better conditions to receive the tag reply, as expected. In all examples there is a very small but constant difference between modulated and unmodulated interference, where the modulated interference is most harmful. The plots of \( P(R|T_{IR}, I_T, Z) \)
under CCI and under ACI ≠ 1 are horizontally shifted approximately 25 dB. This means that a 25 dB better signal is required in case of CCI. At the reader side it is possible to improve the reception capabilities by increasing the receiver complexity, hence this great performance difference is unexpected. For a reader supporting dense-reader-mode however, we would expect a better performance under CCI, as the tag replies in the side bands.

If we compare the read probabilities for reader-tag and reader-reader collisions, we see that for ACI they require approximately the same SIR conditions to maintain a high read rate. The small difference partly represents the imprecision in the measurements and partly the probability of the reader being unable to decode the tag reply.

Under CCI we see a significant difference between reader-reader and reader-tag collisions. The tag is able to reply under an interference level around 15 dB higher than the SIR level a reader is able to receive the reply in. Here we see the effect of the channel filters in the reader, because, for CCI, the reader is unable to filter out the interference, hence the tag response disappears in the interference. It does not matter whether the interferer is unmodulated, since the two carriers are not synchronized. However, for unmodulated CCI the tag is able to respond even with very low SIR. This could indicate that with unmodulated CCI it is possible to help power up the tag, and in this case increase the communication range between reader and tag.

C. Continuous Interference

Finally the collision experiment is repeated using a continuous interferer, where interference is transmitted during the entire interrogation round:

$I_R$: Interference switched off during Query from the reader
$I_T$: Interference imposed during tag response
$Z$: The tag is located inside the interrogation round

In Fig. 7 the measured $P(R|I_R, I_T, Z)$ is plotted, as a function of the SIR. $P(R|I_R, I_T, Z)$ represents the performance when both reader-tag and reader-reader collisions are taken into account. If we compare $P(R|I_R, I_T, Z)$ and $P(R|I_R, I_T, Z)$, from Fig. 7 and 6 respectively, the performance under ACI is similar, but under CCI the resulting performance is limited by the readers ability to extract the tag response from the interfered signal. This is a special case, as the utilized reader is not operating in dense-reader-mode. These results are therefore not representative to the performance under CCI in dense-reader-mode, where the tags replies using sub-carriers enabling a reader to filter out a co-channel interferer.

D. Interference As Power Source

It is desired to test whether interference, in form of an unmodulated carrier wave, from an adjacent reader can aid the communication between reader and tag. To realize this, we consider the case where a tag is located in the intermediate zone between two readers, the buffer zone, where a reader has low probability of reading the tag. We choose $A = 8$ dB where $P(R|I_R, I_T, Z) = 31 \%$. From Fig. 4 and 6 we saw that the ability to read a tag changes from $≈ 1$ to $0$ in a matter of a few dB SIR. With $P(R|I_R, I_T, Z) = 31 \%$ we are therefore focusing on a point on that very steep flank. This means that small changes in the read conditions may cause large changes in read probability. To mitigate this effect we increase the number of samples, $n$, to 1000.

Passive tags requires a carrier wave to constantly beam power to them in order to operate. The unmodulated interference is therefore continuous in the entire interrogation round. It should be noted that in this experiment the interference is not synchronized to the carrier wave from the reader. The resulting $P(R|I_R, I_T, Z)$ is measured for gradually increasing interference power, and plotted in Fig. 8. The dashed line indicates the reading probability when the interferer is switched off. For both CCI and ACI the read probability is fluctuating significantly, even though $n$ is increased, and none exceeds the probability when interference is absent. It is therefore evident, that in this setup, it is not possible to cooperatively energize
a tag. Being unsynchronized the reader and interferer signals collide at random. If it had been possible to synchronize the signals and hereby forcing them to interfere constructively at the tag we might have seen different results. Moreover, a steep decrease in \( P(R|I_R, I_T, Z) \) is visible around SIRs similar to those shown in Fig. 7, since at this interference power, the reader is unable to separate the signals.

IV. DISCUSSION AND CONCLUSION

Interference is traditionally considered a limiting constraint with destructive impact on performance. In this paper we consider interference in Radio Frequency IDentification (RFID) systems, where we investigate its impact, and whether interference has some constructive applications. In particular two applications are considered; 1) Blocking of tag responses, so tags located in a certain area will not respond to an interrogating reader, and 2) Cooperative reading of tags, where interference helps an interrogating reader to energize tags, allowing them to respond.

The experimental results show that by imposing interference on the communication between tag and reader, we can abstain a tag from responding. This is in line with the general perception, seeing interference as a limitation. To keep the tag from receiving the reader commands the type of interference showed important. Using modulated interference in the same channel as the reader requires the least interference power to block the tag. This is preferable as low interference power also keeps the interference towards adjacent readers low. The ability to block a tag effectively makes the probability of a tag responding decrease faster with distance to the reader. This gives a sharper separation between adjacent interrogation zones and reduces the probability of false positive readings of tags, located in the buffer zone between interrogation zones, or in an adjacent zone. Alternatively, it enables a closer deployment of interrogation zones maintaining the same probability of false positive readings.

Using interference to help energize a tag showed however ineffective. From our experiments we saw no indication that interference, in the form of an unmodulated carrier wave, could improve the probability of reading a tag located in the buffer zone. However, using interference synchronized to the readers carrier wave may prove more effective.

It can therefore be concluded that in the utilized setup the interference solely have a limiting impact on the probability of reading tags in RFID systems. An innovative use of this effect, where tag responses are intentionally blocked, is proposed in this paper. In future works we plan to investigate in greater details the potential of blocking tags, with the intention of reducing false positive readings.

APPENDIX A

CHOOSING THE NUMBER OF SAMPLES

The number of samples used to calculate the probability of a tag responding should be chosen such that the response probability is statistically significant. As an example three measurements of modulated CCI have been made, with \( n = 1000 \) samples and SIR of 20 dB, 31 dB and 37 dB, respectively. In Fig. 9 the results are plotted as binary values: 1 if the tag were read, and 0 otherwise. Tests for randomness using Matlab showed that these reading errors does not come in bursts, but appear at random throughout the entire measurement. To determine a suitable size of \( n \), we split the 1000 samples into bins of 500, 250 and 125 samples, respectively, and plot the response probability for each bin in Fig. 10. For small \( n \) we see that the probability is changing significantly from bin to bin, but settles as \( n \) increases. For a bin size of 500 the probability only varies a few percent between the two bins. This is sufficient precision when considering that the response probability changes from \( \approx 1 \) to 0 over a few dB in SIR, see
Fig. 4 and 6. Hence, \( n = 500 \) is utilized when measuring the two types of reader collisions.

**APPENDIX B**

**DETAILED FLOWCHART OF SETUP**

In Fig. 11 the interferer from Fig. 2 is exploded, with each element described. When the reader initiates an interrogation round it starts by transmitting the unmodulated carrier wave a small period of time to power up the tag, before transmitting the Preamble + Select + Query commands. This period is not constant, hence the logarithmic amplifier is used to detect the amplitude modulation from the reader commands. We use this signal to trig waveform generator \( X \) to make pulses with a period corresponding to a bit-length, i.e. 80 \( \mu \)s. The first of the pulses from \( X \) then trigs waveform generator \( Y \). The starting voltage level of \( Y \) depends on the events \( I_R \) and \( I_T \), i.e. whether the initiation of the interrogation round or the tag response should be interfered. For \( I_R \) \( Y \) starts high, and for \( I_T \) \( Y \) starts low. When trigged \( Y \) changes state after a delay of 2.760 ms. This delay corresponds to the duration from the first bit of the preamble to the last bit of the Query.

The interfering carrier wave is created by the signal generator SMP22, and is triggered by the high level of \( Y \). To modulate the carrier wave we add a sinusoid with a frequency similar to the bit rate of the reader commands. Finally the interfering signal is amplified to match the level of the reader signal before entering the adjustable attenuators \( A \) and \( B \). Before being transmitted to the tag the reader and interferer signals are combined.

**REFERENCES**


Fig. 11. Detailed signal flow diagram of the setup used in this work.
Paper 2

Interference Helps to Equalize the Read Range and Reduce False Positives of Passive RFID Tags

Rasmus Krigslund, Petar Popovski, Gert F. Pedersen, and Kim Olesen

Accepted for publication in IEEE Transactions of Industrial Electronics, in 2012.
Abstract—In various applications of RFID systems a reader should reliably get the ID of the tags that are within a bounded proximity region, termed the interrogation zone. This gives rise to two types of errors 1) False Negative Detections (FNDs), when tags within the intended interrogation zone cannot be read and 2) False Positive Detections (FPDs), when tags outside the zone can be read. The detuning effect experienced from the object a tag is attached to exacerbates the occurrence of FND. Solving FNDs by increasing the reader power increase the probability of FPDs for tags outside the zone. Hence, the design of an interrogation zone poses a trade-off between readability inside versus outside the desired zone. We present a novel method to reduce the probability of FNDs and FPDs, and practically equalize the achievable range for tags experiencing detuning. We propose to impose intentional interference on the communication between reader and tag. The expected effects of the proposed method are evaluated using experimental measurements. The results are positive, showing a sharp edge of the interrogation zone, and a strong equalization of the range of tuned and detuned tags. Hence it is concluded that by imposing interference enables design of well-defined interrogation zones for passive RFID systems.

I. INTRODUCTION

Radio Frequency IDentification (RFID) has received great attention in recent years [1]–[3]. RFID is yet primarily utilized in supply chains, where the trend is moving towards item level tagging creating new challenges when deploying RFID systems.

As an example consider a store with item level UHF tagging. Readers are placed at the entrance, as illustrated on Fig. 1, in order to check that all items leaving the store have been paid for. The readers should therefore use sufficient transmission power, such that unpaid items tucked away in pockets and bags are read with high probability. Due to the high range when using high power, this may cause tags from the shelves inside the store to respond as well. This undesirable phenomenon is termed False Positive Detection (FPD).

In this paper we propose a novel method to create interrogation zones covering a confined area, e.g. just around the entrance of the store. By imposing interference while the reader is operating, tags still inside the store and outside the desired interrogation zone, are blocked from responding to the request from the reader. Moreover, tags experiencing detuning are equally affected by the interference. Hence, interference equalizes their read range towards the boundaries of the desired interrogation zone.

The mechanisms considered here are related to the concept of reader collisions, covering over two different types: Reader-tag and reader-reader collisions. The EPC Global Class 1 Gen 2 standard [4] implements a dense-reader-mode, allowing densely deployed readers to operate simultaneously in separate frequency bands. Modern readers are therefore able to filter out the undesired bands. Tags do not have this option, and are thus forced to cope with any interfering signal.

Immense work has been published in the area of reader collision already, proposing different methods to utilize the dense-reader-mode and optimize for low probability of reader collision. In [5], [6] the problem of reader collision is thoroughly described and existing methods to cope with this problem are surveyed. An example is [7], where reader collisions are described as a graph coloring problem, in order to derive a suitable reuse distance between the frequency channels. Alternatively [8] suggests using an algorithm similar to the Q-algorithm, from the Gen 2 standard, as MAC protocol for the network of readers. Most recently [9] proposes a method where readers are synchronized using a polling server, in order to avoid reader collisions. Moreover, [10] investigate what level of interference will cause a tag to not be identified by the reader. Additionally, different measures have been proposed to mitigate the problem of FPDs. In [11] two case studies are presented. They identify parameters in the physical setup of the RFID system in order to minimize false detections. In [12] a probabilistic model is utilized to filter the captured data, and in [13] two additional methods for data filtering are developed in order to avoid false detections. One method offering real-time filtering but with decreased precision compared to the second method, which is applying an offline data filtering. Though existing works present intelligent methods to avoid reader collisions, they are not differing between reader-reader collision and reader-tag collision. Moreover, the existing methods for reducing FPDs accept the presence of false detections and take measures to cope with them when they occur, rather than devising techniques for decreasing the probability of false detections in the first place. In [14] we investigated the potential of blocking tags from responding using interference, with positive results. In this paper we utilize this concept and present a novel idea using reader-tag collisions constructively to equalize the read range of tuned and detuned tags. In this way the probability of a FPD is reduced, making the interrogation zone a well-defined area. By imposing interference we
utilize some of the fundamental features of communication systems based on RF energy harvesting, as the interference is both an additional power source and a means to block tags from decoding the reader commands. The applicability of the proposed method is investigated through experimental evaluation and measurements.

The remainder of this paper is structured as follows: The motivation and proposed method are presented in Section II. Section III presents an analytical view on the interference-based mechanisms proposed in the paper. Section IV describes the experimental setup, and the results are presented in section V. In Section VI we discuss the findings and describe how the proposed method can be utilized and what effect it will have in a sample application. The final conclusions are drawn in section VII.

II. MOTIVATION AND PROPOSED METHOD

There is an inherent trade off between the read probability of tags inside the desired interrogation zone, and tags outside this zone giving rise to two types of reading errors. 1) False Negative Detections (FNDs), when a tag within the intended interrogation zone is not read and 2) FPDs, when a tag outside the intended zone is read. To ensure a high read probability anywhere in the interrogation zone, even for detuned tags, the reader should use a high interrogation power. This increases the probability of reading a tag outside the interrogation zone.

The concept of intentionally blocking tags is applicable whenever a low probability of both FPD and FND is required. For example applications requiring a well-defined zone with high read probability and sharply bounded, such that the read probability is low outside the zone. In order to block the tags that are not supposed to send reply, we adopt the principle of wireless jamming and impose interference on the communication between reader and tag. In [14] we investigated the potential of adopting this simple method in RFID systems, with promising results. The background for [14] was that the reader and tag represents two different levels of complexity, and are thus expected to have different susceptibility to interference. Passive UHF tags are simple devices with two basic requirements in order to respond with their ID: 1) The power "in the air" from the reader signal must be above a certain threshold $\beta$ and 2) the Signal to Noise Ratio (SNR) or Signal to Interference and Noise Ratio (SINR), denoted $\gamma$, must be sufficient for the tag to be able to decode the reader commands. In his book [15] Dobkin specifies $\beta = -10 \text{ dBm}$, and this threshold is utilized throughout this work. It should be noted that with the evolution in tag circuitry since the publication of [15], $\beta$ is today more likely to be less than $-10 \text{ dBm}$. It has not been possible for the authors to find good references for which SINR requirement, $\gamma$, can be expected. But due to the simplicity of the tag, $\gamma$ is expected to be fairly high, between $10 - 30 \text{ dB}$, and variate with different tag types.

In [14] the impact of interference was investigated in an idealized environment inside a shielded box with absorbing material on all sides. In this work we reuse a large part of the setup, but move the measurement to a multi path fading lab environment. This setup is described in more detail in Section IV. As motivation we compare the achievable range in the idealized environment versus the multi path environment in Fig. 2, where the read rate is plotted as a function of distance to the reader antenna. Inside the shielded box, the distance was introduced using adjustable attenuators and an artificial propagation loss coefficient. Two interrogation powers were used, $P_{r,tx}=22.5 \text{ dBm}$ and $P_{r,tx}=19.5 \text{ dBm}$. The performance difference when moving to a more realistic environment is clear, especially at the edge of the interrogation zone where the good propagation conditions inside the shielded box enables a very sharp edge of the zone for both interrogation powers. In comparison the edge of the zone in the multi path environment shows severe fluctuations, making it difficult to talk about an actual zone edge. In fact, we can only define the reading range probabilistically. Clearly, such fluctuations are undesired. Depending on where the zone edge is defined within these fluctuations, their presence either decrease the probability of reading tags in certain positions inside the zone, FNDs, or increase the probability of reading tags outside the zone, FPDs.

The read rate is fluctuating between almost maximum rate and no replies at all. If the SNR requirement was not fulfilled we would expect to see some intermediate read rates as well, hence the problem at the zone edge is to power up the tag.
Ensuring sufficient power for the tags by increasing the interrogation power poses a trade-off. While it does increase the power received by tags inside the zone and with that the SNR, it also increases the SNR for tags outside the desired interrogation zone, which then increases the probability of FPDs. This effect is not desired, as the SNR requirement is already fulfilled, according to Fig. 2.

The same arguments goes for decreasing the interrogation power in order to decrease the probability of falsely reading tags outside the zone, i.e. the probability of FPDs increase especially if a tag is experiencing some level of detuning.

To mitigate the fluctuations at the zone edge we basically want to increase the power received by the tag, without increasing SNR. These are fundamental features of any communication system based on RF energy harvesting. By imposing interference the SNR is unaffected, while the SINR decreases. In this way the power requirement is fulfilled, while by controlling the level of interference we can control the SINR and thereby the range in which tags should be unable to interpret the requests from the reader.

The key point in this method is that interference will have the same effect on a detuned and a tuned tag located inside the interrogation zone. Hence by imposing intentional interference we expect to equalize the performance of tuned and detuned tags, and thus achieve similar read ranges. This means that if the size of the interrogation zone is controlled by adjusting the SINR instead of the interrogation power, the read range for different tags and objects is expected to be more coherent within an interrogation zone reading.

III. ANALYTICAL RATIONALE

The scenario illustrated in Fig. 1 is an example of a real life application, where the proposed method is applicable. However, in order to evaluate the method theoretically, and later experimentally, we have chosen to further simplify the scenario. Instead of considering a store with multiple reader devices and a large tag population, we focus on a two device setup, a reader and an interference source, separated with some distance, as illustrated in Fig. 3. We then investigate how the interference affects the readability of a tag in the area between the two transmitters. In this way we have a simple scenario with only two devices, from which we can obtain the same effects as we would expect in the real life setup.

We utilize interference which is similar to the signal from an RFID reader, i.e. the signal is modulated and lies in the RFID frequency band, from 865 – 868 MHz in Europe. This makes the concept of blocking tags similar to reader-tag collisions. To describe the rationale of this method and illustrate the expected effects, we use a simple analytical approach. The scenario is regarded as a case of diversity, where the powers from the reader and interferer are combined in the physical channel. The power received at the tag from the reader is given by the following model:

\[ P_r = \mu_r \cdot |h_r|^2 \]  \hspace{1cm} (1)

The wireless channel is assumed to be a multi path channel, i.e. the received signal amplitude is following a Rayleigh distribution. This means that the power of the received signal follows an exponential distribution, and \( |h_r|^2 \) is thus the channel coefficient modelled by an exponentially distributed random variable, with a mean value equal to 1. The Probability Density Function (PDF) of \( P_r \) is then given by

\[ f(R_p) = \frac{1}{\mu_r} \exp \left(-\frac{R_p}{\mu_r}\right) \]  \hspace{1cm} (2)

Where the mean power, \( \mu_r \), received from the reader at the tag is given by

\[ \mu_r = P_{r,tx} \cdot t \cdot d_r^\alpha \]  \hspace{1cm} (3)

Where \( P_{r,tx} \) is the reader interrogation power and \( t \) is the tag detuning coefficient. We consider detuning of a tag as a downscaling of its received mean power. Hence \( t \) can take on values in the interval from 0 to 1, where \( t = 1 \) represents a tuned tag, i.e. perfectly matched to the reader signal. The propagation loss factor is calculated from the distance to the reader, \( d_r \), and the propagation loss coefficient, \( \alpha \).

The power received from the interferer, \( I_p \), is modeled similar to \( P_r \) in (1), but instead of the index \( r \), \( i \) is used to refer to the interferer parameters like transmission power, \( P_{i,tx} \), distance to the interferer, \( d_i \), etc. The total power received at the tag, \( T_{rx} \), is then given by

\[ T_{rx} = P_{r,tx} + I_p + N_0 \]  \hspace{1cm} (4)

Where \( N_0 \) is the noise power. To power up a tag, \( T_{rx} \) must be above the threshold \( \beta \). The ability to decode the commands from the reader then depends on the SNR or SINR. Without interference the SNR is given by

\[ SNR = \frac{R_p}{N_0} \]  \hspace{1cm} (5)

The noise floor is in general low, compared to \( R_p \), hence the SNR is expected to be high. When interference is present the SINR is given by

\[ SINR = \frac{R_p}{I_p + N_0} \approx \frac{R_p}{T_p} \]  \hspace{1cm} (6)

Compared to \( I_p \), the power in the noise is small, and the SINR is thus reduced to the Signal to Interference Ratio (SIR).

In order to show the expected effect of the proposed method we have simulated an example using the parameters listed in Table I. The reader and interference source are separated by a distance of \( d_{sep} = 10 \) m. Using (1) and (3) randoms samples of the power from the reader and from the interferer have been obtained, and with (4) and (6) the total received power and
Table 1: Parameters used in the example plotted in Fig. 5.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reader transmission power [dBm]</td>
<td>$P_{r,tx}$</td>
</tr>
<tr>
<td>Interferer transmission power [dBm]</td>
<td>$P_{i,tx}$</td>
</tr>
<tr>
<td>Channel coefficients [-]</td>
<td>$</td>
</tr>
<tr>
<td>Separation distance [m]</td>
<td>$d_{rx}$</td>
</tr>
<tr>
<td>Tuning coefficient [-]</td>
<td>$\tau$</td>
</tr>
<tr>
<td>Path loss coefficient [-]</td>
<td>$\alpha$</td>
</tr>
</tbody>
</table>

Fig. 4. The simulated power from the reader and interferer respectively, received at a tag with an antenna tuned to the correct frequency. The received power is plotted as a function of the distance to the reader antenna. The mean power is plotted as a solid line with samples of the fast fading instantaneous power distributed around it.

Fig. 5. The simulated SINR and the total power received by the tag, i.e. the sum of the instantaneous power from reader and interferer, plotted as a function of distance to the reader antenna.

SINR have been calculated and are plotted as a function of the distance to the reader in Fig. 4. Initially we consider the power received with a tuned tag, and Fig. 4 shows the Received Signal Strength (RSS) from the reader and interferer at the tag respectively, in positions between the two sources. The solid lines represent the mean power and we see the exponentially distributed samples of instantaneous power distributed around those mean values. For a small distance to the reader the $T_{rx}$ is dominated by the interrogation signal, and vice versa when the tag is close to the interferer. In intermediate distances to the reader, the faded samples of the reader signal tends to fall below $-10$ dBm, and thus failing to fulfill the power requirement to power up the tag. However, due to the contribution from the imposed interference the received power at the tag lies above, or very close to, $-10$ dBm, ensuring that there is enough power available "in the air". Moreover, when the two signal components are comparable in size, summing them up evens out the fast fading effect, which is a well known diversity effect.

In this simulation the trend of the SINR is monotonously decreasing, as can be seen in Fig. 5. With the received power above the threshold, the question of whether the tag can reply purely depends on the SINR threshold, i.e. the level of SINR where the tag is no longer able to decode the signal from the reader.

In addition to enable blocking of tags, Fig. 4 shows another feature of the proposed method. When the mean power is just above the threshold multi path effects will have the instantaneous RSS fall below the power threshold. In the same way multi path effect will make the RSS jump above the threshold when the mean power is just below the threshold, albeit this effect is not directly visible on Fig. 4. In effect the range of a reader, or the edge of an interrogation zone, becomes a diffuse concept in the normal case, which corresponds to the graphs in Fig. 2. However, by imposing interference and thereby fulfilling the power requirement, the range of the reader only depends on the SINR. Clearly the SINR is also expected to fluctuate with the multi path fading, given Fig. 5, but the resulting variations at the interrogation zone edge are expected to decrease. This enables sharper defined interrogation zones when adding interference.

When comparing the readability of a tuned tag with that of a detuned tag, the interference has a significant impact. In order to reduce clutter in the graph, only the mean powers have been plotted in Fig. 6, as they are sufficient to show the overall trend. The solid lines in Fig. 6 represent the tuned tag and are just repeated from Fig. 4, whereas the dashed lines represent a detuned tag with $\tau = 0.1$. This means that the tag is receiving $10$ dB less power from either of the sources. Hence the plots for interrogation power, interference power and their sum are shifted $10$ dB. Focusing on the interrogation power in the absence of interference, the mean power falls below the $-10$ dBm threshold around $5.5$ m while the range of a tuned tag is beyond the $10$ m. The span of the interrogation zone is thus depending on the object material and how it detunes the tag.

Adding interference ensures that the total received mean power does not drop below the power threshold between the
reader and the interference source, and the readability therefore solely depends on the SINR. The detuning of a tag affects both the reception of the reader and the interference signal, hence the mean value of the SINR for a detuned tag will be the same as for a tuned tag. It should be noted that due to multi path effects the instantaneous SINR values are not the same, but they follow the same mean. This means that by introducing interference we can equalize the readability of tuned and detuned tags creating a more uniform interrogation zone.

IV. THE EXPERIMENTAL SETUP

The simplified setup, using a single reader and interferer, presented in section III is utilized in the experimental evaluation as well. When imposing interference we are artificially creating reader collisions, where both Co-Channel Interference (CCI) and Adjacent-Channel Interference (ACI) are utilized. The tag is a simple device without the usual filters in the receiver to filter out undesired bands. Both interference types can thus contribute with power to the tag, and are expected to disturb the tags ability to decode reader commands. In this work we focus on reader-tag collisions as the target is to create a sharp edge of the interrogation zone, and therefore ensure that a tag outside the zone is not replying to queries from the reader. Measuring if the tag responds by connecting a probe directly on the tag would change the electromagnetic characteristics and the reception parameters of the tag significantly [16]. Hence we partly reuse the setup from [14], where only the reader commands are interfered, leaving tag responses unaffected by the interference. Due to the high sensitivity of the reader compared to the tag, it can be assumed that when no tag reply is detected, the tag was unable to interpret the reader commands. This way of interfering is complex and only required since we need to know if the tag was blocked. In a real life setup, a simple interferer transmitting during both reader and tag transmissions could be utilized.

In contrast to the results in [14], this work considers the experimental evaluation in a multi path environment. A block diagram illustrating the utilized setup is shown in Fig. 7. The tag is mounted on a motorized slide, that moves the tag between the two antennas. The slide has a range of 1.2 m, and when larger distances are required the offset is changed by moving the reader antenna further away. A detailed description of the utilized equipment and measurement procedure can be found in Appendix A.

When an RFID tag is attached to an object, the antenna is detuned as its antenna characteristics are affected by the object material. For a reflective material the impedance of the antenna conductor changes significantly compared to when the antenna is in free space. Non-reflective materials alter the wavelength of the incoming signal due to the dielectric constant of the material. Further details on how the reflective and dielectric abilities of the object affects the tag antenna is outside the scope of this paper. Basically the input impedance of the antenna change which introduces a matching loss that decreases the reception capabilities of the tag. A matching loss means that the tag receives less power, i.e. $t$ decreases.

In the experimental setup utilized in this work it is not viable to detune the tag by attaching it to an object. Instead we directly alter the antenna dimensions by removing parts of the conductor. Fig. 8 shows the two Alien Squiggle tags utilized in our experiments: One full tag and one where approximately 25% of the antenna has been removed. Reducing the conductor dimensions increases the resonance frequency. This increases the input impedance at the incoming frequency in the interrogation signal, and introduces a matching loss similarly to when the tag is attached to an object. It is not possible to specify the exact value of $t$ as it would require to measure directly on the tag. Instead we denote the detuned tag by $t < 1$ when plotting the measurement results.

The resulting setup is illustrated in Fig. 9, together with the lab environment, where the experimental evaluation was conducted. This is a normal indoor environment with reflecting surfaces like tables, cabinets and various lab equipment. The performance will therefore suffer from multi path fading, representing a real life setup.

V. RESULTS

In order to show how tags can be blocked, and how it is possible to design sharply defined interrogation zones a set of experiments have been conducted. Each test serves an individual purpose and shows different aspects of our findings.

A. Interference Type

The key concept in this work is to impose interference as an additional power source for the tags and to enable control of the read range by adjusting the interference power. In this way tags outside the desired zone are blocked from responding due to the interference. Due to the relatively wide frequency range of the receiver in the tag both CCI and ACI are expected to contribute with power and enable blocking of tags when the SINR gets sufficiently low. However, as we are interested in a well-defined interrogation zone with a sharp
edge we investigate the impact of ACI and CCI respectively. CCI uses the same center frequency as the reader, 865.7 MHz, whereas ACI uses the center frequency of the adjacent channel, 866.3 MHz. In order to show the generality of the results, we use two combinations of powers: Interrogation power of 22.5 dBm with 17 dBm interference and an interrogation power of 27.5 dBm with 20 dBm interference, and the resulting ranges are plotted in Fig. 10. The rate has some fluctuations due to the multi path environment, but here we see the expected intermediate read rates when the range is limited by SINR over power “in the air” to be able to respond, hence in case of detuned tags, the probability of FND is larger compared to tuned tags. Near the zone edge we see rate fluctuates similar to those plotted in Fig. 2.

The range is significantly reduced when interference is added, and Fig. 11(b) shows a close up of these graphs. Decreasing the interference power is equivalent to increasing the SINR, hence it is expected that the achievable range under interference increase for decreasing interference power.

Considering the difference in range between a tuned and a detuned tag under a certain interference power, we see they are only differing with up to 0.2 m. Moreover, the edge of the interrogation zone is free of fluctuations and appears sharp and well-defined. This corresponds to the expectations explained in Section III.

C. Reaching a Specific Range

When designing interrogation zones, a certain range is often desired. Hence in continuation of Section V-B we show how both tuned and detuned tags can meet a certain range under the influence of interference. As an example we target an interrogation zone that spans 1 m from the reader antenna. For the case without interference we adjust the interrogation power to fit the read range of a tuned tag. Investigations showed that an interrogation power of 12 dBm was a good match to the desired range. The objective is then to see if the same range can be reached with a combination of a higher interrogation power and interference. In this case the reader interrogates...
Fig. 11. The read range of a tuned and detuned tag respectively. The introduced interference ensures that the read range of tags with different antenna characteristics will be approximately equal. The power values are specified in dBm.

with 22.5 dBm, and in order to meet the range of the tuned tag, two interference powers have been utilized, 5 and 8 dBm. In Fig. 12 the resulting read ranges are plotted. As expected, the read ranges of a detuned and a tuned tag appear very different in the absence of interference. The read range of the tuned tag is around 1 m, and only about 0.1 m for the detuned tag, which corresponds to decrease in range of ∼ 90 % in this particular setup.

When imposing interference we see that a detuned and a tuned tag have similar range, that lies close to that of the tuned tag without interference. In fact, with an interference power of 5 dBm, we get a range of 1 m for the tuned tag and approximately 0.9 m for the detuned tag, i.e. similar range as the tuned tag without interference.

The largest difference observed in this setup up, between the range of tuned and detuned tags under interference is 0.1 m, when the interference power is 8 dBm. This corresponds to a reduction of 10 % in range when using a detuned tag over a tuned tag. This reduction is significantly less compared to the difference without interference. Hence by imposing interference, the range of the tags are more equalized.

VI. SYSTEM LEVEL IMPLICATIONS

In this work we have proposed an idea that equalize read range and with that enable the design of sharply defined interrogation zones. Through experiments we have shown that the concept works at the link level when interference is imposed on the communication between a reader and a single tag. In this section we discuss the implications of implementing the proposed concept in an RFID system in a more realistic scenario. As an example consider the RFID system illustrated in Fig. 13 covering the floor of a store or a factory.

In order to obtain a good coverage multiple readers have been utilized, denoted $R_1$ to $R_6$, each covering a separate section of the floor. In this application coverage, readability and location are the main concerns, in particular this means the RFID system should cover as much as possible of the floor, and a tag should be identified with ∼ 100 % probability. Additionally it is desired to be able to locate a tag based on the reader who reads. The distance separating readers poses a trade off. In principle a distance twice the longest possible read range should be utilized, i.e. the read range of a tag in free space or at least the read range of a tag attached to the least RF obstructive object in the application. If a lower separation is used the probability of FPDs increase, making the location of the tag ubiquitous. A larger reader separation will however create so-called black spots between the interrogation zones, i.e. areas where tags are read only with low probability. Moreover, from Fig. 2 we have that the range of an RFID tag in a multi path fading environment is probabilistic and depends on the level of detuning of the tag, i.e. which object it is attached to, as it affects the tags ability to harvest energy. This is illustrated in Fig. 13 where each interrogation zone is encircled by a grey scaled belt and the width of this belt represents the interval of the actual read range of the tags. The interference range of a wireless link is known to be larger than
Fig. 13. Rectangular factory floor covered by an RFID system with multiple readers, $R_1$ through $R_6$. The width of the grey scaled belt encircling each interrogation zone represents the interval in which the read range lies of tags experiencing different levels of detuning. The dashed circle marks the interrogation range of each reader.

the communication range, and in this case it is illustrated by the dashed circle around each reader in Fig. 13. This gives rise to the two types of reader collisions:

Reader-reader collision: Normally these collisions are avoided using frequency diversity and assigning different frequency channels to adjacent readers, and in some cases utilize a method for dynamically hopping between channels.

Reader-tag collision: Tags are simple transceivers without internal filters to filter out undesired frequency bands, which potentially will render a tag unable to decode any of the reader signals. The only way to completely avoid these collisions is to restrict readers from interrogating simultaneously.

By embracing the interference between readers, instead of trying to avoid it, we are constructively utilizing the large interference range and the resulting reader-tag collisions in order to block tags from responding. This allows for continuous reading and we have thus no loss of coverage and spatial reuse. The results presented in this work show how the read ranges are equalized for tags experiencing different levels of detuning. The achievable read range decrease due to the interference, but the coverage of a reader becomes more deterministic as illustrated in Fig. 14, where the grey scaled belt have been reduced to a thin line. In order to show the applicability of the proposed concept asynchronous interrogation and interference powers have been applied in this work. This is not desired in an application like the one illustrated in Figs. 13 and 14. However, identifying the optimal combination of interference power and interrogation power is an optimization problem and outside the scope of this work. The achievable read range decrease due to the interference, but the coverage of a reader becomes more deterministic as illustrated in Fig. 14, where the grey scaled belt have been reduced to a thin line. 

Fig. 14. Rectangular factory floor covered by an RFID system with multiple readers, $R_1$ through $R_6$. By embracing the interference between the readers the read ranges of tags are equalized, and the interrogation zones are now bounded by a sharp edge compared to Fig. 13.

for a given environment and reader positions. Moreover, an algorithm is required for implementing the optimal hopping in frequency for the readers, as the impact of the interference at the tag will decrease with frequency distance. However, these are optimization issues which is outside the scope of this work, and what is optimal will vary with equipment, environments and applications.

VII. Conclusion

In this paper we propose a novel way of utilizing interference constructively in Radio Frequency IDentification (RFID) systems. Our focus is twofold: 1) The combination of a large propagation loss and fading from a multi path environment creates very diffuse zone edges. This results in high uncertainty of reading a tag located close to the edge of an interrogation zone. 2) The fact that the achievable read range of a tag decreases with the level of detuning of its antenna. These aspects increase the probability of both False Negative Detections (FNDs) and False Positive Detections (FPDs), and are related to the power required to energize the tag.

We propose to introduce interference intentionally, in order to ensure that sufficient power is available “in the air” and block tags outside the desired interrogation zone. The interference introduces artificial reader-tag collisions and decreases the Signal to Interference and Noise Ratio (SINR). Tuned and detuned tags are experiencing the same SINR, thus their read range are equalized. Moreover, by controlling the interference power, and hereby adjust the SINR, we can control the range of the interrogation zone. Outside the zone, SINR is too low and tags are blocked from responding since they are unable to interpret the reader commands.

These expected effects are described through an analytical background and validated through experiments and measurements. With respect to blocking tags from responding Co-Channel Interference (CCI) showed most harmful. But Adjacent-Channel Interference (ACI) gave the steepest roll-off in read rate, hence this type of interference was used in all subsequent evaluation. The results show that the range of tuned and detuned tags are equalized. A difference in read range...
is still possible, but our results show that it is significantly smaller compared to the difference without interference, i.e. the probability of FNDs is kept low. Additionally the zone edges show only small fluctuations, resulting in a low probability of FPDs. Thus by imposing interference we enable the design of well-defined and sharply edged interrogation zones.

For future work it is desired to further investigate how to calibrate the level of interference required to obtain the desired interrogation zone, as this will depend on the environment and the material of the tagged objects. Moreover, extending this method to a multi reader setup would be an interesting extension to this work.

APPENDIX A
DETAILED MEASUREMENT PROCEDURE

In Section IV a brief overview is given of the experimental setup. However the details of this setup is illustrated in Fig. 15. A PC is used to synchronize the interrogation process and the movement of the tag. This is done through a small Java program alternating between interrogating and moving the tag. The tag, an Alien Squiggle [17], is attached to a motorized slide and to operate the slide we use an Arduino board controlled through the Java program. To control the interrogation process the Java program uploads the reader specifications to the reader, initiates the interrogation and terminates it again after the desired duration of a reading period.

In this setup it is only desired to interfere the readers transmission in order to isolate the impact of the interference to the tags ability to decode the reader signal. Hence the interferer is triggered when the reader transmits information in addition to the constant carrier wave transmitted by the reader. This is realized using a logarithmic amplifier identifying any modulation of the carrier wave. The output of the amplifier is not sufficient to trigger the signal generator creating the interference signal, hence the amplifier triggers a function generator that generates a proper square wave to trigger the signal generator. Table II lists the equipment and various settings used to realize this setup. The measurements are then conducted by letting the tag traverse the distance from the reader antenna to the interferer antenna in steps of 0.1 m. For each tag position the reader interrogates for a period of 12 s, and with a read rate around 90 tags/s this gives approximately $10^3$ samples of the tag response. The average read rate is then calculated over the 12 s reading period for each tag position.

![Fig. 15. A block diagram showing experimental setup in details.](image)

**Table II**

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reader</td>
<td>Impinj Speedway Revolution</td>
</tr>
<tr>
<td>Interferer</td>
<td>Rohde &amp; Schwarz Signal Generator SMP22</td>
</tr>
<tr>
<td>Amplifier</td>
<td>Logarithmic amplifier AD8307</td>
</tr>
<tr>
<td>Function generator</td>
<td>Agilent Function Generator 33250A</td>
</tr>
<tr>
<td>Micro controller</td>
<td>Arduino Mega</td>
</tr>
<tr>
<td>Tag</td>
<td>Alien “Squiggle” ALN9640</td>
</tr>
</tbody>
</table>

**Settings**

<table>
<thead>
<tr>
<th>Tag position</th>
<th>Tag coding</th>
<th>Tag population</th>
<th>Reading time</th>
<th>Step size</th>
<th>Interference modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>Miller-4</td>
<td>1</td>
<td>12 s</td>
<td>0.1 m</td>
<td>BASK, 80 kbps</td>
</tr>
</tbody>
</table>

REFERENCES

Rasmus Krigslund received the B.Sc. degree in Electrical Engineering and Information Technology in 2007 and the M.Sc. (Summa Cum Laude) in Electrical Engineering with specialization in Wireless Communication Systems in 2009, from Aalborg University, Denmark. He is currently pursuing a Ph.D. degree within RFID technology, where he focus on localization of passive tags, passive RFID sensors and reduction of false positive readings in RFID systems. Since 2009 he has been a regular reviewer for IEEE Communication Letters, IEEE Transactions on Wireless Communication and different IEEE conferences.

Petar Popovski received the Dipl.-Ing. in electrical engineering and Magister Ing. in communication engineering from Sts. Cyril and Methodius University, Skopje, Macedonia, in 1997 and 2000, respectively and Ph. D. from Aalborg University, Denmark, in 2004. He was Assistant Professor at Aalborg University from 2004 to 2009. From 2008 to 2009 he held part-time position as a wireless architect at Oticon A/S. Since 2009 he is an Associate Professor at Aalborg University. He has more than 100 publications in journals, conference proceedings and books and has more than 25 patents and patent applications. He has received the Young Elite Researcher award from the Danish Free Research Council. He has received several best paper awards, including the ones from IEEE Globecom, IEEE Communication Theory Workshop and CROWNCOM. Dr. Popovski serves on the editorial board of several journals, including IEEE Transactions on Wireless Communications and IEEE Communications Letters. His research interests are in the broad area of wireless communication and networking, information theory and protocol design.

Gert Frølund Pedersen was born in 1965 and married to Henriette and have 7 children. He received the B.Sc. E. E. degree, with honour, in electrical engineering from College of Technology in Dublin, Ireland, and the M.Sc. E. E. degree and Ph. D. from Aalborg University in 1993 and 2003. He has been employed by Aalborg University since 1993 where he is now full Professor heading the Antenna, Propagation and Networking group and is also the head of the doctoral school on wireless which some 100 phd students enrolled. His research has focused on radio communication for mobile terminals especially small Antennas, Diversity systems, Propagation and Biological effects and he has published more than 75 peer reviewed papers and holds 20 patents. He has also worked as consultant for developments of more than 100 antennas for mobile terminals including the first internal antenna for mobile phones in 1994 with lowest SAR, first internal triple-band antenna in 1998 with low SAR and high TRP and TIS, and lately various multi antenna systems rated as the most efficient on the market. He has been one of the pioneers in establishing over-the-air measurement systems. The measurement technique is now well established for mobile terminals with single antennas and he was chairing the COST2100 SWG2.2 group with liaison to 3GPP for over-the-air test of MIMO terminals.

Kim Olesen was born in 1962. He received the M.Sc. E. E. degree from Aalborg University in 1988. He has been employed in industry until 1994 where he was employed by Aalborg University, Center for Person Kommunikation, CPK and has been with Aalborg University since, now as the head of all laboratories at the Department of IKT. His main contributions has been building several generations of Aalborg Universitys channel sounding systems and conducted numerous measurement campaigns. The latest channel sounder is a true parallel MIMO sounder with 16 transmitters and 8 receivers which can be distributed and on different frequencies.
Paper 3

Potential of RFID Systems to Detect Object Orientation

Rasmus Krigslund, Petar Popovski, Gert F. Pedersen and Kristian Bank

Presented at the IEEE International Conference on Communications (ICC’11). Kyoto, Japan, 2011.
Potential of RFID Systems to Detect Object Orientation

Rasmus Krigslund, Petar Popovski, Gert F. Pedersen and Kristian Bank
Aalborg University, Department of Electronic Systems, E-mail: {rkr, petarp, gfp, kb}@es.aau.dk

Abstract—In this paper we present a novel method for estimating the inclination of passive UHF RFID tags, for use in supply chains to monitor the handling of tagged items. Based on observations of the polarization, a Bayesian estimator of the tag inclination is constructed. The Bayesian estimator has been analyzed and evaluated in an experimental setup. The results show great potential as the estimator is very robust when determining the inclination.

I. INTRODUCTION

The technology of Radio Frequency IDentification (RFID) has been widely deployed in supply chain applications, as it among others enables a high identification rate, a higher level of automation, and control of every aspect of the supply chain. Today various items are therefore transported and handled by automated systems with a minimum of human interaction. Some of these items might be fragile, like chinaware, domestic appliances or electronic equipment, such as LCD televisions. It is desired that items like these are handled carefully. Some of the boxes may even have a This side up marker, meaning that the orientation of the box is important and should be sustained.

In this paper we present a method for identifying the orientation of an RFID tagged object. By monitoring the orientation of an object throughout the entire supply chain a logistic service provider can use the data to prove a certain quality of service, or identify in which segments of the supply chain the items received a rough handling.

The main idea is to identify the orientation of an object through the orientation of the tag attached to it. If it is only desired to identify whether an object has fallen over, only a single tag and its inclination is required. However, if the orientation in three dimensions is desired, each object must be fitted with multiple RFID tags marking the dimensions of the object in three-dimensional space. By identifying the inclination of each tag, we can identify the orientation of the object. This is achieved using multiple reader antennas, each measuring the polarization of the signal, received from each tag. From the observations by each reader antenna, a Bayesian estimator of the object orientation is constructed.

Estimating the inclination of a tag based on its polarization is, to the best of our knowledge, a novel idea, albeit polarization have been used for different purposes previously.

In the area of location based services, localization of RFID tags is an emerging research area. Methods for localization based on ranging in an indoor environment are subject to large errors. In [1], [2] methods for estimating the loss due to polarization mismatch is presented, in order to improve the precision of the final estimated location.

Polarization diversity is another way of utilizing polarization, and is investigated in [3]–[5] as an alternative to spatial diversity. Here co-located antennas use orthogonal polarizations to achieve a diversity gain. This is for example used in radar systems to better detect targets of small radar cross section, [6].

In this paper we assess the potential of an RFID system to detect the orientation of a tagged object. In our experiments we use co-located antennas for the RFID reader, to decompose the received signal into two orthogonal signal components, in order to determine the polarization of the received signal. With multiple reader antennas sampling the polarization of the tag reply, their observations can be combined in a Bayesian estimator of the physical orientation of the tag antenna.

The remainder of this paper is organized as follows: In section II the system environment is described along with the assumptions made in this work. Section III describes the analysis of the polarization and construction of the Bayesian estimator. This estimator is evaluated in an experimental setup, and the results are presented in section IV. The final concluding remarks are given in section V along with options for future work.

II. SYSTEM MODEL

The proposed system is targeting supply chain applications, and is presumed to be installed in an indoor environment, for example as a part of a production line in a factory, or inside the cargo hold of a lorry. The latter represents a more confined and reflective environment, than the former. In such scenarios items are often packed in boxes or crates, and placing an RFID tag on the sides of these boxes effectively reduces the possible inclinations of the tag to either vertical or horizontal.

To meet the supply chain application, we start in this work by investigating a simple case. We use passive UHF tags, as the lack of battery results in a cost effective and environmental friendly product. The tags are assumed to follow the EPC Global Gen 2 standard [7]. When each item is fitted with three tags, one for each spatial dimension, the anti collision algorithm in the Gen 2 standard ensures that each individual tag has a chance to transmit. This means that we can proceed considering a scenario with a single tag, which simplifies the experimental evaluation.

To increase the statistical certainty of the estimated inclination we assume that the RFID reader covers the interroga-
tion zone using multiple antennas, in order to have multiple independent samples of the Received Signal Strength (RSS). Moreover, each antenna collects multiple samples over time of the received signal. The utilized antennas are dual linearly polarized, enabling decomposition of the received signal into two orthogonal components, namely a vertical and a horizontal electromagnetic field component, $E_{\theta}$ and $E_{\varphi}$, respectively. The received signal, $y$, can therefore be written as a tuple of signals, $y_{\theta}$ and $y_{\varphi}$:

$$y_{\theta}(m, n) = h_{\theta}(m, n)x + z_{\theta}$$
$$y_{\varphi}(m, n) = h_{\varphi}(m, n)x + z_{\varphi}$$

Where the indexes $m$ and $n$ refers to the reader antenna id, and the sample number, respectively. The transmitted signal is denoted $x$, and $z$ refers to the thermal noise in the reader antenna. The channel coefficient $h$ represent the fading in an indoor environment, where reflecting objects distort the wireless transmission. Since tags can be placed on any side of an object, Line Of Sight (LOS) may not be available. Hence, the power of the received signal, denoted $Y$, is assumed to follow an exponential probability distribution, characterized by a single parameter, the mean power $\sigma$. The inclination of the tag introduces a polarization mismatch between tag and reader antennas, this affects the mean power making $\sigma$ dependent of $\beta$.

With the reader antennas distributed around the interrogation zone, their received signal will be affected by different parts of the environment, so the channels experienced by each antenna, i.e. $h(m, n)$ for $m = 1, \ldots, M$, will be independent. Moreover, when each antenna collects multiple samples of the RSS, i.e. $n = 1, \ldots, N$, each sample experience approximately the same multi-path fading, as the environment seen from each antenna is constant. However, it is assumed that these samples are conditionally independent if the orientation is known, in order to simplify the construction of the Bayesian estimator.

With the signal model and the corresponding assumptions described, the proposed method for estimating the object orientation can be analyzed in details.

III. ANALYSIS

The Bayesian estimator of the tag inclination is based on two key aspects; 1) The inclination of the linearly polarized signal received from the tag, and 2) The assumption that the two orthogonal components of the received signal are uncorrelated throughout the wireless channel. These aspects are therefore described before presenting the Bayesian estimator.

A. Polarization Primer

The polarization is defined as the orientation of the electric field with respect to the direction of propagation. Most UHF tags antennas are variants of a dipole [8], and have a linear polarization. This means that the polarization vector, defining the magnitude of the electrical field, is a tangent to the half-circle connecting the two ends of the antenna. Hence, the polarization vector and the conductor of the dipole are not necessarily parallel, but they will always lie in the same plane, as illustrated in Fig. 1.

When a tag is rotated, its linear polarization is rotated as well. It is desired to estimate the inclination, i.e. the angle, $\beta$, of this polarization with respect to a vertical orientation.

To measure the polarization we use two orthogonal measurements of the RSS, provided by dual-polarized reader antennas. The magnitude of the vertical and horizontal field components is given by the field vectors $E_{\theta}$ and $E_{\varphi}$, respectively. The angle $\beta$ seen from a receiving antenna is then given by:

$$\beta = \arctan \left( \frac{|E_{\varphi}|}{|E_{\theta}|} \right)$$

By combining observations of $\beta$ from several antennas, a reader can increase the statistical certainty about the estimated inclination, $\beta$.

B. Correlation of $y_{\theta}(m, n)$ and $y_{\varphi}(m, n)$

When an electromagnetic wave hits an object, e.g. a wall or the ground, its energy is partly absorbed, with the absorption coefficient depending on the material of the object. The remaining energy is reflected as a attenuated replica of the original signal.

As an example consider a tag transmitting a signal $x_t$. The tag is approximately oriented horizontally, so $x_t$ can be decomposed into two orthogonal components, $E_{\theta}$ and $E_{\varphi}$, where $|E_{\theta}| \ll |E_{\varphi}|$:

$$x_t = E_{\theta} + E_{\varphi}$$

Both $E_{\theta}$ and $E_{\varphi}$ are field vectors of the electrical field and perpendicular to the direction of propagation.

When a smooth surface reflects a signal, the signal component parallel to the reflecting surface is reversed, i.e. the orthogonal components do not mix. Unfortunately most indoor surfaces are rough, and then the signal components mix upon reflection. This means that even though $x_t$ is transmitted in one dimension it will, after sufficiently many reflections have equal power on the two orthogonal polarizations.

With multiple reader antennas covering the same interrogation zone, it is reasonable to assume that at least one antenna has LOS to the tagged object. The approach presented in this paper is based on the observation that the LOS component is dominant compared to the reflections from the environment. Hence we assume that the orthogonal components of the received signal, $y_{\theta}(m, n)$ and $y_{\varphi}(m, n)$, have low correlation and fade individually, due to the environment. This is an approximation that helps simplify the construction of the Bayesian estimator, but it may be degraded in setups where LOS is absent.
C. Bayesian Estimator

The estimated inclination, \( \hat{\beta} \) is constructed as a Bayesian estimator, based on observations of the signal strength. As mentioned in Section II, each receiving antenna measures the RSS in both the horizontal and vertical polarization creating the tuple \( Y_\theta(m,n) \) and \( Y_\varphi(m,n) \). To simplify notation we write the observations from the \( M \) reader antennas as a vector, so \( \mathbf{Y}_\theta(n) = [Y_\theta(1,n), \ldots, Y_\theta(M,n)] \) and represents the dataset containing the \( n \)-th RSS sample in horizontal polarization for all \( M \) reader antennas. The a posteriori probability of \( \beta \), given the observed RSS, is then given by:

\[
P(\beta|Y_\theta(n), Y_\varphi(n)) = \frac{P(Y_\theta(n)|Y_\varphi(n)|\beta) \cdot P(\beta)}{P(Y_\theta(n)|Y_\varphi(n))} \tag{3}
\]

We are interested in the Maximum A posteriori Probability (MAP) of the orientation angle \( \beta \) given the observed dataset. Since the denominator of Eq. (3) is independent of \( \beta \) we focus on the numerator when estimating the inclination:

\[
P(\beta|Y_\theta(n), Y_\varphi(n)) \propto P(Y_\theta(n)|Y_\varphi(n)|\beta) \cdot P(\beta) = P(Y_\theta(n)|\beta) \cdot P(Y_\varphi(n)|\beta) \cdot P(\beta) \tag{4}
\]

Where the likelihood, \( P(Y(n)|\beta) \), refers to the exponentially distributed RSS, where \( \beta \) affects the mean received power as described in Section II. The a priori knowledge of \( \beta \) is given by the prior distribution \( P(\beta) \). Initially nothing is known, hence \( \beta \) is assumed to be uniformly distributed. Since the RSSs received by \( M \) reader antennas are independent the resulting a posteriori probability is uniformly given by:

\[
P(\beta|Y_\theta(n), Y_\varphi(n)) \propto \left\{ \prod_{m=1}^{M} P(Y_\theta(m,n)|\beta) \cdot P(Y_\varphi(m,n)|\beta) \right\} \cdot P(\beta) \tag{5}
\]

If we let each reader antenna collect multiple samples of the RSS we can update the prior based on the previous observations. As an example consider the a posterior distribution based on two successive observations, i.e. \( N = 2 \):

\[
P(\beta|Y_\theta(1), Y_\varphi(1), Y_\theta(2), Y_\varphi(2)) \propto P(Y_\theta(2)|Y_\varphi(2)|\beta) \cdot P(Y_\varphi(2)|Y_\theta(1)|\beta) \cdot P(\beta) \tag{6}
\]

From Eq. (6) we see that for each succeeding observation we can use the posterior distribution, calculated from the preceding observation, as an updated prior distribution. This makes the complexity of calculating the Bayesian estimator, \( \beta \), increase linearly with the number of observations. Letting each antenna collect \( N \) observations gives the following recursive posterior probability:

\[
P(\beta|Y_\theta(N), Y_\varphi(N)) \propto P(Y_\theta(N)|Y_\varphi(N)|\beta) \cdot P(\beta|Y_\theta(N-1), Y_\varphi(N-1)) \tag{7}
\]

The estimated inclination is then given by the MAP:

\[
\hat{\beta} = \arg\max_\beta \{ P(\beta|Y_\theta(N), Y_\varphi(N)) \} \tag{8}
\]

IV. RESULTS

The Bayesian estimator, \( \hat{\beta} \) from Eq. (8), is evaluated in an experimental setup in an indoor office environment. We utilize three dual-polarized horn antennas as RFID reader antennas, i.e. \( M = 3 \). One is depicted in Fig. 2(a), along with the utilized tag antenna in Fig. 2(b). We use a folded meander dipole antenna printed on PCB, as tag antenna, and to power the antenna we fitted and optical diode on the antenna and used optical cables for the signaling. This removed the electromagnetic influence of copper cables, making the meander antenna operate approximately like a real RFID tag.

The horn antennas, denoted \( A_1, A_2 \) and \( A_3 \), are placed at a distance of 1.5 m from the tag, and evenly spaced in a circle around it, as illustrated in Fig. 3. This is a constraint of the utilized setup, but as we are only pursuing the assessment of the potential of estimating the orientation, this setup is used as a starting point. Experiments with the tag placed randomly between the reader antennas, and thereby favoring one antenna over the others, are planned for future work.

The tag and reader antennas are raised 1 m and 1.85 m above ground, respectively, creating a difference in hight of 0.85 m. This can be seen from the environment, which is a lab and office environment, depicted in Fig. 4. This represents a normal indoor environment with lots of reflecting objects and surfaces.

In the targeted supply chain application the tag is assumed to be placed on the side of some box, e.g. vertical oriented, and if the box is knocked over the tag is then oriented horizontally, or vice versa. This means that the inclinations of interest are
vertical and horizontal, \( \beta = 0 \) and \( \beta = \frac{\pi}{2} \) respectively, and additionally we use a tilted inclination, \( \beta = \frac{\pi}{4} \), i.e. in total three different inclinations are measured.

Since the tagged objects can be oriented in any direction we need to test in the entire azimuth spectrum. Hence, for each inclination the tag is rotated \( 2\pi \) radians in 12 steps of \( \frac{\pi}{6} \) radians, denoted \( s_i \), where \( i = 1, \ldots, 12 \), as illustrated in Fig. 3. In each step each reader antenna measures the two dimensional RSS from the tag. This is repeated four times giving each antenna four independent observations of the RSS in each azimuth orientation, i.e. \( N = 4 \). The exponential distribution describing the likelihood is characterized by a single parameter, the mean power of the RSS, \( \sigma \). Using the dataset of measured RSSs, \( \sigma \) is calculated for each inclination respectively, as the mean RSS across all azimuth orientation and all repetitions.

This procedure is repeated for four different scenarios; One with the tag antenna by itself, and three where the tag is attached to different objects. It is expected that the objects will affect the radiation of the tag antenna, hence the size and material of the objects must represent real life object that can occur in a supply chain. We have used a porcelain plate, and a metal plate, both protected by polystyrene and packed in a cardboard box (21 cm × 24 cm × 30 cm), and as the third object an empty box of plywood (30 cm × 30 cm × 30 cm) was utilized.

The parameters for the experimental setup are summarized in Table I.

In Fig. 6 the results from each of these four scenarios are plotted. To easier obtain an overview of the results we have defined a new metric, the a posteriori difference, denoted \( P_{\text{diff}} \). This is defined as the difference between the posterior probability for the true inclination, \( \beta_{\text{true}} \), and the maximum posterior of the two remaining inclinations, \( \beta_{1} \) and \( \beta_{2} \):

\[
P_{\text{diff}} = P(\beta_{\text{true}}|\overline{Y}_0(4), \overline{Y}_\phi(4)) - \max \left\{ P(\beta_{1}|\overline{Y}_0(4), \overline{Y}_\phi(4)); P(\beta_{2}|\overline{Y}_0(4), \overline{Y}_\phi(4)) \right\}
\]

(9)

If \( P_{\text{diff}} \) is positive it means that the true inclination yields the maximum a posterior probability, and therefore gives the correct \( \beta \). The closer \( P_{\text{diff}} \) is to 1 the more certain we are on this decision.

Without any objects disturbing the operation of the tag antenna, the method is very robust, and determines the correct inclination with a large margin for every azimuth orientation, see Fig. 6(a).

The effect from the introduced objects is evident as it decreases the certainty of the decisions. For a cardboard box containing porcelain, in Fig. 6(b), we see a dip to around 0.75 in \( s_{10} \) for the tilted and vertical inclination, where the horizontal inclination has a dip to 0.8 in \( s_{10} \). When the cardboard box contains a metal plate we see a dip in \( s_{14} \), in Fig. 6(c), for

---

**Table I**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>#reader antennas (M)</td>
<td>3</td>
</tr>
<tr>
<td>#observations (N)</td>
<td>4</td>
</tr>
<tr>
<td>Inclination angles (( \beta ))</td>
<td>( {0, \frac{\pi}{4}, \frac{\pi}{2}} )</td>
</tr>
<tr>
<td>Azimuth angles</td>
<td>( {0, \frac{\pi}{6}, \ldots, 2\pi} )</td>
</tr>
<tr>
<td>Objects</td>
<td>1) Cardboard box with a porcelain plate 2) Cardboard box with a metal plate 3) Plywood box</td>
</tr>
</tbody>
</table>
Fig. 6. Plot of the difference, $P_{\text{diff}}$, between the posterior probability of the correct inclination and the second largest posterior probability in each of the 12 azimuth steps. The vertical inclination is marked with +, tilted with ×, and horizontal inclination has no markers.

tilted and vertical inclination, but this time to around 0.65 and 0.85 respectively. These dips are caused by an unfortunate combination of the change in radiation, due to the object material, and the reflectors in the environment, e.g. furniture and cabinets. If the environment were furnished differently we would most likely see a similar effect but at different azimuth orientations.

When the object is a box of plywood we see the most significant effect on the posterior probability, as can be seen in Fig. 6(d). For horizontal inclination, $P_{\text{diff}}$ is close to 1 in all azimuth orientations. But for the tilted and vertical inclinations we see a significant dip however, as $P_{\text{diff}}$, in $s_{10}$, respectively drops to around 0.45 and 0.55. Except for these two cases, the posterior probability for the true inclinations surpass the others with more than 0.6, for any abject and orientation. This is considered sufficient for making a confident decision.

It should be noted that the azimuth orientations resulting in severe dips in posterior probability should be avoided if the system is used in a supply chain application. In the utilized indoor environment examples of good azimuth orientations are $s_{1}$, $s_{2}$, $s_{7}$ and $s_{12}$. As mentioned above this depends on the reflecting surfaces in the environment, and for another environment the good azimuth orientations will be different.

V. Conclusion

In this paper we have presented a novel method for identifying the inclination of a UHF RFID tag. The method is targeted at supply chain applications as a way to monitor the handling of fragile items tagged with passive RFID tags. By monitoring the inclination of these tags, it can be identified when items have been knocked over or been subject to a rough handling. The tag inclination is estimated by a Bayesian estimator based on observations of the polarization of the signal received from the tag at multiple reader antennas.

The method have been analyzed, and evaluated in an experimental setup with the tested tag antenna attached to different objects. The results shows great potential, as the Bayesian estimator proves very robust, and gives the correct tag inclination for all possible azimuth orientations.

For future work it would be interesting to evaluate the proposed method when the tagged object is placed at random between the reader antennas, i.e. favoring one of the antennas, and also include multiple tags on each object.

REFERENCES

Orientation Sensing Using Multiple Passive RFID Tags

Rasmus Krigslund, Petar Popovski and Gert F. Pedersen

Accepted for publication in IEEE Antennas and Wireless Propagation Letters, in 2012.
Orientation Sensing Using Multiple Passive RFID Tags

Rasmus Krigslund, Petar Popovski and Gert F. Pedersen
Aalborg University, Department of Electronic Systems, E-mail: \{rkr, petarp, gfp\}@es.aau.dk

Abstract—Knowing the inclination of an object can be valuable information in a supply chain application, e.g. when handling orientation sensitive objects. In this work we present a method for sensing the inclination using Radio Frequency IDentification (RFID) technology. The method requires standard RFID equipment and assumes that each object is tagged with a passive UHF tag. We use a simple statistical estimator based on the Received Signal Strength (RSS) of the tag reply. The performance is evaluated via experimental measurements, and the results are positive with a good precision within distances of 2 m.

Index Terms—Wireless sensing, Passive RFID sensors, Orientation sensing.

I. INTRODUCTION

Radio Frequency IDentification (RFID) technology has been widely deployed in supply chain applications, as it, among others, enables a higher level of automation. Some items handled in such an automatic system might have a This side up marker, meaning that the orientation of the box is important and should be sustained.

In this work we devise an approach to estimate the orientation of an RFID tag based on the polarization of the signal received from the tag. This is a constructive utilization of polarization mismatch between tag and reader antennas. An example of previous work utilizing polarization diversity, \cite{1}, where co-located antennas with orthogonal polarizations provide a diversity gain as an alternative to spatial diversity. Polarization diversity is also utilized in polarimetric radar systems providing a more complete set of information about the target and environment \cite{2}. Polarization mismatch is however often considered a nuisance, e.g. in the area of localization, where a polarization mismatch decrease the precision, especially for methods based on ranging. In \cite{3} methods for estimating the loss due to polarization mismatch are presented, in order to improve the precision of the final estimated location.

In \cite{4} we investigated the potential of detecting the orientation of a passive RFID tag solely based on its response. The orientation estimate was constructed as a Bayesian estimator, where the likelihood required the mean Received Signal Strength (RSS) to be known a priori. Proper calibration for each different object and environment was therefore necessary. In this paper we use a simple generalized statistical estimator that effectively removes the requirement for calibration. Since the calibration represents knowledge of the environment, removing it is potentially at the price of precision. However, by using multiple tags per object, and estimate their joint orientation we decrease uncertainty of the estimate.

II. PROBLEM DEFINITION AND PROPOSED METHOD

Sensing the inclination based on the RSS from the tag is valuable since it can be used to identify the orientation of the object. The proposed method was essentially based on decomposing the RSS from the tag into horizontal and vertical directions using dual polarized reader antennas, in order to extract the inclination angle from the polarization of the RSS. In order to achieve precision the method requires calibration and object specific calibrations, which in general is undesired. Hence in this work we seek to identify a statistical estimator in order to remove the calibration requirement. However, this comes at the price of precision, so to decrease uncertainty of the estimate we propose to use multiple tags per object.

In this work we delimit the number of tags per object to two, tag A and B. To identify the orientation of the object, it is assumed that the relative inclination of these tags with respect to the object is known in advance, and here tag A and B are orthogonal. Their inclinations are respectively denoted, $\theta_a$ and $\theta_b$, as illustrated in Fig. 2. It should be noted that tag A and B...
are not required to be orthogonal, but their angular relationship must be known. In order to estimate their joint inclination we consider an artificial line, C, defined in the plane spanned by the tags. The inclination of C is referred to as \( \theta_c \), and \( \theta_a \) and \( \theta_b \) are in this work related to \( \theta_c \) by shifts of +\( \frac{\pi}{2} \) and -\( \frac{\pi}{2} \) respectively, i.e. \( \theta_c \) is centered in between the inclinations of tag A and B. Basically the artificial line C could have any inclination, given that the angular relationships towards tag A and B are known.

III. A SIMPLE ESTIMATOR

The RSS of a tag response, \( y_i \), is obtained in two dimensions using dual polarized reader antennas, and can be written as:

\[
y_i = y_{i0} + j \cdot y_{i0}V \cdot y_b = y_{b0} + j \cdot y_{b0}V
\]

The two dimensional structure of \( y_a \) and \( y_b \) allows us to consider them as vectors, as illustrated in Fig. 3, and each power component is modeled based on the following model for the received signal amplitude:

\[
r_{ij} = h_{ij} x + z_{ij}
\]

Where the index \( i \) and \( j \) takes values from the sets \{a; b\} and \{V; H\} respectively. The transmitted signal is denoted \( x \), \( h_{ij} \) refers to the channel coefficient and \( z_{ij} \) is the noise component. We assume that no information about the signal parameters is available a priori, hence both the channel coefficient and the noise component are assumed to be modeled as two-dimensional Gaussian random variables, i.e. \( h_{ij} \sim N(0, \sigma_h^2) \) and \( z_{ij} \sim N(0, \sigma_z^2) \).

For convenience we assume \( x \) is constant and equal to 1. Hence all power variations are caused by the channel model, which is a reasonable assumption for an RFID backscattered signal. We can then rewrite the received signal as:

\[
r_{ij} = h_{ij}^t = (h_{1,ij} + z_{1,ij}) + j(h_{2,ij} + z_{2,ij})
\]

\[
h_{ij}^t = h_{1,ij} + jh_{2,ij}
\]

Where \( h_{1,ij}^t, h_{2,ij}^t \sim N(0, \sigma_h^2 + \sigma_z^2) \), since \( h_{ij} \) and \( z_{ij} \) are independent random variables. Hence \( |r_{ij}| \) is thus Rayleigh distributed, and \( |r_{ij}|^2 \) is distributed exponentially, i.e.:

\[
|r_{ij}|^2 = y_{ij} \sim \frac{1}{\mu_{ij}} \exp \left( \frac{-y_{ij}}{\mu_{ij}} \right)
\]

Where \( \mu_{ij} \) is the mean received power from the tag:

\[
\mu_{ij} = 2\sigma^2 = 2(\sigma_h^2 + \sigma_z^2)
\]

The mean received power is thus a combination of the mean signal power and noise power.

A. Estimating The Inclination

In order to derive a statistical estimator for \( \theta_c \), \( \hat{\theta}_c \), we obtain data sets of \( N \) samples of the received signal powers: \( y_{a0} = \{y_{a0}[0], y_{a0}[1], \ldots, y_{a0}[N - 1]\} \) and \( y_{b0} = \{y_{b0}[0], y_{b0}[1], \ldots, y_{b0}[N - 1]\} \). The ratio between each samples of the \( V \) and \( H \) components depends on the polarization angle, and hereby the inclination of the tag antenna. We use a simple estimator for estimating the mean received power, \( \mu_{ij} \), from the tag, and then calculate the tag inclination based on that estimate. The estimated mean power is given by the sample mean over \( N \) RSS samples:

\[
\hat{\mu}_{ij} = \frac{1}{N} \sum_{n=0}^{N-1} y_{ij}(n)
\]

The sample mean is the Maximum Likelihood Estimator (MLE) of the parameter \( \mu_{ij} \) in (4). This estimator is a random variable with mean equal to \( \mu_{ij} \). The variance is given by the Cramer Rao Lower Bound (CRLB), and has been derived to be \( \frac{\mu_{ij}}{N} \). The estimator of the mean received power is thus an unbiased estimator of \( \mu_{ij} \), and its variance is inversely proportional to \( N \). From (5) we know that \( \mu_{ij} = 2(\sigma_h^2 + \sigma_z^2) \), hence for small distances between reader and tag the noise power will be negligible compared to the signal power. For large distances however, the noise power becomes dominant. The estimated mean power is therefore expected to have the best precision for relatively small distances between reader and tag. The estimated inclination of a tag is then given by:

\[
\hat{\theta}_c = \arctan \left( \frac{\hat{\mu}_V}{\hat{\mu}_H} \right)
\]

The joint angle, \( \theta_c \), is then estimated by combining \( \hat{\theta}_a \) and \( \hat{\theta}_b \) according to their angular relationship know in advance. In this work we have defined \( \theta_c \) as the inclination centered between tag A and B. Hence \( \hat{\theta}_c \) is given by:

\[
\hat{\theta}_c = \frac{\theta_a + \theta_b}{2} \quad \Rightarrow \quad \hat{\theta}_c = \frac{\hat{\theta}_a + \hat{\theta}_b}{2}
\]
Four examples of vectors whose components have equal absolute value. All angles are mapped to the first quadrant, which effectively reduces the range of $\theta_c$.

Fig. 5. The utilized experimental setup.

In principle this estimator is scalable to more than two tags, but it is an open question how to map the collected RSS samples and preserve their angular relationship.

B. Combining Information From Two Tags

Signal power is positive by definition which introduces an ambiguity when estimating the inclination. As an example consider Fig. 4(a) where the true inclination of $\theta_a$ is $20^\circ$, and the vector is marked with a solid line and an additional index $t$. The dashed vectors with index $f$ all have the same absolute value as the true vector. However, since the received power is positive, the estimated inclination will be in the interval from $0 - 90^\circ$, i.e., in the first quadrant, when using (7). In Fig. 4(b) the inclinations of $\theta_{a,t}$ and $\theta_{b,t}$ are therefore interpreted as that of $\theta_{a,f}$ and $\theta_{b,f}$ respectively.

To maintain the orthogonal relationship between $\theta_a$ and $\theta_b$ it is therefore required to map $\theta_a$ to the fourth (or second) quadrant. This reduces the range of the estimated $\theta_c$ to $\{-45^\circ; 45^\circ\}$, and will thus give a wrong estimate when the true inclinations of tag A and B are outside the first and fourth quadrant, respectively.

IV. RESULTS

In order to evaluate the estimator, we have measured the practical performance in a real life setup using commercial devices. The experimental measurements were conducted in a lab environment with reflecting surfaces like desks, cabinets etc. using an Impinj Speedway Revolution reader [5] and two Alien Technology "Squiggle" ALN9640 Passive UHF tags [6]. Compared to [4] we use only one dual polarized antenna in this work, and the tags are mounted orthogonally on a piece of cardboard raised 1.25 m above the ground, see Fig. 5.

It is desired to investigate the ability to determine the joint inclination within the range of $\theta_c$ and as a function of distance between reader and tags. In each measurement the RSSs from tag A and B are sampled continuously for 12 s using an interrogation power of 27.5 dBm. This gives approximately $N = 500$ samples of the tag reply in the horizontal and vertical dimension respectively. By inspecting the measurement data we found that the variance in the RSS values was in the order of 0.01 to 0.2 dBm. It is therefore reasonable to assume that similar precision can be achieved using less samples and thereby less time, as the RSS is approximately constant. It should be noted that the CRLB on the mean received power, described in Section III-A, is not useful when interpreting the results, as our reference is in degrees not power. Due to the non-linear nature of the tangens function it is not possible to map an error in degrees to a power ratio, or magnitude, of the vertical and horizontal power components.

A. $\theta_c$ As A Function of Distance

The tag inclinations are fixed to $\theta_a = 30^\circ$ and $\theta_b = -60^\circ$ giving a $\theta_c = -15^\circ$. The distance from reader to tag is then changed from 50 cm to 450 cm in steps of 50 cm, and for each distance the tag replies are sampled for 12 s. In Fig. 6 the estimated joint angle, $\theta_c$, is plotted as a function of distance. The estimated joint angle $\theta_c$ appears to be fairly constant, albeit $10 - 15^\circ$ below the true angle, up to a distance of 200 cm. At greater distances we see some significant fluctuations corresponding to the dips in mean power in one or both dimensions. An RSS of $-90$ dBm is an artificial value specified in the situations where a tag is not read, as some value is required in both dimensions in order to estimate the angle. This occurs when polarization mismatch and multi path fading make the RSS drop below the sensitivity of the reader.
As expected we see large estimation errors in both ends of the interval. This is best seen by considering the estimated inclination of the individual tags, where we can see how it approaches the true inclination as the tags approach the 0 cm position. Averaging the two angles we get a joint inclination with a precision between $2^\circ$ and $10^2$ in the interval from $-10$ to $10$ cm. In $40$ and $80$ cm we see some quite significant fluctuations, and by inspecting the measurement data it is seen that the fluctuations are caused by sudden dips of $\sim 6$ dB in the horizontal power component of tag A, and can be ascribed to reflections from the environment.

V. CONCLUSION

In this work we use a simple statistical estimator of the tag inclination based on the RSS from the tag. This extends our work in [4] and effectively removes the requirement for calibration. We enable the use of multiple tags per object in order to increase certainty of the estimated inclination.

The estimator has been evaluated experimentally, and results show a robust inclination estimate up to a distance of $200$ cm and the expected diversity effect when estimating the joint inclination using multiple tags. For tags passing by in front of the reader antenna we showed how the method had superior performance when the tags were located in the area right in front of the reader antenna, as expected.

For future work it would be interesting to see how the estimator performs with tags attached to real life objects, as the material affects the characteristics of the tag.

REFERENCES


A Novel Technology for Motion Capture Using Passive UHF RFID Tags

Rasmus Krigslund, Strahinja Dosen, Petar Popovski, Jakob L. Dideriksen, Gert F. Pedersen and Dario Farina

Accepted for publication in IEEE Transactions on Biomedical Engineering, in 2012.
Abstract—Although there are several existing methods for human motion capture, they all have important limitations and hence there is the need to explore fundamentally new approaches. Here we present a method based on a Radio Frequency Identification (RFID) system with passive Ultra High Frequency (UHF) tags placed on the body segments whose kinematics is to be captured. Dual polarized antennas are used to estimate the inclination of each tag based on the polarization of the tag responses. The method has been validated experimentally for the shank and thigh in the sagittal plane during treadmill walking. The reference joint angles for the validation were obtained by an optoelectronic system. Although the method is in its initial phase of development, the results of the validation are promising and show that the movement information can be extracted from the RFID response signals.

I. INTRODUCTION

Measurement of human movement is of interest in many fields, such as biomechanics, rehabilitation engineering, motor control, as well as in gaming and movie industries. Human movement is characterized by the kinematic trajectories (i.e., relative and/or absolute angles) of body segments, which can be recorded using several existing technologies [1].

The golden standard for human motion capture is the optoelectronic system with infrared cameras. The cameras track the positions of markers placed on the body segments, and from this information a segment 3D pose (i.e., position and orientation) is obtained. This system has high precision, but the measurement requires expensive laboratory equipment, and thus the analysis is typically confined to a laboratory space. Moreover, the measurement may be influenced by light reflections (i.e., ghost markers) and marker occlusions (i.e., a line of sight problem). Alternative to optoelectronic systems, goniometers can be used to directly measure joint angles. The most common goniometers for motion analysis comprise two plastic bars that are placed on the body segments and to place consistently. Inertial sensors measure acceleration (accelerometers) or angular velocity (gyroscopes) [2]. These are practical sensors convenient for daily use since they have low cost and small size. However, computing joint angles from noisy velocity/acceleration signals is undermined by several sources of error (e.g., integration drift, collision accelerations) [1]. Typically, a cluster of sensors has to be used, and the angle is estimated employing sensor fusion methods (e.g., Kalman filtering) to improve robustness. However, this also increases the complexity and cost of the measurement system. Magnetic systems, which use sensors placed on the body to measure the field emitted by a source, are also available, but have not been widely used due to restrictive limitations [1]. Finally, markerless motion tracking methods based on computer vision are currently under extensive investigation but are still of very limited utility [3].

The aforementioned methods offer a wide variety of possibilities for studying human movement. However, these techniques, whose basic principles are well known since long ago, share limitations as described above. Therefore, it is beneficial to explore fundamentally new approaches that would solve some of the open problems and also stimulate further development in the field (out-of-the-box thinking). In this study we thus propose a novel method to address the problem of assessing body segments orientation in space. The method is based on the use of passive Radio Frequency Tags (RFID). It has to be noted that although RFID has been previously used for some biomedical applications (e.g., see [4] and [5]), these previous studies all applied RFID in the classical context, i.e., for object identification and gross localization. Conversely, in this paper we propose for the first time the use of dual polarized antennas to capture the polarization profile of UHF
RFID tags in order to record the actual orientation in space of human segments/joints during movement (i.e., human motion capture). This approach is therefore fundamentally different from the previous biomedical applications of RFID, both for the way in which the sensor signals are processed and used (i.e., estimating the tag orientation in space instead of reading the tag ID) and for the final type of information extracted (i.e., motion capture instead of gross body localization). The method that we propose (i.e., polarization profile measurement) was initially applied in a static context unrelated to human motion capture [6]. The goal of the present study is to provide a proof of concept of the feasibility of measuring joint angles during human walking using a fundamentally new methodology with respect to the current efforts in this field.

II. PROPOSED METHOD

We focus on the movement in the sagittal plane of a single leg during walking. The thigh and shank are equipped with Radio Frequency IDentification (RFID) tags, denoted T and S respectively, as illustrated in Fig. 1. The absolute angle of the individual leg segments with respect to the horizontal axis is obtained from the inclination of the tags, $\theta_i$ and $\theta_s$. The inclination can be determined by estimating the polarization angle of the RFID tag response signals.

The tag antennas have a single linear polarization, hence the direction of the electric field backscattered from the tag antenna follows the longitudinal degrees from end to end of the antenna conductor. Using a dual polarized reader antenna we decompose the Received Signal Strength (RSS) of the tag response $y_i$, where index $i$ belongs to $\{s, t\}$, into horizontal and vertical dimensions, termed $y_iH$ and $y_iV$ respectively. The estimated polarization angle is then $\hat{\theta}_i = \arctan \left( \frac{y_{iV}}{y_{iH}} \right)$.

III. EXPERIMENTAL SETUP AND DATA PROCESSING

To evaluate the proposed method, the leg movement was simultaneously measured using an RFID system and an optical motion capture system, while a male subject (h: 187 cm, w: 68 kg, 28 yrs.) was walking on a treadmill at a constant speed of 2.4 km/h (slow walking) and 4.8 km/h (normal walking). After warming up, the subject walked 5 min at each speed. The subject held his hands above the hips (elbow flexed) in order not to occlude the RFID tag placed on the thighs. The experiment was approved by the local ethical committee.

The RFID system comprised an Impinj Speedway Revoloution Reader [7] and a single dual polarized antenna. The antenna was positioned to a similar height as the knee at a distance of 80 cm from the subject. This distance was selected due to a limited space available, although the actual range of the UHF RFID is much larger (several meters). The reader antenna was oriented with an observation angle normal to the sagittal plane. The tags were Alien "Squiggle" tags, since they have small dimensions (94.8 x 8.15 x 0.25 mm) and good dipole characteristics [8]. They were attached to each leg segment with the long tag axis aligned with the longitudinal segment axis. The RFID tags were placed on a 30 mm thick plastic support which was secured to the leg segments using a double sided tape. This plastic support, transparent to the electromagnetic field, was used in order to reduce the effect of biological tissues on the electromagnetic radiation. During walking, the shank and thigh segments are mainly vertical, i.e., the long segment axes rotate within the second and first half of the III and IV quadrant of the world coordinate system CSW (lab horizontal and vertical), respectively. The long axis of the tag is aligned with the long axis of the segment, and the tag antenna therefore moves identically. In order to obtain a good response from each tag in both dimensions of the dual polarized reader antenna, the reader antenna was rotated by $+45^\circ$. By using this configuration, we avoid 100% polarization mismatch and bias towards the vertical component response. The tag antenna now moves through the III quadrant of the slanted coordinate system of the reader antenna (CSRA), and the polarization changes symmetrically along both axes. However, since the power levels are positive, the estimated angles are always obtained as if they belong to the first quadrant of CSRA. To obtain the angles in CSW, constant offsets have to be added, i.e., 180 degrees to map the angle from the 1 to III quadrant of CSRA followed by 45 degrees for the shift from CSRA to CSW, hence:

$$\hat{\theta}_i = \arctan \left( \frac{y_{iV}}{y_{iH}} \right) + 180^\circ + 45^\circ \quad (1)$$

The reader samples each tag with a sample rate of about 25 Hz, and the interrogation is based on the EPC Global Gen2 protocol [9]. The order of identified tags is thus random, and it is necessary to match the samples in order to ensure that the inclination estimates are based on vertical and horizontal samples with approximately the same time stamp.

The optical motion capture system used for reference (ProReflex cameras, Qualisys AB, Sweden) included eight infrared cameras encircling the treadmill. Reflective markers were attached using a double sided tape to the hip knee and ankle joints of the left leg. The sampling rate for the camera system was set to 100 Hz. From the recorded joint trajectories, we derived the absolute, sagittal plane angles for the thigh and shank segments with respect to the horizontal. The angles were filtered by a first order zero phase shift Butterworth filter with the cutoff frequency of 6 Hz [10].

The estimated segment angles were checked visually and outlier points, which occurred very rarely, were manually deleted. As described above, the estimated angles are mapped to the world coordinate system. We have observed two additional systematic errors. The estimated thigh angle overshot the reference signal, and there was a slight phase shift of few samples between the estimated and reference signals for both angles. These discrepancies were consistent during the measurement and thus they were corrected by time-aligning and rescaling the signals according to the reference system.

For direct comparison with the reference results, the estimated angles were up-sampled to 100 Hz by using linear interpolation and then filtered by the same filter as the reference signals. The obtained smoothed angles were considered as the final outcome of the measurements.
To evaluate the quality of the measurements by the new system, we calculated the cross correlation coefficient (CORR) and the mean absolute error (MAE) between the angles estimated using RFID tags and the angles recorded by the motion capture system (reference).

### IV. Results

Representative results are shown in Figs. 2 and 3. Fig. 2 illustrates the spatial precision of the measurement. It shows several snapshots of the subject leg during the swing phase of a representative gait stride. The estimated configurations are close to the reference ones and the error in joint positions is less than a few centimeters. The error increased from proximal to distal locations. The average absolute distance error (standard deviation) was 1.5 cm (±1.2 cm) for the knee and 2.8 cm (±1.5 cm) for the ankle joint.

Fig. 3 depicts six strides that were recorded at the walking speed of 2.4 km/h. Panels 3(a) and 3(b) represent the estimated angles with random and systematic errors corrected. Panels 3(c) and 3(d) are the resampled and smoothed signals that are the final outputs of our measurement. Note that the RFID system uses sparse and non-equidistant sampling. Nevertheless, the output follows the angle trajectory. This is an important result demonstrating that the polarization profile actually contains the information of interest. The task of the future steps will be to refine the extraction of this information. Furthermore, the final outcomes, i.e., the smoothed signals, closely track the reference value. It should be noted that the tracking is worse around the limits of the reference signals.

Table I reports a summary of the results as CORR and MAE computed for the entire walking trial. The cross-correlation coefficients were higher than 0.9 in all cases, and the thigh angle estimation was more accurate than the shank angle. The estimation accuracy was similar at both speeds.

### V. Discussion

In this work, we have demonstrated the feasibility of a radically novel approach for measuring human movements. The trajectories of the shank and thigh segments during walking were successfully recorded, and this was done with a good accuracy (Table I). The performance should be evaluated by taking into account that the method is in its initial phase of development. The goal of this study was to provide a first proof of concept of the approach, and the task of the subsequent research will be to refine the accuracy (see below). The current precision is not high enough for a rigorous biomechanical analysis, but even at this stage, the method could be used in some applications for which high precision is not critical (e.g., electrical stimulation triggering). Overall, the first tests are very promising since the current results were obtained with basic components and a simple heuristic model with no assumptions on the nature of the signal to be estimated. Therefore, the precision can be improved significantly by further developments in hardware and software, optimizing the sampling and decision procedures, as indicated below.

As indicated in section III, there was a difference in phase between the estimated and reference angles. This is due to a slight time mismatch between the samples collected by two orthogonal reader antennas, introducing a systematic error in the estimated angle, which appears as a phase shift. Moreover, in some cases the estimated angle overshot the reference values. This is likely due reflections and nonlinear inverse tangent function (equation (1)). The change in received power is thus non-proportional to the change in angle. However, the influence of these effects can be minimized by a special antenna design or in the post processing of the data.

The presented setup is practical and only requires placing the passive tags along the segments of interest. The plastic separation can be reduced significantly by designing an application specific antenna. Therefore, the tags, which are very thin, can be integrated within a motion capture suit. However, this is outside the scope of this work.

The main advantages of the proposed system over the existing methods are simplicity, low cost and the way each leg segment is marked with the unique ID from the RFID tags. Hence, the data is directly coupled with the correct segment. This property of the proposed system is particularly important since automatic marker identification in optoelectronic systems with passive markers is an open problem [1], [11].

As can be seen in Fig. 3, the direct output of the RFID system is non-smooth, but this is only due to the technical limitations of the currently used equipment. The sampling rate (~ 25 Hz) and resolution of RSSI measurements (~ 1 dBm) were relatively low [10]. The recorded RSSI during subject walking was in the range from -66 to -45 dBm. The mapping from RSSI levels to angles is nonlinear, and the resolution (delta RSSI to delta angle) depends on the ratio between the horizontal and vertical power components, i.e., the angular change for a change of 1 dBm in either component can range from less than a degree to a few degrees (for components

![Fig. 2. Stick figure model of the recorded walking for a swing phase of a gait stride. The estimated (RFID) and reference (cameras) model snapshots are shown with dashed and solid lines, respectively. The two configurations are close together throughout the movement.](image-url)
similar in size). The next step in the development of the system hardware is to increase the fidelity of the recording by increasing the precision of the sensing antenna and also by increasing the speed/rate of tag readings. The latter can be done by using a custom designed tag reader.

Parallel to the hardware development, it will be necessary to refine the precision of the system by developing more sophisticated estimation techniques that would use prior information, more signal samples and/or sensor fusion methods (e.g., Kalman filtering) to refine the estimate.

In this experiment, we have used a single dual polarized antenna to capture planar motion, i.e., the motion of the tag in the sagittal plane. In this setup, the out of plane motion of the tag affects the estimate by introducing a polarization mismatch in the two dimensions observed by the antenna. To account for this distortion, multiple reader antennas observing the tags from multiple directions can be used. This might enable reconstruction of the tag orientation in multiple planes (i.e., full 3D capture). The goal of the current study was to test the feasibility of the method, using the simplest scenario.

In conclusion, we have demonstrated the potential of a radically novel method for detecting human movements. The true performance and capabilities of the novel technology are yet to be tested. Even if it may not be possible to achieve a precision similar to optoelectronic systems, further research efforts following this proof of concept could lead to a very practical, simple and low cost system. The novel solution would bring a number of unique features with respect to the currently used technology (e.g., automatic identification, sensors seamlessly integrated into the mocap suit). Depending on the obtained performance, this research can lead to a general purpose motion capture system (e.g., gait recording and analysis) or an application specific solution (e.g., electrical stimulation triggering). In both cases, it would be an important addition to the current state of the art.

REFERENCES

Paper 6

Experimental Assessment of 3D Gesture Recognition Using Passive RFID Tags

Rasmus Krigslund, Petar Popovski and Gert F. Pedersen

Submitted in June 2012 to IEEE Transactions on Industrial Electronics.
Experimental Assessment of 3D Gesture Recognition Using Passive RFID Tags

Abstract—This paper investigates the application of passive UHF Radio Frequency IDentification (RFID) tags for recognizing gestures in three dimensions. We use the passive tags as simple orientation sensors and assess experimentally the possibility to differentiate among several predefined motions with a tag or object. We propose a novel method estimating and tracking the tag orientation in 3D based solely on the physical characteristics of the tag reply, collected from multiple reader antennas distributed around the interrogation zone. The results demonstrate a good potential, as even with simple data processing the proposed method enables differentiation of simple gestures. To use passive tags as dedicated orientation sensors requires, however, more sophisticated methods for data processing. Nevertheless, our investigation clearly shows that the orientation information is available, and can be extracted using suitable data and signal processing techniques.

I. INTRODUCTION

The research field of Radio Frequency IDentification (RFID) technology has been very active for several years, and most recently there has been a trend towards using RFID tags as more than just a mean for identification of objects, namely RFID sensors. This means using RFID tags to collect information about the object they are attached to or the environment around them, in addition to collecting their unique ID. This could for example be temperature [1], humidity [2] or strain [3], all based on standard passive UHF tags. Within sensor applications especially on-body sensor networks are of interest [4], i.e. sensors that are monitoring key parameters and vital signs [5].

In this work we propose to use passive RFID tags for orientation sensing in three dimensions, in order to enable recognition of gestures, i.e. predefined motions with the tag or tagged object. This is achieved by illuminating the interrogation zone with multiple reader antennas. Each antenna collects information about the polarization characteristic in the tag reply, from which the orientation is estimated and tracked. Basically this means that standard passive UHF RFID tags, without any customization, can be utilized in this application.

Related work on RFID motion sensing considers motion detection rather than recognizing certain kinds of motion, i.e. a binary sensor detecting if there is motion or not [6], [7]. For capturing the motion inertial sensors, measuring acceleration (accelerometers) and/or angular velocity (gyroscopes), are usually applied [8]. The advances within integrated circuitry continuously decreases the size and power requirements of Inertial Measuring Units (IMUs) and recently [9], [10] presents small low power sensor devices for tracking the orientation of human body limbs and thus enable human motion capture using wireless sensors. In [11] and [12], devices are presented for capturing the detailed motion of for example the hand and fingers, in order to be able to reconstruct haptic of the hand with respect to the physical world. However, computing the orientation from noisy velocity/acceleration samples are subject to several sources of error, e.g. integration drift and collision accelerations [13]. Moreover these wireless sensors requires an internal power source and their lifetime is thus limited.

In this work we focus on passive RFID tags, as they are cheap and have a long life time. Moreover, recognizing motion, or gestures, is to the best of the authors knowledge a novel application for passive RFID tags. The tags motion information is collected by continuously estimating and tracking the orientation of the tag, based on tag replies collected by multiple reader antennas. These antennas are dual linearly polarized antennas and thus capable of decomposing the Received Signal Strength (RSS) in the tag reply into horizontal and vertical dimensions. From this RSS vector we then have information about the polarization of the tag antenna. This method was initially presented in [14] and utilized for motion capture in two dimensions in [15]. In this paper we extend these ideas to three dimensions by fusing the data collected by multiple reader antennas with a Kalman filter. The ability of the proposed method to recognize gestures is investigated through experimental evaluation and measurements.

The remainder of this paper is structured as follows: In Section II the details of the proposed method are described. The utilized experimental setup is presented in Section III, and the initial results and data processing required before the proposed method can be applied are described in Section IV. Section V presents the final results and their potential and applicability are discussed in Section VI. The final conclusions are drawn in Section VII.

II. PROPOSED METHOD

In order to collect information about the orientation of the RFID tag, we reuse the method from [14]. For convenience we briefly recapitulate the method here, but for further details the reader is referred to [14]. Essentially the reader is interrogating the tag using a dual linearly polarized reader antenna, i.e. with two orthogonal and linearly polarized antenna elements, oriented vertically and horizontally. The total RSS in the tag reply is thus decomposed into horizontal, $H$, and vertical, $V$, dimensions, as illustrated in Fig. 1. This two dimensional vector, denoted $t$, holds information about the angle of the tag, seen from the observation direction of the reader antenna.
However, the RSS is positive by definition, and in effect all orientations of a tag is mapped to the first quadrant. As an example, a tag inclined by an angle of 110° appears as having an inclination of 70°. Hence this mapping of $t$ represents an ambiguity regarding the true angle of the tag.

A. Using Multiple Reader Antennas

Where we utilized a single dual polarized reader antenna in [14], [15], we need multiple reader antennas to estimate the orientation in three dimensions. These $M$ antennas are distributed around the area in which the tag is located, and the directions from which they each observe the tag therefore differs significantly, hence the orientation of the tag appears different depending on which antenna is collecting the RSS samples. This is referred to as a projective transformation between coordinate spaces. As an example consider the illustration in Fig. 2. The orientation is given by a three dimensional rotation of the $A_i$ vector observed by antenna $A_i$. For $i \in \{1, \ldots, M\}$, can then be described as a three dimensional rotation of $t_0$ from the world coordinate space to the coordinate space of $A_i$, followed by a projection to the $xz$-plane:

$$
\begin{bmatrix}
    t_{i,x} \\
    t_{i,y} \\
    t_{i,z}
\end{bmatrix} = R_i \cdot t_0
$$

(1)

In practice the projection means that $A_i$ only observes $t_{i,x}$ and $t_{i,z}$, i.e. $t_i = [t_{i,x}, t_{i,z}]^T$. The rotation matrix $R_i$ represents a rotation around three axes, $x$, $y$ and $z$ in that order, according to the three rotation angles $\theta_{x,i}$, $\theta_{y,i}$ and $\theta_{z,i}$:

$$
R_i = R_{z,i} \cdot R_{y,i} \cdot R_{x,i} =
\begin{bmatrix}
    \cos \theta_{z,i} & -\sin \theta_{z,i} & 0 \\
    \sin \theta_{z,i} & \cos \theta_{z,i} & 0 \\
    0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
    \cos \theta_{y,i} & 0 & \sin \theta_{y,i} \\
    0 & 1 & 0 \\
    -\sin \theta_{y,i} & 0 & \cos \theta_{y,i}
\end{bmatrix}
\begin{bmatrix}
    1 & 0 & 0 \\
    0 & \cos \theta_{x,i} & -\sin \theta_{x,i} \\
    0 & \sin \theta_{x,i} & \cos \theta_{x,i}
\end{bmatrix}
$$

(2)

For convenience we write $R_i$ as a function of the three rotation angles, i.e. $R_i(\theta_{x,i}, \theta_{y,i}, \theta_{z,i})$. It is assumed that the position and orientation of all $M$ antennas with respect to the world coordinate space is known in advance, and with that all rotation matrices $R_i$. The rotation from the antenna coordinate space back to the world coordinate space is given by the inverse rotation matrix, $R_i^{-1}$, and one may argue that knowing $R_i$ and $t_i$, then estimating $t_0$ would simply be a matter of back-rotation. However, it should be noted that $t_i$ is two dimensional, since the $y$-component is not obtained, and three dimensional back-rotation is thus not feasible.

B. Kalman Filter

The vector $t_i$ obtained by $A_i$ represents the orientation of the tag from the observed direction. The Kalman filter estimates the tag orientation vector in the world coordinate space, based on the two dimensional RSS samples collected from the $M$ reader antennas. To a given time $n$ the orientation vector element $t_{i,z}$ can be written as:

$$
t_{i,z}[n] = t_{i,z}[n-1] + v_{i,z}[n-1] \cdot \Delta
$$

(3)

Where $t_{i,z}[n-1]$ is the orientation, and $v_{i,z}[n-1]$ the angular velocity, in the $z$-dimension for the previous time instance. $\Delta$ refers to the time interval from $n-1$ to $n$. The angular velocity can be written as:

$$
v_{i,z}[n] = v_{i,z}[n-1] + u_z[n]
$$

(4)

Where $u_z[n] \sim \mathcal{N}(0, \sigma_z^2)$ and represents the random changes in the motion velocity. The magnitude of $\sigma_z^2$ depends of the type of motion to be captured, but it also represents the certainty of the model. For large $\sigma_z^2$, the filter relies more on the data directly, and less on the data model. We then write the orientation vector to time $n$ as:

$$
t_i[n] = t_i[n-1] + v_i[n-1] \cdot \Delta
$$

(5)

From this we have that the problem of capturing the motion of a tag means updating estimates of the three dimensional orientation and angular velocity. We concretate these parameters in the state vector, $s[n] = [t_{i,z}[n], t_{i,y}[n], t_{i,x}[n], v_{i,z}[n], v_{i,y}[n], v_{i,x}[n]]$, given by the state equation:

$$
s[n] = A \cdot s[n-1] + u[n]
$$

(6)
Where:

\[
A = \begin{bmatrix}
1 & 0 & 0 & \Delta & 0 & 0 \\
0 & 1 & 0 & 0 & \Delta & 0 \\
0 & 0 & 1 & 0 & 0 & \Delta \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix},
\]

\[
u[n] = \begin{bmatrix}
u_x[n] \\
u_y[n] \\
u_z[n]
\end{bmatrix}
\]

The input to the Kalman filter is the obtained RSS samples from the reader antennas concatenated into a vector \(x[n]\), which can be modeled as:

\[
x[n] = H \cdot s[n] + w[n] \tag{7}
\]

Where \(w\) is the measurement noise, assumed to be zero mean Gaussian, and \(H\) is the function that maps the state vector from the world-coordinate space to the coordinate spaces of the reader antennas. The rotation matrices given in (2) performs a mapping from the three dimensional world coordinate space to the \(i\)-th antennas coordinate space, also in three dimensions. However, each antenna observes only an orientation vector component in the \(x\) and \(z\) dimension. The matrix \(H\) represents thus a mapping from three dimensions to two, using only the first and last row from the rotation matrix in (2). For convenience we refer to a rotation matrix comprised by the first and last row of \(R_i\) as \(R'_i\). \(H\) is then given by:

\[
H = \begin{bmatrix}
R'_1 \\
R'_2 \\
\vdots \\
R'_{M}
\end{bmatrix} \tag{8}
\]

In order to accommodate multiplication with \(s[n]\) of length six the size of \(H\) is increased by adding the \(2M\)-by-three zero matrix, \(0\).

The Kalman filter is then an iterative process traversing the following steps for each new observation of the tags orientation vector:

1) Prediction:

\[
\hat{s}[n|n-1] = A \hat{s}[n-1|n-1]
\]

2) Minimum prediction MSE:

\[
M[n|n-1] = AM[n-1|n-1]A^T + Q
\]

3) Kalman gain:

\[
\]

4) Correction:

\[
\hat{s}[n|n] = \hat{s}[n|n-1] + K[n](x[n] - H\hat{s}[n|n-1])
\]

5) MSE:

\[
M[n|n] = (I - K[n]H)M[n|n-1]
\]

Where \(Q\) is the data model variance. When specifying the change in the angular velocities we assume that the change in each dimension is independent, and equally likely to affect the motion in any of the three dimensions, hence:

\[
Q = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \tag{9}
\]

Moreover, for simplicity we assume that the estimation errors in each dimension are independent and the variances are time invariant, hence:

\[
C[n] = C = \begin{bmatrix}
\sigma^2_x & 0 & 0 \\
0 & \sigma^2_y & 0 \\
0 & 0 & \sigma^2_z
\end{bmatrix} \tag{10}
\]

The initialization of \(\hat{s}[n], \hat{s}[-1| -1]\), is not required to be precise, as the filter will converge to a more suited estimate within the first iterations. Hence \(\hat{s}[-1| -1]\) and \(M[-1| -1]\) is thus initiated as \(0\).

III. EXPERIMENTAL SETUP

In order to test the proposed methods ability to capture the motion of an RFID tag and recognize gestures, we have designed a test scenario with a well defined motion for the sake of repeatability. Moreover, the motion throughout the measurement should be continuous and three dimensional. However, the available equipment for automated motion, in this case an step motor, is limited to motion in a single plane. The utilized setup is illustrated in Fig. 3. The world coordinate space is indicated with a cardboard shape in the figure, and the three antennas utilized in this setup, i.e. \(M = 3\), is placed so their direction of observation is parallel with one of the world coordinate axes: \(A_1\) is parallel with the \(y\)-axis, \(A_2\) with the \(x\)-axis and \(A_3\) with the \(z\)-axis. This gives the following rotation matrices:

\[
R_1(0, 0, 0) \\
R_2(0, 0, 90) \\
R_3(90, 0, 0)
\]

The tag, \(A_1\) and \(A_2\) are raised 110 cm from the ground and the distance to the tag is 130 cm for all three antennas. The communication with the tag, an Alien 9640 “squiggle” tag [16], is facilitated by an Impinj Speedway Revolution Reader [17]. The dual linearly polarized reader antennas are custom made horn antennas, matched to the RFID frequency band around 900 MHz.

IV. INITIAL RESULTS AND DATA PROCESSING

In order to check that the setup is providing RFID data in the expected dimensions initial measurements have been conducted. Using the step motor the tag is rotated five times 360° in each of the three planes spanning the world coordinate space, i.e. the \(xy\)-plane, \(xz\)-plane and \(yz\)-plane. Fig. 4 shows the RSS samples collected from the tag rotating in the \(xy\)-plane, while the reader was interrogating the tag with a
power of 27 dBm on all antennas. \( A_3 \) is receiving tag replies in both polarizations as expected, and these RSS samples are therefore omitted in order not to clutter the figure. For \( A_1 \) and \( A_2 \) we see that the RSS samples received in the horizontal polarization are developing as expected. The power level is changing periodically due to the changing polarization mismatch caused by the rotation. However, with the applied rotation in the horizontal \( xy \)-plane it is not expected to receive RSS samples in the vertical polarization, but from Fig. 4 it is evident that the vertical antenna elements are in fact collecting samples. This is due to the high interrogation power and the lab environment with several reflecting surfaces mixing the polarization of the signals. This is undesired since any power in an unintended polarization will contribute with error in the resulting orientation estimate. To mitigate this effect the readers interrogation power is reduced to 19 dBm, which removes the RSS samples in the undesired polarizations, and this is also the case when measuring tag rotation in the \( xz \)- and \( yz \)-planes. Hence this power level is used henceforth. This makes the polarization vectors from \( A_1 \) and \( A_2 \) one-dimensional, and the method for estimating the tag orientation relies on two dimensional RSS samples from each of the dual polarized reader antennas. We therefore introduce artificial samples whenever an interrogation round for a given antenna element returns empty. These samples should ideally have no power content, and are thus set to \(< -90 \) dBm.

Of the three utilized reader antennas, \( A_1 \) and \( A_3 \) are prototypes, and their characteristics are therefore expected to differ slightly from \( A_2 \). From Fig. 4 we see that even though the horizontal antenna elements are equally distanced from the tag, they received very different RSS values. Investigating the RSS for the tag rotations in the \( xz \) and \( yz \) planes shows similar difference. These differences in RSS level will contribute with errors in the final orientation estimate, hence the RSS levels are aligned (calibrated) by adding 3 dB to the samples received in both elements of \( A_1 \) and 2 dB to the samples received in the horizontal element of \( A_3 \).

Moreover, if we consider Fig. 4 from a signal processing point of view, then the RSS plot resembles 10 wavelengths within the period of motion, i.e. \( \sim 90 \) s, and represents thus a signal of \( \sim \frac{1}{2} \) Hz. The quantization, due to the 1 dBm resolution in the RSS from the reader, can then be regarded as a high frequency noise component that can be filtered away. The Nyquist criteria dictates a sampling rate of twice the highest frequency component to be represented, and with a sampling rate of \( \sim 16 \) Hz the RSS signal is oversampled significantly. To filter the RSS samples we use a second order Butterworth low pass filter, where we use a cut-off frequency of \( \frac{1}{2} \) Hz in order to not have the attenuation in the cut-off frequency affecting the magnitude of the RSS values. A filter introduces a delay causing a horizontally shift of the RSS curves. This delay is undesired and can be minimized using more advanced filter techniques, but this is outside the scope of this work.

V. Results

The proposed method is tested in the setup described in Section III. We use two simple gestures, i.e. the circular gesture with five consecutive rotations in each of the three planes, \( xy \), \( xz \) and \( yz \), as introduced in Section IV, and a semicircular gesture, where the tag is rotated in three consecutive half circles. Initially we focus on gestures in the \( xy \)-plane, and the individual components of the estimated orientation vectors for circular and semicircular gestures are plotted in Fig. 5 as a function of time. We see that the Kalman filter is able to reconstruct some periodic behavior in the orientation of the tag for both types of gestures, and the magnitude of the estimated vector components vary between the two gestures. However, from the vector components alone it is not clear which are from the circular and which are from the semicircular gesture. To make this difference more visible the orientation vector components vary between the two gestures. However, from the vector components alone it is not clear which are from the circular and which are from the semicircular gesture. To make this difference more visible the orientation vector components.
As described in Section II, the estimated orientation components are plotted individually as a function of time.

For both gestures in the $xy$, $xz$ and $yz$-planes are plotted in 3D, in Fig. 6. We see that the estimated orientation vector from the circular gesture forms a crude circular shape, while the semicircular gesture forms a lunar-shape. This indicates that we may be able to differentiate between the circular and half circular motions. But to enable automatic classification of these gestures we define two heuristic metrics, one for determining the plane of the gesture, and one to distinguish between the circular and half circular gestures. From Fig. 5 it is quite clear from the variations in the vector components in which plane the gesture is performed. Hence to identify the correct plane of the gesture we simply use the standard deviation of the individual vector components in $\hat{t}$, denoted $\sigma_{\hat{t}x}$, $\sigma_{\hat{t}y}$ and $\sigma_{\hat{t}z}$ respectively. The two dimensions with the largest standard deviation are then spanning the plane of motion. In Table I the standard deviations are listed for the three planes, respectively. The vector components are plotted individually as a function of time.

To distinguish between the gestures we use a simple metric exploiting the difference in the shape of the gestures. Both gestures are performed with the same rotational speed, and both are periodic. One rotates $180^\circ$, changes direction and returns to the initial orientation, while the other makes a full $360^\circ$ rotation before the tag returns to its initial orientation, and they have thus equal periods. In Fig. 7 the trajectory for one period of the two gestures are drawn with dashed lines. We assume a period contains $k$ samples and in total $N$ samples have been collected during a measurement ($N >> k$). On the trajectories in Fig. 7, two points, $p_1$ and $p_2$, have been marked, and they are separated by a half period in time, i.e. $\frac{k}{2}$ samples. As described in Section II, the estimated orientation vector plotted in 3D for both gesture types in the $xy$, $xz$ and $yz$ planes, respectively. It should be noted that in order to increase the readability of the figure, all axes have been scaled with $10^3$. For both gestures and all three planes

Table I

<table>
<thead>
<tr>
<th></th>
<th>$\hat{t}x$</th>
<th>$\hat{t}y$</th>
<th>$\hat{t}z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\hat{t}x}$</td>
<td>$5.89E-10$</td>
<td>$1.60E-5$</td>
<td>$2.02E-5$</td>
</tr>
<tr>
<td>$\sigma_{\hat{t}y}$</td>
<td>$1.27E-5$</td>
<td>$1.04E-5$</td>
<td>$2.26E-7$</td>
</tr>
<tr>
<td>$\sigma_{\hat{t}z}$</td>
<td>$2.90E-5$</td>
<td>$5.20E-10$</td>
<td>$1.87E-5$</td>
</tr>
</tbody>
</table>

Fig. 5. The estimated orientation vector $\hat{t}$ for circular and semicircular gestures respectively. The vector components are plotted individually as a function of time.

Fig. 6. The resulting orientation vector plotted in 3D for both gesture types in the $xy$, $xz$ and $yz$ planes, respectively. It should be noted that in order to increase the readability of the figure, all axes have been scaled with $10^3$. Examples.
vector for a given time instance \( n \) is denoted \( \hat{t}[n] \), where \( n \in \{0; N - 1\} \), hence we can write \( p_2 = \hat{t}[n' - \frac{1}{2}] \) and \( p_2 = \hat{t}[n'] \), where \( n' \in \{ \frac{1}{2}; N - 1\} \). We define \( D \) as the cartesian distance between \( p_1 \) and \( p_2 \), which is continuously calculated throughout the measurement of the gestures. The vector \( D \) then refers to the complete set of \( D \) samples, and represents the development in the distance between two points on the gesture, separated by half a period in time. In theory the values in \( D \) for a circular gesture would equal the diameter of the circular trajectory of the orientation vector, while a half circular gesture would yield a \( D \) varying between 0 and the diameter. In Fig. 8 we have plotted the \( D \) for both gesture types and all three planes, and we can see that \( D \) is fluctuating significantly, even for the circular gestures. However, these fluctuations are expected given the crude trajectories in Fig. 6. The metric for differentiating between the two gestures is therefore chosen as the mean value of \( D \), denoted \( \mu \), and in Table II, \( \mu \) is listed for both gesture types in each of the three planes. The indexes \( h \) and \( c \) refer to the half-circular and the circular gestures, respectively. The magnitude of \( \mu_c \) is expected to be greater than \( \mu_h \), and the simplest way of differentiating between the two is to define a threshold. In this case if the threshold is set to \( 1.9 \times 10^{-5} \) the method makes the wrong decision for the circular gesture in the \( xy \)-plane, while the rest of the gestures are correctly classified. This means that even with the relatively simple methods used in this work for data processing and classification we are able to differentiate between two types of gestures. Using more advanced methods the reliability of the classification can be improved as well as enable the identification of more complex gestures.

A. Passive Tags as Dedicated Orientation Sensors

It is desired to investigate the potential for extending the work from [15] using the proposed method, and thus enable motion capture in 3D using passive RFID tags. As a simple example we consider the orientation vector components from Fig. 5(a) and compare with a reference vector obtained analytically, based on the known initial orientation of the tag and its predefined motion. The reference vector is denoted \( \hat{t}_0 \) and plotted in Fig. 9 along with the estimated orientation vector, \( \hat{t} \), where the magnitude of the reference components have been scaled to match \( \hat{t} \). We see that the estimated vector components are very different from the analytical reference components. This mismatch is primarily caused by the mapping of all orientation vectors to the first quadrant in each of the antenna coordinate spaces. Moreover, the non-linear effect of the polarization mismatch, as described in Appendix A, is causing an overshoot in the ratio between the horizontal and vertical power component which further contributes with error in the estimated orientation.

From the figure we see that \( \hat{t}_y \) fluctuates between positive and negative values, while and \( \hat{t}_x \) is positive at all times. The resulting estimated motion will therefore not move in all four quadrants in the \( xy \)-plane, which also can be seen from Fig. 6(a).

Limiting the rotation to one of the three planes spanned by the reader antennas is a simplified scenario. A more complicated scenario would contain motion that mixes the three dimensions to a higher degree. As an example consider motion in the \( yz \)-plane, then rotate the rotational plane \( \approx 60^\circ \) around the \( y \)-axis, as illustrated in Fig. 10. In this way all three reader antennas collect RSS samples during the five consecutive rotations, and the resulting orientation estimate is plotted as individual vector components in Fig. 11(a) and in 3D in Fig. 11(b). From these figures it is evident that when
The tilted rotational plane. One dimension is spanned by $y_w$, while the other is a mix of $x_w$ and $z_w$.

Fig. 11. The resulting estimated orientation vector when the rotational plane is tilted between the $yx$ and $yz$ planes. 11(a) shows the vector components plotted individually as a function of time, while in 11(b) the resulting orientation vector is plotted in 3D. It should be noted that in order to increase the readability of the three dimensional plot, all axes have been scaled with $10^3$.

the true motion is mixing the dimensions then, as expected, it becomes increasingly complex to make inference about the type of motion and its orientation in 3D. In Fig. 11(a) we see some indication of the motion, as the $\hat{t}_y$ component reaches significantly higher values compared to the $\hat{t}_x$ and $\hat{t}_z$ components. This is because the $y$-axis spans one dimension of the rotational plane, while the other is mixed between the $x$ and $z$ axes. However, in general these investigations show that more advanced processing is required to enable applicable motion capture in 3D based on orientation sensing.

VI. DISCUSSION

These investigations have shown how the proposed method allows for simple gesture recognition using simple processing based on Kalman filtering and basic heuristic metrics extracted from the estimated orientation vector. Using more advanced methods the reliability of the classification can be improved as well as enable the identification of more complex gestures, or gestures outside the planes spanned by the reader antennas. Moreover, the proposed method is able to make a crude estimation of the tag orientation. However, this estimate offers too low precision for doing motion capture of the tag movements. But the experimental measurements show that the orientation information is available in the physical characteristic of the tag reply, and can be put to use given proper processing techniques. However, instead of capturing the motion of a tag, and thereby an object, the proposed method may be applicable for capturing relative motion, i.e. determine whether the orientation of an object has changed since last time the tag was interrogated.

From the investigations we saw that the estimated orientation was significantly better when the plane of motion was aligned with one of the antenna elements in the reader antennas. Hence the proposed method may be applied in order to determine orientation with a significantly lower granularity, e.g. simply if the tag is vertical or horizontal. Moreover, the two orthogonal linearly polarized antenna elements in a reader antenna can be used to make a linearly polarized signal with any polarization angle. This is achieved by transmitting simultaneously on both antenna elements and the resulting polarization angle can be adjusted through the phase difference between the two signals. In the current setup the reader operates each antenna individually as it switches between the antenna ports. It would therefore not affect the current operation if both antenna elements where fed the same reader signal, and in one time instant a phase difference resulting in one polarization angle, while in the next time instant another phase difference and polarization angle. This would increase the complexity of the experimental setup, and require comprehensive control of the phase differences in order to identify the plane of motion. However, each dual polarized reader antenna will then only occupy a single antenna port on the reader, and thus effectively reduce the required number of ports by a factor of 2.

Moreover, since the proposed method is based on the polarization of the received signal, it sets certain requirements to the utilized antennas. But the method is not restricted to RFID systems, and can therefore be ported to other wireless technologies where linearly polarized antennas are applicable, e.g. Bluetooth and WiFi devices.

VII. CONCLUSION

The experimental investigations in this paper seeks to assess the potential of recognizing gestures, i.e. predefined motions, performed with standard passive UHF Radio Frequency
IDentification (RFID) tags. The proposed method is estimating the orientation of the tags based solely on the polarization characteristic in the tag reply, and the passive tags are thus utilized as orientation sensors. The polarization of the tag reply is obtained by sampling the Received Signal Strength (RSS) in the horizontal and vertical dimensions using dual linearly polarized reader antennas, whose combined data is fused using Kalman filtering. The results show good potential, as the proposed method using simple metrics enables differentiation of predefined motions, or gestures, performed with the RFID tag. Albeit, the estimated orientation vector offers too low precision to be used as a mean for motion capture in 3D. But the successful gesture recognition using the simple data processing in the proposed method reveals that the orientation information is available in the physical characteristic of the tag reply. For future work it would be interesting to use more advanced data and signal processing, in order to enable recognition of more complex gestures and a more reliable orientation estimate.

Appendix A

LINEARITY OF TAG INCLINATION

In order to investigate the significant errors in the orientation estimate, we compare the tag inclination with the angular relationship between the samples collected in two orthogonal dimensions by the dual linearly polarized reader antenna. This is realized by comparing Finite Difference Time Domain (FDTD) simulations in Matlab, of a tags radiation pattern, with experimental measurements. In the simulations a replica of the Alien “Squiggle” tag is utilized [16], and it is oriented vertically, i.e. parallel with the z-axis, in a three dimensional coordinate space. In Fig. 12 the radiation pattern of the tag in the xz-plane is plotted in a Cartesian coordinate system with linear scale. It should be noted that due to the well known “donut”-shaped radiation pattern, the radiation pattern in the yz-plane is the same. When a tag is inclined in an angle between 0° and 90° it introduced a polarization mismatch in the vertical and horizontal elements in the reader antenna. For a certain inclination angle and a normalized transmission power, the received power corresponds to the gain coefficient in the corresponding angle in Fig. 12(b).

As an example consider a tag being rotated from \( \theta = 0^\circ \) (horizontal) to \( \theta = 90^\circ \) (vertical), in steps of 10°. The power received by the horizontal reader antenna element can be obtained from Fig. 12(b) for the angle equal to \( \theta \), while the power received in the vertical element can be obtained for the angle equal to \( 90^\circ - \theta \). The resulting estimated angle, \( \hat{\theta} \), can then be calculated directly from the vertical and horizontal power components. In the same way we obtain experimental samples of the received power in the horizontal and vertical dimension, while rotating a tag from 0° – 90° (vertical), in steps of 10°. The analytical and experimentally obtained angles, \( \hat{\theta}_h \) and \( \hat{\theta}_v \), respectively, are then plotted in Fig. 13. From the figure we see that the estimated angle is systematically overshooting the true tag inclination. In this work we are not estimating the angle of the tag, albeit this angular mismatch represents a mismatch between the ratio of the horizontal and vertical power components and the geometrical ratio between the true horizontal and vertical vector components. This mismatch is causing the large errors we see in the magnitude of the orientation vector components.

References


Related Contributions Not Part of The Thesis

Contents

Paper 7: Green Communication: Where Can It Really Help and How It is Related to RFID . . . . 85
Paper 8: Using ICT in Greening: The Role of RFID 91
Paper 7

Green Communication: Where Can It Really Help and How It is Related to RFID

Petar Popovski, Rasmus Krigslund, Gert F. Pedersen and Boris Manev

GREEN COMMUNICATION: WHERE CAN IT REALLY HELP AND HOW IT IS RELATED TO RFID

Petar Popovski, Rasmus Krigslund, Gert F. Pedersen
Antennas, Propagation and Radio Networking
Aalborg University
Denmark
E-mail: {petarp, raskri, gfp}@es.aau.dk

Boris Manev
E-mail: borismanev@gmail.com

ABSTRACT
In the recent years, the awareness about the harmful long-term effects of the greenhouse gases (GHG) has markedly increased. As information and communication technologies (ICT) have successfully and irreversibly pervaded everyday life, many technology leaders have started to look into the green ICT, i.e. ICT solutions that have reduced carbon emissions. A sobering report from WWF has indicated that only 2% of the current carbon emissions can be attributed to the ICT systems. Therefore, the real green impact of ICT can be made by using ICT to make the other systems more energy-efficient, such as the buildings, transportation, power grid, industry and production. In this paper we argue that the RFID technology can be one of the key drivers for implementing green ICT solutions in the systems that are not originally associated with ICT, e.g. transportation.

In particular, the passive, battery-less RFID systems have potential to map the physical world to the virtual one and drive actions back from the virtual to the physical world with positive carbon balance, i.e. the carbon emissions saved by those actions are larger than the carbon emissions caused to operate the RFID systems. Motivated by that observation, we list several example green applications of the RFID systems.

I INTRODUCTION
The information and communication technologies (ICT) have brought profound improvements in all the areas of human activity and the quality of life. The latter relies mostly on impact that the ICT has had on the people through the immediate rewards provided by those systems. For example, the mobile phone brings reachability, which is almost ubiquitous, while the Internet provided unprecedented access to information and created countless opportunities for novel social interactions. Nevertheless, ICT has yet to unleash its potential in solving the global problems that will have long-term effects, such as the reversal of the trends in global warming, reduction of greenhouse gases (GHG), dealing with the scarce resources (energy, water), protection of the environment, and sustainable global growth. These objectives are significantly interdependent, while the reduction of carbon emissions will have the largest effects.

Carbon dioxide (CO2) is the most important anthropogenic greenhouse gas (GHG) accounting for almost 80% of the overall GHG emissions in the atmosphere [1]. The usage of ICT for reducing carbon emissions has been a subject of many recent analyses, see [2] and the references therein. It is also seen as one of the areas that can direct the research and innovation within ICT in the coming years. The understanding of the interaction between ICT and GHG is still in its infancy, although some indicators are already emerging. For example, the WWF report [2] has indicated that only 2% of the current carbon emissions can be attributed to the ICT systems. This is a strong message that the benefits obtained from making, for example “green wireless networks” or “green server farms”, can be almost negligible as compared to the benefits obtained if the ICT actions are targeted to ameliorate the activities that are responsible for the dominant part of the carbon emissions, such as the power production sector, buildings, industry and production, transport, etc.

The overall task of putting ICT to work towards making the world greener is enormously complex and includes several subtasks. The first is data collection and analysis, in order to make assessment of the GHG production in relation to all the human activities, and thus make projections about the quantitative impact that the ICT will have on the GHG emissions rooted at those activities. Another subtask is development of the technology that will enable low-carbon operation in the targeted activity areas, as well as innovation of applications that can replace some of the present activities with low-carbon counterparts. The “usual suspect” related to the latter is the replacement of the travels by video-conferencing, but many more applications and examples are needed to drive the environmental impact. A proper milieu for green ICTs to be put to work can be created by suitable policies and strategies. Such policies should be created by accounting for the opportunities and capabilities of the technology. For example, the system of incentives that can be introduced regarding the GHG activities can be built around rules for monitoring/acting that are assuming certain level of technology sophistication.

In this paper we advocate the Radio Frequency Identification (RFID) technology as one of the key components of the green ICT. Before summarizing the arguments behind such a claim, we need to briefly introduce the RFID technology. A RFID system provides automated identification and information gathering from objects and people. The two key components of an RFID system are tags and readers. A tag is a small microchip equipped with antenna which is attached to the physical object or the person. The most interesting types of tags are the passive, batteryless tags, as they can have low cost and thus be deployed in large volumes. The readers (or interrogators) are devices, usually deployed at strategic locations in order to efficiently collect information from the tags in their radio range. The tags attached to the objects or humans and thus make the
physical world perceptible for the computers. That is why the passive tags are enablers of the “Internet of things”. Particularly important developments related to the RFID technology can be seen in RFID sensors and energy harvesting. With RFID sensors, the tag is integrated with a sensor or multiple sensors and the radio link to the reader is used to convey the sensed data. Furthermore, energy harvesting will augment the computation/communication capabilities of the passive tags.

We argue that the role of RFID in enabling green ICT is multilateral. In the data collection process, it enables gathering of information to a very detailed level, which is an important step to relate different activities to the GHG. The usage of RFID tags can have direct impact on the environment by enabling more efficient waste management and recycling. Being the bond between the physical and the cyber world, the tags can be the key drivers in attacking the 98% opportunity of the carbon emissions, by enabling real time planning in the virtual domain and sensing/acting in the physical domain. Finally, the passive tags can enable enforcement of policies and strategies and be instrumental to introduce incentive systems in GHG emission and the carbon trading schemes.

The paper is organized as follows. The next section provides some facts and figures related to emission of greenhouse gases. Section III introduces the basics of RFID and some related technologies. In Section IV we discuss several promising applications that can have tangible impact on the carbon emissions. This section is followed by the concluding section.

II CARBON EMISSIONS: FACT AND FIGURES

Carbon dioxide (CO2) is the most important anthropogenic greenhouse gas (GHG) accounting for almost 80% of the overall GHG emissions in the atmosphere. According to statistics by the International Panel on Climate Change (IPCC) the global atmospheric concentration of CO2 has increased to 379 ppm in 2005, which exceeds by far the natural range over the last 650,000 years (180 to 300 ppm). The concentration of CO2 has grown with increased intensity during the last decade. Thus, while from 1960 to 2005 CO2 concentration had an average growth rate of 1.4 ppm per year, only from 1995 to 2005 the average growth rate has been 1.9 ppm per year [3]. This is a direct consequence of the fact that annual fossil CO2 emissions increased from an average of 23.5 billion tons per year in the 1990s, to 26.4 billion tons of CO2 per year in 2000-2005, see Fig. 1.

II.A Sector Approach

Statistical data shows that largest CO2 emitter is the power production sector with 28% of total emissions [1]. Another 32% of the global CO2 emissions coming from industry, transport, and residential services and agriculture, are emitted by power consumption when energy is processed into final products. Nevertheless, attention should not be concentrated only on CO2 emission but also on other GHG gasses such as CH4, N2O, SF6, HFC, and PFC as they account for almost one fourth, or 23% of the total GHG emissions. Sector- emission percentages are as listed in Table 1.

II.B Intervention

By 2050 global emissions of CO2 need to be reduced by 85% in order to keep the temperature increase below 2C degrees. To achieve this, interventions in each of the GHG emitting sectors is needed by improvement of energy efficiency; increase in the share of renewables in the energy-mix; as well as “cleaning” of the fossil- fuel energy generation sector. Increase in efficiency is mostly relevant in the sectors such as industry, buildings, transport and power generation where energy and materials are being transformed into products and services [1]. The power production sector has on average very low efficiency. Old coal power plants have an average efficiency of 30%. Yet, with new components and optimized process integration, their efficiency could improve up to 50%, which would mean a reduction of 1.4 million tons of CO2 annually [1].

Electric grids, also, contribute to the loss of efficiency. During the transportation of electricity to consumers certain percentage is lost due to electrical resistance in the cables in the grid. Future development of Smart Grid power network will provide sustainable development, efficiency and cost benefits [4]. The Smart Grid leverages on ICT concepts in order to provide information flow and control over the electric grid in order to make the grid more efficient.

A very important and promising sector, where energy efficiency can be increased while CO2 emissions can be significantly reduced is the building sector which is accountable for one third of the global energy related CO2 emissions [5]. Energy efficiency in both commercial and residential buildings can be improved by using variety of technologies, designs and materials. Some technologies and concepts for improvement of energy efficiency are through efficient lighting, for example Light-Emitting Diode (LED). Other interventions that can contribute to energy efficiency include introduction of equipment
with lowest stand-by power, reduction of energy outside office hours, efficient cooling/heating. A good example for such an energy efficient building is the passive house which can save up to 75% energy consumption and thus decrease its carbon footprint [6].

Improvement in energy efficiency requires investments in R&D in new low carbon, and energy efficient technologies. Since 20% of the world’s population that is mostly located in the developed countries consumes 80% of the world’s natural resources including energy, they should be accountable for investment in energy efficiency. Yet, according to predictions by the US Department of Energy, world’s energy consumption will grow by 50% from 2005 to 2050 [7], mostly due to increased demand in emerging economies such as China and India. China and India for instance perceive the western developed countries historically accountable for the concentration of GHG in the atmosphere. They would not agree to cut GHG emissions and invest in energy efficiency if developed countries do not commit to higher GHG emission reduction, share of low carbon technologies as well as investment in energy efficiency in developing countries. Developed countries will have to commit to invest in improvement of their energy efficiency, yet will also have to invest in improvement in the energy efficiency in the developing world without affecting their path to development. According to Greenpeace, G8 countries will only put up the Post-Kyoto negotiation on a path towards success if they commit to contribute USD 106 billion every year by 2020 to help developing countries face the climate change challenges [8].

The dichotomy related to the issue in which countries the investment in energy efficient technologies should be dominant, can be mapped into a dichotomy of two radically different technology approaches. In the developing countries many of the systems (which are major sources of carbon emissions in the developed countries) have not yet been deployed. This gives opportunity for a clean slate system design, which starts to build the powersystem, transportation, industry, etc. based on the level of technological sophistication that is available today or in the near future and, most importantly, not being strongly bound by backward compatibility. Such a clean slate design can, for example, result in a transportation system that is as flexible and personalized as the car, but far more friendly to the environment. In such newly developed systems, ICT will have a decisive role, as the systems will rely on rich information flow and control among the system components.

Contrary to the clean slate approach, in the developed countries there are systems that are widely deployed and cannot be completely and instantaneously replaced, but they need to be gradually evolved, accounting for the backward compatibility. Hence in this case we need wean slate system design, where the existing systems should be upgraded to be weaned on the requirements for low carbon emissions.

III RFID AND SOME RELATED TECHNOLOGIES

There exist several opportunities for using ICT to reduce carbon emissions. Some of these are listed in [2]. One example is to use ICT to optimize scheduling and resource allocation in the physical world. In order to do this the physical world must be made perceptible in the digital world. As an example consider Smart Grid, where measuring devices are sampling the current power usage of a building and maybe estimates near-future power requirements, e.g. by knowing which devices that are currently using power [9]. Using communication systems this information is fed back to the supplier, who can then determine how to distribute the power to the customers most efficiently. A promising technology for coupling the physical world with the digital world is Radio Frequency IDentification, RFID.

III.A Basics of RFID Systems

RFID technology has been around for quite some time now, but recently this area has received immense attention due to reduced costs of implementation and production. An RFID system has two basic parts: Readers and Tags, as illustrated in Fig. 2. The reader is a transceiver that can activate the tag and reads its content. A tag is a device small enough to be embedded into an object, and it consists basically of a microchip with modest storage capacity connected to an antenna. When activated on demand by an external reader the tag backscatters its unique identifier and the information saved in its memory.

There exist different types of tags: Active tags, where an internal power source allows it to transmit its information at any time. However, having its own power source puts a limit to the lifetime of the tag, but it increases the communication range of the tag. The tags that have large potential for wide deployment and usage are the passive tags, which are powered by inductively coupled power from the signal transmitted by the reader. In other words, the passive tags harvest the required energy from the over-the-air transmission by the reader. By omitting the internal power source decreases the production cost and increases the lifetime of the tag.

III.B RFID Sensor Systems

Wireless sensor networks consist of a large number of small sensing, self-powered nodes that gather information and ultimately transmit this information to a base station in a wireless fashion. [10] Recently battery free wireless sensors based on RFID has been considered. RFID sensors is basically a passive RFID tag paired with a small sensing device. In this way the resulting device is a uniquely identifiable sensor with a wireless interface, as illustrated with a block diagram in Fig. 3. An example of such a device has been presented in [11].

Figure 2: The RFID tag and reader comprising a simple RFID system.
This means that the advantages of RFID is brought to wireless sensor networks creating devices with a small form factor and a long lifetime. Similar to the RFID system described in section III.A the RFID sensor is powered from inductively coupling when it is in the range of a transmitting reader, and the RFID sensor then backscatters its unique identifier and the state of the sensor. Since readers are not transmitting continuously, the power source for an RFID sensor is intermittent and unpredictable. This type of communication provides sufficient power for standard RFID systems, where a tag only backscatters the identifier. However, RFID sensors requires more power to operate the sensing device compared to standard tags. Hence it is difficult for the RFID sensor to assure that its tasks are completed based on the power received from the reader. It can therefore be beneficial to consider harvesting energy from other sources than the transmitted power from the reader [12].

III.C Energy Harvesting

Recently energy harvesting has been considered in order to prolong battery life of mobile phones [13], but in the context of small wireless devices, e.g. RFID sensors, it has the potential to make batteries in small wireless devices obsolete. The concept of energy harvesting can therefore decrease production costs as well as the required level of maintenance, while increasing the lifetime of the wireless sensor networks.

There exist several options for harvesting energy from the surroundings [14]. For example energy from light, which requires a large surface, or vibrations which requires mechanical apparatus. However, for wireless sensors a small form factor is desired, hence light and vibrations are not suited as energy sources for this application. Instead, inductive coupling may be an interesting option. In today’s RFID system the tag uses such power to backscatter its identifier to the reader, but this might evolve towards tags that store such energy for later usage. Considering the ubiquity and abundance of various wireless transmitters, a wireless device is not confined to harvest energy from the communication with its own base station, but has the possibility of continuously harvesting energy from ambient transmitters.

IV GREEN APPLICATIONS INVOLVING PASSIVE WIRELESS DEVICES

We have already stated that the potential of RFID regarding green operation of various systems is seen in the fact that RFID provides the link between the physical and the virtual world. In this section we will concretize this, rather abstract, claim through three example green applications of the RFID system or, more general, systems with passive wireless devices.

IVA Supply Chain Management

Today RFID technology is currently used to automate supply chain management. Using RFID tags allows for each item to be uniquely identified providing a complete overview of the supply chain. This knowledge can be utilized in order to cluster items for more efficient transportation and distribution, which would help reduce carbon emissions. Moreover, complete control of the supply chain decrease the requirement of stock, hence each retailer can do with a smaller and more accurate stock. RFID can be used to closely monitor the carbon emissions associated with each product in all the phases (production, distribution, retail) and thus contribute to the price of the product or the carbon tax of the product. Clearly, such carbon-monitoring RFID records should be readable only by authorities. It is easy to see that such a monitoring can be a strong incentive for all involved parties to introduce low-carbon practices for each product.

Moreover, with respect to food products complete control over the supply chain and production line will help reduce waste in case of accidents. As an example consider the case where a number of cartons with milk are damaged due to detergent in the milk. If RFID is utilized it is possible to uniquely identify and destroy only the inflicted cartons which reduce waste in the production line. This does not have a direct impact on carbon emission, but it reduces the average carbon footprint for each successfully produced item and it provides more security for the consumers. Furthermore, it is “green” in a sense that it has environmental impact.

IVB Smart Buildings

Implementing RFID technology in buildings and combine the information gathered by the RFID readers with the installed appliances can realize what is referred to as Smart Buildings. As an example consider an office building equipped with an RFID sensor network. In addition each employee is equipped with an RFID tag, e.g. in their name tag or access card. Using these tags the sensor network installed in the building can adjust the utilized resources in order to minimize carbon emission. As an example the air condition could be controlled by temperature sensors and the light installations could sense if any tagged employees were in its proximity. If not, the light should be dimmed, or completely turned off.

Current implementations of wireless sensor networks in buildings show a decrease of approximately 20 % in energy consumption [15]. Comprehensive control of utilized resources in buildings therefore possess a large potential when a reduction in carbon emissions is desired. Moreover, in addition to reduced energy consumption, wireless sensor networks also enable low cost monitoring of occupants, e.g. elder citizens living at home, in order to alert care givers in the event of accidents or illness [16], which indirectly has green effect, by sparing the transportation for regular personal visits.

IVC Intelligent Transportation

Sensor networks can be used to make transportation intelligent in order to reduce carbon emission. For example a sensor network distributed throughout the infrastructure makes it possi-
ble to gather information on for example roadwork and traffic load. This data can then be used by the navigation systems in each vehicle to plan the most energy efficient route, e. g. by avoiding traffic jams. Moreover, implementing systems for communication between cars and traffic lights makes it possible to automatically turn off the engine in the cars waiting at a red light. This will reduce the time engines are running idle, which reduces carbon emission. This would also enable traffic lights to sense the traffic density and adjust the lights to the actual traffic load. These approaches are transparent to the users, as the energy consumption is taken into account automatically.

However, in order to really make a change towards green transportation we need to change the mind set of the users. One approach could be road pricing, where the tax is based on driven distance, number of people in the car and driving style. In order to keep the tax to be payed at a minimum people are encouraged to drive green, i.e. energy efficient, and take the environment into account. Here RFID again plays a role, since it can enhance the precision of the road pricing - e. g. the distances driven when the car has three passengers can be priced less than the distances driven when the car has a single passenger. RFID can be used to closely and securely log transportation data and thus be a key technology for introducing incentives towards achieving low-carbon transport.

V Conclusion

In this paper we have addressed the issue of using ICT systems to decrease emissions of greenhouse gases and thus reverse the global warming trend. The real green role of ICT can be seen if it is applied to the systems that bear the chief responsibility for increased carbon emissions, such as the power distribution grid, transportation, buildings, production processes, etc. We have identified RFID and, more general, the technologies based on passive wireless devices, as the ones holding large potential to facilitate low-carbon operation of the future systems. We have exemplified such usage of RFID through several applications. We believe that the observations in this paper will motivate further studies on the green potential of RFID as well as innovative thinking regarding other green applications that rely on passive wireless devices.

REFERENCES


Using ICT in Greening: The Role of RFID

Petar Popovski, Rasmus Krigslund, Gert F. Pedersen and Boris Manev

Using ICT in Greening: The Role of RFID

Rasmus Krigslund  rkr@es.aau.dk
Petar Popovski  petarp@es.aau.dk
Iskra Dukovska-Popovska  iskra@production.aau.dk
Gert F. Pedersen  gfp@es.aau.dk
Boris Manev  borismanev@gmail.com

a  Department of Antennas, Propagation and Radio Networking
b  Department of Production
Aalborg University
Denmark
c  Institute for Environmental Studies
Vrije University Amsterdam
Nederlands

Abstract

In the recent years, the awareness about the harmful long-term effects of the greenhouse gases (GHG) has markedly increased. As information and communication technologies (ICT) have successfully and irreversibly pervaded everyday life, many technology leaders have started to look into the green ICT, i.e. ICT solutions that have reduced carbon emissions. A sobering report from WWF has indicated that only 2 % of the carbon emissions can be attributed to the ICT systems. Therefore, the real green impact of ICT, at least in short term, can be made by using ICT to make the other systems more energy-efficient, such as the buildings, transportation, power grid, industry and production. In this chapter we argue that the RFID technology can be one of the key drivers for implementing green ICT solutions in the systems that are not originally associated with ICT, e.g. transportation. In particular, the passive, battery-less RFID systems have potential to map the physical world.
Green Communication

to the virtual one and drive actions back from the virtual to the physical world with positive carbon balance, i.e. the carbon emissions saved by those actions are larger than the carbon emissions caused to operate the RFID systems. Motivated by that observation, we list several example green applications of the RFID systems.

2.1 Introduction

The information and communication technologies (ICT) have brought profound improvements in all the areas of human activity and the quality of life. The latter relies mostly on impact that the ICT has had on the people through the immediate rewards provided by those systems. For example, the mobile phone brings reachability, which is almost ubiquitous, while the Internet provided unprecedented access to information and created countless opportunities for novel social interactions. Nevertheless, ICT has yet to unleash its potential in solving the global problems that will have long-term effects, such as the reversal of the trends in global warming, reduction of greenhouse gasses (GHG), dealing with the scarce resources (energy, water), protection of the environment, and sustainable global growth. These objectives are significantly interdependent, while the reduction of carbon emissions will have the largest effects.

Carbon dioxide (CO2) is the most important anthropogenic greenhouse gas (GHG) accounting for almost 80% of the overall GHG emissions in the atmosphere [6]. The usage of ICT for reducing carbon emissions has been a subject of many recent analyses, see [24] and the references therein. Greening is also seen as one of the impulses that can direct the research and innovation within ICT in the coming years. The understanding of the interaction between ICT and GHG is still in its infancy, although some indicators are already emerging. For example, the WWF report [24] has indicated that only 2% of the current carbon emissions can be attributed to the ICT systems. This is a strong message that, in a short term, the benefits obtained from making, for example “green wireless networks” or “green server farms”, can be almost negligible as compared to the benefits obtained if the ICT actions are targeted to ameliorate the activities that are responsible for the dominant part of the carbon emissions, such as the power production sector, buildings, industry and production, transport, etc. On the other hand, the volume of devices related to ICT will increase rapidly in the coming years, and, if those computing/communication devices remain to operate with the same power budget as today, then it is clear that the carbon footprint of ICT will be much
larger than 2%. In that sense, one important research area remains to be how to make ICT green and more energy efficient, in order to be prepared to sustain the incoming proliferation of computing/communication devices.

In this chapter we focus on the problem how to use ICT for greening rather than greening ICT itself. The overall task of putting ICT to work towards making the world greener is enormously complex and includes several subtasks. The first is data collection and analysis, in order to make assessment of the GHG production in relation to all the human activities, and thus make projections about the quantitative impact that the ICT will have on the GHG emissions rooted at those activities. Another subtask is development of the technology that will enable low-carbon operation in the targeted activity areas, as well as innovation of applications that can replace some of the present activities with low-carbon counterparts. The “usual suspect” related to the latter is the replacement of the travels by video-conferencing, but many more applications and examples are needed to drive the environmental impact.

A proper milieu for green ICTs to be put to work can be created by suitable policies and strategies. Such policies should be created by accounting for the opportunities and capabilities of the technology. For example, the system of incentives that can be introduced regarding the GHG activities can be built around rules for monitoring/acting that are assuming certain level of technology sophistication. Using ICT to reduce the overall emissions has a great potential, as illustrated in Fig. 2.1.

![Figure 2.1 The RFID tag and reader comprising a simple RFID system.](image-url)
In this chapter we advocate the Radio Frequency Identification (RFID) technology as one of the key components of the green ICT. Before summarizing the arguments behind such a claim, we need to briefly introduce the RFID technology. A RFID system provides automated identification and information gathering from objects and people. The two key components of an RFID system are tags and readers. A tag is a small microchip equipped with antenna which is attached to the physical object or the person. The most interesting types of tags are the passive, batteryless tags, as they can have low cost and thus be deployed in large volumes. In fact, batteryless, passive devices capable of computing and communication are by definition compatible with green requirements. The readers (or interrogators) are devices, usually deployed at strategic locations in order to efficiently collect information from the tags in their radio range. The tags are attached to the objects or humans and thus make the physical world perceptible for the computers. That is why the passive tags are enablers of the “Internet of things”. Particularly important developments related to the RFID technology can be seen in RFID sensors and energy harvesting. With RFID sensors, the tag is integrated with a sensor or multiple sensors and the radio link to the reader is used to convey the sensed data. Furthermore, energy harvesting will augment the computation/communication capabilities of the passive tags.

We argue that the role of RFID in enabling green ICT is multilateral. In the data collection process, it enables gathering of information to a very detailed level, which is an important step to relate different activities to the GHG. The usage of RFID tags can have direct impact on the environment by enabling more efficient waste management and recycling. Being the bond between the physical and the cyber world, the tags can be the key drivers in attacking the 98% opportunity of the carbon emissions, by enabling real time planning in the virtual domain and sensing/acting in the physical domain. Finally, the passive tags can enable enforcement of policies and strategies and be instrumental to introduce incentive systems in GHG emission and the carbon trading schemes.

Before describing the details of how RFID has the potential to reduce carbon emissions, in the next section we give a brief overview of the current global situation with respect to GHG emissions.

### 2.2 Carbon Emissions: Fact and Figures

Carbon dioxide (CO2) is the most important anthropogenic greenhouse gas (GHG) accounting for almost 80% of the overall GHG emissions in the
atmosphere. According to statistics by the International Panel on Climate Change (IPCC) the global atmospheric concentration of CO2 has increased to 379 ppm in 2005, which exceeds by far the natural range over the last 650,000 years (180 to 300 ppm). The concentration of CO2 has grown with increased intensity during the last decade. Thus, while from 1960 to 2005 CO2 concentration had an average growth rate of 1.4 ppm per year, only from 1995 to 2005 the average growth rate has been 1.9 ppm per year [22]. This is a direct consequence of the fact that annual fossil CO2 emissions increased from an average of 23.5 billion tons per year in the 1990s, to 26.4 billion tons of CO2 per year in 2000-2005, see Fig. 2.2.

![Figure 2.2](http://cait.wri.org/figures.php?page=ntn/1-2)

### 2.2.1 Sector Approach

Statistical data shows that largest CO2 emitter is the power production sector with 28% of total emissions [6]. Another 32% of the global CO2 emissions coming from industry, transport, and residential services and agriculture, are emitted by power consumption when energy is processed into final products. Nevertheless, attention should not be concentrated only on CO2 emission but also on other GHG gasses such as CH4, N20, SF6, HFC, and PFC as they account for almost one fourth, or 23% of the total GHG emissions. Sector-emission percentages are as listed in Table 2.1.
### 2.2.2 Intervention

By 2050 global emissions of CO2 need to be reduced by 85% in order to keep the temperature increase below 2°C degrees. To achieve this, interventions in each of the GHG emitting sectors is needed by improvement of energy efficiency; increase in the share of renewables in the energy-mix; as well as “cleaning” of the fossil-fuel energy generation sector. Increase in efficiency is mostly relevant in the sectors such as industry, buildings, transport and power generation where energy and materials are being transformed into products and services [6]. The power production sector has on average very low efficiency. Old coal power plants have an average efficiency of 30%. Yet, with new components and optimized process integration, their efficiency could improve up to 50%, which would mean a reduction of 1.4 million tons of CO2 annually [6].

Electric grids, also, contribute to the loss of efficiency. During the transportation of electricity to consumers certain percentage is lost due to electrical resistance in the cables in the grid. Future development of Smart Grid power network will provide sustainable development, efficiency and cost benefits [14]. The Smart Grid leverages on ICT concepts in order to provide information flow and control over the electric grid in order to make the grid more efficient.

A very important and promising sector, where energy efficiency can be increased while CO2 emissions can be significantly reduced is the building sector which is accountable for one third of the global energy related CO2 emissions [33]. Energy efficiency in both commercial and residential buildings can be improved by using variety of technologies, designs and materials. Some technologies and concepts for improvement of energy efficiency are through efficient lightning, for example Light-Emitting Diode (LED). Other interventions that can contribute to energy efficiency include introduction of equipment with lowest stand-by power, reduction of energy outside office hours, efficient cooling/heating. A good example for such an energy efficient
building is the passive house which can save up to 75% energy consumption and thus decrease its carbon footprint [13].

Improvement in energy efficiency requires investments in the corresponding R&D activities. Since 20% of the world’s population that is mostly located in the developed countries consumes 80% of the world’s natural resources including energy, they should be accountable for investment in energy efficiency. Yet, according to predictions by the US Department of Energy, world’s energy consumption will grow by 50% from 2005 to 2050 [3], mostly due to increased demand in emerging economies such as China and India. Developed countries will have to commit to invest in improvement of their energy efficiency, yet will also have to invest in improvement in the energy efficiency in the developing world without affecting their path to development. According to Greenpeace, G8 countries will only put the Post-Kyoto negotiation on a path towards success if they commit to contribute USD 106 billion every year by 2020 to help developing countries face the climate change challenges [16].

The dichotomy related to the issue in which countries the investment in energy efficient technologies should be dominant, can be mapped into a dichotomy of two radically different technology approaches. In the developing countries many of the systems (which are major sources of carbon emissions in the developed countries) have not yet been deployed. This gives opportunity for a clean slate system design, which starts to build the power system, transportation, industry, etc. based on the level of technological sophistication that is available today or in the near future and, most importantly, not being strongly bound by backward compatibility. Such a clean slate design can, for example, result in a transportation system that is as flexible and personalized as the car, but far more friendly to the environment. In such newly developed systems, ICT will have a decisive role, as the systems will rely on rich information flow and control among the system components.

Contrary to the clean slate approach, in the developed countries there are systems that are widely deployed and cannot be completely and instantaneously replaced, but they need to be gradually evolved, accounting for the backward compatibility. Hence in this case we need wean slate system design, where the existing systems should be upgraded to be weaned on the requirements for low carbon emissions.

These two approaches have different perspective, but the same goal, i.e. reducing emissions. With this overview of the current situation with respect to emissions we have identified in which sectors the largest reduction can be
achieved. In the following we present ICT technologies that have the potential of a great green impact on these sectors.

2.3 RFID and Some Related Technologies

There exist several opportunities for using ICT to reduce carbon emissions. Some of these are listed in [24]. One example is to use ICT to optimize scheduling and resource allocation in the physical world. In order to do this the physical world must be made perceptible in the digital world. As an example consider Smart Grid, where measuring devices are sampling the current power usage of a building and maybe estimates near-future power requirements, e.g. by knowing which devices that are currently using power [27]. Using communication systems this information is fed back to the supplier, who can then determine how to distribute the power to the customers most efficiently. A promising technology for coupling the physical world with the digital world is Radio Frequency IDentification (RFID).

2.3.1 Basics of RFID Systems

RFID technology has been around for quite some time now, but recently this area has received immense attention due to reduced costs of implementation and production. An RFID system has two basic parts: Readers and Tags, as illustrated in Fig. 2.3. The reader is a transceiver that can activate the tag and reads its content. A tag is a device small enough to be embedded into an object, and it consists basically of a microchip with modest storage capacity connected to an antenna. When activated on demand by an external reader the tag backscatters its unique identifier and the information saved in its memory.

![Figure 2.3 The RFID tag and reader comprising a simple RFID system.](image-url)
There exist different types of tags: Active tags, where an internal power source allows it to transmit its information at any time. However, having its own power source puts a limit to the lifetime of the tag, but it increases the communication range of the tag. The tags that have large potential for wide deployment and usage are the passive tags, which are powered by inductively coupled power from the signal transmitted by the reader. In other words, the passive tags harvest the required energy from the over-the-air transmission by the reader. By omitting the internal power source decreases the production cost and increases the lifetime of the tag.

A reader does not require line-of-sight in order to identify a tag and read its content which means that RFID is a technology which can be utilised for many different purposes, and in many different scenarios. If physical objects are tagged and readers are placed in suitable locations the presence of unique objects can be identified along with the information stored in their memory. Moreover using RFID sensors and actuators it is not only possible to identify the presence of physical objects, but also interact with the physical world.

### 2.3.2 RFID Sensor Systems

Wireless sensor networks consist of a large number of small sensing, self-powered nodes that gather information and ultimately transmit this information to a base station in a wireless fashion. [26] Recently battery free wireless sensors based on RFID has been considered. An RFID sensor is basically a passive RFID tag paired with a small sensing device. In this way the resulting device is a uniquely identifiable sensor with a wireless interface, as illustrated by the block diagram in Fig. 2.4. An example of such a device has been presented in [28].

![Figure 2.4 The blocks of an RFID sensor device.](image)

This means that the advantages of RFID is brought to wireless sensor networks creating devices with a small form factor and a long lifetime. Similar to the RFID system described in section 2.3.1, the RFID sensor is powered from inductive coupling when it is in the range of a transmitting reader, and the RFID sensor then backscatters its unique identifier and the state of the sensor. Since readers are not transmitting continuously, the power source for
an RFID sensor is intermittent and unpredictable. This type of communication provides sufficient power for standard RFID systems, where a tag only backscatters the identifier. However, RFID sensors require more power to operate the sensing device compared to standard tags. Hence it is difficult for the RFID sensor to assure that its tasks are completed based on the power received from the reader. It can therefore be beneficial to consider harvesting energy from other sources than the transmitted power from the reader [7].

2.3.3 Energy Harvesting

Recently energy harvesting has been considered in order to prolong battery life of mobile phones [15], but in the context of small wireless devices, e.g. RFID sensors, it has the potential to make batteries in small wireless devices obsolete. The concept of energy harvesting can therefore decrease production costs as well as the required level of maintenance, while increasing the lifetime of the wireless sensor networks.

There exist several options for harvesting energy from the surroundings [25]. For example energy from light, which requires a large surface, or vibrations which requires mechanical apparatus. However, for wireless sensors a small form factor is desired, hence light and vibrations are not suited as energy sources for this application. Instead, inductive coupling may be an interesting option. In today’s RFID system the tag uses such power to backscatter its identifier to the reader, but this might evolve towards tags that store such energy for later usage. Considering the ubiquity and abundance of various wireless transmitters, a wireless device is not confined to harvest energy from the communication with its own base station, but has the possibility of continuously harvesting energy from ambient transmitters.

2.4 Green Applications Involving Passive Wireless Devices

We have already stated that the potential of RFID regarding green operation of various systems is seen in the fact that RFID provides the link between the physical and the virtual world. In this section we will concretize this, rather abstract, claim through three example green applications of the RFID system or, more general, systems with passive wireless devices.
2.4 Green Applications Involving Passive Wireless Devices

2.4.1 Supply Chain Management

RFID has been initially used in the logistics operations of the supply chains to track and manage assets through railroad, shipping and trucking. Due to the emergence of passive tags and technology costs decrease, the use of RFID has been expanded through the different parts of the supply chain. Some of the frequently reported RFID enabled improvements have been: automation of inventory update and discrepancies detection, liberation of considerable human labor from certain workflows, as well as decrease of the possibilities of human errors in repetitive activities. Another significant advantage of RFID is the potential for objects and associated process/environment information visibility to all the participants through the supply chain.

Nevertheless, there are quite few RFID applications that enable the greening aspect of the supply chains. Reverse logistics, i.e. from customer to manufacturer or waste centres, has been traditionally seen as the “green” part of the supply chain. Therefore, most of the reported RFID applications in greening the supply chain are related to reverse logistics. The advantages of implementing an RFID-based system are through the increase of recovered products, tracking of returned products, simplification of the operations of collecting, sorting, and disassembly, as well as reduction of the quantities of toxic components in the environment. Overall, the RFID enables minimization of the complexities of the reverse logistics processes that comes mainly from irregular material flow as well as inventories that are in different conditions, e.g. repaired, defective, damaged, etc.. RFID combined with other computational intelligence techniques [21] can help determine the economical transportation from collection points to collection centers. It minimizes the holding time and depreciating value for the returned products at the same time. Therefore, an improved reverse information flow supported by RFID would reduce resource consumption, e.g. transportation, storage, obsolescence, and thus reduce the environmental impact in the total product lifecycle. However, there are no case applications that report emissions and resource reductions enabled by RFID.

Greening related applications of RFID in forward supply chain, i.e. from producer to customer, have not been reported up to our knowledge. Nevertheless, some potentials of the technology can be speculated. RFID technology can be utilized as a diagnostic mechanism by enabling screening of different processes through the supply chain over any period of time (days or weeks) in order to identify the emission rates and energy efficiency of different components of the process. This information could be used in re-planning and
Green Communication

re-designing of different processes and the supply chain as a whole with the aim of reducing resource consumption and GHG emissions.

In logistics, a trade-off between warehouse size and increased transportation needs to be evaluated, and RFID can help in diagnosing different situations. Although the general logic has been towards decreasing stocks at different points, such philosophy leads to increased inventories in transport, which is affecting the environment negatively. RFID can enable significant reductions in logistic-related costs by helping eliminating unnecessary transportation and finding the optimal mode of transportation for all shipping. This can provide significant carbon benefit and can be perceived as being green, and thus contribute to the price of the product or the carbon tax of the product. Clearly, such carbon-monitoring RFID records should be readable only by authorities. It is easy to see that such a monitoring can be a strong incentive for all involved parties to introduce low-carbon practices for each product.

Regarding degree of utilization of transport equipment, a tag can be envisaged which carries the information about the dimensions, weight, or volume of the package. A tag could also be placed at the container carrying the information about the volume/dimensions of the container. In such way, an explicit contribution is created from the use of RFID technology, by enabling higher utilization of the transport equipment. Moreover, with respect to food products complete control over the supply chain and production line will help reduce waste. The most significant environmental effects are not achieved by treating the end-of-pipeline waste, but rather the inherent upstream wastes related to cultivation of crops and livestock, processing of these, production of additives etc. When food is wasted, all activities upstream and their related emissions are in vain [23]. Therefore, an RFID supported systems can enable dynamic planning and fulfilment of the demand, which would decrease the wastes across the whole chain. Another application is envisaged in the case of accidents in the food supply chains. As an example consider the case where a number of cartons with milk are damaged due to detergent in the milk. If RFID is utilized it is possible to uniquely identify and destroy only the inflicted cartons which reduce waste in the production line. This does not have a direct impact on carbon emission, but it reduces the average carbon footprint for each successfully produced object and it provides more security for the consumers. Furthermore, it is green in a sense that it has environmental impact.
2.4 Green Applications Involving Passive Wireless Devices

2.4.2 Smart Buildings

Implementing RFID technology in buildings and combine the information gathered by the RFID readers with the installed appliances can realize what is referred to as Smart Buildings. As an example consider an office building equipped with an RFID sensor network. In addition each employee is equipped with an RFID tag, e.g. in their name tag or access card. Using these tags the sensor network installed in the building can adjust the utilized resources in order to minimize carbon emission. As an example the air condition could be controlled by temperature sensors and the light installations could sense if any tagged employees were in its proximity. If not, the light should be dimmed, or completely turned off.

Current implementations of wireless sensor networks in buildings show a decrease of approximately 20 % in energy consumption [31]. Comprehensive control of utilized resources in buildings therefore possess a large potential when a reduction in carbon emissions is desired. Moreover, in addition to reduced energy consumption, wireless sensor networks also enable low cost monitoring of occupants, e.g. elder citizens living at home, in order to alert care givers in the event of accidents or illness [10], which indirectly has green effect, by sparing the transportation for regular personal visits.

2.4.3 Intelligent Transportation

Sensor networks can be used to make transportation intelligent in order to reduce carbon emission. For example a sensor network distributed throughout the infrastructure makes it possible to gather information on for example roadwork and traffic load. This data can then be used by the navigation systems in each vehicle to plan the most energy efficient route, e.g. by avoiding traffic jams. Moreover, implementing systems for communication between cars and traffic lights makes it possible to automatically turn off the engine in the cars waiting at a red light. This will reduce the time engines are running idle, which reduces carbon emission. This would also enable traffic lights to sense the traffic density and adjust the lights to the actual traffic load. These approaches are transparent to the users, as the energy consumption is taken into account automatically.

However, in order to really make a change towards green transportation we need to change the mind set of the users. One approach could be road pricing, where the tax is based on driven distance, number of people in the car and driving style. In order to keep the tax to be payed at a minimum people are encouraged to drive green, i.e. energy efficient, and take the environment...
into account. Here RFID again plays a role, since it can enhance the precision of the road pricing - e.g. the distances driven when the car has three passengers can be priced less than the distances driven when the car has a single passenger. RFID can be used to closely and securely log transportation data and thus be a key technology for introducing incentives towards achieving low-carbon transport.

2.5 Current State Of RFID Usage

Even though RFID is already gaining foothold in areas like logistics and retailing the technology still have to be developed in order to utilize the full potential of RFID. As an example consider a large retailer like Wal-Mart, who has implemented RFID for inventorying when pallets arrive at each supermarket. This has proven beneficial for the supermarket itself, however, RFID holds the potential of being beneficial to the customers as well, in terms of easier checkout and more comprehensive information on the life cycle of each unique object in the supermarket. In order to make applications like that secure, reliable and cost-effective the research community still needs to solve some limitations in the RFID technology. These limitations are in this section introduced along with the current state of the art, in 2009, in each area.

2.5.1 Costs

One clear limitation of RFID systems is still the price per tag and to some extend the installation costs. This means that RFID systems is so far mainly used in applications where there is a reasonable ratio between tag and object price. In this chapter we focus on passive UHF tags, where prices so far have come down to around 7 to 15 US cents per tag, depending on the quantity and packaging of the tag, i.e. whether it is encased in plastic or embedded in a label [1].

In order to further reduce tag prices production costs must be brought down. The solution to cheaper tags is twofold. Research in chip and antenna design and production apparatus towards cheaper manufacturing and production of tags [30]. In order to drive, and probably also finance, this research large quantity demands for RFID from the industry is necessary, as mass production will contribute to a lower average price per tag [32]. However, demands for RFID and research towards cheaper tags are interdependent. Cheaper tags will increase the interest in, and demand for, RFID systems. Increased demand for RFID drives the research towards lower productions
costs in order to increase profit, and due competition between tag manu-
factures, the free market will eventually cause the tag price to be reduced. 
Hence we need someone to initiate this development by taking the first step. 
Example of front-runners like this are Wal-Mart, Airbus and United States 
Department Of Defence, who, due to their size, can afford the risk [2]. More 
initiatives like this will help fueling the development within RFID systems. 

Moreover when integrating RFID systems we are facing the same consid-
erations with respect to clean and wean slate design, as described in section 
2.2.2. There will most probably be a difference in Return Of Investment, ROI, 
time when RFID systems and their possibilities are taken into account from 
the earliest phases when planning a new facility, compared to installation 
in an existing facility, where it may replace older equipment. The wean slate 
design may not be cost-effective at all, neither with respect to price nor carbon 
footprint.

2.5.2 Tag Antenna

In a passive UHF tag the antenna is essential as it harvests the energy to power 
up the tag. However, the antenna dimensions tend to be large compared to the 
desired tag dimensions, even when UHF antennas is considered. In order to 
fit into these dimensions the antenna may undergo different deformations, 
which influences the antenna characteristics. [9] Moreover, placing the tag 
on an object will have an effect on the antenna parameters as well, as the 
reflection and polarization coefficients may change significantly. This has 
the potential of causing the power received by the tag from the reader to 
change accordingly, which may cause false negative or false positive read-
ings, respectively. These types of erroneous readings are described in detail 
in section 2.5.3. This means that a manufacturer can develop a tag with an 
antenna that fulfills the requirements with respect to dimension, directivity 
and frequency. But when the tag is attached to an object of certain materials, 
e.g. liquid or metal, the antenna parameters are impacted to a degree that 
may render the tag completely useless. Knowledge of these effect is very 
important when designing the antenna for RFID tags. Unless different types 
of antennas is used for different objects materials, a cheap universal antenna 
needs to be developed, e.g. by shielding from the object, in order for RFID 
tags to become ubiquitous.
2.5.3 Erroneous Readings

If multiple tags are located in the proximity of a reader they will respond simultaneously to the reader and the reader experiences tag collision. Hence the protocol stack implemented at the reader, usually EPC Global Gen2 stack for passive UHF tags [12], should contain anti-collision protocols to resolve this collision [29]. In the ideal case, all the tags are identified, but only inside the readers interrogation zone, i.e. in a radius of approximately 3 m [9]. However, in real communication scenarios the reader can experience two types of erroneous readings, namely negative readings (or missed tags) and false positive readings. The details of these two types of erroneous readings and the current state of the art in order to cope with them are described in this section.

Missing Tags

A tag will not respond to a reader if the received power or Signal-to-Noise Ratio, SNR, is too low. This can occur even if the tag is located within the communication range of the reader, due to objects blocking the signal or the tag antenna has been deformed causing the gain in the direction of the reader to be too low to correctly receive the reader request. In this case the tag location is referred to as a blind spot. The problem of identifying tags in blind spots is called the missing tag problem. The case where a tag, supposedly in communication range, does not respond to a reader request is referred to as a False Negative reading, FN. As described in section 2.5.2 the material of the object is also of importance as it can change the antenna parameters significantly. In [8] some typical identification rates are listed, and depending on the material the rate varies from 33.0 % to 95.0 %, for Chocolate Mousse and Rice Cake respectively.

There exist multiple approaches for decreasing the probability FNs due to tags located in blind spots. In [4] a method to increase the completeness of the interrogation is presented. This method is aimed at static tag populations and let each tag store a reference to another tag in the interrogation zone. The reader then compares the set of identified tags with the set of reference tags, i.e. the tags the identified tags refer to. If a reference tag is not in the set of identified tags the set is incomplete and the reader must interrogate again in order to identify the tag in the blind spot. In [8] two independent samples are used to estimate the cardinality of the tag set, with is then compared to the actual number of identified tags in order to determine if an additional reading is required. Another approach is utilized in [17], where in addition to
estimating the tag cardinality, also estimates the number of required readings to guarantee, with some probability, that no tags are missing.

**False Positive Readings**

If a reader successfully receives a reply from a tag located outside its communication range it is referred to as a False Positive reading, FP. This type of erroneous reading is difficult to cope with as it is a valid response and therefore causes ambiguity about the presence/proximity of the tag [11].

In [20] it is stated that false positive readings occurs in approximately 5% of all readings, and in order to cope with these errors different measures have been presented. In [19, 18] deterministic data cleaning is utilized to sort out the FP readings. However, due the ambiguity of these false positives a deterministic model is not suited, hence in [20] a probabilistic model is proposed for cleaning the data. Another simpler approach, presented in [5]. The motivation of the approach is, since FNs occur due to the probabilistic nature of the wireless channel, then a simple way to decrease the number of false positives is to utilize these stochastic behavior. This approach defines an inventory request from a single reader as a window of \( N \) readings. A tag is said to be present in the interrogation zone only if it is identified in \( k \) out of \( N \) readings. For large \( N \) and \( k \) the probability of a tag being absent from the interrogation zone to be identified as being present becomes low.

This concludes the description of the problems and limitations in RFID systems, in the current state of the technology. When solutions to these obstacles has been developed, RFID systems can be ubiquitous and makes therefore a great candidate for an ICT that can be put to work in order to reduce GHG emissions.

**2.6 Conclusion**

In this chapter we have addressed the issue of using ICT systems to decrease emissions of greenhouse gases and thus reverse the global warming trend. The real green role of ICT, at least in a short term, can be seen if it is applied to the systems that bear the chief responsibility for increased carbon emissions, such as the power distribution grid, transportation, buildings, production processes, etc. In order to z the potential of ICT working towards a greener world, the deployment of wireless devices will explode, hence it is equally important to develop low power solutions and applications where energy efficiency is provided by ICT. We have identified RFID and, more general, the technologies based on passive wireless devices, as the ones hold-
26 Green Communication

... large potential to facilitate low-carbon operation of the future systems. We have exemplified such usage of RFID through several applications. Finally we have described some problems and challenges for the RFID technology in its current state. These problems are identified as some of the main limiting factors with respect to developing innovative RFID applications and motivating market penetration for RFID systems. Hence we believe that the observations in this chapter will motivate research and innovation in the area of RFID and further studies on the green potential of RFID. Moreover, motivate the continuous development of low power solutions and innovative thinking regarding other green applications that rely on passive wireless devices.

References

References 27

28 Green Communication


Complete List of Publications

Journal Papers


Complete List of Publications

Conference Proceedings


Book Chapters

Posters