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Identifying and Controlling Stray Reads at RFID Gates

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ABSTRACT OF THE
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A modern UHF RFID system can reach a read range of over ten meters. Long read range and difficulties to create uniform interrogation zone lead to stray reads. Interrogation zone can be adjusted by controlling the transmit power of RFID reader, selecting antennas and RFID tags carefully for the purpose, and with different signal quality validation methods. It is common that industry processes prevent using optimal RFID tag size and location for best read reliability. In these situations reader transmit power is increased to gain better read reliability. This extends the interrogation zone over the designed and leads to stray reads.

At UHF band the interrogation zone is not sharp edged. This is due to orientation differences between tags, tag to tag differences, multipathing and interference caused by multipathing.

In this thesis, different methods to identify RFID-tags moving along specified routes in the far field on the specific interrogation zone and discard other read events as stray events, are studied. Algorithm to detect lay around tags is proposed.

Keywords: RFID, detection, portal, phase angle, stray read, RSSI, Doppler shift

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Modernin UHF RFID-järjestelmän lukuetäisyys on parhaimmillaan yli kymmenen metriä. Suuri lukuetäisyys ja hankaluudet lukualueen tarkassa rajaamisessa johtavat hajalukuihin. Lukualuetta voidaan säätää RFID-lukijan lähetystehoa muuttamalla, antenni- ja RFID-tunnistevalinnoilla, sekä erilaisilla signaalin laatuun liittyvillä menetelmillä. Teollisuuden prosessit eivät aina mahdollista tunnisteen sijoittamista lukuvarmuuden kannalta parhaaseen paikkaan. Tällaisissa tapauksissa joudutaan usein kasvattamaan RFID-lukijan lähetystehoa lukuvarmuuden parantamiseksi. Tämä taas kasvattaa lukualuetta suunniteltua suuremmaksi, mikä johtaa hajalukuihin.

UHF taajuuksilla lukualue ei ole tarkkareunainen, johtuen RFID-tunnisteiden asentoeroista, tunnisteiden yksilökohtaisista eroista sekä monikanavakuulumisesta ja siihen liittyvästä interferenssistä.

Tässä tutkimuksessa on etsitty ja kokeiltu menetelmiä, joilla voidaan tunnistaa määritellyllä lukualueella lukijan kaukokentässä haluttuja reittejä liikkuvat RFID-tunnisteet ja hylätä muut lukutapahtumat hajalukuina. Tutkimuksessa esitetään uusi algoritmi hajalukujen tunnistamiseksi.

Avainsanat: RFID, tunnistus, portti, vaihekulma, hajaluku, RSSI, Doppler siirtymä

Preface

The process of writing this thesis began during the summer of 2011. It has been a long but fulfilling journey from the first brain storming sessions to this finished Masters Thesis with hard black covers and a golden title.

I have had the chance to familiarize with RFID technology while working at Vilant Systems Oy for almost four years. When my studies at Aalto University were at a stage to select the field of study for my thesis the choice was obvious. However, the title under which to put the work was not that obvious. I wanted to study some field within RFID technology and its applications, which would have some use after the thesis work has finished. The most promising of the titles was related to a quite common problem confronted while implementing RFID systems – stray reads.

There are magnificent people without whom this thesis would not have been completed. I want to thank my instructor Reino Aavikko for guidance through this thesis work, my supervisor Professor Jussi Suomela for all the academical support during the process, Henrik Nyman for inspiring conversations about the details in depth of how RFID systems function and Antti Virkkunen for pushing the work towards usable results. There are special friends you can call eleven o'clock in the evening and ask them to make a small change to the software used in testing. More special ones commit changes within 5 minutes. Thanks Aketzu! I want to thank my beloved wife Nina for all the support through the struggle.

This thesis is devoted to my dear son Aatos, who was born in the middle of the project. I am grateful to him for pointing out the fact that now it is a good time to graduate.

Helsinki, 19.2.2012

Antti S. Toivonen

Contents

Abbreviations and Glossary

Abbreviations

AEN	Ambient Electromagnetic Noise
ASK	Amplitude Shift Keying
CRC	Cyclic Redundancy Check
CW	Continuous Wave
DRM	Dense Reader Mode
DSB	Double Sidenband
EIRP	Equivalent Isotropically Radiated Power
EPC	Electronic Product Code
ERP	Equivalent Radiated Power
ERP	Enterprise Resource Planning
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FHSS	Frequency Hopping Spread Spectrum
FOV	Field of View
GR	Goods Receive
HF	High Frequency
IC	Integrated Circuit
ISM	Industrial, Science and Military
IO	Input / Output
IFF	Identify Fried or Foe
LBT	Listen Before Talk
LLRP	Low-level Reader Protocol
MES	Manufacturing Execution System
OSI	Open Systems Interconnection
PIE	Pulse Interval Encoding
PSK	Phase Shift Keying
PR-ASK	Phase Reversal Amplitude Shift Keying
RAF	Royal Air Force
RF	Radio Frequency
RFID	Radio Frequency Identification
RSSI	Return Signal Strength Indicator
SCM	Supply Chain Management
SNR	Signal to Noise Ration
SSB	Single Sideband
UHF	Ultra High Frequency
VHU	Virtual Handling Unit
WMS	Warehouse Management System

Glossary

Air interface	The complete communication link between an Interrogator and a Tag including the physical layer, collision arbitration algorithm, command and response structure, and data-coding methodology
Business logic	High level logic transactions related to the application
Cross read	RFID-tag is detected from neighboring RFID-gate
Cross talk	Nearby RFID-reader powers up a tag which becomes visible for RFID-reader further away. Causes cross read.
Dense-Interrogator mode	A set of Interrogator-to-Tag and Tag-to-Interrogator signaling parameters used in dense-Interrogator environments
Doppler shift	Shift of perceived frequency due to movement
FM0-encoding	Data encoding method
Frequency Hopping Spread Spectrum (FHSS)	Reader can use each channel for only 0.4 seconds, before changing channel
Half-duplex	Device can either transmit or receive using a data channel; not possible to do both at the same time
Handling unit	Container used in logistics (e.g. pallet or roller cage)
Interrogator	RFID reader
Interrogation zone	Area where the signal sent by the reader is strong enough to power up a tag and allow it to backscatter a response to the reader
Item	Smallest tracked object for logistics process (e.g. card board box, envelope)
Listen Before Talk (LBT)	Reader must listen that no other reader is transmitting at the selected frequency before it starts transmission
Miller-encoding	Data encoding method in which symbols are repeated for higher redundancy and lower RF foot print
OSI-model	Open Systems Interconnection reference model
Phase angle	Phase angle of RF signal
Q	A parameter that an interrogator uses to regulate the probability of tag response in EPCglobal Gen2 Air Interface protocol. Number of slots is 2^Q.
Session	An inventory process comprising an interrogator and an associated tag population
Shipment	One or several handling units which form one logical unit to be transported between specified locations

Stray read	RFID tag detected by reader which is not related to the process or the phase of the process monitored
Tari	Reference time interval for a data-0 in interrogator-to-tag signaling

1 Introduction

1.1 Introduction to the Research Problem

Radio Frequency Identification (RFID) technology [1] is used to connect events taking place in the physical world to IT-systems automatically without human intervention. RFID technology is used in many every day applications like public transport ticketing, identifying flying aircraft (IFF), paying purchases without contact (NFC), collecting road tolls, timing laps on a sports track, automatizing orders in vendor managed inventory (VMI) and locating containers within shipping fields.

In future one every day application for RFID could be self service grocery store. Customer enters the store and picks RFID tagged items from the shelves. RFID tags of the groceries are read at the exit and list of purchased items is shown for customer for acceptance. The payment of the groceries can also be done using RFID enabled credit card without removing it from the pocket.

There are many security and privacy concerns not to forget technological ones which need to be addressed before applications like are made available for the public. Customer must not be able to remove the RFID tags from the purchases or otherwise prevent reading the tags at the exit. RFID tags at the items should be disabled immediately after the purchase for privacy purposes. Otherwise it would be easy to track movements of the customer based on the RFID tags in the purchases. The reliability of the used technology must be on very high level to allow effortless buying experience. The benefits of applications like this are clear – time savings from not having to read all items separately at the cash register, resource savings from automated cash registers registers and traceability of purchases from the manufacturer all the way to customer as RFID allows all items to have unique serial numbers.

One specific type of RFID technology works at UHF band, which has proven to be suitable for wide variety of applications. Key drivers for general purpose UHF RFID technology are

- Adjustable long read range (starting from few centimeters up to 15 meters)
- High throughput performance
- Low cost
- Standardized operating environment

Typical location for UHF RFID system can be a logistics center where RFID is utilized to track shipments leaving from and arriving at the site. In this type of environment RFID can provide visibility to the logistics processes, reduce human errors and reduce amount of work related to the shipping transactions. It is a challenge to implement a reliable, high performance, RFID system at low cost in warehouse environment. Issues with *stray reads* are commonly encountered.

RFID interrogation zones, at Ultra High Frequency (UHF) -band, are far from being sharp edged. Typically the dependency between signal strength and the distance from the antenna is not linear because of constructive and destructive interference and antenna suboptimalities. This needs to be considered when RFID systems are designed.

Difficulties to control interrogation zone in RFID applications often lead to stray reads – unwanted RFID read events, which are not related to the process or phase of the process being monitored and/or controlled.

Factors affecting the size and shape of the interrogation zone are

- Transmit power of the reader
- Signal loss on cables and connectors
- Antenna gain
- Tag sensitivity
- Near by RFID reader operation
- Ambient Electromagnetic Noise (AEN)
- Destructive and constructive interference

There are direct methods for shaping the interrogation zone. The most obvious of these methods are altering RFID reader transmit power and choosing the right antenna and tag combination for the purpose. Due to the great variety of items marked with RFID tags, signal strength received by RFID tag can change from item to item. This item-to-item signal strength variation encourages using higher transmit power to increase read reliability. Trade-off for this is increased number of stray reads. Interrogation zones may also be shielded using absorbing and reflecting structures. Shielding increases the cost of the RFID system and adds environmental requirements for the location where the system is built.

In addition to these direct methods of reducing the number of stray reads, the signal received from RFID tag carries properties which can be used as the quality factors of the signal. These factors can be used to identify stray read events.

1.2 Scope of Thesis

In this thesis methods in order to identify and control stray reads are explored in three basic use cases. *I.* First case involves *lay around* tags inside an *extended interrogation* zone. *II.* The second case involves stray reads from handling units which do not go through the RFID gate. *III.* The third use case involves stray reads from handling unit going through neighboring RFID gate. This third case is also known as the *cross read* case. First to cases are explored in theory and by experimenting. Third case is explored only in theory.

Both, direct methods to shape the interrogation zone and signal property based methods to identify stray reads and lay around tags are explored. Emphasis is on the latter.

The focus of this thesis is on portal applications utilizing passive UHF RFID technology using GS1 EPCglobal Generation 2 standards and protocols on ETSI regulatory area.

There are several regional regulatory bodies, which limit the usage of UHF RFID technology. Most important of these are *Federal Communications Commission* (FCC) in the United States of America and *European Telecommunications Standards Institute* (ETSI) in Europe. Because of practical reasons I focus on ETSI regulatory area. Results are mainly applicable on FCC regulatory area as well. As wavelength is a function of frequency some methods studied in this thesis might work better on FCC frequency bands due to wider bandwidth available.

2 RFID Technology

2.1 History of Radio Frequency Identification

The idea to identify objects over distance without line of sight arose hand-in-hand with the development of radar technology in the beginning of the 20th century. First radars were able to tell that something was coming. What, when and how were questions which could be answered. “Who” was a more problematic question. Strength of the reflected part of the signal carried information about the size of the object, but there was no method of distinguishing two objects with similar size without *a priori* information.

First attempts to encode information to the backscattered part of the signal were made by the *Luftwaffe*, the German Air Force, during the 2nd World War. Luftwaffe’s pilots performed a flat spin when their aircraft was illuminated by radar waves. This flat spin altered the backscattered signal in such way, that the radar operators were capable of distinguishing their own aircraft from the enemy aircraft. This can be understood as the first utilization of passive RFID technology.

More sophisticated method was soon introduced by the *Royal Air Force* (RAF). RAF installed a device in aircraft, which responded to the radar signal with changing code [2]. This response message not only allowed to identify RAF’s aircraft from the enemy aircraft, but it also made possible to identify between RAF’s own aircraft from each other. This was the first implementation of active RFID technology. Since then transponders and *Identify Friend or Foe* (IFF) systems have become a standard in civil and military aircraft.

The cost of identifying an object must not exceed the value of knowing the identity of the object[2]. This fundamental constraint limits the possible applications to utilize RFID technology. The development of passive backscattered RFID systems was a great leap towards low cost RFID solutions and allowed the principle to be used in wide variety of different applications. Passive backscattered RFID is based on a tag which modulates the response to the backscattered part of the carrier wave sent by the reader [3].

It took about fifty years from the first implementations for RFID to become mainstream technology in applications like supply chain management, ticketing, highway toll collecting, production control and asset management. This era started when Wall-Mart, DoD, Metro Group and few other large corporate retailers and institutions applied a mandate about RFID tagging for their suppliers[4]. This mandate had a great impact on the price and availability of the UHF RFID technology and speeded up the standardization.

In the beginning of year 2000, there were many competing proprietary UHF RFID standards, which had laid a negative impact on the adaptation of UHF RFID technology. EPCglobal Class 1 Generation 2 UHF RFID standard development was started in MIT Auto-ID laboratory to create a unified standard. Standard was ratified by EPCglobal in 2004. Air interface protocol of the same standard was ratified as ISO18000-6C in year 2006.

2.2 Overview of RFID System

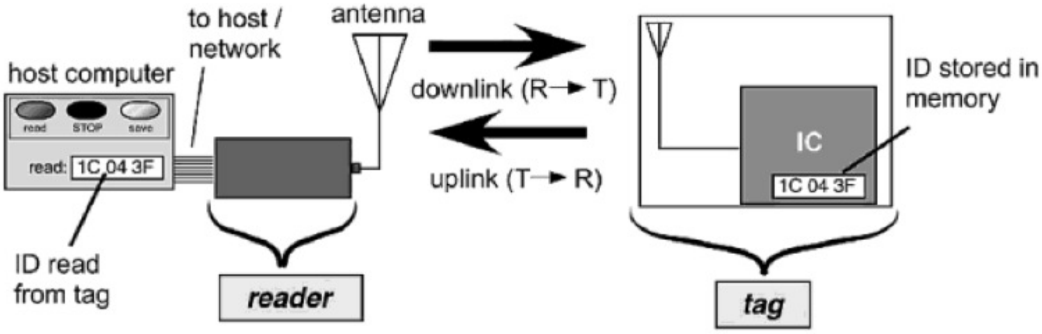

Figure 1: An overview of passive UHF RFID System.[2]

An overview of UHF RFID system is presented in Figure 1. In the simplest form the system consists of a *RFID reader*, an *antenna* and a *tag*. The RFID reader sends signal to the tag using the antenna. Tag receives the signal and responds back by modulating identification code to the the backscattered part of the carrier wave sent by the reader. This identification code is stored in the internal memory of the tag. RFID reader receives the backscattered signal from the tag and encodes the identification code the tag sent.

Communication from reader to the tag is called *downlink* or *forward link* and communication from the tag to the reader is called *uplink* or *reverse link*. The terms mentioned before are used in this thesis.

RFID reader may be connected to back-end computer systems which consume the information about RFID events. This makes the RFID system a subsystem of an IT system which is used to monitor or control material flow related process. RFID is used to connect events taking place in the physical world to the IT-systems. These transactions can be operator initiated or automatic.

RFID systems are categorized into passive, semipassive and active systems depending on the usage of internal power. Semipassive tags are also known as *Battery-Assisted Passive* RFID tags (BAP). This categorization is presented in Figure 2. Passive RFID tags do not have any internal power available. They use only the energy harvested from the carrier wave transmitted by the reader. Semipassive tags can have internal power supply to power the tag circuitry. This allows semipassive tags to have simple sensors, such as temperature sensor[4], embedded. Semipassive tags do not use internal power supply for communication purposes. Active tags have internal power supply and embedded radio circuitry. Embedded radio is powered by the internal power supply.

Typical shelf life for tag depends on the tag type. Passive tags have typically very long shelf lives. Semipassive and active tags have shorter shelf lives, because of draining battery. Typical shelf life for a tag varies from few months on active tags to several years of semipassive tags. Shelf life for passive tags is indefinite.

Open Systems Interconnection reference model (OSI) describes 7 layers on which

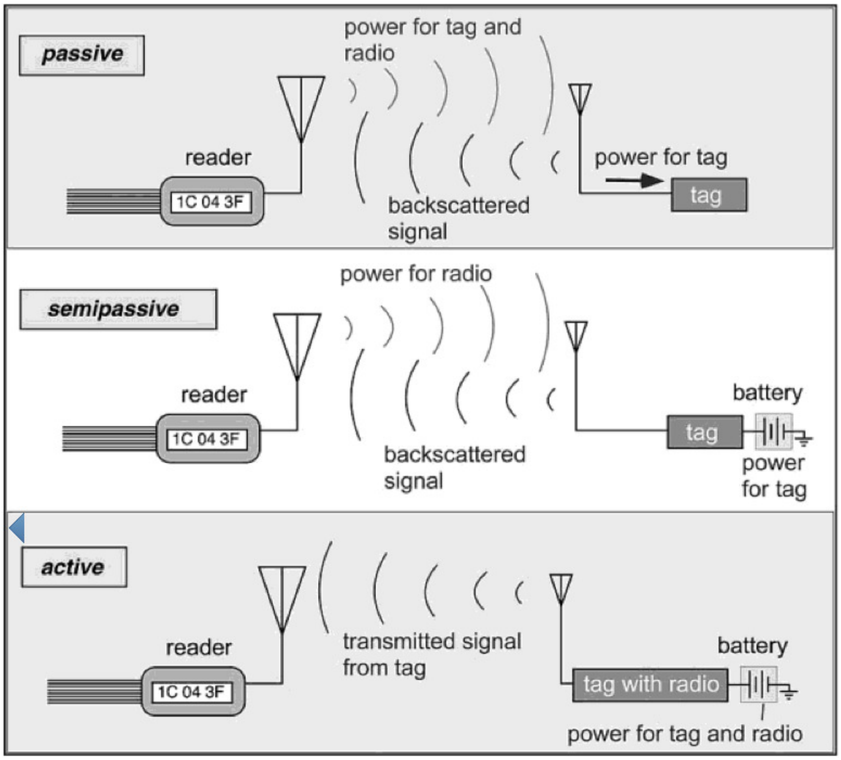

Figure 2: RFID Systems can be classified as passive, semipassive and active.[2]

serve as a framework for the definition of standard protocols [5]. OSI model is presented in Table 1. Gen2 UHF RFID utilizes layers 1, 2, 6 and 7 on OSI model [6]. The 5th layer is about session and this should also be included in the utilized layers list contrary to what is mentioned in literature[6].

2.3 Frequency Bands

RFID systems can be built to operate on different frequency bands. Commonly used frequency bands for RFID are presented in Table 2.

Coupling between the antennas of a reader and a tag depends on the used frequency band. Capacitive coupling can be used on very short distances. Inductive coupling is used in LF and HF RFID systems. UHF RFID systems utilize radiative coupling [2].

When using inductive coupling, the antenna size matters more than the transmit power. Read distance is roughly comparable to the antenna size, which makes it difficult and expensive to build HF systems with long read distance.

UHF RFID systems utilize radiative coupling. The read range is mostly limited by transmit power, which is typically regulated to 2 W ERP at ETSI regulatory area. Using high base frequency allows higher read rates to be used for the communication between the tag and the reader.

LF and HF systems are more insensitive for metals and liquids present than UHF RFID systems. UHF RFID systems operating at frequency range from 860 MHz to

Table 1: OSI-Model. [5]

OSI Model			
	Data unit	Layer	Function
Host layers	Data unit	7. Application	Network process to application
		6. Presentation	Data representation, encryption and decryption, convert machine dependent data to machine independent data
		5. Session	Inter host communication, managing sessions between applications
	Segments	4. Transport	End-to-end connections, reliability and flow control
Media layers	Packet/Datagram	3. Network	Path determination and logical addressing
	Frame	2. Data link	Physical addressing
	Bit	1. Physical	Media, signal and binary transmission

920MHz are studied in this thesis.

2.4 Readers

There is wide variety of different devices capable to read RFID tags on the market. These devices are built for different purposes. There are stand alone readers, handheld devices, fixed readers and RFID modules to be integrated into other devices. RFID readers are in most cases capable to alter the information stored on RFID tag.

Typically, readers are embedded computer systems running linux or Windows CE/Mobile operating systems.

Some earlier RFID readers were *bi-static*, which means that the readers had radio components built in a way which needed different antennas to be used for transmit and receive. All modern RFID readers are *monostatic* which allows single antenna to be used for both, transmit and receive.

Typical features which need to be considered when selecting RFID reader for application are

- Supported air interface protocol (see section 2.9.3)
- Supported regions (see section 2.9.1)

Table 2: Commonly used frequency bands for RFID systems.

Frequency	Characteristics	Standards	Typical Applications
LF 125/34 kHz	Passive, low read speed, short range	ISO 11784 ISO 18000-2A/B	Access control, livestock and pet identification
HF 13.56 MHz	Passive, medium read speed, medium range	ISO 15693 ISO 14445 ISO 18000-3	Access control, ticketing, library control, production automation
UHF 433.92 MHz	Active, medium read speed, long range	ISO 18000-7 (DASH7)	Building automation, location based services, automotive, logistics
UHF 860 - 960 MHz	Passive, fast read speed, long range, sensitive to liquids and metals, low cost	ISO 18000-6A/B EPC Global standards ISO 18000-6 Type C	Supply chain applications, asset management
UHF 2.4 GHz	Active, very high read speed, high cost	ISO 18000-4 ISO 18185	Road toll collecting, cargo container tracking

Figure 3: Impinj Speedway Revolution UHF RFID Reader

- Number of antenna ports
- Maximum transmit power
- Sensitivity
- Form factor
- IO-capabilities
- Network connectivity

- Performance
- Price.

Impinj Speedway Revolution R420 is a modern widely used stand-alone UHF RFID reader with a relatively small form factor and good performance characteristics. Impinj Speedway Revolution R420 can be seen in Figure 3. It has been chosen to be used in the experimental part of this thesis as software of the reader grants access to low level information about the transactions between the reader and the tag. Phase angle rotation and Doppler shift over transaction time is included this low level information.

2.5 Tags

Passive RFID inlay or a tag consists of an antenna and integrated circuit, which has the needed components to modulate the backscattered signal and small memory to store EPC code and other information.

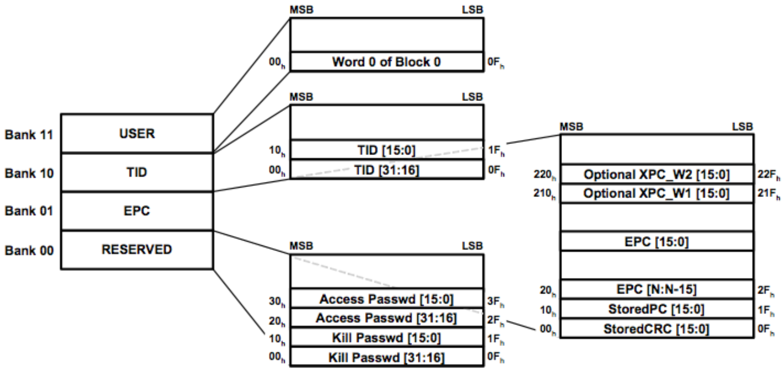

Figure 4: Logical memory map of Gen2 RFID tag.[7]

Size of the memory on IC varies from a few bits in to several kilobytes. Most common memory sizes for Gen2 tags are 128-bit and 512-bit. Memory mapping of EPCglobal Gen 2 RFID tag can be seen in Figure 4. EPCglobal Gen 2 tag has 4 memory banks – user memory, tag ID, EPC and reserved.

Variety on different types of RFID tags available is high. Assortment of RFID tags can be seen in Figure 5. Figure 5 shows five hard tags of different sizes, a flag tag and wet inlay. Figure 6 shows a roll of UMP Raflatac DogBone wet inlay labels. Paper face labels allow printing human readable text or machine readable barcodes on the paper surface of the tag. Wet inlay is usually a transparent sheet of plastic with an antenna, chip and glue on the other side. Dry inlay is the same as wet inlay without the glue and die-cutting.

A tag can also be integrated into a piece of plastic, which makes the tag more rugged and allows attachment to metal or other material with RF absorbing or reflecting properties.

The antenna of a tag can be designed to work primarily in near field (inductive coupling) or far field (radiative coupling).

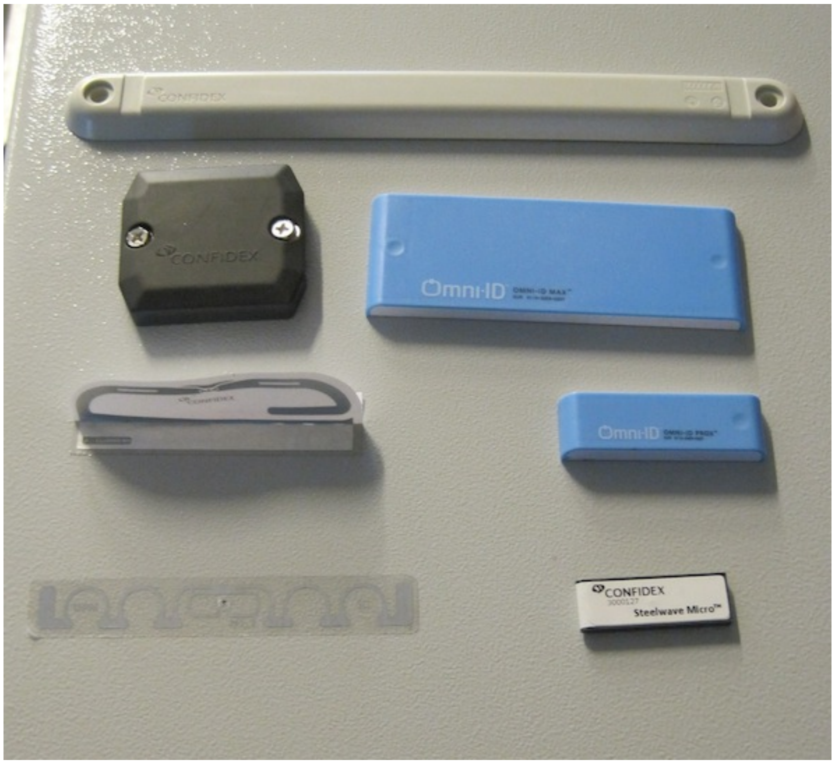

Figure 5: Assortment of different kinds of RFID tags.

2.6 Antennas

Different types of reader antennas can be used in RFID applications. Right antenna needs to be chosen for the application. Typical UHF RFID patch antenna is shown in Figure 7.

Dipole antennas radiate uniformly along a plane around. Patch antennas have gain properties which allow directed antenna beam.

Antenna polarization needs to be considered in system design. Linear polarization allows longer reach, but limits applications as reader antenna and tag antenna needs to be aligned correctly. Circular polarized antennas allow more freedom to the antenna and tag placement with the cost of reduced read range.

2.7 Portals and Read Points

RFID Systems utilize different types of read points and portals. In logistics most common type of a RFID portal is a gate, which tracks items going through the gate. A typical example of an RFID gate is presented in Figure 8. The RFID gate consists of two pylons on the sides of the docking door. In the example case the pylons hold two antennas each. Number and location of the antennas depends on the application. RFID reader is located inside the cabinet attached to the pylon on the right. Light indicating the gate activity can be seen on the top of the right pylon.

Shipment Verification Station (SVS) is a box made typically out of metal. One

Figure 6: UPM Raflatac DogBone wet label with Monza 3 chip.

side of the box is partly open allowing a handling unit to be put inside. The station has antennas inside the metal box. The box works as a Faraday cage and allows only those tags to be read which are inside the gate. This type of read points are used to form logical handling units also known as *Virtual Handling Units* (VHU) out of separate items on a handling unit (e.g. pallet).

Kanban systems can use RFID mailboxes to track consumption of production materials. When one unit of materials is consumed the Kanban card representing this unit of materials is put inside the RFID mailbox. The RFID reader integrated to the mailbox reads the tag attached to the card and sends information about the transaction to back end systems.

In access control applications interrogation zone of a RFID read point can be understood as a lock. When a tag containing right code is brought to the interrogation zone the lock is opened.

2.8 RFID Middleware and Integration

A RFID reader and a couple of tags alone do not enable that many useful applications in business environment. To get most use of the system and make different applications possible, it is essential to build computer systems which integrate to other systems used in business environment.

“Savant is software that sits between tag readers and enterprise applications, providing variety of computational functions on behalf of applications” [8]. Savant

Figure 7: MTI UHF RFID Antenna.

is an old name for RFID middleware used by Auto-ID labs. RFID middleware is responsible on functions like reader health monitoring, reader configuration and data filtering. Middleware typically implements some business logic related to the application. RFID middleware offers interfaces allowing it to be integrated to backend computer systems like ERP, MES, SCM and WM. Integration to backend systems is often done using SOAP methods like WebServices. Direct database integration is also possible.

A subset of RFID middleware is called edgeware. Edgeware is running on the reader and it provides certain amount of functions which can be used to trigger reader operations and refine the raw tag read data from the reader before it is uploaded to centralized integrated systems [6]. Main idea in edgeware is to reduce server and network load by reducing the amount of events which need to be processed centrally.

2.9 Regulations and Standards

2.9.1 Regulatory Bodies

Usage of RFID technology is regulated by RF regulatory bodies like The European Telecommunications Standards Institute (ETSI) and The Federal Communications Commission (FCC). Regulatory bodies set the boundaries within which RFID systems must operate. Fundamental restrictions are the maximum transmit power allowed and the operating frequency. Furthermore, these regulations limit the utilization of the given frequency band etc. This is done to prevent interruptions be-

Figure 8: RFID Gate at docking door.

tween different RF-systems. Allowed frequencies for UHF RFID systems are shown in Figure 9.

Methods to allow several readers to operate in the same environment are Listen Before Talk (LBT), Frequency Hopping Spread Spectrum (FHSS) and Dense Reader Mode (DRM).

The simple rule of thumb for Gen2 is that due to the regional RF regulations readers are regional but the tags are global, which makes it possible to utilize RFID in global logistics networks.

2.9.2 ETSI EN 302 208-1 v 1.4.1

The ETSI EN 302 208-1 regulation covers the minimum characteristics considered necessary in order to make the best use of the available frequencies [9]. The document defines the limits for short range RFID devices operating at the frequency range 865 MHz to 868MHz using up to 2 W ERP.

The frequency range is divided up to four channels of 200kHz each as can be seen in Figure 10. Tags respond using adjacent low power channels.

2.9.3 GS1 EPCglobal Class 1 Generation 2 UHF RFID Standard

There are different standards set by different organizations for RFID systems utilizing different frequency bands. This thesis focuses on UHF RFID, thus the most

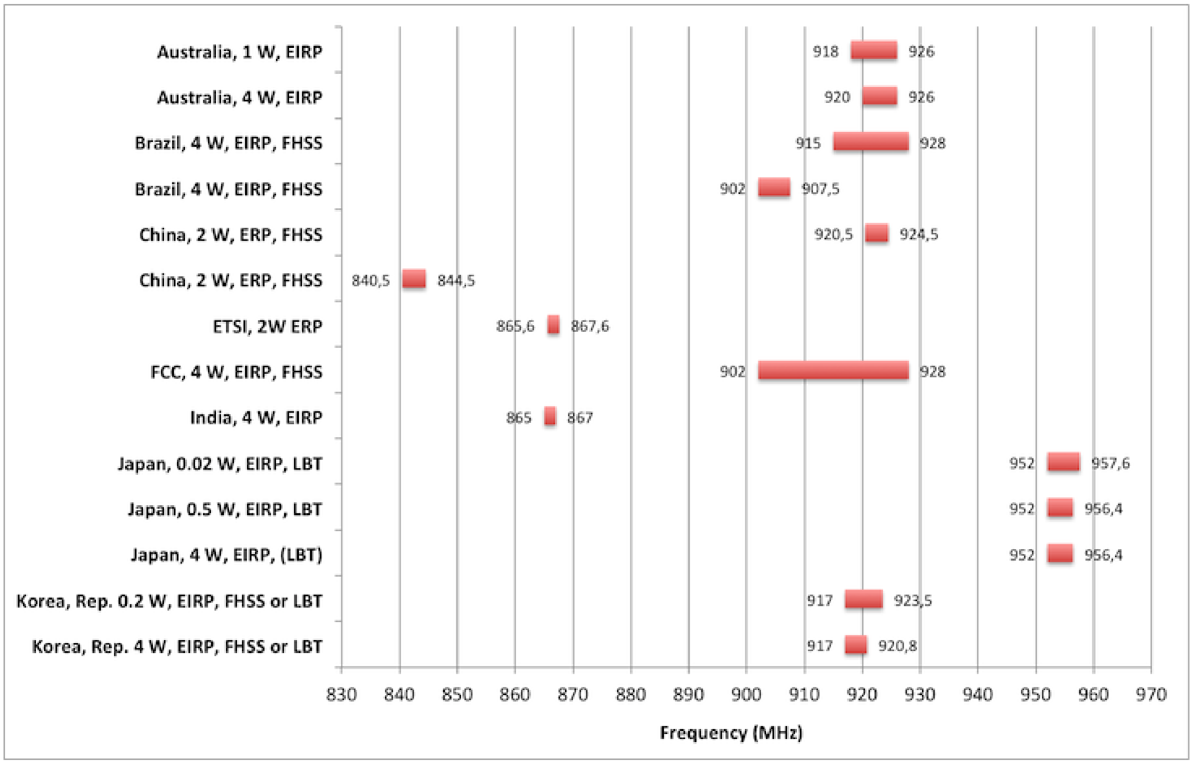

Figure 9: Regulatory status of RFID in UHF spectrum for some countries. ETSI covers countries in EU. FCC covers USA. [10].

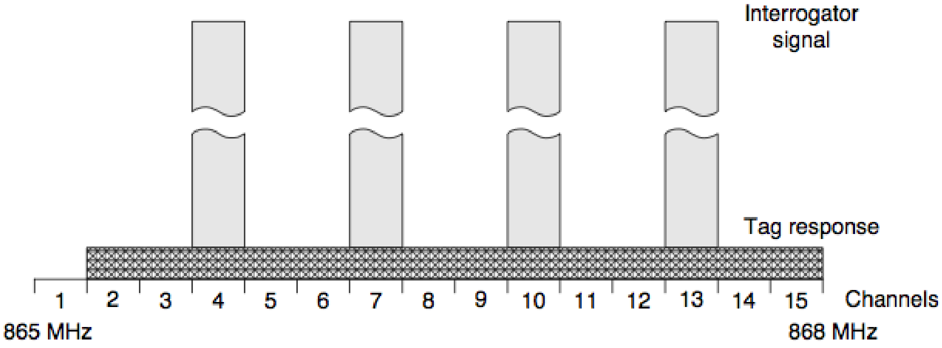

Figure 10: ETSI EN 302 208-1 channel plan [9].

remarkable UHF RFID standard is *GS1 EPCglobal Class 1 Generation 2*. This standard will be later referenced as *Gen2*. Gen2 set of standards is currently the most widely adapted one and offers very good level of interoperability between devices from different manufacturers.

GS1 EPCglobal has issued a set of global standards defining how UHF RFID systems should operate from the way data is encoded in the tag memory, how tag and reader communicate all the way to how the RFID data is integrated into back end systems. An overview of EPCglobal standards is presented in Figure 11. Another

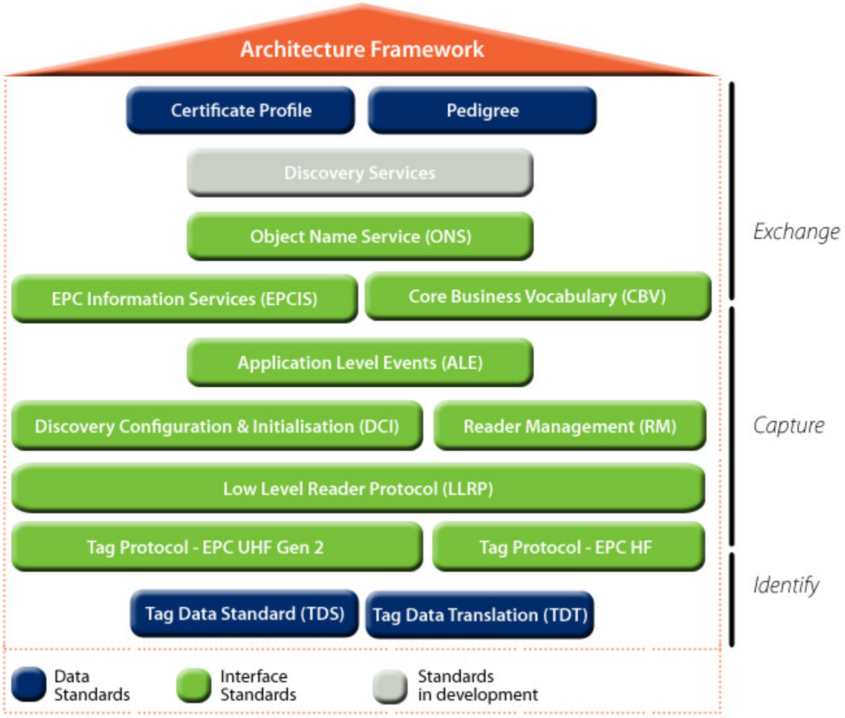

Figure 11: GS1 EPCglobal has issued a set of standards covering most aspects of RFID technology.

widely acknowledged standard ISO 18000-6C was developed from Gen2, but it only covers the RF- and communication part of the standard.

The Electronic Product Code (EPC) is a unique number that is used to identify a specific item in the supply chain [11]. EPC is used in information systems which need to track or otherwise refer to physical objects [12]. Usually, EPC codes are encoded on RFID tags, but other media is not excluded.

2.9.4 Air Interface

An interrogator sends information to one or mode tags by modulating a RF carrier using double-sideband amplitude shift keying (DSB-ASK), single-sideband amplitude shift keying (SSB-ASK), or phase-reversal amplitude shift keying (PR-ASK) using pulse-interval encoding (PIE) format [7]. Used PIE symbols can be seen in Figure 12. Symbol length is dependent on the set Tari parameter which is in range from 6.25μs to 25μs.

After the interrogator has finished the transmission it sends an unmodulated RF carrier and listens for a backscattered reply from a tag. Tags modulate the amplitude and/or phase of the RF carrier to send information back to the interrogator. Encoding format is either FM0 or Miller-modulated subcarrier. Communications between the reader and the tag is half-duplex, meaning that both cannot transmit simultaneously.

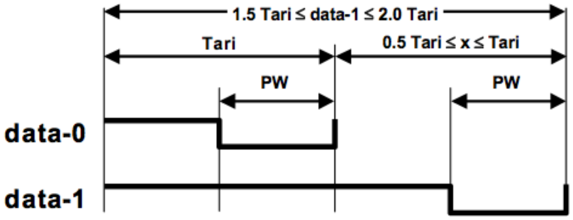

Figure 12: PIE Symbols. [7]

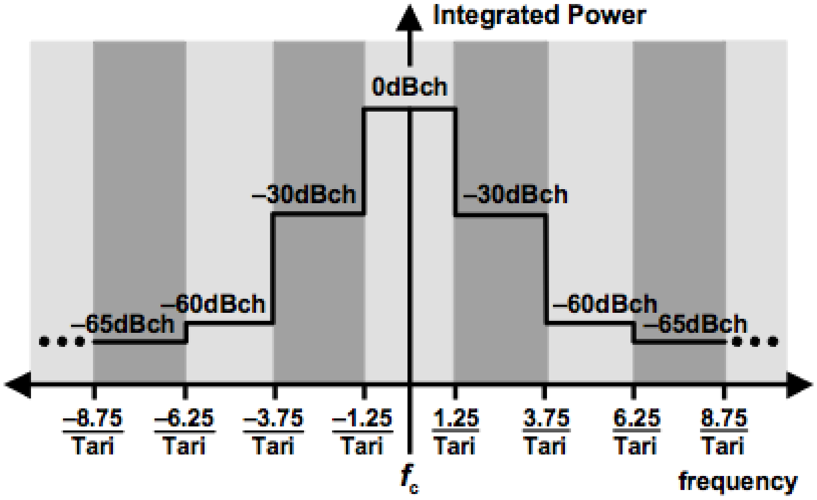

Figure 13: Transmit mask for dense reader environment. [7]

Gen 2 protocol defines a mask for dense reader environment. The mask limit's how much transmit power is allowed to leak from the channel frequency. This mask is presented in Figure 13.

Medium Access Control and tag anti-collision in Gen2 is based on Q protocol, which is a variant of slotted Aloha algorithm. The protocol operates in following way.

1. The reader specifies the number of slots in the inventory round (Q value)
2. Each tag uses pseudo random number generator to pick a number which is put to the slot counter
3. The reader issues commands to mark the beginning of each slot within the round
4. The tag decreases the slot counter by one for each of the rounds
5. Tag replies with a random number when it's slot counter is 0
6. Reader deciphers the random number and sends an ACK to the tag
7. Tag responds with EPC code

This protocol allows the reader to have unique logical sessions with the tags even though some tags would have the same EPC code. Random number sent by the tag acts as a handle within this inventory round.

If there are many collisions (many tags respond in the same slot) the reader can increase the Q value for next inventory round. Also if tags respond only from very few slots, the reader can decrease Q value to make inventory cycle faster.

Table 3: Tag flags and persistence values. [7]

Flag	Required persistence
S0 inventoried flag	Tag energized: Indefinite Tag not energized: None
S1 inventoried flag	Tag energized: Nominal temperature range: 500ms $<$ persistence $<$ 5s Extended temperature range: Not specified Tag not energized: Nominal temperature range: 500ms $<$ persistence $<$ 5s Extended temperature range: Not specified
S2 inventoried flag	Tag energized: Indefinite Tag not energized: Nominal temperature range: 2s $<$ persistence Extended temperature range: Not specified
S3 inventoried flag	Tag energized: Indefinite Tag not energized: Nominal temperature range: 2s $<$ persistence Extended temperature range: Not specified
Selected (SL) flag	Tag energized: Indefinite Tag not energized: Nominal temperature range: 2s $<$ persistence Extended temperature range: Not specified

There are four distinct sessions on which the reader can do inventory rounds. Sessions are presented in Table 3. The persistence times between different sessions determine how often the tag takes part in the inventory cycle of the reader. These sessions are independent.

Inventoried flag of a tag can have two states **A** and **B** for each session. Inventoried flags of each sessions are independent. Inventoried flags of sessions are presented in Figure 14. A reader operating at session **S1** can inventory a tag population from **A** to **B**. Immediately after that another reader operating at session **S2** can inventory the same tag population from **A** to **B**. This is very useful in multi reader environment.

Let's assume that a reader inventories tags from **A** to **B**. If the reader is operating on a session **S0**, it will get one read event from each of the tags as long as the tags are powered on. Each time the tag loses power and receives it again it responds during inventory cycle of the reader.

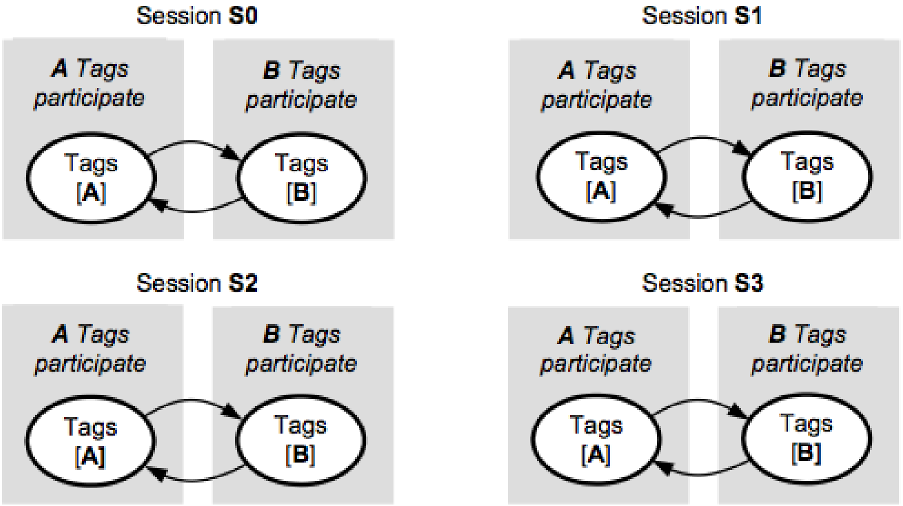

Figure 14: Session diagram. [7]

If the reader is operating at session **S1**, it will read tag population continuously and receive read events from a single tag within interval 500 ms to 5 seconds, wether the tag has kept its power on or not. Obviously, it is not possible to read an unpowered tag.

If the reader is operating at sessions **S2** or **S3**, it will receive a read event once for each of the tags as long as the tags are powered. If the tag loses it's power for less than 2 seconds the inventoried flag will stay at **B** and no read event occurs.

Some tag manufacturers set different persistence values for sessions **S2** and **S3** as the protocol allows this. For example the persistence for session **S2** can be 5 seconds and for **S3** 15 seconds.

A good example on using the inventoried flag is the Impinj readers' dual target mode. When the reader is configured to use dual target mode, it will first inventory tags from **A** to **B** and right after that from **B** to **A**. If this mode is used, continuous read events are received from powered tags in sessions **S2** and **S3** too.

3 Definitions and the Research Problem

3.1 Cases to Study

In this thesis three different cases of stray reads are studied. All three cases are commonly faced while implementing RFID systems for distribution centers or other similar locations.

I. In the first case to study, RFID tagged handling units are left laying around inside the interrogation zone of RFID gate. This is a common situation at distribution centers. It is beneficial to detect lay around tags and ignore such read events received. First case is presented in Figure 15. The figure presents two adjacent docking doors equipped with RFID gates. The point of view is from above. Truck trailers are parked at the docking doors. Wall of the logistics center is marked with

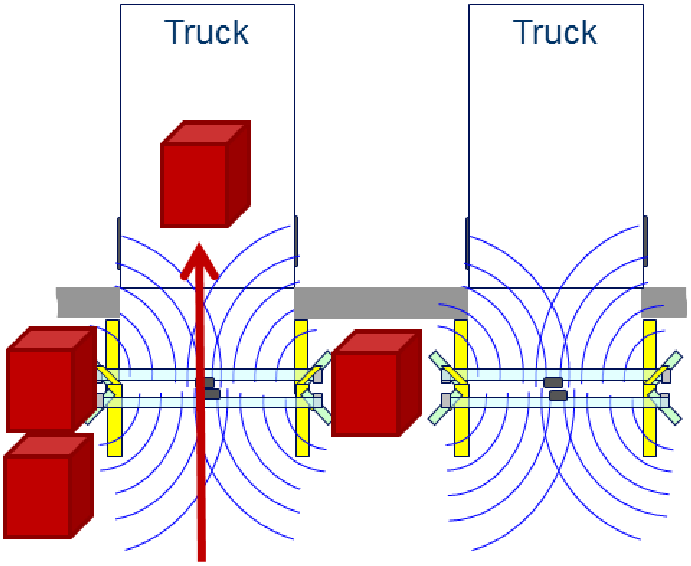

Figure 15: RFID tagged handling units laying around stationary inside interrogation zone.

bold grey bar. RFID gates are marked with vertical yellow bars. Antennas at the gates are marked with diagonal bars. The antenna setup presented in the figure is typical direction sensing configuration with two antennas pointing at the direction of the trailer and two antennas pointing at the direction of the logistics center. Approximate interrogation zones are marked with radial blue lines starting from the antennas. Handling units are marked with red boxes. A picture of similar RFID gate with normal (non direction sensing) antenna setup can be seen in Figure 8.

II. The second case to study is presented in Figure 16. This case is about a RFID tagged handling unit passing by the interrogation zone of a RFID gate without going through the gate. This is an essentially different case compared with the lay around case as read events indicate that the tag is moving. However, the direction of the movement is different from those tags which go through the gate.

III. The third studied case is about cross reading. The docking doors of warehouses are usually placed next to each other as can be seen in Figure 17. There can be tens of docking doors right next to each other. In these situations, RFID gates are also placed next to each other and their interrogation zones can be partly overlapping. In the Figure 17, the interrogation zone of the RFID gate on the left is overlapping with the interrogation zone of the RFID gate on the right. Leftmost antennas of the gate on the left are pointing towards the interrogation zone of the gate at the right. The handling unit moves through the gate at the right, but some tags are read also by the gate at the left. It is essential to know through which gate

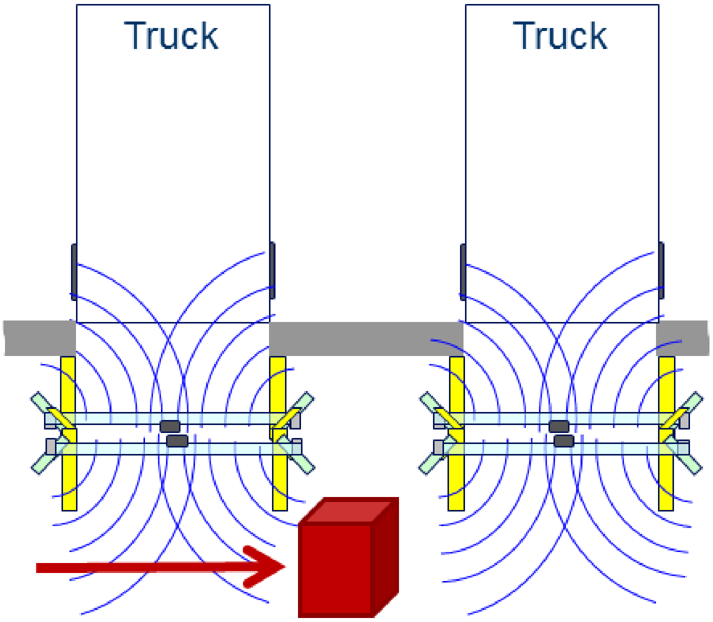

Figure 16: RFID tagged handling unit moves through interrogation zone without going through the gate.

the handling unit left or entered the warehouse. Due to overlapping interrogation zones, this is not always so obvious to detect.

In all the studied cases, the number of tags can vary from one to several hundred per handling unit.

Experiments are conducted on first two cases. Third case is explored only theoretically.

3.2 State-of-the-art Stray Read Detection

The number of academic studies which focus on identifying or controlling stray reads at RFID gates is limited. Academic work shows many studies about methods which can be utilized for this need. A number of patents about methodology to address this type of problems have been issued.

Academic research focuses on estimating 3D location for the tags [13] [14] [15] [16] [17] or locating the mobile vehicle carrying the RFID reader [18]. The tag count is very small in these studies, usually only one tag to be located, which limits the usefulness of the results. However, it does not mean that the same methods must not provide similar results in many reader many tags environment.

On commercial field, Intermec uses doppler shift to detect tags belonging to load on fork lift trucks [19]. Fork lift truck lifts a load. Read cycle is initiated by a RFID reader after the fork lift truck starts to move. Those tags which belong to

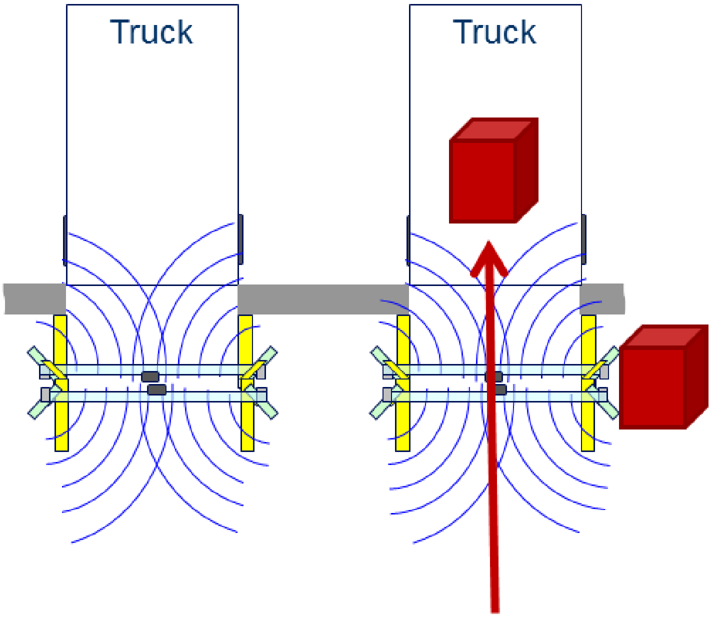

Figure 17: RFID tagged handling units are loaded at the neighbouring gate, which is partly inside the interrogation zone of the gate.

the load which was just lifted present lower Doppler shift values (0 values in theory) compared to those tags which are attached to stationary items.

Impinj provides lay around tag suppression as an proprietary extension to LLRP protocol [20]. Repeated observations of the same tags are suppressed for extended periods of time while the tag is energized. This method cannot be used in systems where multiple reads per tag are needed as it does not try to determine actual lay around tags.

Thingmagic has patented methodology to determine tag distance based on phase angle change over frequency change [21]. It allows estimating a distance form RFID reader to a tag based on multiple measurements of phase angle rotation using different frequencies. The drawback of this method is, that at least two measurements are needed and the tag nor the reader should move in between the measurements.

A patent issued to Nofilis describes a method how to compare the reads from tags received through different antennas to find out wether the tag passed the gate [22].

7iD has patented methods to determine through which adjacent gate the tag went [23]. The RFID read events from different gates are collected to a central processing unit for further analysis to find the relevant events.

3.3 The Interrogation Zone and the Extended Interrogation Zone

Rao et al. define read range as the maximum distance at which RFID reader can detect the backscattered signal from the tag [24]. Read range can be calculated using Friis free-space formula

$$r = \frac{\lambda}{4\pi}\sqrt{\frac{P_t G_t G_r \tau}{P_{th}}} \tag{1}$$

where λ is the wavelength, P_t is the power transmitted by the reader, G_t is the gain of the transmitting antenna, G_r is the gain of the receiving antenna, P_{th} is the minimum threshold power necessary to provide enough power for the RFID tag chip and τ is the power transmission coefficient affected by antenna and chip impedances. This states that most passive RFID systems are uplink limited. It is more difficult to power up the chip on the tag than hear the backscattered signal.

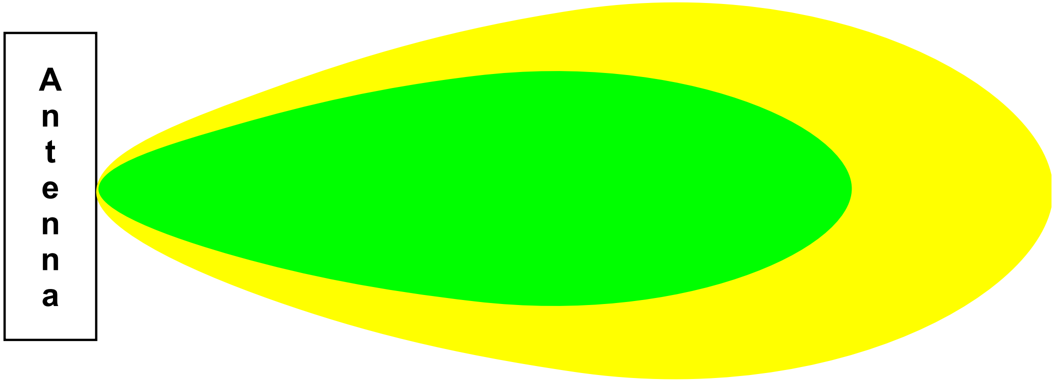

Figure 18: Typical interrogation zone generated by antenna used in RFID systems. Interrogation zone is marked with green and extended interrogation zone with yellow.

According to *RFID for Dummies* [25], interrogation zone is *"a radio frequency field that can be thought of as a giant bubble coming out of the antenna"*. It is useful to define the interrogation zone more accurately. The logical limit for the interrogation zone would be an area where the RF-field generated by the reader is strong enough to activate the RFID tag and give it enough power to backscatter detectable and qualified signal to the reader. The interrogation zone is marked with green color in the Figure 18.

When this definition is used, it is obvious that interrogation zone is dependent on the reader and the tag used as some tags and readers are more sensitive than others. Additionally, the interrogation zone depends on the operating environment. Large amounts of ambient electromagnetic noise will limit the size of interrogation zone, as backscattered signal is lost in the noise. The interrogation zone is also shaped by RF-absorbing or RF-reflecting materials within the interrogation zone.

The qualified aspect of the signal refers to the main problem studied in this thesis. The signal will be qualified over criteria which depends on the measured properties of the signal like Received Signal Strength Indicator (RSSI). In industrial applications read reliability plays the key role in the usefulness of the applications. In some applications, the environment or tag position might not be optimum for read reliability, the RF properties of tagged items vary and tags have tag-to-tag differences in backscattering ability. In these cases reader transmit power needs to be increased to increase RF-field strength to allow these not optimally located RFID tags to be read. Increasing transmit power widens the interrogation zone over the desired limits.

The area on which the RF-field generated by the reader is strong enough to activate the tag and give it enough power to backscatter detectable but unqualified signal to the reader is referred as *the extended interrogation zone* in this study. Extended interrogation zone is marked with yellow color in the Figure 18.

3.4 RFID Event

A RFID event is one logical transaction at the interrogation zone. When a tag passes through the gate, it may interact with the reader several times depending on the settings on the reader. The maximum read rate with current state-of-the-art readers is close to one thousand reads in one second. Small number of readers operating at full speeds could bring very high load on back end systems, if read events would be transmitted unfiltered. The number of events is reduced greatly by using RFID parameters like session in reasonable way. In any case these single read events and their quality indicators can be processed to create more sophisticated information which can be used in business logic.

A bunch of one hundred read events can be refined to a single RFID event which contains information like tag with EPC code A, went through portal B, to direction C at time D. This is reasonable at the system design point of view also. Especially if the amount of RFID readers is large, they can produce huge amounts of information within a short time interval [25].

In addition to the one RFID event type described in previous paragraph, there can also be many other types of RFID events.

- Tag entered the interrogation zone
- Tag left the interrogation zone
- Tag was seen at the interrogation zone
- Tag was encoded
- Tag was commissioned (printed)
- Tag was killed

The exact types of RFID events which are reported by the middleware depends on the application.

3.5 Environmental Considerations

3.5.1 Warehouse Environment

Industrial warehouse environment, which is typical for logistics RFID applications, lays challenges on RFID systems. Typically the environment is not fully controllable and there may be interference in physical environment and possibility for process error. Although storage and transfer areas are separated in most cases, it is not always possible due to limited space available. There is a need to design RFID systems to tolerate handling units left in the extended interrogation zone.

Most of the problems can be solved by warehouse layout design. Layout must be designed so that there are no other than RFID transaction related activities at the interrogation zone. Interrogation zones can be placed far from each other and antennas can be placed so that they do not point to other interrogation zones. Material flow must be designed so that no materials are stored near interrogation zones.

Issuing a kill command for those tags, which are not used anymore to avoid interference with the tracked process is a good practice. Sometimes this is not possible and these discarded tags can end up near interrogation zones of RFID gates. These kind of tags present the same problem than the lay around handling units waiting to be handled in the previous paragraph. The operating environment should be kept clean of discarded RFID tags.

3.5.2 Dense Reader Environment

If a warehouse is fully RFID enabled, it usually means that there are several adjacent docking doors. It is possible that a RFID reader detects a tag going through an adjacent docking door. This is known as *cross reading*. There is also a possibility that a tag powered up by a reader nearby, responds to inventory command of a reader much farther away. This phenomenon is known as *cross talk*. In cross talk the tag behaves as a semi-passive tag would. The reader near-by provides the energy to power up the tag circuits. In most cases passive RFID communication is downlink limited [2]. If the communication would be uplink limited, cross talk would not be possible. These issues must be in control for successful implementation of a RFID system.

Communication protocols used by RFID readers take multi-reader environments into account with functions like *Listen Before Talk* (LBT), *Dense Reader Mode* (DRM) or *Frequency Hopping Spread Spectrum* (FHSS). If LBT is used, the reader is obliged to listen that the selected channel is free of transmission before it starts to transmit. DRM operating modes of the reader use Miller-modulation to reduce the bandwidth of the signal by increasing the symbol length. Miller-modulation uses 2, 4 or 8 subcarrier cycles for one symbol. Increasing the symbol length decreases the data rate. FHSS distributes the transmission over many different randomly chosen frequencies and thus reduces the interference between readers as two readers use the same frequency only for a very short time.

3.5.3 RF-absorbing and -reflecting Materials

Both the operating environment and the items tagged may be made of or may contain RF-absorbing and -reflecting materials. Liquids absorb RF-energy transmitted by readers and may prevent reading nearby tags. Metals reflect the RF-field generated by the reader shaping the interrogation zone and preventing nearby tags from responding. Reflecting materials can also focus RF-energy to some spots outside the interrogation zone, and make it possible for tags outside of interrogation zone to respond.

In general RF-absorbing and -reflecting materials should be avoided in the interrogation zone between the reader and the tag.

3.5.4 Other RF-issues

Physical structures like floor, roof, walls and portal structures have RF-reflecting properties. This causes phenomenon called multipathing. RF-signal sent by the reader or backscattered signal sent by the tag may not pass using the shortest route – the line of sight. These signals may be reflected from some nearby structures. When signal arrives the destination through different routes, the phase of these signals does not match. Signals add to each other causing constructive and destructive interference. Multipathing weakens backscattered signal and causes variance to the signal parameters, thus making qualification problem more difficult.

Ambient Electromagnetic Noise (AEN) reduces *Signal to Noise Ratio* SNR of the backscattered signal making detection more difficult. Electric motors and other electronic devices can work as a source for AEN. In FCC regulated countries RFID devices use the *Industrial, Science, Military* (ISM) band which is unlicensed but regulated. Many different RF systems like remote controls may operate on this same band causing interference.

3.6 Reducing Interference Caused by Dense Reader Environment

Special attention needs to be paid to reduce the interference between readers in multi-reader environment. Non-controlled interference can reduce reliability and throughput of an RFID system.

There is a vast difference in the power of a signal transmitted by the reader and a backscatter of a tag. The magnitude difference between a tag response and a signal from some other reader is 2×10^{10} fold. Pointing antennas of two readers towards of each other should be avoided, because it will affect reader capabilities to receive transmissions from tags. A RFID reader with multiple antennas of a single reader can be towards each other, as the reader multiplexes the antennas and transmit using one antenna only [2].

Transmitting should happen only when necessary. RFID gates can be equipped with motion sensors which trigger reader to read when motion is detected at the gate. This will decrease RF-noise in the environment.

Impinj Speedway Revolution R420 supports low duty cycle mode which minimizes transmission when no tags are present [20]. When reader is operating in low duty cycle mode it pings *Field of View* (FOV) of each antenna for tags at slow rate. When a tag is seen, the reader moves to full duty cycle mode.

Readers operating on adjacent docking doors at distribution centers can be coordinated in a such manner that only right- or left-looking antennas are activated at any given moment. This reduces the AEN received by the readers.

Interference coming from outside to interrogation zone and interference caused by the reader to environment can be reduced by proper shielding. RF-absorbing materials can be placed around the interrogation zone. In most cases this is not very practical so other options should be considered.

Readers operating near each other can be forced to use different frequency channels in ETSI region. This will reduce the interference caused by each other. On FCC region, the number of available channels per reader cannot be reduced, but it is possible to tell the reader to decrease transmit power on some particular frequencies [20].

3.7 Locating Tags

There are many studies considering RFID localization. Some of the previous study use RFID tags as beacons and the RFID reader is moving in the area [27]. This kind of localization applications are usually related to navigation in predefined environment. Typical applications include field robotics and positioning forklift trucks in a warehouse. Other studies let the tag move and readers are stationary [28]. Different localization techniques have been compared by Bouet [17]. These studies are close to the research problem, but do not present ready methods to solve the problems studied in this thesis.

3.7.1 Detecting Tags at Extended Interrogation Zone

Cross reads often cause a problem for RFID gates. Sometimes adjacent RFID gates are placed near each other – the distance between gates can be less than 1.5 meters. Some of the tags moving through an adjacent RFID gate are read. These read events from the wrong gate need to be identified and discarded.

Cross talk increases the number of cross reads as the nearest gate powers up the tag to make it visible for a reader further away. Known fact is that the RSSI of read events from cross talking tags is significantly lower than RSSI of the tags in the interrogation zone of the reader. Hence cross talk reads can usually be suppressed by RSSI filtering.

One solution to this has been presented by 7iD. This patented solution chooses the first antenna which sees the tag in direction from the antenna beam as the correct antenna [23]. The idea is presented in Figure 19. A handling unit with RFID tags moves through the gate on the right. All antennas on adjacent gates pointing right detects some of the tags. Blue arrow shows the direction of antenna beams. Based on this logic the read events from the right-looking antennas of the right most gate

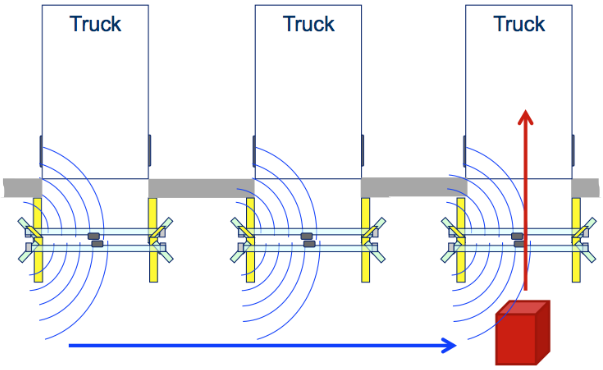

Figure 19: Cross read detection by comparing read events from different gates.

are the meaningful ones. This is a very straight forward solution to solve the cross reading issue, but needs decision making and filtering on higher than reader level.

3.7.2 Multi-level Localization Problem Solving

Each message sent by a RFID gate has a cost related to the amount of data transferred and processed within the RFID system. This is why it is advantageous to create, filter and analyse the RFID events at as low system level as possible. Nevertheless cross reading issue might need to be solved on a higher level, when information from several different readers is available. The knowledge of the geometry and mutual locations of the interrogation zones allows to form unions and intersections of interrogation zones. This enables more detailed localization information to be refined from the events received.

3.8 Detecting Tag Movement

Tag movement detection can base on changing RSSI or phase angle values between two read events of the same tag or on Doppler shift information on single read event.

3.8.1 Detecting Non-Moving Tags

One of the main questions to answer in this study is to find methods how to detect static (non-moving) tags. These tags are referred as lay around tags in this thesis. This is also one of the most common problems in logistics environment. A handling unit may be left near a docking door, which allows a RFID reader to read at least some of the tags inside the handling unit. These tags have not gone through the interrogation zone and no RFID event should be created for them.

Intermec has patented a method to determine which items are part of the fork lift truck load and which are not. The methods relies on phase angle to detect stationary tags [19]. The movement information of tags is combined to the information about movements of the fork lift truck. A RFID reader and an antenna is mounted on the fork lift truck. If a tag is found stationary compared to the antenna (and the fork lift truck) while the fork lift truck is moving the tag is considered as a part of the load.

Doppler shift based tag movement detection methods have been explored by Sensormatic. The company has patented Doppler shift based methodology to be used in fork lift truck application [29].

3.8.2 Detecting Tags Moving Across Interrogation Zone

Commonly the operating environment has space limitations. In such cases it is possible that the handling units marked with tags are pulled across the extended interrogation zone of an RFID gate. Some tags within the handling unit are read, but should be discarded using the suitable qualification criteria.

A positive detection problem is to detect tags moving through a RFID gate and create according RFID events. This capability must not be compromised by the methods to solve the two negative detection problems mentioned above.

4 Methods

4.1 Controlling the Interrogation Zone

In this chapter few typical ways of adjusting the interrogation zone are introduced. Generally the ideal interrogation zone would match with the extended interrogation zone. Due to limitations in antennas and multipathing in the real world environment, it is difficult to create RF-field with clean envelope, high intensity and sharp edges, where intensity suddenly drops to very low levels.

Known interrogation zone controlling methods are considered in the following. Most of the methods are based on the factors in Friis free-space equation 1.

4.1.1 Reader Transmit Power

In most cases read range is limited by the downlink [2]. A tag needs to harvest enough energy from the signal transmitted by the reader to power up the IC. In most cases this amount of energy is sufficient to backscatter detectable response to the reader. The amount of energy transmitted can be adjusted by changing the reader transmit power within the limitations set by regulatory body and antennas used.

4.1.2 Choosing the Right Antenna for the Application

The size and shape of the interrogation zone depend on the antenna(s) used. There are several types of antennas, each type shapes antenna beam differently. The beam might be e.g. wide and uniform or narrow and one sided.

The European RF-regulatory body ETSI limits the maximum *Equivalent Radiated Power* (ERP) to 2W. This means that if a high gain antenna is used, the transmit power needs to be reduced. Meanwhile the American RF-regulatory body FCC limits the maximum *Equivalent Isotropically Radiated Power* (EIRP) to 4W. This corresponds to 2.44W ERP.

High gain antennas, also known as narrow beam antennas, emit narrow RF-field. These type of antennas can be used to limit the extended interrogation zone in front and in back of the gate. The interrogation zone is more intense between the gate pylons. The downside is that the interrogation zone is much narrower and gives a moving tag less time to be read. Throughput of the system is limited.

If antennas are placed on the top of the gate facing down, the interrogation zone is physically limited to the floor. Depending on the reflecting and absorbing properties of the floor this can be a very efficient option on handling unit level tagging, but not very usable on item level tagging, when tags are usually placed on the sides of the items.

4.1.3 Antenna and Tag Positioning

Tag location determines how antennas should be positioned. The main principles are that there should be antennas facing all sides of the handling units on which the tags may be located. Line-of-sight helps to get the read reliability on high level but it is not a necessity.

In handling unit level tagging cases, when there is only one or several tags with the same ID on the handling unit, positioning antennas on top of the gate is a good option. It helps to limit the interrogation zone and reduces possibility to cross read. In this case the tag should be positioned on the top of the handling unit.

If the handling unit contains several items which are tagged individually, tags should generally be facing to the sides of the handling unit. This allows stacking items on top of each other. If the items contain RF-absorbing or RF-reflecting materials, no tags should be placed inside the handling unit as reading of such tags becomes more difficult.The drawback is that when the antennas are on the sides of the gate, confronting cross read issues becomes more probable.

The number of antennas needed is determined by the size of the handling unit and the shape and the size of the antenna RF-field. Most typical cases can be solved by placing two antennas on each side of the gate. One antenna near the maximum height of the handling unit and the second antenna near ground.

Some methods involving advanced RF-level processing (e.g. Doppler shift) may require adjusting the antennas to the right angles towards the expected tag movement. Measurement of the signal path length from the transmitter within the reader to the antenna is needed, if phase shift rotation measurements are used for triangulation.

4.1.4 Third Antenna Trick

The third antenna trick covers a number of methods to divide interrogation zones into smaller sections by using unions and intersections of the tag visibility data. The third antenna trick can be used to convert sections of the interrogation zone to extended interrogation zone. This is done by putting an additional antenna(s) facing away from the interrogation zone. If a tag is seen by one of these additional antennas, it can be determined to be at the extended interrogation zone and no RFID event is created.

In Figure 20 the RFID gate has two antennas facing inside the RFID gate. The interrogation zone of these antennas is shown on blue. Additionally, there is a third antenna with an interrogation zone marked with red. The lay around handling unit is partly on the blue and the red interrogation zones. As long as the handling unit is seen with the third antenna, it is considered as a lay around handling unit and no RFID event is created. In this case the interrogation zone is an union of the two antennas with blue interrogation zones, excluding the intersection marked with red.

4.1.5 Triggered Reading

One way to reduce unwanted RFID events and conserve electricity is triggered reading. Photo cell or similar sensor is installed to detect activity at the interrogation zone. The RFID reader is activated only when this sensor is triggered.

A camera can also be used as a motion trigger. There are methods to calculate optical flow from the consecutive images provided by the camera. The optical flow

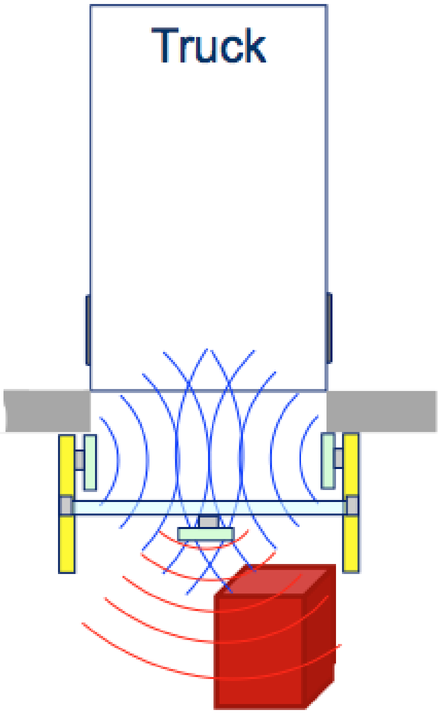

Figure 20: Third antenna trick is used to control stray reads.

measurements reveal the direction and intensity of the movement, which can be thresholded and used as a trigger for RFID gate.

Triggered reading reduces the amount of stray reads, especially when RFID gates are adjacent. However the method does not provide final solution for issues with lay around tags, stray reads or cross reading. When a handling unit containing RFID tags is pulled through the gate, there still might be some lay around tags in the extended interrogation zone.

Triggered reading should be considered if large amount of RFID readers or other RF-emitting devices are located in the same place. In this type of environment triggered reading will reduce ambient electromagnetic noise, as the RFID readers do not need to query for the tags constantly.

Triggered reading may hinder the operation of lay around tag detection as number of read events from lay around tags is decreased. This limits the possibilities to use statistical methods to identify lay around tags with high certainty.

4.2 Signal Quality Indicators

Backscattered signal received from tag has three main parameters, which are provided by commercially available RFID readers: *Return Signal Strength Indicator* (RSSI), signal phase angle rotation and Doppler shift. These can be used to find the qualities which differ in tags located in the interrogation zone and the extended interrogation zone. These parameters also offer methods of distinguishing moving tags from stationary tags.

4.2.1 Return Signal Strength Indicator (RSSI)

Return Signal Strength Indicator is the strength of the backscattered signal from the tag. It is usually presented in dBm. It tells how strong is the downlink from the RFID tag to the RFID reader. Received signal strength can be derived from Friis equation

$$P_r = P_t \tau G_r^2 G_t^2 \left(\frac{\lambda}{4\pi r} \right)^4 \tag{2}$$

where P_r is the signal power received, P_t transmit power of the reader, τ backscatter transmission loss, G_r reader antenna gain, G_t tag antenna gain λ carrier wavelength in meters and r distance reader and tag antennas. This states that received signal strength is dependent on the distance by factor of $1/R^4$.

It is obvious that generally RSSI decreases when distance to the tag increases. The received signal strength decays monotonously as mentioned above in free space, but in typical operational environment for a RFID system the decay over distance is more complex due to constructive and destructive interferences caused by the reflections of the signal.

It is known that reader transmit power, antenna gain, cable losses and tag design affect the RSSI. There can even be tag to tag differences between similar make of tags which are caused by small differences in chip to antenna coupling. Tags with degraded performance should be eliminated while tagging.

RSSI can be used as a thresholding criteria: Tags which respond with RSSI value lower than the set limit are discarded. This can lead discarding bad tags, tags in difficult locations or tags seen through reflection which needs to be taken to account.

Thresholding can be based on absolute RSSI values or relative RSSI values to some known tag. A reference tag can be placed in the interrogation zone and read events from load tags can be compared with read events from reference tags. Thresholding has proven to be very useful in filtering out the read events caused by cross talk.

4.2.2 Signal Phase Angle Rotation

In this thesis a term *signal phase angle rotation* is used instead of the more general alternative *signal phase angle*. This is due to the nature of the measurement done by the reader. The reader does not report the phase angle of backscattered signal received from the tag. Instead it reports the difference of phase angles of the sent and the received signals. This justifies adding the *rotation* extension to the the term for the sake of clarity.

Relation between wavelength and frequency of RF carrier wave is given by

$$\lambda = \frac{c}{f} \tag{3}$$

where c is the speed of light, f is the frequency and λ is the wavelength.

Phase angle rotation of the backscattered signal can be expressed as

$$\theta = 2\pi \left(\frac{2R}{\lambda} + \theta_T + \theta_R + \theta_{TAG} \right) \tag{4}$$

where R is the distance between the reader and the tag, λ is wavelength, θ_T phase angle rotation caused by reader's transmit circuits, θ_{TAG} is phase angle rotation caused by the tag's reflection characteristics, and θ_R is the phase angle rotation caused by the reader's receive circuits.

The phase angle is a periodic function with period of 2π radians, thus phase angle values repeat at distances separated by the integer multiples of one-half of the carrier wavelength.

$$R_n = \frac{n\lambda}{2}, n = 1, 2, \ldots \tag{5}$$

In theory phase angle rotation remains the same as long as the signal path, the wavelength and the phase angle rotation characteristics of the reader's and the tag's circuits remain the same. These qualities make the phase angle rotation change a good measure for a tag movement at least in theory.

There are several factors which need to be considered when using phase angle rotation to determine relation between the tag and the reader. Multipathing in the operating environment can alter the signal path between read events. FCC regulations oblige reader to frequency hopping, which affects the wavelength and this way has a small change in phase angle rotation. Readers operating at ETSI region change channels to overcome operating environment limitations. FCC allows wider 26MHz bandwidth for RFID. Within this bandwidth the phase angle rotation changes remarkably. The phase angle rotation needs to be treated antenna- and frequency-wise.

Sophisticated methods have been developed to use signal phase rotation to locate tags, measure their orientation and speed [19]. These methods include TD-PDOA (Time Domain Phase Difference of Arrival), FD-PDOA (Frequency Domain Phase Difference of Arrival) and SD-PDOA (Spatial Domain Phase Difference of Arrival) [13]. Povalac et al. have further studied the FD-PDOA method [14] and Hekimian et al. have studied the SD-PDOA method [15].

Last two methods are interesting in the RFID point of view. ETSI and FCC regulations allow changing the frequency within the given range. In theory it would be possible to calculate the distance to the tag based on how much phase angle rotation changes when frequency changes. If this information would be gathered from several antennas with known locations, it would be possible to tell the tag location related to the antennas.

Phase angle rotation measurement can also be used to determine tag movement and distinguish stationary tags from moving. If measured phase angle rotation changes, the tag is moving or an object is moving between the tag and the antenna.

Cyclic type of phase angle rotation can cause problems on this approach. Inconsistencies in phase angle rotation change need to be handled. The wavelength of electromagnetic radiation at frequencies around 860 MHz is 34 cm. Also two-way signal path needs to be considered which further increases the resolution of one phase angle rotation cycle to 17 cm. Thus read events should be received at least one from each 8.5 cm, which limits the highest allowed speed for the tag with the read rate of the reader. It would be possible to follow a small number of tags accurately, but the number of tags must not be too high.

The typical geometry of a RFID gate reduces the phase angle rotation change. Antennas are on the side and handling unit moves in front of the antennas. The phase angle rotation change rate decreases gradually and starts to increase when the handling unit passes the middle point of the gate.

The most promising use for phase angle rotation data of read events can be to calculate standard deviation over measured phase angle rotation values for each antenna separately. Especially at ETSI region the narrow bandwidth will not cause significant shift in phase angle rotation for the distances used. Standard deviation of the phase angle rotation values could indicate wether the tag is moving or not.

4.2.3 Doppler Shift Over Read Cycle

Doppler shift forms when there is a relative motion between reader and a tag [18]. The perceived wavelength of the signal is shortened, if the tag is moving towards the reader and lengthened, if the tag is moving away from the reader. Perceived phase angle rotation over received data packet transmit duration is given by

$$\Delta\theta = 2\pi\left(2f_m\Delta T\right) \tag{6}$$

where f_m is Doppler frequency, and ΔT data packet transmit duration.

The Doppler frequency perceived by the reader is given by

$$f_m = \frac{\Delta\theta}{4\pi\Delta T} \tag{7}$$

This measurement is greatly affected by the data rate used in the communications between a RFID tag and a RFID reader. In the high throughput mode, when the data rate is fast, Doppler shift measurements have proved to be inaccurate [26]. The accuracy of Doppler shift measurements can be increased by slowing down the data rate e.g. by using Dense Reader Mode (DRM) settings for the reader or by increasing the amount of data to be transmitted by using tags with longer EPC codes [26].

Doppler shift is very useful in RFID applications, as it provides estimate of speed of tag within a single read event. Doppler shift does not only reveal the speed, but also the direction of the movement relative to the given antenna. This makes it an effective tool for detecting stationary tags.

4.3 Using Geometry of Antenna Setup to determine Tag Movement

Antenna layouts designed for direction sensing purposes can be utilized to detect lay around tags. Some algorithms used for direction sensing provide lay around tag identification as side result. Those tags which were seen, but the direction of wich could not be determined are identified as lay around tags.

There are two commonly used antenna layouts for direction sensing. First utilizes two separate interrogation zones and second tilted antennas and Doppler shift measurement.

4.3.1 Two Interrogation Zones

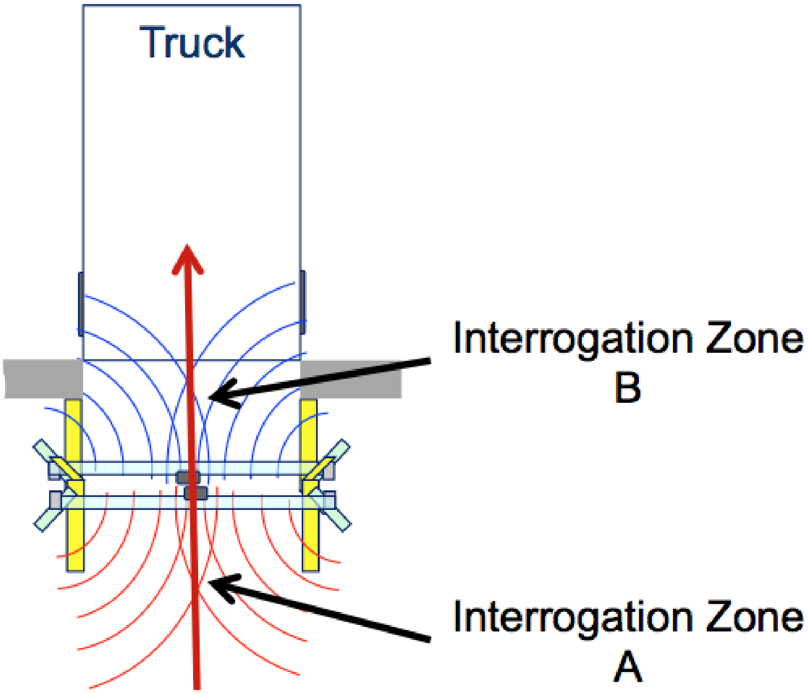

Figure 21: Direction sensing with two separate interrogation zones.

If RFID Gate is equipped with two or more antennas, it is possible to divide the interrogation zone in two parts in the direction of the movement as can be seen in Figure 21. If the tag is seen first in the interrogation zone **A** and then in the interrogation zone **B**, it can be assumed that the tag has moved from **A** to **B**. This kind of interrogation zone layout can also be used to detect lay around tags. In this case those tags which have been seen only at **A** or at **B**, but not at both, can be determined as lay around tags.

Usually dividing interrogation zone in two parts is done by installing one pair of antennas facing front of the RFID gate and another pair of antennas to the back of the RFID gate. Drawback with two interrogation zones is that it increases the footprint of the RFID gate.

Common algorithm to be used when two interrogation zones are used to detect direction of the movement is presented using Python code in Listing B1. Simple direction sensing algorithm receives a list of RFID read events for a single tag and determines a movement based on these events. If currentSide is unknown in the end, the tag is identified as lay around tag.

4.3.2 Antennas Tilted to the Direction of the Movement

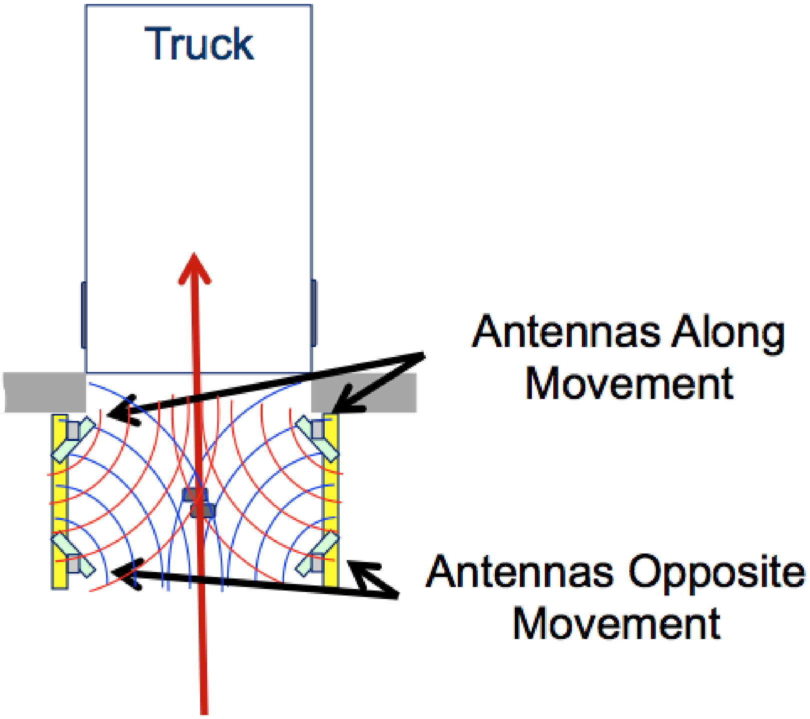

Figure 22: Direction sensing with antennas tilted towards the movement.

Doppler shift values of RFID read events reveal the perpendicular to antennas component of tag speed. These measurements can be used to determine direction of the movement. In Figure 22 is presented simple direction sensing gate which utilizes Doppler shift measurement.

Doppler shift based algorithm to detect the direction of tag movement is presented in Listing B2. If *currentSide* is left at *unknown* the tag is identified as a lay around tag. Proper threshold value needs to be determined.

4.4 Layout Based Processing the RFID Event Data

To address issues with cross read, it is possible to use the information about the layout of the RFID system. If read events of the same tag come from two different gates with directed antennas, it is possible to determine what the closest antenna to the tag was by comparing the antenna directions. The tag must have been in front of the antenna furthest away in the direction the antenna beams are pointing, if it has been seen with several antennas pointing the same direction [23]. Cross read possibility is eliminated if the antennas of both sides of the gate read the tag.

4.5 Statistical Analysis of Multiple Read Events of RFID Tag

In this thesis statistical properties of several consequent read events of the same RFID tag are used for two purposes – to determine the movement of the tag and wether the tag is in interrogation zone or in extended interrogation zone. To get high certainty for results, high number of read events are needed, which can be considered as a limitation for these methods. Hence it is not possible to use statistical methods if a tag is seen only once.

Statistical analysis is carried out offline for recorded data after the experiments. The data is analysed using purpose built program written in Python. Analysis is done on testrun basis. Statistical analysis is based on all read events of the same tag during one test run. In practice, this means that the individual experiments performed in this thesis cover time ranges from 15 seconds to 1 minute. The algorithms should be generalized for running continuously in order to exploit the algorithms in production environment.

The program used for analysis recognizes tags by their EPC codes. An object is created for each tag identified by a unique EPC code. The object contains data about all tag read events and it is updated with new information each time the tag is read.

Monitored variables are:

- RSSI
- Mean RSSI
- Standard deviation of RSSI
- Phase angle rotation
- Standard deviation of phase angle rotation
- Doppler shift
- Mean of Doppler shift absolute values

All mean or standard deviation variables are calculated over all the read events of the same tag during one test run.

RSSI values are monitored on read event basis. Too weak events may be rejected by RSSI threshold as weak events may be caused by cross talk.

Mean RSSI calculation is done by PyLab *mean* function. Mean RSSI contains information about the signal strength of the tag over time.

Standard deviation calculation is done by *std* function of PyLab. Standard deviation of RSSI values tells about the possible movement of the tag. Tags passing through the gate should show first increasing and then decreasing trend in the RSSI values, which will increase deviation. Non-moving tags should have quite stable RSSI, excluding temporary changes caused by moving objects in the perimeter.

Phase angle rotation has similar properties than RSSI, excluding that it should not be as sensitive to near-by moving objects as long as the signal path length does not change. Phase angle rotation depends on the signal path and used frequency. Measurements through different antennas need to be handled as separate, as signal path changes when antenna changes.

Phase angle is cyclic parameter which changes between 0 ° and 180 ° (- 360 ° if quadratic detection is used). Thus directional statistics methods need to be used for analysis.

Circular standard deviation is defined by Gaile in Directional Statistics paper [30]. PyLab implementation of circular standard deviation was insufficient as it scaled all values to range $[0, 1]$. Function was overloaded with function presented in Listing B3.

Positive Doppler shift values are expected to be measured on handling units approaching the gate and negative values on handling units departing the gate. Overall movement can be detected by using absolute Doppler shift values. Mean of Doppler shift absolute values is expected to be different on moving tags and non-moving tags. Absolute values of Doppler shift measurements is calculated using *abs* function of PyLab. Mean is calculated by using *mean* function of PyLab.

4.5.1 Lay Around Tag Detection Algorithm

Lay around tags are detected using lay around tag detection algorithm. This algorithm is presented in Listing B4.

Algorithm relies to the knowledge that absolute Doppler shift mean and standard deviations of phase angle rotation and RSSI of the lay around tags are low. Furthermore event count of lay around tags is typically high. In most cases lay around tags are seen by only one antenna. Moving tags have typically 1 or 2 read events from a single antenna which is compensated in the algorithm.

While the algorithm is running and data is analysed, all these known facts increase the vote count by one. All votes from different antennas are added together and if the total count of votes is higher than 3, the tag is identified as a lay around tag. Proper threshold values need to be adjusted based on used reader configuration. The presented algorithm allows each criteria can also have different weights.

4.6 Virtual Handling Units

Virtual Handling Units (VHU) can be used to track movements of item level tagged handling units. For example, a handling unit can be a pallet containing one or more cardboard boxes. If tagging is done on item level, and no specific tag for shipment is used, VHU can be formed from the items on the pallet. The handling unit can be tracked on system level using the knowledge of which items are on the handling unit. This can be useful in cases where the number of items per handling unit is high. Required level for the read rate of RFID gate is decreased. For example, if 70% of items creating one VHU have been seen at the RFID gate at a certain time, an assumption can be made that all the items contained by the VHU passed through the gate.

VHU information can also be used in lay around detection. If assumed, that all the items of VHU move as a single unit, and more than 50% of the tags are detected as lay around tags, all the rest tags with insufficient data can also be regarded as lay around.

5 Experiments

Experiments need to be done in a controlled environment in order to avoid unmeasured variables affect the results. Experiments in this thesis are planned and conducted in such way, that the effect of unmeasured variables is minimized.

5.1 Test Environment

Previous study shows that walls, floor and roof can cause interference to RSSI and phase angle measurements [13]. This is due to the constructive and destructive interference caused by multipathing. Proper test environment is a key to get reliable results. An anechoic chamber would improve the repeatability of the conducted experiments. Nevertheless the focus of the thesis lays in applied experimenting and solving the issues caused by the echoes. The results from an anechoic chamber would have little value for this thesis.

Large free space reduces interference caused by floor and roof. For example the experiments can be performed outside or in a large warehouse with a high roof.

Antenna and tag placement need to be considered. Keeping the antennas and the tags as high as possible will reduce the interference caused by the floor. Position should not be higher than the middle point between the floor and the roof or the interference increases again.

The test environment needs to be clean in RF point of view. *Ambient Electromagnetic Noise* (AEN) is minimized by removing any RF-emitting devices from the test environment. AEN is controlled by measuring the test environment using spectrum analyzer before conducting the experiments. This is important as solving interference problems caused by multipathing is important part of this study and interference caused by AEN would affect the results of the experiments.

Wavelength of the used signal sets the resolution for the measurements. At the RFID band wavelength is from 34.54 cm (865 MHz) to 34.66 cm (868 MHz). Cyclic nature of phase angle rotation needs to be considered. Phase angle rotation value changes full 360° cycle within 34.6 cm. To efficiently measure the cyclic changes, resolution needs to be approximately 5 cm.

Distances to the antenna are marked on the floor of the test environment using tape. Distance between markings varies from 5 cm to 30 cm. This makes it more convenient to move the tag from a measurement position to another.

The test environment in the first part of the experiments is the entrance hall of the company. The hall is about 10 meters wide, 20 meters long and 15 meters high. Antenna is placed on the middle of the hall, about 3 meters from the other end. The tag is placed on a polyurethane stand in front of the antenna. The distance between the stand and the antenna is within a range of 0.3 to 5 meters during the testing. The second applied part of the experiments is conducted in the garage of the company. Garage has a roof lower than the entrance hall. Height of the experiment area is about 2.5 meters. Width of the experiment area in garage is about 10 meters and length is about 40 meters.

Possible AEN is measured using Rohde & Schwarz FSH3 spectrum analyzer. Measured AEN must stay below -90 dBm on 865 – 868 MHz band.

5.2 Equipment Used in Experiments

5.2.1 Impinj Speedway Revolution R420 UHF RFID reader

Experiments were performed using a set of Impinj Speedway Revolution R420 UHF RFID readers. The reader can be seen in Figure 3. Key factors which led to selecting this reader for the experiments were

- Very good performance
- Very good sensitivity
- Low level reader data available through reader protocol
- Ability to run custom software on the reader

Table 4: Specifications of Impinj Speedway Revolution UHF RFID Reader

	Speedway R420
Air Interface Protocol	EPCglobal UHF Class 1 Gen 2 / ISO 18000-6C
Antennas	4 monostatic antenna ports
Transmit Power	+10.0 to +32.5 dBm
Max Receive Sensitivity	-82 dBm
Application Interface	EPCglobal Low Level Reader Protocol (LLRP) v1.0.1
Network Connectivity	10/100BASE-T

Table 4 shows the main features of Revolution reader. Readers used in experiments had firmware versions 4.8.0 and 4.8.3.

5.2.2 Antennas

Read tests were performed with a set of MTI MT-242027/NRH/K and Cushcraft circular polarization antennas. Specifications of MTI antenna can be seen in Table 5.

Radiation pattern of used MTI antenna is shown in Figure 23.

Antennas with linear polarization would have produced more reproducible read results, especially when placed in a such way that the polarization is vertical [2]. Focus of the thesis is on applications. Using linear polarized antennas in applications limits the placement options for the tags and generally discouraged in most applications.

Table 5: Specifications of MTI MT-242027/NRH/K antenna

	MTI MT-242027/NRH/K
Frequency Range	865 – 870 MHz
Gain	8.5 dBic
VSWR	1.3:1
Azimuth 3dB Beamwidth	65°
Elevation 3dB Beamwidth	65°
Polarization	Right hand circular polarization
Input Impedance	50Ω

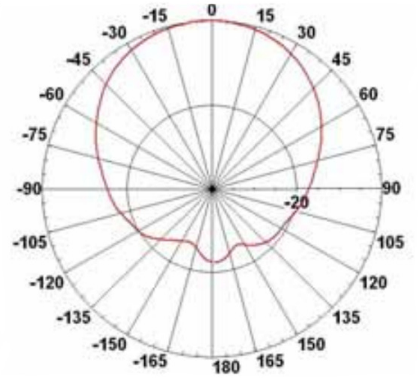

Figure 23: Azimuth radiation pattern of MT-242027 antenna at 867 MHz.

5.2.3 Stand for the Antenna

Antennas were placed on stands typically used for lights and loudspeakers. These kind of pylons are light to handle and provide good possibilities to attach antennas pointing in different directions. The stand used in the experiments can be seen in Figure 27.

Portal for cross read testing was built using two of these stands. The portal measured from wall to wall. The space between walls was divided to three sections presenting the docking doors. Each stand had two antennas pointing opposite directions.

5.2.4 Light Roof Portal Assembly

Lay around tag detection is tested using a light portal assembly attached over the docking door. The light roof portal assembly can be seen in Figure 24. Portal consists of 4 directional circular polarized antennas, UHF RFID reader and aluminum structure to hold the antennas. Angles between the antennas are set up so that two antennas face to the direction of the movement and two antennas the opposite. The antennas are tinted towards the middle point of the expected handling unit route.

When this antenna configuration is used with Doppler shift methods, it is possible to determine the direction of the movement in both directions – through the portal and across the portal. This helps to detect lay around tags and stray reads.

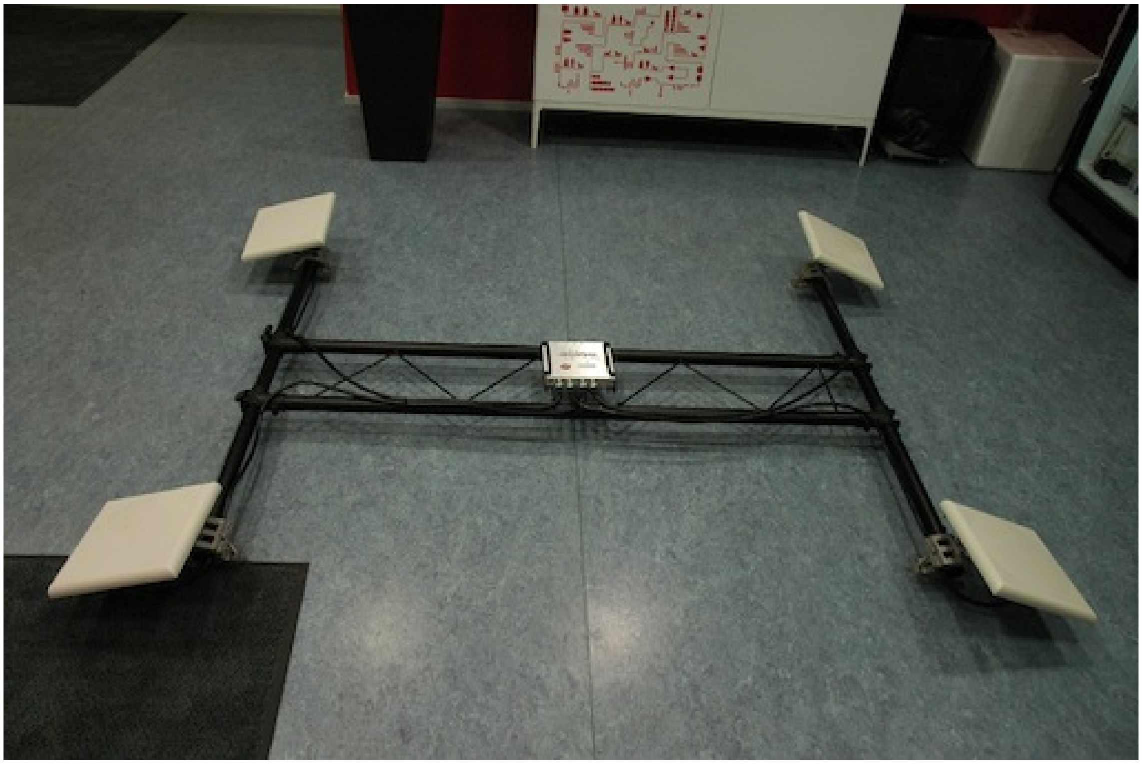

Figure 24: Light roof portal assembly for lay around tag detection using direction sensing methods.

Alternatively the light portal assembly can be configured to utilize one interrogation zone. This reduces the read rate as the interrogation zone is smaller than with the default setup. The benefit is a smaller foot print for the portal.

5.2.5 Styrofoam Structure to Hold a Tag

RFID tags used in initial testing are attached to styrofoam structure which will cause as little interference as possible to the RF-signals. Styrofoam is light and easily moldable allowing flexible testing arrangements. A structure of 1.5 meters high is built from styrofoam to hold the tags while testing. The structure is easy to move and stable enough to stand still during the measurements.

5.2.6 Handling Units Used in the Experiments

Two handling units were built to be used in the experiments. Both of them were pallets. First pallet had four cardboard sheets set up in A form. Each sheet holding 45 UPM Dogbone paperface UHF RFID labels. Total number of labels was 180 for this type of pallet. The cardboard sheets were placed over wooden EUR-pallet. First pallet can be seen in Figure 25. Dogbone labels had NXP G2XL chips.

The first pallet turned out not to have enough tags for testing purposes, so another type of pallet was designed. Second pallet type contained three plastic sheets made of polystyrene (PS). These sheets held one hundred Belt UHF RFID

Figure 25: Pallet with four cardboard sheets holding total of 180 UPM Dogbone paperface tags.

Figure 26: Pallet with 6 sheets of PS plastic holding total of 600 UPM Belt tags.

paperface labels each. Belt labels have a smaller footprint than Dogbone labels allowing greater label density. Sensitivity of Belt labels is very low when attached on a cardboard surface. The cardboard sheets needed to be replaced with plastic sheets. Belt labels had Impinj Monza 4 chips. Figure 26 shows a pallet with two test load units with three hundred tags on top of it. Most of the experiments were conducted with one unit of three hundred tags.

Tags were encoded in a such way, that the location of the tag on the pallet can be seen from the EPC code. Number on the right indicates the column of tag. Second number from the right indicates the row. Third number from the right indicates sheet number and fourth number indicates the pallet.

5.3 Preliminary Experiments

There are multiple parameters which may affect the measurements. To understand the effect of each parameter, series of measurements were performed in the beginning.

Altered parameters were:

- Transmit power of the reader
- Antenna model
- RFID chip on the tag
- Operating mode of the reader

Two levels of transmit power is used in the experiments. 25dBm and 30 dBm. Typically transmit power is 25dBm or more in portal applications.

Experiments are conducted using two different antennas. One MTI model and one Laird model. Both have similar gain and frequency response characteristics. There can be differences in the length of signal path with these two antennas, but specifications do not reveal these differences.

Two different models of RFID chips are used in the experiments. Both of the chip types are on UPM Dogbone paperface labels, so the tag antenna remains the same. Part of the tags used in experiments have Impinj Monza 4 chips and rest have NXP G2XL chips.

Impinj Revolution R420 has six different operating mode settings. Operating mode is set of EPC Gen2 air interface protocol settings, which affect how the communications take place between a tag and a reader. Different operating modes have been optimized for different use cases by the reader manufacturer. In general operating modes change the reader gradually from high-throughput operation to efficient operation in a very noisy environment (Dense Reader Mode).

Four different operating modes are tested. These modes are listed in Appendix A. The fifth tested mode is so called *auto* mode which let's the reader choose the best operating mode for the environment.

Measured variables were:

- RSSI
- Phase angle rotation average
- Phase angle rotation variance

Based on these initial measurements the antenna, the tag and the RFID reader operating mode were chosen for further experiments at the portal.

Picture of test setup used in initial testing is portrayed in Figure 27. The tag is attached on a pylon made of styrofoam. The antenna is attached to a loudspeaker stand. The height of the antenna is 1.5 meters. The tag is on the height. The reader utilizes four channels within ETSI regulated RFID bandwidth 865 – 868 MHz.

Figure 27: Test setup to measure phase angle rotation and RSSI over distance.

5.3.1 Measurement Process

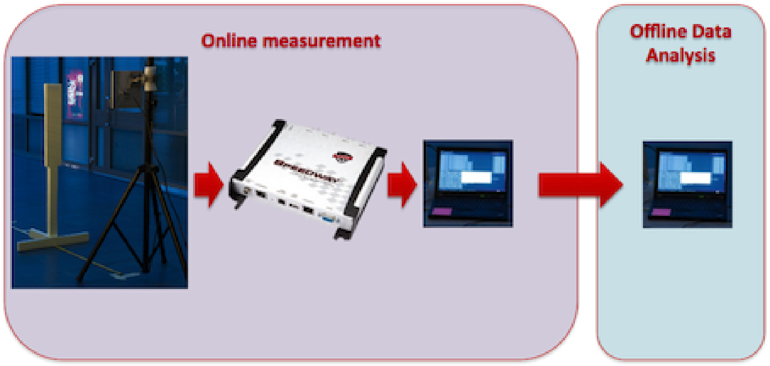

Figure 28: Measurements related to experiments were performed online and data analysis offline.

The measurement process is shown in Figure 28. VilantEngine v0.9.35 software was run on a laptop with linux operating system. VilantEngine software communicated with the RFID reader using LLRP protocol. Software wrote all read events with timestamps and other parameters on a file. The file was processed with a piece of Python software which extracted the read events from the log file and applied algorithms presented in this thesis. The python software used for offline analysis uses PyLab environment for numerical analysis and Matplotlib for plotting the data.

5.3.2 RSSI and Phase Angle Rotation over Distance

Preliminary experiments start by measuring how RSSI and phase angle rotation changes over distance. Previous study shows that the relation between RSSI and distance is complex outside anechoic chamber [13]. RSSI increases and decreases while distance changes, but the overall trend is decreasing while distance increases. Phase angle rotation is expected to change in cycles of half of the wavelength used.

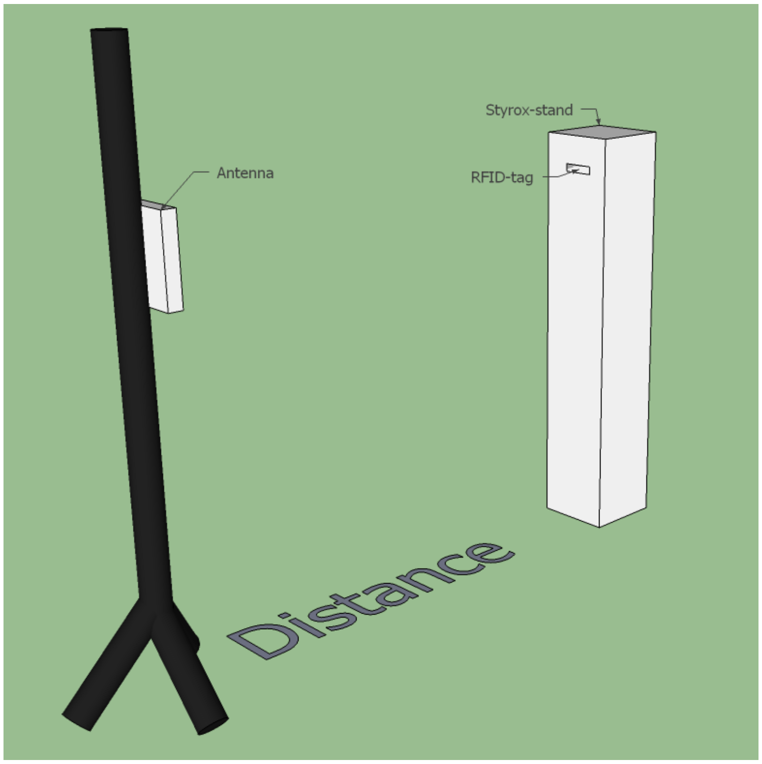

Figure 29: RSSI and phase angle rotation is measured from different distances between antenna and RFID tag.

Phenomena is measured by changing distance between the antenna and the tag while transmit power is kept constant, like in Figure 29.

Table 6: Plan for measurements.

Measured values	RSSI: average Phase angle rotation: average and variance
Number of measurements	15 seconds of measurements at maximum rate
Range	40-700 cm
Resolution	5 cm between 30-200 cm and 30 cm between 200-700 cm

Measurements are repeated with different power settings, different antennas, different tags and different operating modes for the reader. Plan for experiments is presented in Table 6.

5.4 Experiments at RFID portal

Experiments at RFID portal are planned in such way that methods to solve the two use cases in the scope of this thesis are explored. Use cases were to identify lay around tags and stray reads from handling unit moving in front of the gate. Third case which is about stray reads from neighboring gate (cross read) is not explored by experimenting. It is studied in theory only.

Figure 30: Typical configuration for experiment at the portal.

The typical configuration for experiments at the portal can be seen in Figure 30. There is one handling unit on the fork lift. Test run path is marked to the floor using black duct tape. Two lay around handling units are on the sides of the test run path. The light roof portal assembly is configured in low footprint mode as the antennas are pointing to single interrogation zone.

Experiments at the RFID portal are done using item level tagging. Each pallet has approximately three hundred tags. Other pallets with three hundred tags present lay around or stray read tags.

Applied experiments are done offline. This means that data which contains EPC codes, timestamps, RSSI-, Doppler shift and phase angle rotation values is recorded while tests are done. This data is to be analyzed after the experiments. This kind of arrangement allows more versatile data processing methods to be used, as the best methods to identify the stray tags is not known beforehand. Offline data analysis does not prevent implementing the found solutions for online data analysis later on, but this is not in the scope of this thesis.

Each experiment is repeated several times to get statistical reliability for the methods developed from the data.

The first series of experiments studies statistical properties of RFID events received from a RFID gate. Target for this study is to find the differences between events of lay around tags and events of moving tags.

The second series of experiments studies methods to identify lay around tags. Methods are based on direction sensing and statistical analysis of the events.

The third series of experiments studies stray reads from pallet moving front of the gate. Direction sensing based methods are used to determine wether the pallet is moving through the gate or not.

5.4.1 Statistical Measurements to understand Dynamics at a RFID Gate

Series of experiments are conducted to investigate how RSSI, phase angle rotation and Doppler shift values show up in time, RSSI, phase angle rotation and Doppler shift domains.

Phase angle rotation is dependent on signal path. Events received through different antennas are not comparable with each other and they need to be handled separately. To fully utilize possibilities of phase angle rotation, the system should be calibrated. During calibration process the cable length and other factors affecting on signal path length would be measured. On a calibrated system the phase angle distance measurements could be done when location of the antennas is known. This is out of the scope of this thesis.

Variables measured for each RFID read event are

- RSSI
- Doppler shift
- Phase angle rotation
- Receiving antenna
- Channel

Means and standard deviations are calculated during offline analysis. Data is analyzed on run basis. This means that only one transaction which triggers a RFID event for each tag is expected happen during the run. Tag can pass the gate exactly once during the experiment run to keep the offline analysis sane.

Measurements follow the pattern: moving pallet, lay around pallet, moving tag and lay around tag. Data collected is analyzed in time, RSSI/Phase angle rotation and RSSI/Doppler shift domains.

5.4.2 Lay Around Tag Detection Analysis based on RSSI, Phase Angle Rotation and Doppler Shift Statistics

Series of experiments are run to find out if there is a meaningful difference between the RSSI, phase angle rotation and Doppler shift values between the lay-around and the moving tags. Experiments are repeated with different operating mode and session settings.

5.4.3 Identifying Lay Around Tags

Series of experiments will be conducted using an antenna layout typically used for direction sensing applications. This type of antenna layout utilizes two separate or partly overlapping interrogation zones. The interrogation zones are set up along the direction of the movement. There are several different algorithms used to determine the tag movement. Some of these algorithms can be used to identify lay around tags. In these cases tags which are seen, but of which movement direction cannot be detected are identified as lay around tags.

Algorithms are used to detect lay around tags are

- Simple Direction Sensing algorithm (Listing B1)
- Doppler Shift algorithm (Listing B2)
- Lay Around Tag Detection Algorithm (Listing B4)

Table 7 tells which measurements are done for each experiment.

Table 7: Measurement definitions

Measurement	Definition
Read Events (n)	Total number of RFID read events per test run.
Time (s)	Time from the first read event to the last in the test run.
Events per Second (n)	Number of events divided by the time.
Read Rate (%)	Percentage of population tags which were seen. Population is known.
Lay Around Tags Detection Rate (%)	Percentage of lay around tags identified as lay around tags. Given for each algorithm used.
False Positive Rate (%)	Percentage of tags on pallet which were identified as lay around tags. Given for each algorithm used.

5.4.4 Identifying Stray Reads

An experiment is conducted to find out if it is possible to detect stray reads from pallet moving in front of the gate but which does not go through the gate. The Doppler shift algorithm and the simple direction sensing algorithm are used to detect the stray reads.

The experiment is conducted by pulling a pallet sideways across interrogation zone in front of the gate.

6 Results

6.1 Preliminary Experiments

On the first test round the target was to find a configuration which could be used in applied testing. The variables were tags, antennas and reader settings. At the same time preliminary experiments gave information about how the measured variables change over distance.

6.1.1 RSSI, Phase Angle Rotation and Doppler Shift Over Distance

In following results channel represent used frequencies as presented in Table 8

Table 8: RF channels used in experiments.

Channel	Frequency
1	865.7 MHz
2	866.3 MHz
3	866.9 MHz
4	867.5 MHz

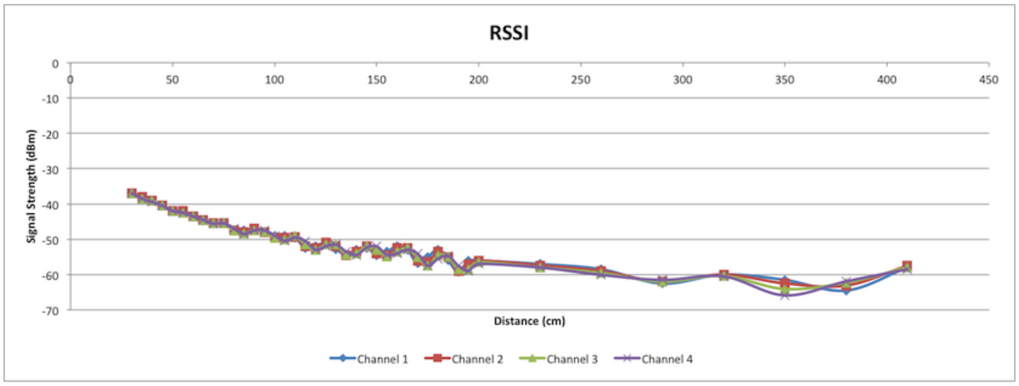

Figure 31: Return Signal Strength Indicator over distance.

Figure31 shows that measured RSSI values ranged from -36dBm to -65 dBm in the distances from 30 cm to 420 cm. Within the range of 30 cm to 100 cm, RSSI decreased almost linearly when distance increased. There is cyclic variation in RSSI starting at 100 cm. This is most probably caused by signal reflecting from the ground. This is also known as multipathing and it causes constructive- and destructive interference on the signal. Measurement resolution changes at 200 cm and the cyclic component cannot be seen anymore. There is no noticeable difference in RSSI between different channels used.

How the phase angle rotation changes over distance can be seen at Figure 32. The results are projected to scale of π, because the quadrature detection of the reader was not flawless causing sudden changes to opposite quadrature in the values. The resolution of 30 cm was barely enough to show the pattern in phase angle rotation

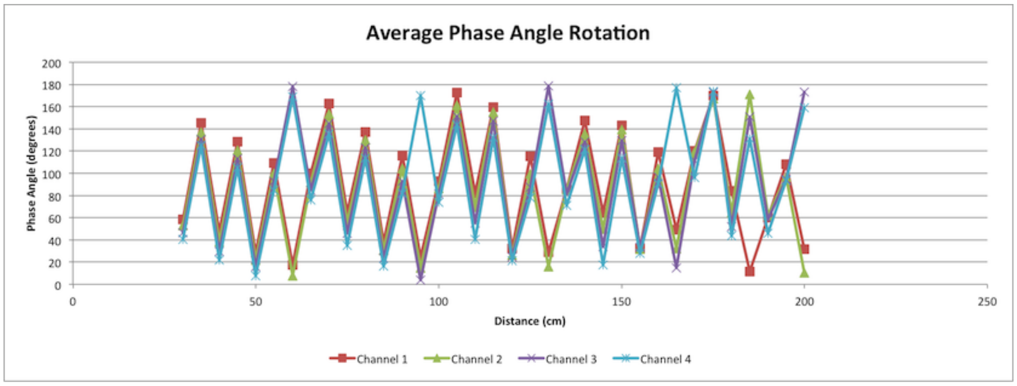

Figure 32: Average phase angle rotation over distance.

change over distance. Figure 32 shows the small difference in phase angle rotation when using different channels.

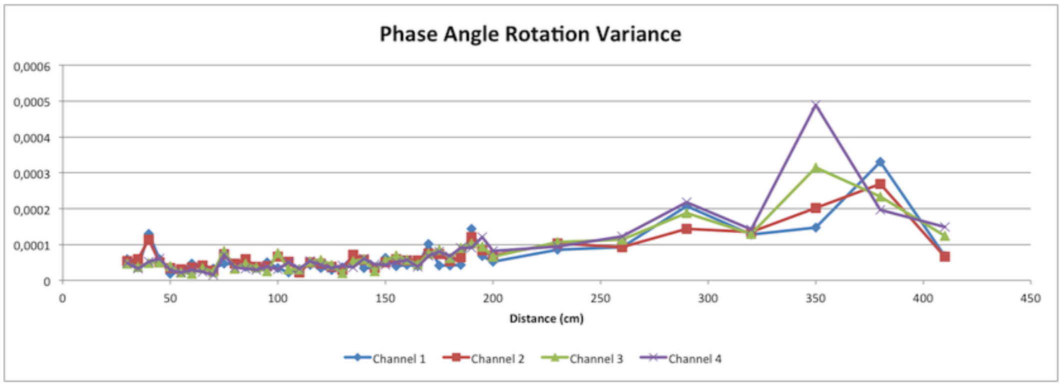

Figure 33: Phase angle rotation variance over distance.

Phase angle rotation variance stays at low level up to distances of 2.5 meters as can be seen in Figure 33. There is no noticeable difference in variances between channels.

6.1.2 Transmit Power Change

Experiments were repeated with different transmit power settings. Measurements were done using distances from 200 cm to 500 cm as this is the most interesting range for portal applications.

Figure 34 shows that transmit power increases read distance, but has only little effect to RSSI as expected. RFID is downlink limited. At 25dBm transmit power the tag stopped responding in greater distances than 420 cm. Increasing transmit power to 30dBm provided read range of over 500 cm.

Phase angle rotation does not change when reader power is changed as can be seen in Figure 35. Phase angle rotation is dependent only from the length of the signal path. As the distance between the antenna and the tag increases, reflections can cause large changes in the phase angle rotation over small distance change.

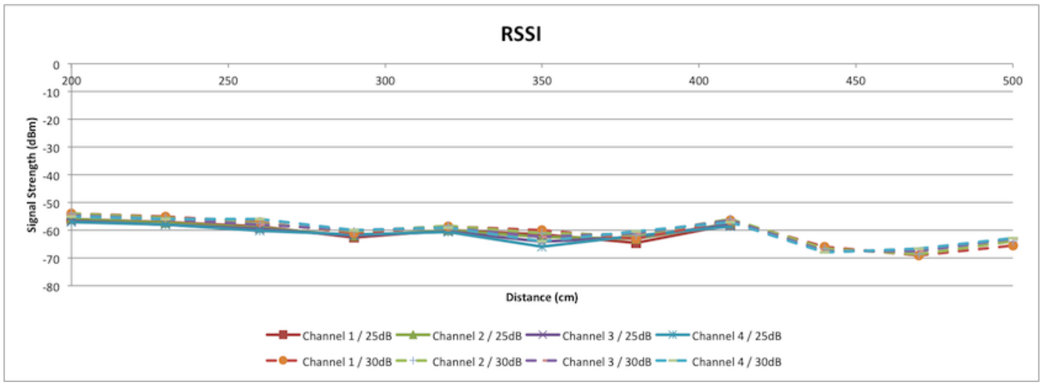

Figure 34: Return Signal Strength Indicator with different power settings.

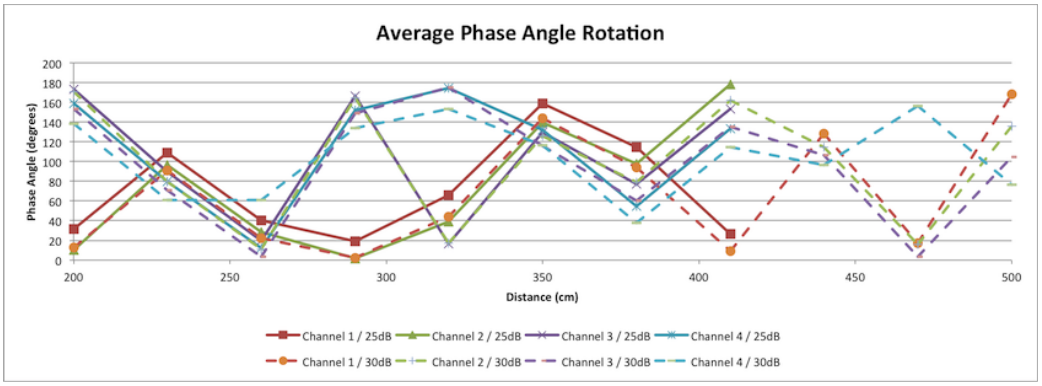

Figure 35: Average phase angle rotation with different power settings.

Changing reader transmit power does not affect directly on the phase angle rotation variance as can be seen in Figure 36. Increasing power allows reading the tags further distances away. These read events show higher variance in phase angle.

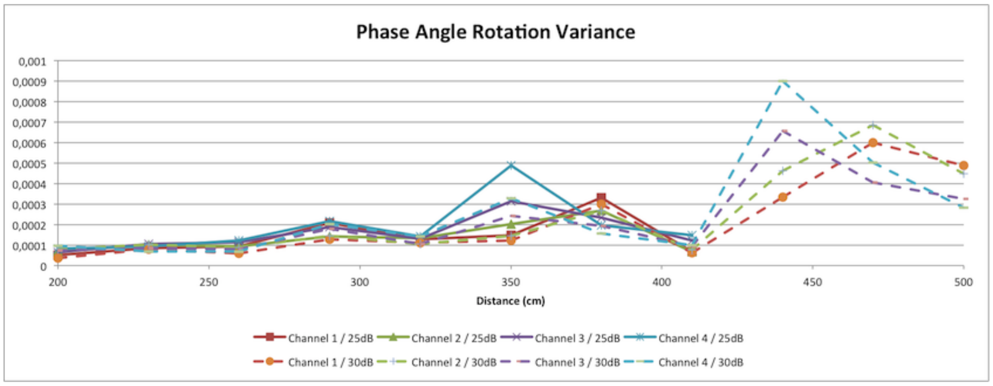

Figure 36: Phase angle rotation variance with different power settings.

6.1.3 Antenna Change

Experiments were repeated with two different models of antennas to understand, how a different antenna affects the measurements.

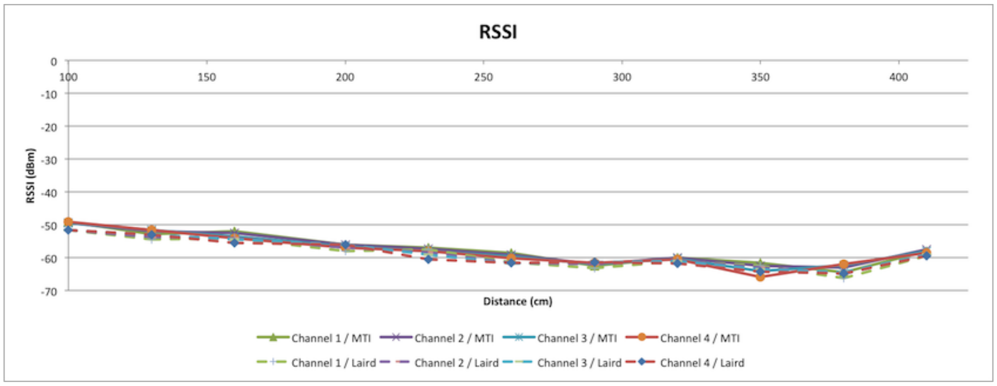

Figure 37: Return Signal Strength Indicator with different antennas.

Antennas tested do not show differences in received RSSI. If the antennas had remarkably different gain values, it would show up also in RSSI measurements.

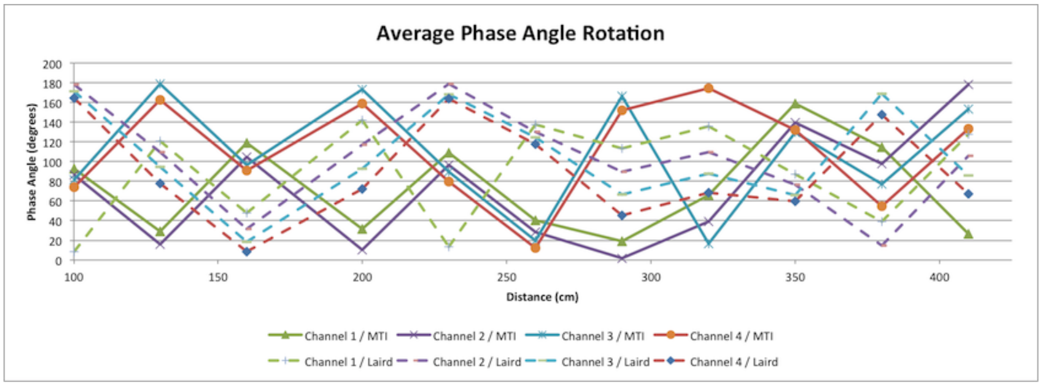

Figure 38: Average phase angle rotation with different antennas.

Different antennas had different phase angles on the same distances as can be seen in Figure 38. This can be explained by measurement errors. Quarter of a wavelength error while adjusting the distance between the tag and the antenna causes 180° error in measurement. This is because the signal travels twice the distance between the tag and the reader. It is also possible that the signal travels different distance within the antennas.

Measurements with different antennas would need a calibration to be performed before the measurements. This measurement was not that important for the thesis so this was not experimented any further.

There were differences on phase angle rotation variance on different antennas over same distances. This may have been caused by reader antenna compatibility. Some readers and antennas couple better than others. MTI antenna was found to be better as it has less variance as shown in Figure 39.

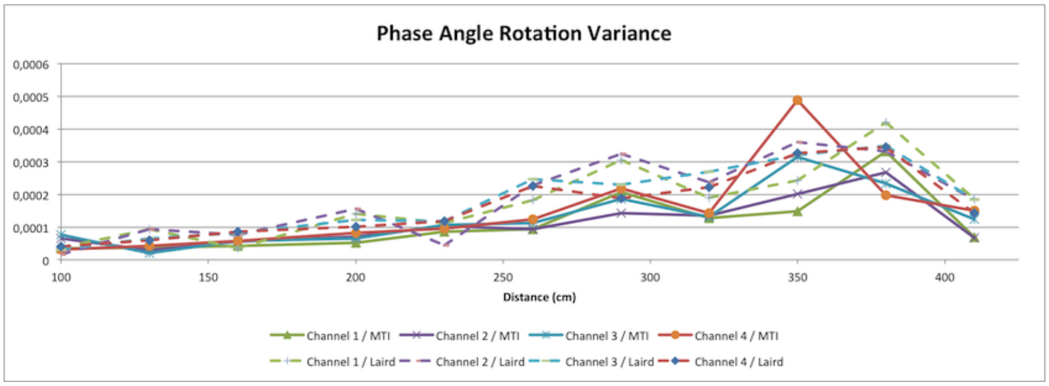

Figure 39: Phase angle rotation variance with different antennas.

6.1.4 RFID Chip Change

Experiments were repeated with two different chip types on the same UPM Dogbone RFID tag layout.

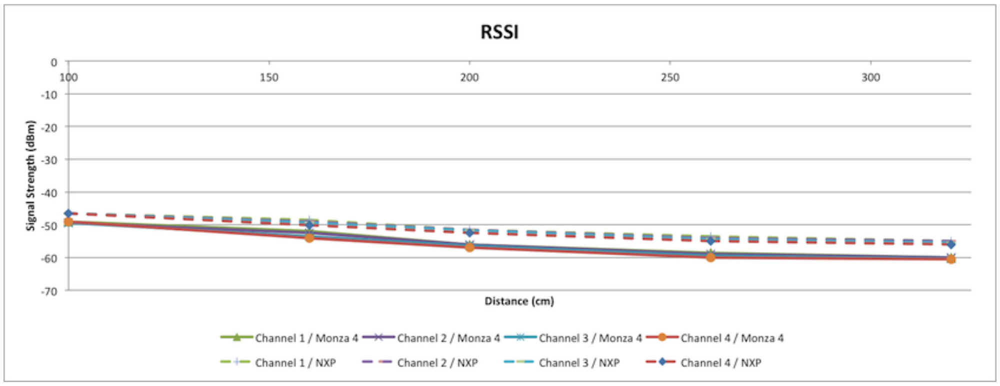

Figure 40: Return Signal Strength Indicator with different tags.

Figure 40 shows that NXP chip showed higher RSSI values over distance. It indicates that the NXP chip is able to reflect more energy back to the reader. It does not tell about maximum read distance or sensitivity as RFID is downlink limited. Measurements suggests that the NXP chip can harvest less energy from the carrier wave, which can lead to a shorter read distance. Maximum read distance on the NXP chip was not measured as it is not in the scope of this thesis.

There was no noticeable difference in the phase angle rotation between the two chip types as shown in Figure 41. Differences at the points of measurement are within the tolerances of the test setup.

The chip had effect on the phase angle variance. The NXP chip showed very constant phase angle variance characteristics as can be seen in Figures 41 and 42. On Monza 4 phase angle variance increased over distance. This can be a desired effect as it can be used to determine the distance to the tag.

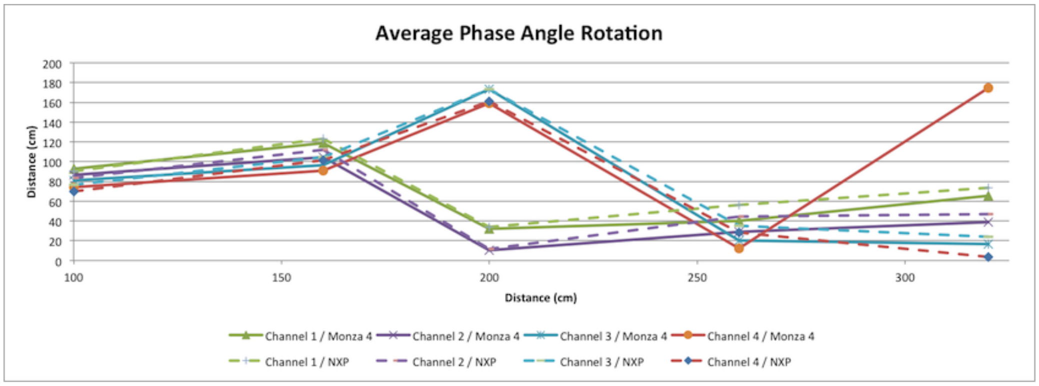

Figure 41: Average phase angle rotation with different tags.

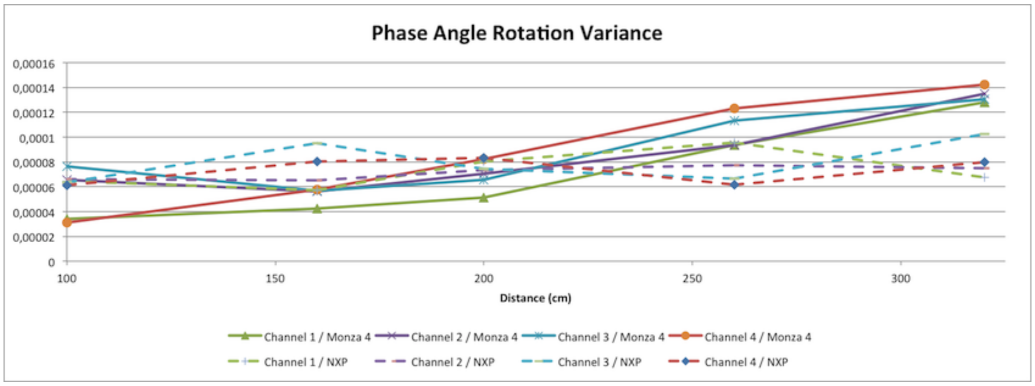

Figure 42: Phase angle rotation variance with different tags.

6.1.5 Operating Mode Change

Experiments were repeated using different operating modes of the reader.

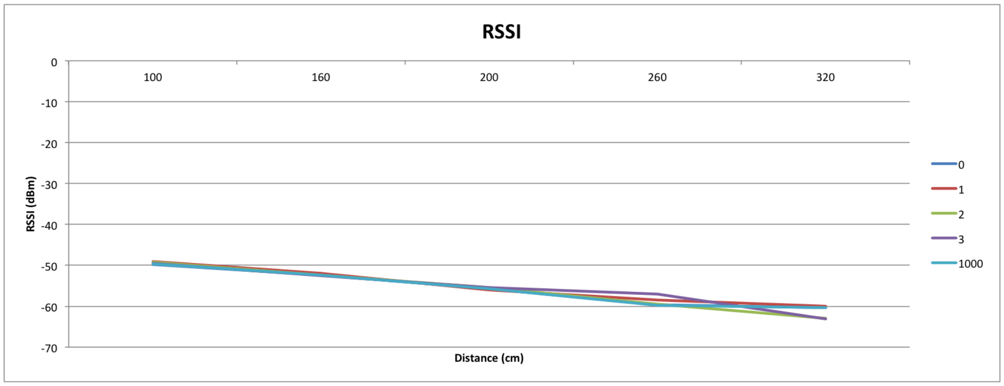

Figure 43: Return Signal Strength Indicator with different operating mode settings.

Different operating modes of the reader show no differences in RSSI measurements as can be seen in Figure 43.

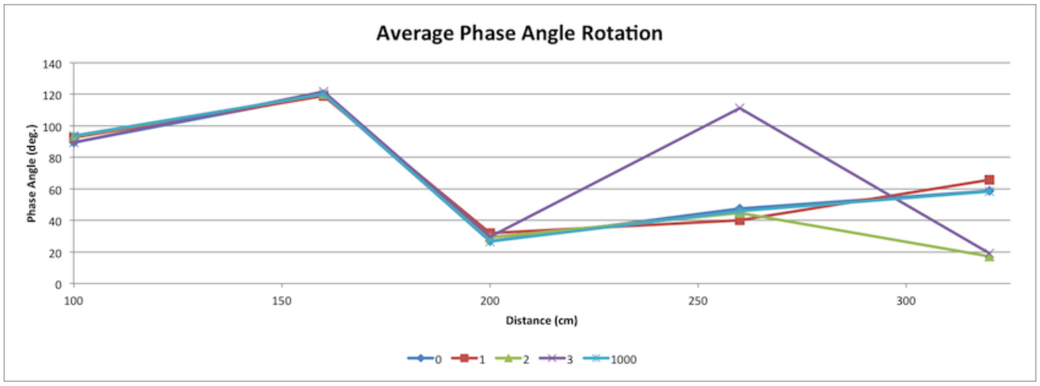

Figure 44: Average phase angle rotation with different operating mode settings.

Figure 44 reveals that phase angle rotation is not affected by operating mode. There are some differences at 260 cm and 320 cm measurements.

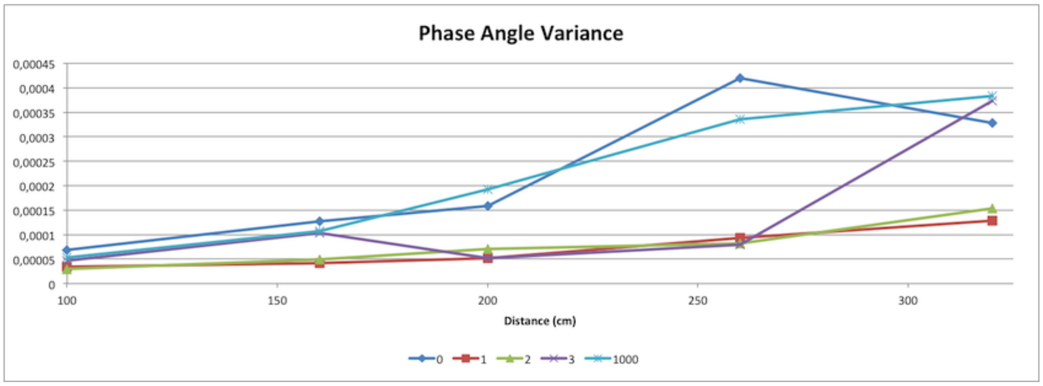

Figure 45: Phase angle rotation variance with different operating mode settings.

Figure 45 shows that DRM operating modes 1 and 2 showed low phase angle variance characteristics. High throughput mode 0 has high variance throughout the measurements. Most probably the auto setting 1000 has ended up using high throughput mode as well as there were no other readers present in the same operating environment. This is due to similar variance behavior.

All operating modes except operating mode 0 (High throughput, FM0) resulted to problems detect full 360° phase angle. On other operating modes the phase angle made 180° hops in random pattern. This behavior varied over distance. On operating mode 0 the reader showed none of this activity. Unfortunately the variance on operating mode 0 is the highest, which limits the usability.

6.1.6 Other Findings

One experiment was conducted placing five UPM Dogbone tags right next to each other as portrayed in Figure 46. On very short distance all tags could be read, but if the distance from tag to a reader was more than one meter, some tags were not possible to be read. This needs to be considered when building handling units for

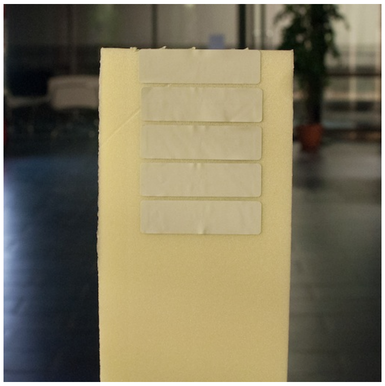

Figure 46: Poor read rate as the tags are too close each other.

further testing as it limits the tag density. Tags should be placed at least half a wavelength or 15 cm from each other in further experimenting.

6.2 Statistical Measurements to understand Dynamics at a RFID Gate

Series of experiments were done to investigate how RSSI, Doppler shift and phase angle rotation parameters change while a pallet passes the RFID gate. The RFID gate has four antennas installed. The reader operates in four different channels during normal operation. If a stationary tag is read with four different antennas, all these read events can indicate different phase angle rotation and RSSI values, as these parameters are dependent on the distance between the tag and the antenna of the reader. Doppler shift measurements are dependent on tag movement compared to the antenna. This has been taken into account on the result charts by showing which antenna received the event and which frequency was used. Creating different charts for each of the antenna and frequency combinations would have multiplied the number of charts by 16.

6.2.1 Events in Time Domain

Results are presented first in time domain. These figures help to visualize what happens at the RFID gate when a pallet passes through. In following figures the blue circles represent events from an antenna facing opposite to the movement and the red crosses an antenna facing along the movement on the other side of the portal.

One figure represents one test run. There were at least five test runs executed for each experiment. One point in the figure is one read event of one tag. If same tag is seen multiple times, it will have multiple markers in the figures.

Graph on the top is the Doppler shift graph which shows the measured Doppler shift value of the particular event represented by the marker. The second from top shows the RSSI value of the event. The third graph shows the phase angle rotation of the event. The fourth graph shows through which antenna the event came from. The bottom graph shows which channel was used for communication.

High Throughput Configuration

Experiments were first done using session 2 and high throughput operating mode 0. Number of tags on the load was 300 and operating environment had 600 lay around tags. The pallet moved at walking speed which is about 1.2 m/s. Each experiment was repeated for 10 times. The experiment parameters can be seen in Table 6.2.1.

Table 9: Parameters

Setting	Value
TX Power	30 dBm
Session	2
Operating Mode	0
Number of tags on load	300
Number of lay around tags	600
Speed of Pallet	1,2 m/s
Repeats	10

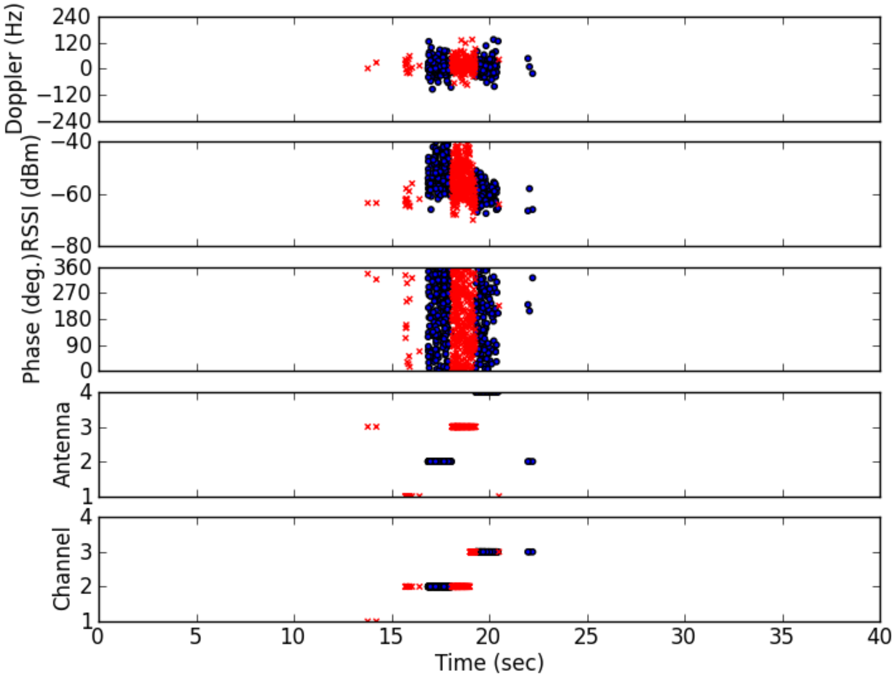

Figure 47: Pallet moving through portal. Session 2, Operating Mode 0.

Session 2 with dual target mode sets the reader to change antenna once in a second as seen in Figure 47. This rate is a bit slow for portal with multiple interrogation zones. Reader utilizes channel for four seconds before moving to next channel. This does not have major implications on the results. Phase angle rotation changes a bit when the frequency changes.

Figure 47 tells that Doppler measurements are useless with very fast data rates of operating mode 0. RSSI values behave as expected. Tag sensitivity is around -70 dBm. RSSI values spike at -40 dBm when the pallet is right in the middle of the port and after that decrease back to low levels.

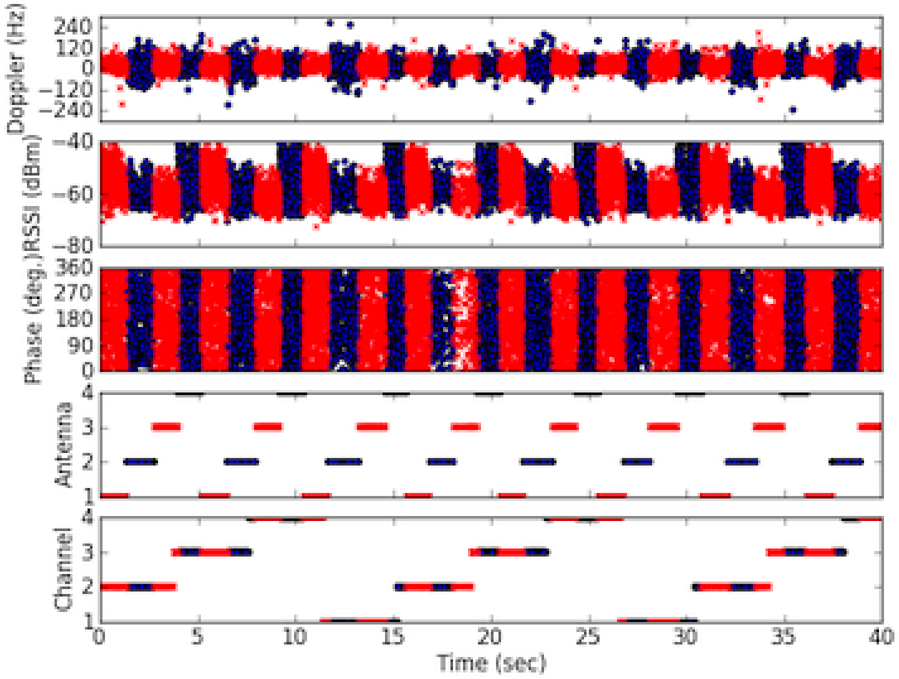

Figure 48: Lay around pallet. Session 2, Operating Mode 0.

Similar results for lay around pallet are shown in Figure 48. The variation in RSSI values can be explained by antennas 1 and 4 being closer to the lay around pallets than antennas 2 and 3. Near 20 seconds tick there is temporary reduction in number of events. This matches to Figure 47 showing a pallet passing the gate at this moment.

The tag presented in Figure 49 got five read events while passing the gate. Surprisingly the Doppler shift variance is low, but as we noticed from the previous experiments with lay around pallets, the Doppler shift measurement is not very useful while using operating mode 0. The antennas in this setup were set to single interrogation zone configuration. The inbound and outbound antennas were pointing to the same interrogation zone. This explains why the moving tag were first seen at the inbound antennas then at the outbound antennas and then again at the inbound antennas.

The RSSI values follow the same pattern than in the moving pallet experiment reaching the maximum at 17 seconds. Phase angle rotation variance results cannot be calculated as the tag got only two measurements from antenna 2 and 3 and one at antenna 4.

Figure 50 shows a clear pattern which can be used to identify lay around tags.

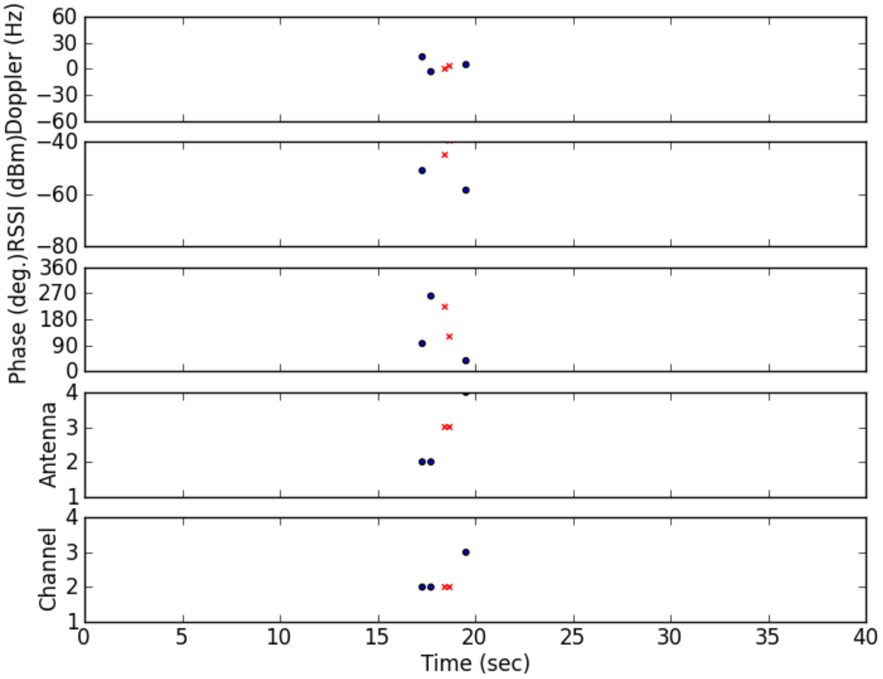

Figure 49: Tag moving through portal. Session 2, Operating Mode 0.

Read events show up as pairs because Session 2 with Dual Target mode was used and tags are first inventoried to **A** and then to **B**. Using operating mode 0 limits the usability of the Doppler measurements as shown in figure. Expected Doppler shift for stationary pallet would be 0 Hz, but values up to 240 Hz are measured. RSSI values are dependent on the antenna used. Frequency does not seem to affect much the phase angle rotation or RSSI measurements.

Dense Reader Environment Configuration

Experiments were repeated using session 1 and dense reader environment optimized operating mode 3, which has much lower data rate than operating mode 0. Especially the Doppler shift values should be more useful now.

Operating mode 3 increases accuracy of Doppler shift measurements as the data rate is slowed down. This can be seen clearly in Figure 51. The Doppler graph shows first positive values which change to negative at around 15 seconds. This is the moment when the pallet passes the middle point of the RFID gate and starts to move further from the antennas. Blue markers represent the inbound antennas and red markers outbound antennas. These antennas are located about one meter from each other. RSSI values spike -40 dBm at 15 seconds for inbound antennas and at 17 seconds for outbound antennas. This is a clear sign of movement through the gate.

Phase angle rotation chart is missing any events near the 180 degree line. This

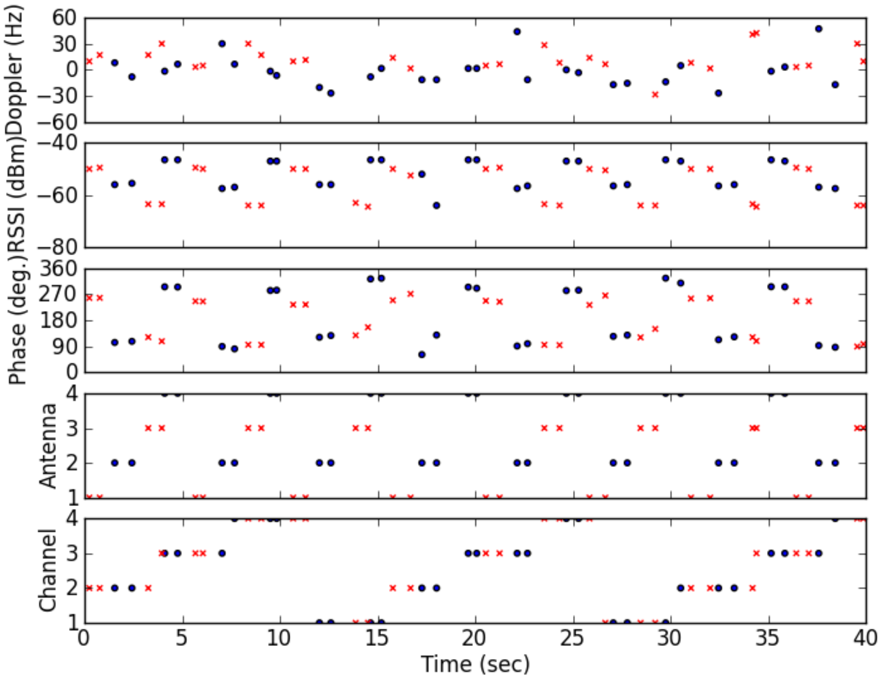

Figure 50: Lay around tag. Session 2, Operating Mode 0.

could be because circular polarized antennas were used. Belt tags are direction sensitive and it could be so that the tags are very difficult to read when the circular polarized signal is in the minimum phase for reflected power.

Session 1 changes the reader's antenna usage pattern. Now the reader is changing antennas at very fast pace. This is good for tracking moving pallets which stay only for a short time within the interrogation zone of one antenna.

Lay around pallet presented in Figure 52, indicate much better Doppler values than the previous measurement in Figure 50 thanks to lower data rate of operating mode 3. The average Doppler shift is around 0 Hz, but there is some deviation even on lay around tags. Lay around pallets are closer to the inbound antennas as the RSSI is higher on those.

The tag passing through the gate got only two measurements as can be seen in Figure 53.

In Figure 54 the lay around tag has very steady Doppler, RSSI and phase angle rotation values. The tag is seen only by the antenna 2.

6.2.2 Events in RSSI, Phase Angle Rotation and Doppler Domain

High Throughput Configuration

Experiments were conducted first using session 2 with operating mode 0, a typical high throughput configuration. These figures show RSSI over Doppler and RSSI over phase angle rotation graphs for each of the four antennas. These graphs should

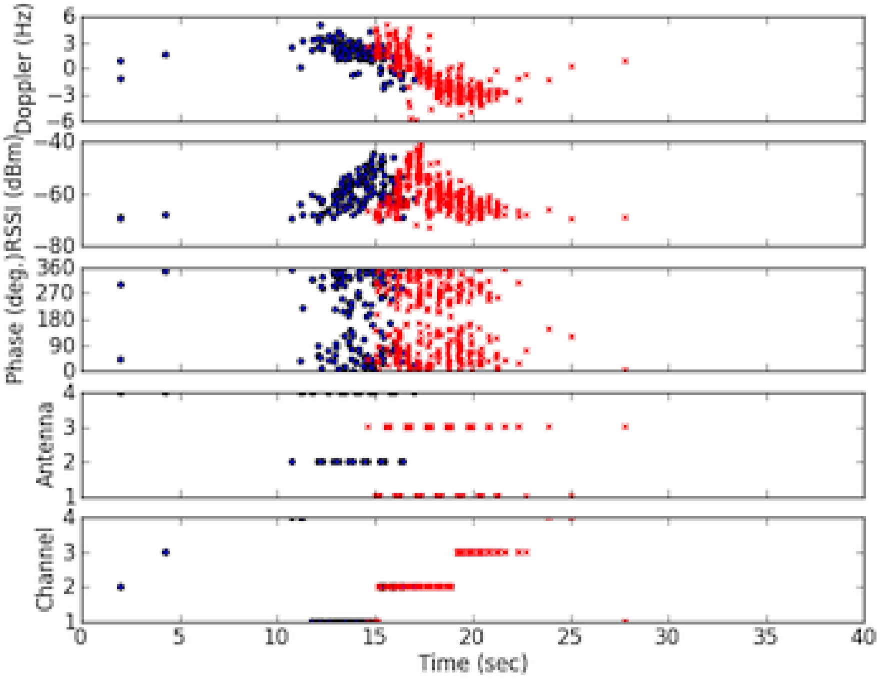

Figure 51: Pallet moving through portal.

show how the characteristics of a lay around tag differ from a moving tag.

Figure 55 shows that the Doppler shift values depend on the signal strength. Deviation of Doppler shift is smaller on read events where signal strength was high. Doppler shift deviation is on a very high level on a high throughput operating mode 0 with a high data rate.

RSSI over phase angle rotation graphs are not very useful at pallet level as the number of data points is very high. These graphs should be useful for tag level measurements and they are presented here as only reference.

Pallet moving through portal is shown in Figure 56. Antennas 1 and 4 read only some of the tags at quite low RSSI level. Deviation of Doppler shift is lower on the moving pallet. This may be caused by overall higher RSSI level of successful read events. Share of very weak read events at -70 dBm is low compared to Figure 55. Lay around pallets were located under antennas 1 and 4 which has decreased the amount of read events of moving pallet through those antennas.

Figure 57 reveals that lay around tags will have low RSSI deviation. There is deviation on phase angle rotation, which does not seem to be dependent on RSSI. Data points form short lines along phase angle rotation axis, which is explained by reader operating on different channels. Doppler shift deviation is much smaller on antennas 1 and 4 with the highest RSSI.

Again low number of read events from a tag going through RFID gate is shown in Figure 58. There are two events from antenna 3 and one event from antennas 2 and 4, but no event from antenna 1.

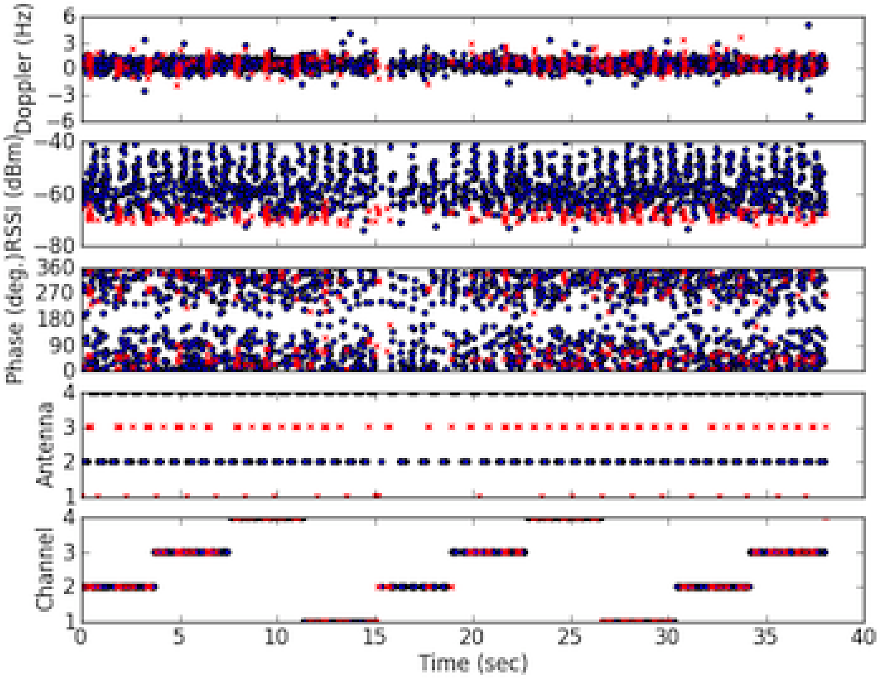

Figure 52: Lay around pallet. Session 1, Operating Mode 3.

Dense Reader Environment Configuration

Operating mode provides better accuracy for Doppler shift as shown in Figure 59. Outbound antennas 1 and 3 show negative tendency for Doppler shift values as inbound antennas 2 and 4 show positive tendency. When RSSI is high, the Doppler shift values are low. This is expected. When the pallet is right under the antennas, the distance to the antennas is shortest so the RSSI is highest. At the same point the pallet stops approaching and starts departing the antennas.

Doppler shift for most read events at lay around pallet stay below 2 Hz as shown in Figure 60.

6.3 Lay Around Tag Detection Analysis based on RSSI, Phase Angle Rotation and Doppler Shift Statistics

Data from experiments conducted was analysed to determine if it is possible to discriminate lay around tags from pallet tags based on mean and standard deviation of measured RSSI, phase angle rotation and Doppler shift values.

π was subtracted from phase angle rotation values over π, because the current software on the reader has problems recognizing the quadrature of the signal. This reduces deviation caused by sudden moves from quarter to another.

Means and standard deviations were calculated over all the events for one tag received through one antenna. Signal path varies on events received by different

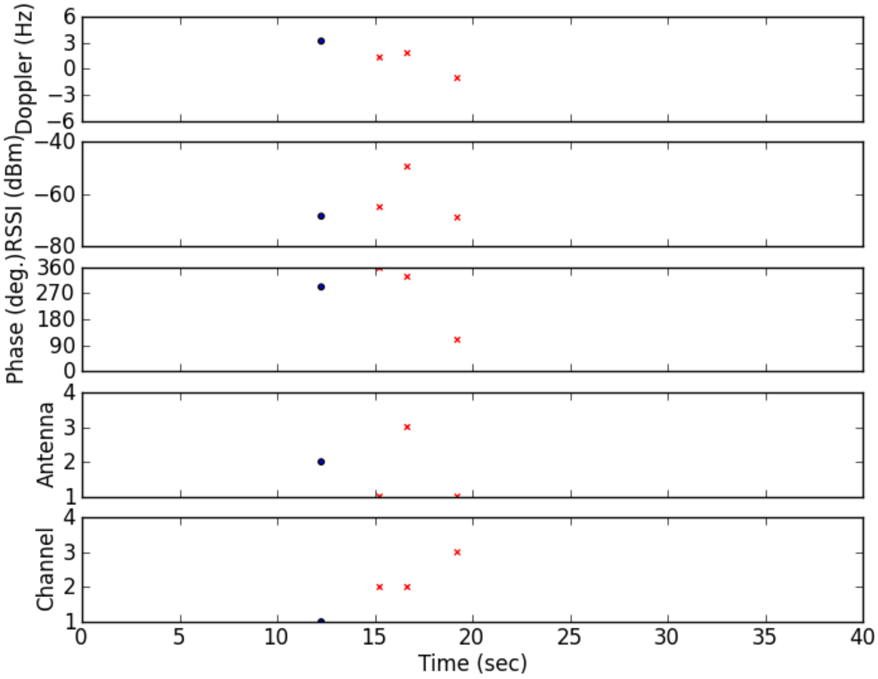

Figure 53: Tag moving through portal. Session 1, Operating Mode 3.

antennas so the phase angle rotation and RSSI measurements are not comparable. Thus one tag can have as many data points on the graphs as there were antennas used.

Absolute Doppler shift values were used to calculate means. This is sufficient as the focus of the experiments conducted was not to sense the direction of the movement.

High Throughput Configuration

Session 2 with Operating Mode 1 gives a bit higher differences in standard deviation of phase angle rotation as seen in Figure 61.

Differences in standard deviations of RSSI and phase angle rotation values and also in absolute Doppler shift mean can be seen between lay around and pallet tags as can be seen in Figure 61. Lay around tags are marked with blue 'x' and pallet tags with red circle.

Pallet tags show higher standard deviation in phase angle rotation and RSSI. Absolute Doppler shift mean shows little difference between the lay around tags and the moving tags. This is mostly because the low accuracy of the Doppler shift measurement with high throughput operating mode. Unfortunately it is not possible to set dividing limits on these measurements which could be used to discriminate all read events directly. The area of confusion is large. Some lay around tags got rather high standard deviations of RSSI and phase angle rotation and some moving

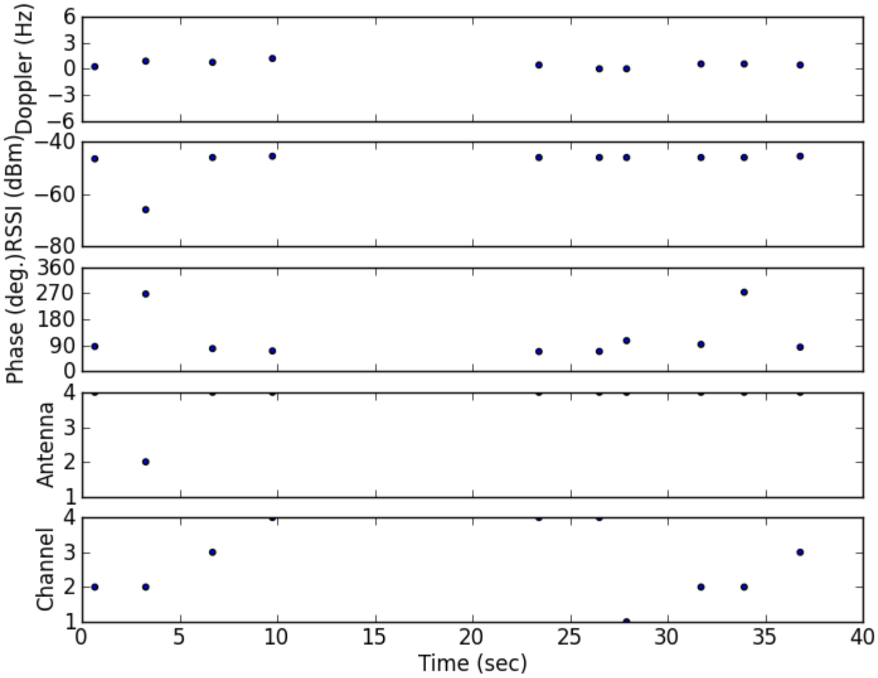

Figure 54: Lay around tag. Session 1, Operating Mode 3.

tags got low standard deviations. Latter is more common, as the number of read events of moving tags is generally low.

Tag / antenna combinations with just one event cause another problem. Standard deviation for one measurement is always 0. This can be seen as many of data points having 0 standard deviation of phase angle rotation.

Minimum of two events for each tag antenna combination used for detection is needed in these methods, but to improve data reliability more than 5 events should be received.

Dense Reader Environment Configuration

Session 2 Operating Mode 3 is slower but provides better accuracy in Doppler shift measurements. Figure 62 shows that there is a clear distinction between lay around tags and pallet tags in Absolute Doppler Shift Mean for those tag / antenna combinations with more than one measurement.

6.4 Direction Sensing and Lay Around Tag Detection Testing

Experiments at the RFID gate were started using one pallet with 180 Dogbone labels with NXP chips. Load of the pallet was done from two cardboard sheets put in A shape. Cardboard sheets had 45 tags each side. Tags were placed 15 cm from each

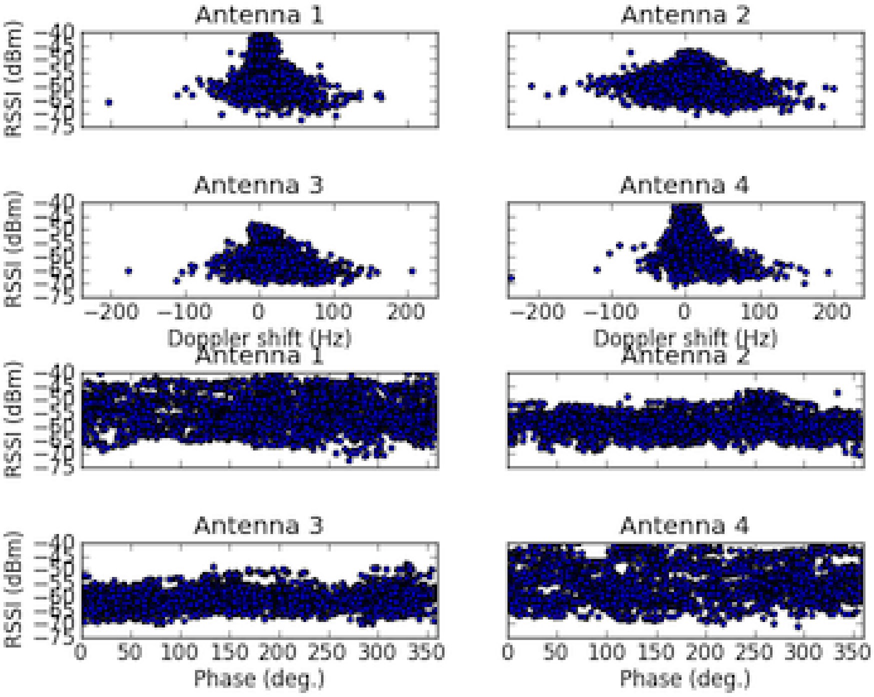

Figure 55: Lay around pallet. Session 2, Operating Mode 0.

other. In the initial tests was found out that if the tags are too near each other, it is not possible to read all tags.

Direction sensing antenna setup on top of the track. Two antennas each side pointing opposite directions.

Results of all experiments conducted are presented in Appendix C.

6.4.1 Read Rate Testing

The first test run was done without lay around tags. This was done to measure overall read rate at the portal. Pallet was pulled through the portal at walking speed (1.2 m/s).

Results presented at Table C2 indicate that both methods are prone to false positive lay around tag identifications. This means that some of the tags on the load were identified as lay around tags. The simple method is a bit better. In general the number of false positives is low, and it should not cause problems at least if pallets are processed at Virtual Handling Unit (VHU) level. Lay around tag detection provided flawless results – no false positives detected.

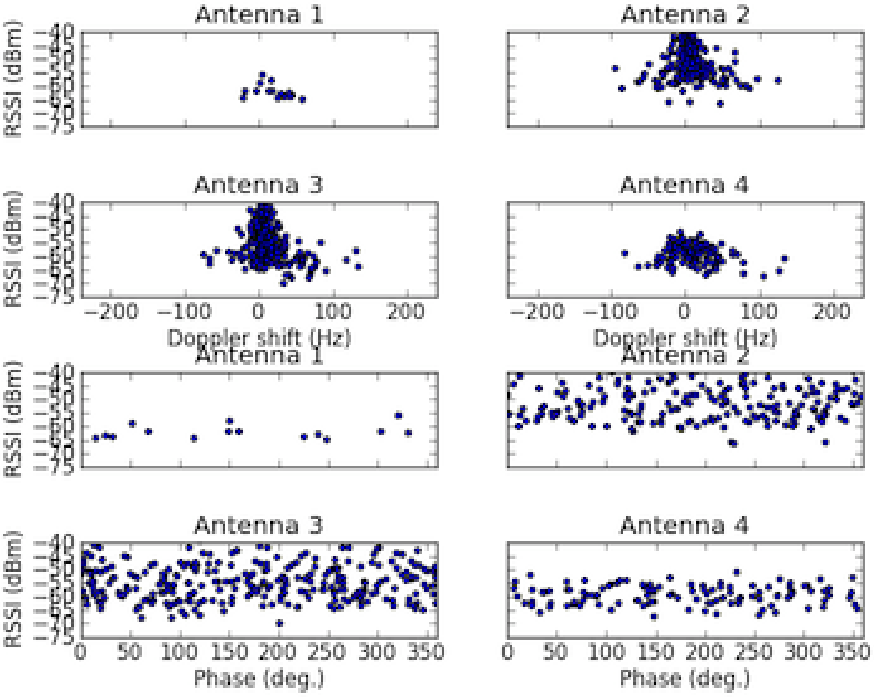

Figure 56: Pallet moving through portal. Session 2, Operating Mode 0.

6.4.2 Lay Around Tag Identification Testing

Dense Reader Environment Configuration

Lay around tag identification testing started with ten lay around tags put to the sides of the track in lay around tag detection testing. Results at Table C4 indicate that both used methods were able to identify all read lay around tags as lay around tags. False positive rates were similar than in run without lay around tags in Table C2.

Lay around tag detection algorithm provided good results without being dependent on direction sensing antenna setup. On average, it could detect 80% of the lay around tags as lay around tags. No pallet tags were detected as lay around.

The number of tags was increased to make the test setup more demanding for the algorithms. Higher number of tags should reveal the differences between the algorithms better.

First test case was done without moving pallet. Only the lay around tags were at the interrogation zones. Doppler shift and simple methods provided good lay around detection rate as shown in the results Table C6. Lay around tag detection algorithm provided poor results due to the high number of tags and a relatively short run time. Most of the tags received only 1 or 2 read events overall, which prevented the statistical analysis methods to function properly.

Next test run was done with one moving pallet with 300 tags. 600 lay around tags were put near the interrogation zones. Both direction sensing based methods identified lay around tags at good accuracy. False positive rate is remarkably high

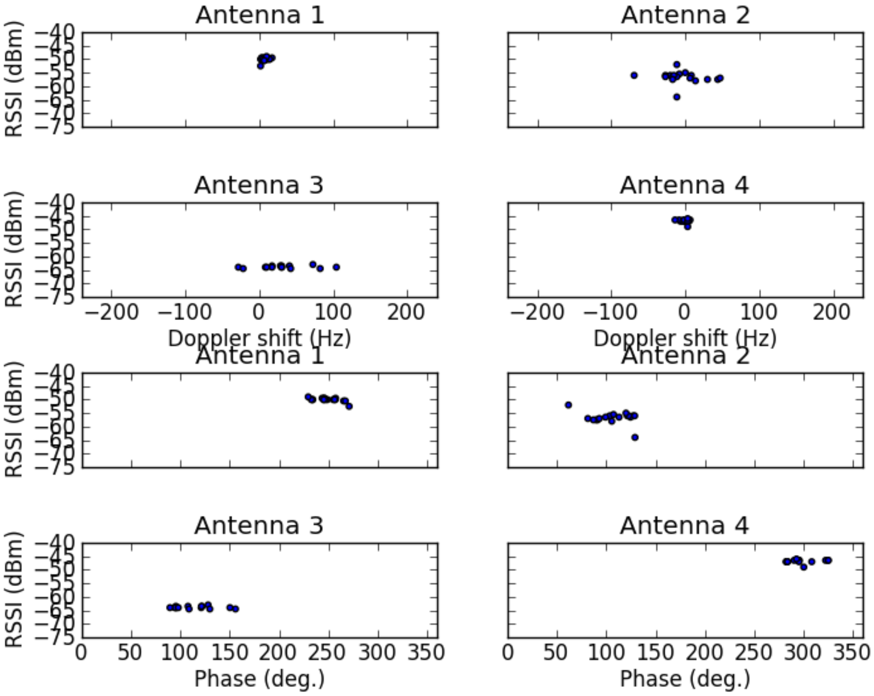

Figure 57: Lay around tag. Session 2, Operating Mode 0.

with both algorithms as shown in Table C8. Over 50% of the pallet tags were identified as a lay around tag, which is too much for any application to tolerate. Lay around tag detection algorithm provided rather low lay around tag identification rate, but none of the pallet tags were identified as a lay around tag.

Direction sensing based algorithms faced difficulties with high number of tags. High number of tags combined with relatively slow operating mode (3) leads to situation, where tag has only been seen at one of the two interrogation zones and is identified falsely as a lay around tag.

False detection rate could be lowered with following actions:

- Lower total number of tags
- Slower moving speed through the portal
- Faster operating mode of the reader (Less DRM)
- Session 2 with dual target mode could increase total number of reads too

The drawback of selecting a faster operating mode would is lower tolerance for AEN. The system becomes less robust if many readers operate in the same environment.

These results also indicate, that handling units tagged with item level should be handled as VHUs if total number of tags is very high.

Based on the experiments the optimum reader configuration for direction sensing based lay around tag detection would be Session 2, dual target inventory search mode

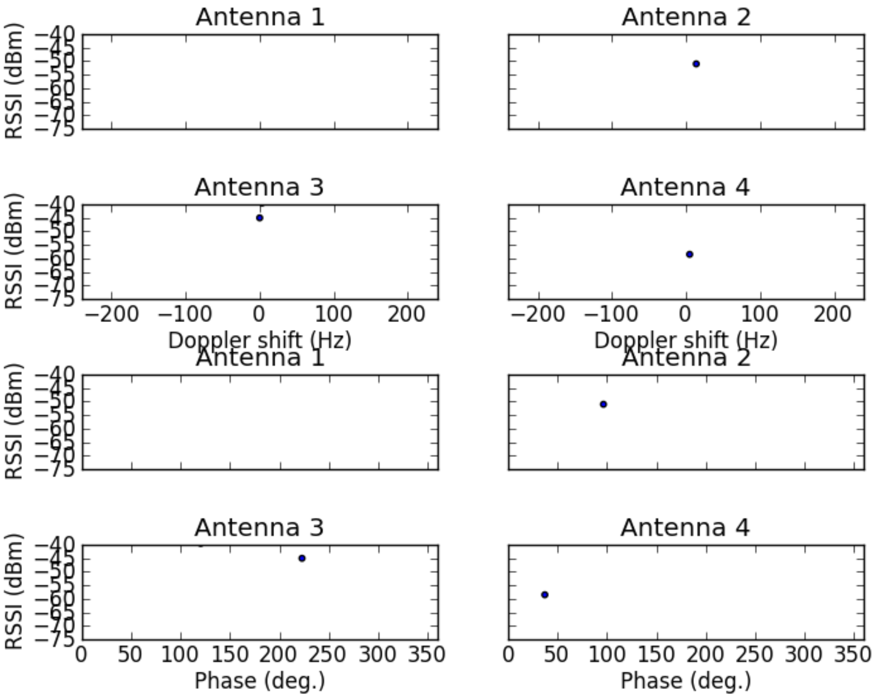

Figure 58: Tag moving through portal. Session 2, Operating Mode 0.

and operating mode 3. Number of tags should be reduced as the read rate limited the accuracy of the system in the experiments.

Session 2 with dual target inventory search mode should provide the highest number of read events. Session 1 has persistence time of about 1 second which limits read rate for a single tag for 1 event per second. Session 2 has persistence time of 5 to 15 seconds, but dual target inventory mode overcomes this limitation as the tags are first inventoried to state **B** and then immediately after back to **A**.

Operating mode 3 slows down the data rate between the tag and the reader which increases accuracy of Doppler shift measurements.

Further experiments were run with settings mentioned above. Results can be seen in Table C10. Lay around detection rate increases a bit, but unfortunately these settings have no effect on false positive rate which was considered as the major drawback of identifying lay around tags based on direction sensing.

Lay around tag detection algorithm provided now good results. It could identify over 87% of the lay around tags as lay around with no false positives. This indicates that the algorithm deserves to be studied further.

High Throughput Configuration

Limits of these methods were tested by increasing the data rate between the tag and reader by using operating mode 1, which is a high throughput mode optimized for a very high number of tags. Result of this experiment run can be seen in Table C12.

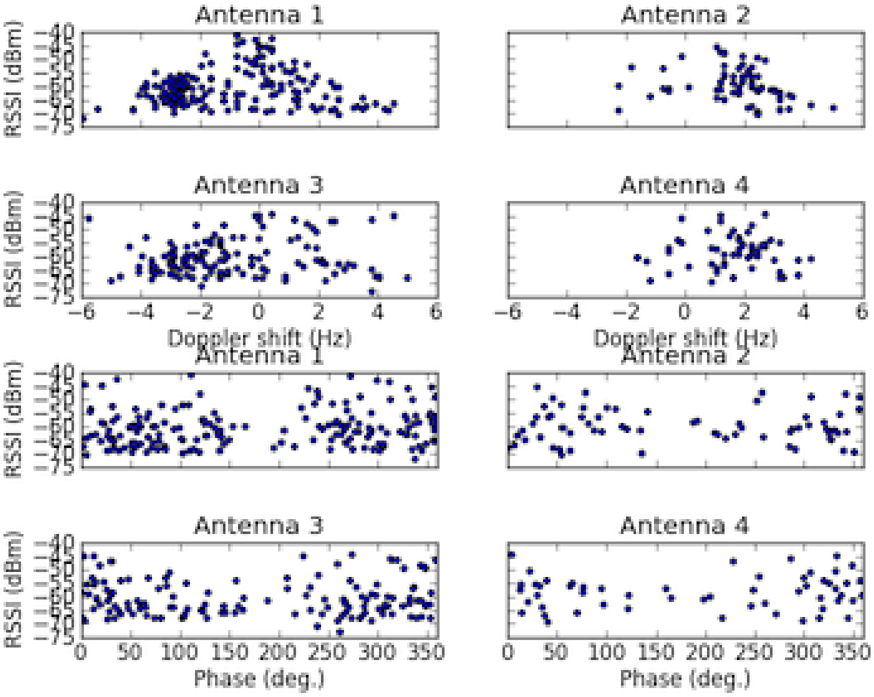

Figure 59: Pallet moving through portal. Session 1, Operating Mode 3.

Lay around tag identification rate of Doppler shift method dropped a little. Lay around tag detection algorithm provided mediocre results. The identification rate dropped from the tests conducted with operating mode 3. This is mostly because of increased deviation in Doppler shift measurements. Still no pallet tags were identified as lay around tags.

6.4.3 Stray Read Detection

Experiments were done to measure how well the methods detect stray reads from tags which do not pass through the gate. Those tags of which status was *unknown* after the test run were identified as stray reads.

Direction sensing based methods provided flawless results on identifying stray reads in these setups as shown in Table C14. This is mostly because the stray reads usually come from other side of the gate and are not seen in both of the interrogation zones within short time period, which is the basis of direction sensing.

Some of the lay around tags were so near both interrogation zones that they were detected as tags moving through the gate.

6.5 Discussion

The results indicate that the methods described in this thesis can be used to identify stray reads and lay around tags if the tagging is done on item level and VHUs are

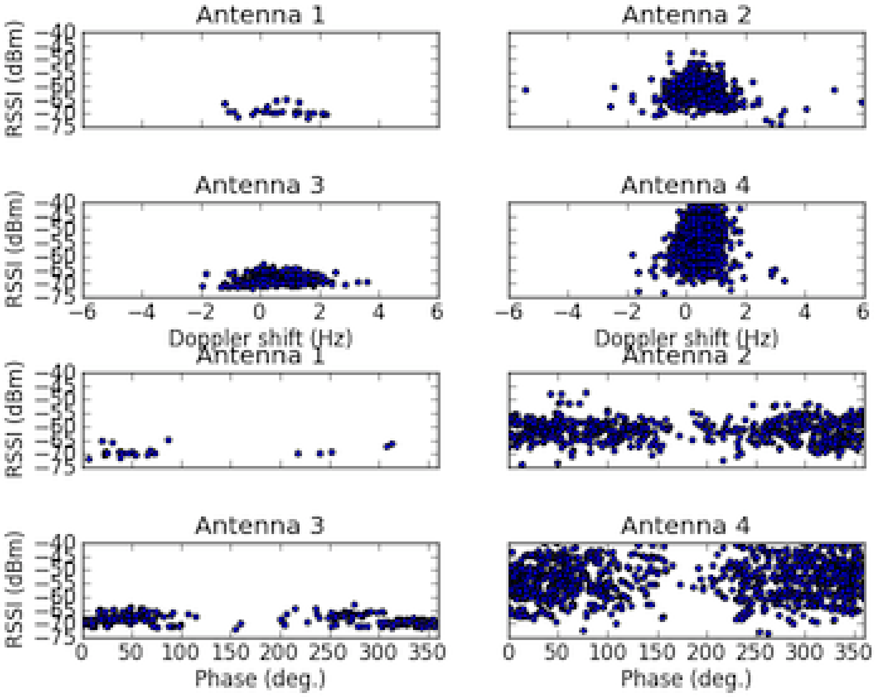

Figure 60: Lay around pallet at the portal. Session 1, Operating Mode 3.

used. Number of tags can be up to 1000. It can be assumed, that the methods would provide a very good accuracy on low number of tags (up to 100) even without using VHUs. The number of the read events per tag is increased as the total number of tags goes down.

Study shows that throughput of a single reader and number of other readers in the same operating environment depend on each other. If there is only one reader in operating environment it can be used in high throughput operating mode. In dense reader environment data rate of a reader needs to be reduced to decrease RF-noise levels. On the other hand phase angle rotation and Doppler shift measurements work better in slow speed operating modes. To fully utilize the potential in statistical analysis of phase angle rotation and Doppler shift measurements the number of events need to be high, which courages to use high throughput operating mode. It becomes clear that the configuration of RFID system is always a compromise between throughput and capabilities to detect lay around tags and stray reads.

Experimenting was done with cardboard loads on the pallets. This type of load is quite easy for a RFID system as it has very weak RF-absorbing properties. All tags were visible for the reader from the both sides of the pallet. This is seldom true in real industrial applications. Further testing should be conducted to experiment the proposed methods using more difficult loads.

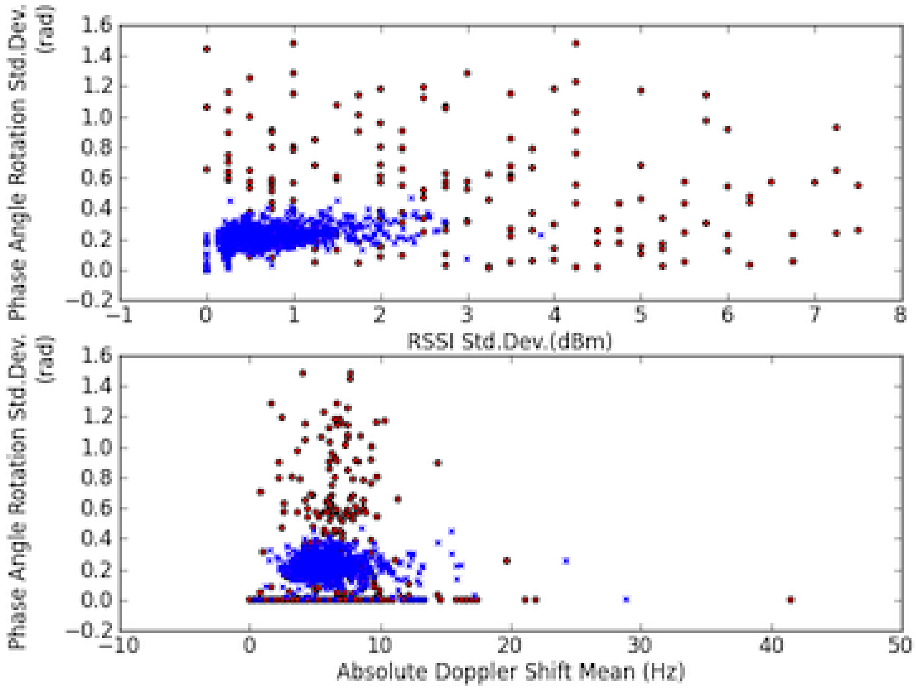

Figure 61: Session 2, Operating Mode 1 statistics.

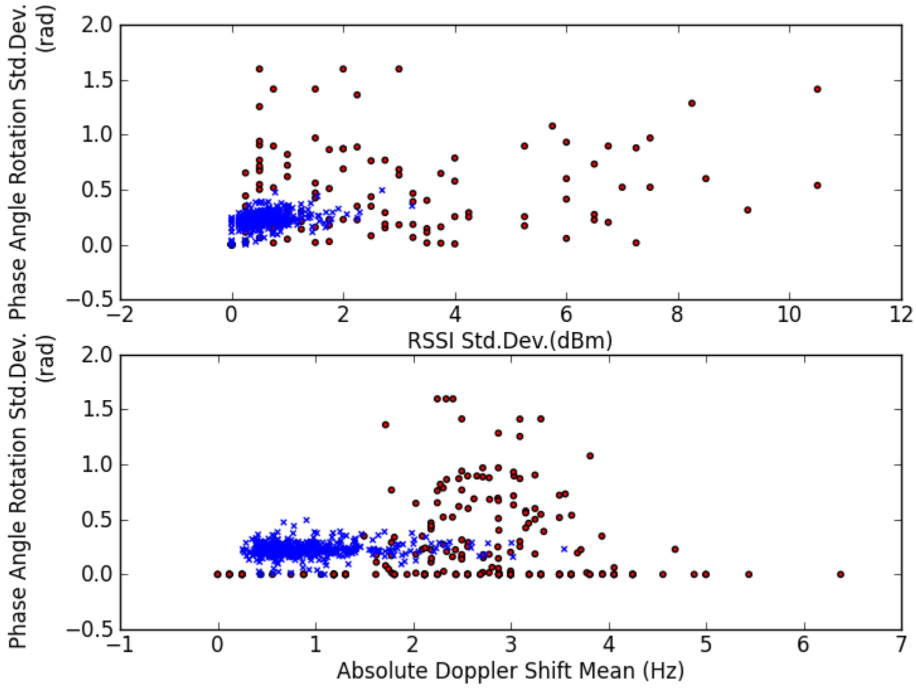

Figure 62: Session 2, Operating Mode 3 statistics.

7 Conclusions

Interrogation zone of a RFID system operating at UHF band is not sharp edged due to constructive and destructive interferences. The interrogation zone can be adjusted directly by controlling the transmit power of the RFID reader and selecting antennas and tags carefully for the purpose. Quite often suboptimal placement of the RFID tag and the properties tagged objects decrease the read rate at the RFID gate. The read rate can be increased by using a higher transmit power on the reader, which extends the interrogation zone over the desired and leads to stray reads.

The stray reads can be eliminated in the first place by designing the RFID system layout in a way, that possibility for stray reads is minimized. Shielding is to be considered where cross reading possibility exists. RFID parameters need to be adjusted so that the transmit power is the lowest needed to achieve the desired read rate. Also using a RSSI threshold for the RFID events can be used to discard the weak read events.

There are promising approaches to identifying stray reads based on Doppler shift and phase angle rotation. The Doppler shift can be measured for a single RFID read event. It carries information about the speed and direction of the movement. With smart positioning of antennas and use of specific algorithms, it is possible to detect how the tag is moving related to the RFID gate. This information can be used to identify stray reads and lay around tags. The weakness in Doppler shift based methods is that they are dependent on the movement. If a handling unit moves through the gate at very slow speed or even stops within the gate, the Doppler shift based methods may not work well.

Phase angle rotation data from RFID read event provides another approach to implement algorithms for stray read and lay around tag identification. Standard deviation of phase angle rotation on lay around tags was shown low, which can be used for identification purposes.

Based on the experiments conducted the most promising approach to identify lay-around tags seems to be using standard deviation of both phase angle rotation and RSSI and absolute mean of Doppler shift. These parameters were identified to differ most between lay around tags and moving tags.

The use case with cross reading from adjacent gate is the most difficult of studied cases to solve. The direction of the movement is through the gate which makes it difficult to identify using Doppler shift based methods. The number of read events is usually low, which prevents using statistics based on phase angle rotation. Cross reading seems to be solved best on higher data processing level. When data received from different RFID gates is compared within specific time window and orientation of antennas is known, it is possible to determine through which gate the handling unit went. It is also suggested that triggered reading reduces the amount of cross reads, but does not solve the issue, when docking is taking place on two adjacent RFID gates at the same time.

Further study on this field must be done to develop the methods found on such level, that they can be implemented to production applications. One key question which needs to be answered is how to turn these offline analysis to functioning online algorithms.

Development in antenna technology may bring new possibilities to identify lay around tags. Small phased array antennas could provide tools to set up interrogation zones more accurately. Beam shaping could help to locate RFID tags more accurately. If there is sufficient amount of events available and the RFID system has been calibrated properly, phase angle rotation provides means to calculate distance to the object. This would allow setting the limits of the interrogation zone with higher precision.

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A Impinj Speedway Revolution Specific Settings

Table A1: OctaneLLRP Operating Modes

Value	Description
0	Max Throughput
1	Hybrid Mode (High throughput (M=2))
2	Dense Reader (M=4)
3	Dense Reader (M=8)
4	Max Miller (High throughput (M=4))
5	Dense Reader (M=4) 2 Faster forward link than mode 2, available with regions; ETSI, China, India, Korea and South Africa.
1000	AutoSet
1001	AutoSet Single Interrogator – This mode is now identical to mode 1000

Table A2: OctaneLLRP Inventory Search Modes

Value	Description
0	‘Reader selected mode’ (default)
1	‘Single target inventory’ High tag count, high-throughput applications where a reduction in repeated tag observation is acceptable.
2	‘Dual target inventory’ Low to medium tag count or low-throughput applications where repeated tag observation is desirable.
3	‘Single target inventory’ (with suppressed duplicate observations). Maximum tag count, high-throughput applications where a single observation of each tag is acceptable. This search mode suppresses repeated observations for extended periods of time while tags are energized. (Available only for use with Session 1.)
4-65535	Reserved for future use

A.1 ImpinjRFPhaseAngle Parameter

Report the RF phase angle of a singulated tag during normal inventory (EPC backscatter) using this custom parameter. The PhaseAngle field is a scaled, 12-bit value, with 0 representing 0° (0 rad), and 4096 representing 360° (2π rad).

As an example, if the reported phase angle is 1985, the corresponding angle can be calculated as:

$$1985 \times \left(\frac{360^\circ}{4096}\right) = 174.46^\circ \text{ or } 1985 \times \left(\frac{2\pi \text{ rad}}{4096}\right) = 3.04 \text{ rad} \tag{A1}$$

A.2 ImpinjRFDopplerFrequency Parameter

Report the estimated RF carrier Doppler frequency shift using this custom parameter. The estimate is made over the duration of each tag EPC and has units of Hz. This 16-bit parameter has twelve integer bits and four fractional bits. Accuracy and precision depend on Reader mode and measurement length.

If report accumulation is enabled via the ROReportSpec for the currently executing ROSpec, the RF Doppler frequency reported via this parameter is the Doppler frequency of the last tag singulation. No accumulation of Doppler frequency data is available.

B Listings

```
def simpleAlgorithm(self, events):
  currentSide = "unknown"
  pendingSide = "unknown"
  movements = []
  for event in events:
    if pendingSide == "unknown":
      if event.ant in self.sideA:
        pendingSide = "A"
      elif event.ant in self.sideB:
        pendingSide = "B"
    elif pendingSide == "A":
      if event.ant in self.sideB:
        movement = DirectionSensingEvent(event.epc, event.dateAndTime,
            vent.msec, "AtoB")
        movements.append(movement)
        currentSide = "B"
    elif pendingSide == "B":
      if event.ant in self.sideA:
        movement = DirectionSensingEvent(event.epc, event.dateAndTime,
            event.msec, "BtoA")
        movements.append(movement)
        currentSide = "A"
  return currentSide, movements
```

Listing B1: Simple Direction Sensing Algorithm

```
def dopplerShiftAlgorithm(self, events, threshold):
  currentSide = "unknown"
  movements = []
  antASum = 0.0
  antBSum = 0.0
  antAn = 0
  antBn = 0
  for event in events:
    if event.ant in self.sideA:
      antASum += event.doppler
      antAn += 1
    elif event.ant in self.sideB:
      antBSum += event.doppler
      antBn += 1
  try:
    antAAverage = antASum / antAn
  except ZeroDivisionError:
    antAAverage = 0.0
  try:
    antBAverage = antBSum / antBn
  except ZeroDivisionError:
    antBAverage = 0.0
  if antAAverage == 0.0 or antBAverage == 0.0:
    return currentSide, movements
  if (antAAverage - threshold) > antBAverage:
```

```python
    movement = DirectionSensingEvent(events[-1].epc, events[-1].
        dateAndTime, events[-1].msec, "AtoB")
    currentSide = "B"
    movements.append(movement)
  elif (antBAverage - threshold) > antAAverage:
    movement = DirectionSensingEvent(events[-1].epc, events[-1].
        dateAndTime, events[-1].msec, "BtoA")
    currentSide = "A"
    movements.append(movement)
  return currentSide, movements
```

Listing B2: Doppler Shift Based Direction Sensing Algorithm

```python
def circ_std(self, samples, high=2*pi, low=0):
  ang = (samples - low)*2*pi / (high-low)
  res = mean(exp(1j*ang), axis=0)
  V = sqrt(-2*log(abs(res)))
  return ((high-low)/2.0/pi) * V
```

Listing B3: Circular Standard Deviation Function

```python
def updateLayAroundStatus(self):
  if self.layAroundRef > 3:
    self.layAround = True
  else:
    self.layAround = False

def updateLayAroundRef(self):
  res = 0
  for ant, datum in self.phaseDev.iteritems():
    if self.dopplerMean[ant] < 1.5:
      res += 1
    if self.phaseDev[ant] < 0.4:
      res += 1
    if self.RSSIDev[ant] < 1:
      res += 1
    if self.antCount[ant] > 10:
      res += 1
    if self.antCount[ant] in range(1,3) :
      res -= 1
  self.layAroundRef = res
```

Listing B4: Lay Around Tag Detection Algorithm

C Results of the Experiments

Table C1: Parameters

Setting	Value
TX Power	30 dBm
Session	1
Operating Mode	3
Number of tags on load	180
Number of lay around tags	0
Speed of the pallet	1.2 m/s
Repeats	10

Table C2: Results

	μ	Min	Max	σ
Read Events (n)	992.50	872	1212	98.66
Time (s)	15.93	12.46	22.37	3.67
Events per Second (n)	64.19	46.27	74.44	8.86
Read Rate (%)	99.06	97.22	100.00	1.12
Simple Method False Positive Rate (%)	3.80	0	10.23	3.66
Doppler Shift Method False Positive Rate (%)	6.22	1.11	14.77	4.86
Lay Around Tag Detection Algorithm False Positive Rate (%)	0.00	0.00	0.00	0.00

Table C3: Parameters

Setting	Value
TX Power	30 dBm
Session	1
Operating Mode	3
Number of tags on load	180
Number of lay around tags	10
Speed of the pallet	1.2 m/s
Repeats	5

Table C4: Results

	μ	Min	Max	σ
Read Events (n)	1062.80	937	1123	65.87
Time (s)	46.23	42.71	47.93	1.86
Events per Second (n)	23.05	19.89	26.29	2.03
Read Rate (%)	98.67	96.11	100.00	1.67
Simple Method				
Lay Around Tag Identification Rate (%)	100.00	100.00	100.00	0
False Positive Rate (%)	4.16	0.56	9.66	4.19
Doppler Shift Method				
Lay Around Tag Identification Rate (%)	100.00	100.00	100.00	0
False Positive Rate (%)	6.63	3.33	11.36	3.77
Lay Around Tag Detection Algorithm				
Lay Around Tag Identification Rate (%)	80.00	71.43	85.71	7.00
False Positive Rate (%)	0.00	0.00	0.00	0.00

Table C5: Parameters

Setting	Value
TX Power	30 dBm
Session	1
Operating Mode	3
Number of tags on load	0
Number of lay around tags	900
Speed of the pallet	1.2 m/s
Repeats	5

Table C6: No movement

	μ	Min	Max	σ
Read Events (n)	1647	1630	1695	24.24
Time (s)	14.42	14.10	14.57	0.16
Events per Second (n)	114.25	112.49	116.33	1.40
Read Rate (%)	N/A	N/A	N/A	N/A
Simple Method				
Lay Around Tag Identification Rate (%)	99.13	98.30	99.72	0.51
False Positive Rate (%)	N/A	N/A	N/A	N/A
Doppler Shift Method				
Lay Around Tag Identification Rate (%)	98.84	98.01	99.72	0.51
False Positive Rate (%)	N/A	N/A	N/A	N/A
Lay Around Tag Detection Algorithm				
Lay Around Tag Identification Rate (%)	2.71	2.54	2.88	0.13
False Positive Rate (%)	0.00	0.00	0.00	0.00

Table C7: Parameters

Setting	Value
TX Power	30 dBm
Session	1
Operating Mode	3
Number of tags on load	300
Number of lay around tags	600
Speed of the pallet	1.2 m/s
Repeats	10

Table C8: Pallet moves, lay around tags

	μ	Min	Max	σ
Read Events (n)	4108.60	3699	4772	340.34
Time (s)	37.06	33.27	43.16	3.12
Events per Second (n)	110.86	110.35	111.51	0.39
Read Rate (%)	84.92	81.27	88.29	2.02
Simple Method				
Lay Around Tag Identification Rate (%)	93.10	91.51	94.51	0.73
False Positive Rate (%)	64.99	58.82	71.04	3.77
Doppler Shift Method				
Lay Around Tag Identification Rate (%)	96.50	95.65	98.11	0.72
False Positive Rate (%)	68.83	64.31	75.59	3.38
Lay Around Tag Detection Algorithm				
Lay Around Tag Identification Rate (%)	32.48	25.79	41.21	4.44
False Positive Rate (%)	0.00	0.00	0.00	0.00

Table C9: Parameters

Setting	Value
TX Power	30 dBm
Session	2
Inventory Search Mode	2 (Dual Target)
Operating Mode	3
Number of tags on load	300
Number of lay around tags	300
Repeats	10

Table C10: Pallet moves, lay around tags

	μ	Min	Max	σ
Read Events (n)	5588.1	4921	6141	381.82
Time (s)	42.83	37.87	47.05	2.59
Events per Second (n)	130.44	121.27	133.09	3.32
Read Rate (%)	59.80	34.00	77.33	12.83
Simple Method				
Lay Around Tag Identification Rate (%)	99.37	98.60	99.65	0.31
False Positive Rate (%)	80.27	67.24	89.36	6.23
Doppler Shift Method				
Lay Around Tag Identification Rate (%)	99.68	98.95	100.00	0.37
False Positive Rate (%)	82.33	68.53	90.43	5.98
Lay Around Tag Detection Algorithm				
Lay Around Tag Identification Rate (%)	87.41	79.65	92.25	3.29
False Positive Rate (%)	0.00	0.00	0.00	0.00

Table C11: Parameters

Setting	Value
TX Power	30 dBm
Session	2
Operating Mode	1
Number of tags on load	300
Number of lay around tags	600
Repeats	5

Table C12: Pallet moves, lay around tags

	μ	Min	Max	σ
Read Events (n)	13150.80	11133	14679	1333.86
Time (s)	38.56	37.10	40.98	1.44
Events per Second (n)	340.91	300.08	393.12	31.29
Read Rate (%)	80.07	68.33	93.00	8.23
Simple Method				
Lay Around Tag Identification Rate (%)	97.50	97.05	97.89	0.32
False Positive Rate (%)	52.81	27.24	73.66	15.90
Doppler Shift Method				
Lay Around Tag Identification Rate (%)	97.72	97.05	98.18	0.45
False Positive Rate (%)	55.84	30.47	76.10	15.93
Lay Around Tag Detection Algorithm				
Lay Around Tag Identification Rate (%)	47.62	44.44	49.58	1.73
False Positive Rate (%)	0.00	0.00	0.00	0.00

Table C13: Parameters

Setting	Value
TX Power	30 dBm
Session	1
Population size	1024
Operating Mode	1
Inventory Search Mode	1 (Single Target)
Number of tags on load	300
Number of lay around tags	600
Repeats	5

Table C14: Pallet moves but not through, lay around tags

	μ	Min	Max	σ
Read Events (n)	3597.80	3233	4179	355.87
Time (s)	28.24	25.19	32.73	2.82
Events per Second (n)	127.42	126.47	128.34	0.66
Read Rate (%)	36.60	30.33	38.67	3.17
Simple Method				
Lay Around Tag Identification Rate (%)	93.50	92.91	94.20	0.46
Stray Read Identification Rate (%)	100.00	100.00	100.00	0.00
Doppler Shift Method				
Lay Around Tag Identification Rate (%)	95.92	95.20	96.34	0.42
Stray Read Identification Rate (%)	100.00	100.00	100.00	0.00