

Investigation of RFID tag motion estimation in real-world scenarios

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Abstract

Radio Frequency Identification, already incorporated into several fields such as supply chain management, theft control and inventorying, still has a lot of potential to grow. It is possible to gain more information from tagged objects, than just the serial number. The signal response from an RFID tag present the RFID reader with much more than just a code that you can find on a barcode. Phase and RSSI are only two of the several parameters that form part of the signal response from an RFID tag.

It is possible to use these additional signal response parameters to perform a motion estimation of a moving tag. Motion estimation is defined mainly as the velocity at which the tag is moving, the general direction of travel and a broad distance estimation. Building on previous work it is important to consider not only the abilities but also the limitations of these methods and how the techniques can be adjusted to adhere to all standards, in order to be implemented in real-world scenarios.

Previous work in this field did not include all the local standards, placing limitations on the practical application of these techniques. Only limited characterization of real-world challenges, encountered when using these techniques, were conducted by previous research. Thus, a further study on the impact of these limitations as well as the influences from real-world environments is necessary. Against this background the aim for this study is to investigate the possibilities offered by motion estimation of RFID tags while adhering to local standards, and to characterize the effects from real-world conditions on the implementation of these methods.

Thorough literature studies were performed on the following topics: challenges posed by RFID, localization mapping systems, direction estimation with RFID, phase difference on arrival techniques for velocity estimation, indoor location systems, Kalman filtering, phase unwrapping and antenna setups.

Practical experimentation was conducted to determine the ideal antenna setup for motion estimation techniques. This was based on the literature review and was implemented with commercial off-the-shelf (COTS) equipment to inform further experimentation later in the study.

Complete designs for the velocity estimation, direction estimation and distance estimation techniques were presented. These designs include practical limitations and implementation requirements using COTS equipment. Kalman filter designs were implemented for different scenarios using different combinations of measurements as inputs. These designs include the models used for motion estimation and the covariances for the different noise parameters present. A Kalman filter for sensor fusion was designed and implemented using both distance

estimation from the signal strength parameter and phase-based velocity estimation to predict the motion of a moving tag.

Experimental designs on how to test the different motion estimation techniques in real-world scenarios are discussed. The different influences on the accuracy of the techniques are investigated by means of simulated real-world conditions. Worst case scenarios are explored and possible applications in the case of inaccurate measurements are proposed.

Comparisons between different velocity estimation techniques in a variety of different controlled circumstances were completed. These comparisons serve as a benchmark of how accurate the estimation technique is, as well as which estimation technique is better suited to what environments.

From this study, it is also possible to determine which environmental conditions will influence the accuracy of these techniques and what the limits are of these techniques. The techniques were implemented to function both in a real time application as well as to record first and process later.

Finally, it is proven that motion estimation of a RFID tag is possible in certain real-world scenarios, while adhering to local broadcasting channels. The practical benefit of this study is that more information can be provided by RFID systems, without additional hardware cost. This allows industrial and commercial users to improve the monitoring of tagged object as well as to define certain behavioural patterns of the movement of the objects which can be used to improve the monitoring accuracy of these systems.

Key words: *RFID, Motion Estimation, Kalman Filter, Velocity estimation, Distance estimation, Sensor Fusion, COTS.*

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List of Abbreviations

AoA	Angle of Arrival
COTS	Commercially of The Shelf
CLR	Common Language Runtime
EIRP	Equivalent Isotropic Radiated Power
EPC	Electronic Product Code
ERP	Equivalent Radiated Power
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
ILS	Indoor Location System
MUSIC	Multiple Signal Classification
NFC	Near Field Communication
ONS	Object Name Service
PPE	Personal Protection Equipment
FD-PDOA	Phase-Domain Phase Difference on Arrival
RFID	Radio frequency identification
RMS	Root Mean Square
RSSI	Received Signal Strength Indicator
RTLS	Real Time Location System
SD-PDOA	Spatial-Domain Phase Difference on Arrival
TARI	Type a reference interval
TDMA	Time Division Multiple Access
TD-PDOA	Time-Domain Phase Difference on Arrival
ToF	Time-of-Flight
UHF	Ultra High Frequency

1. Problem statement

In this chapter the main problem with passive RFID tag tracking using current systems and setups is discussed. The research questions are defined and definitions from the title are included.

1.1. Introduction

Radio Frequency Identification (RFID) has come a long way since the technology has first been introduced. The tags have grown to be small and reasonably affordable, meaning it can be attached to a lot of different items and shipments. By being able to tag shipments it enables companies to track assets as they move by strategically placing RFID readers and RFID systems at certain points. At the moment RFID systems can determine the direction of travel of a tag by placing different antennas along path that the tag is following [1][2]. If the tag is read at consecutive antennas the direction of the movement of the shipment can be tracked in this manner. The more detailed movement like in which direction the tag was moving as it passed through the antenna checkpoint is not available. This means that the end-user is not able to tell whether a tagged shipment was going in the wrong direction, at that specific instance. This means that the behavioural flags cannot be raised at individual antenna points. The lack of information can lead to a security risk or rather if this information was available it would enable a company to improve the accuracy of tracking of items and security of their system.

1.2. Problem statement

RFID tags are already very important in the supply chain management, asset tracking and stocktaking market [3][4]. Businesses are using RFID tags to analyse the movement of their goods and to optimise their floor space and placement of stock.

Standard RFID systems employed in businesses use several antennas to track movements of tags. If a tag is read at a certain antenna, the system knows definitely that the tag was there. The direction, that the tag was traveling, the velocity of the tag and what the distance to the antenna at a specific time was is not known, only that the tag was there. Specialist equipment makes it possible to track the direction, velocity and even position of tags, these are systems like the Impinj Xarray architecture, which is much more expensive than other COTS RFID systems [5][6]. These systems also have to be installed in a specific manner to be effective. Replacing current systems is not necessarily an option, because of cost and downtime in current systems. Several data parameters regarding the tag signal is noted in most standard RFID systems, this includes received signal strength indicator (RSSI), phase and doppler parameters. This data along with other statistical Low Level Read (LLR) data, can provide more detailed information of the movement of the tag if interpreted correctly[7].

The problem is thus that currently most standard RFID systems do not provide information about the directionality of tag movements. This includes basic directionality like whether the tag moved in or out through a door. Information regarding the distance of the tag and velocity of the moving tag is also lacking. This information can be used in several applications to prevent theft, raise a flag if certain parameters is over the standard movement limits (an item is traveling at speeds higher than normal or direction it is not allowed) and can even be used to optimise certain setups since more information will be available about the movement of the tags.

Systems that do provide this type of information, uses specifically designed architecture, tags and antennas to track the tag along a certain axis and has to be installed in a specific manner, this means that some other applications won't be able to use this setup since the desired setup for the rest of the application is different. Therefore, there is a desire for current systems to be able to provide additional information about the directionality, velocity and distance of the tag movement. In many instances it is not practically viable to replace the current hardware systems with a completely new setup that is designed to track the movement of the tags. Standard software however does not include tag motion estimation as a feature.

The main research question is thus, whether it is possible to determine the motion estimation of an RFID tag, while adhering to all local standards in real-world scenarios? A second question would be, how accurate these estimations will be for different scenarios? Finally, what will influence the accuracy of these estimations, in what way will the estimation be influenced and are there any ways to improve the standard estimation? This dissertation will aim to answer these questions.

1.3 Title definitions

The definition of motion estimation is an important part of this thesis. Motion estimation in the context of RFID tags and this study is comprised of two main focal points. The first is the general direction of travel, and more specifically whether the tag is moving closer towards the antenna or moving away from the antenna. This can then be used to generally determine if a tag moved through a portal and in what direction. The second part of motion estimation is the velocity at which the tag is traveling; for this part it is important to know how accurate this value can be determined. Velocity inherently has a direction, thus solving the velocity of the tag reveals the direction of the tag as well. If the velocity value can be trusted it means that the directionality accuracy is also increased.

Lastly, the term "real-world scenarios" need to be clarified. This represents scenarios that do not exclude factors such as reflections, multipath and interference. What this means is that it

is not comprised of synthetic lab environments using reflection removing surfaces and equipment that would not normally be used in industry. It also means that the setup, which is comprised of how the antennas and tags are placed, is derived from applications that can be seen in the real-world. The equipment is COTS (custom off the shelf), including the tags used. Real-world scenarios also describe that the type of movement made by the tagged items (speed and directionality) during experiments must be similar to the movement that would be found in specific types of applications. Finally, this means that all the techniques be designed in such a way that it can be implemented in a system used in industry, including programming language and systems running the algorithms.

1.4 Publications and submissions for peer review

In order to receive feedback on the completed study as well as to learn from industry experts, an effort was made to submit work included in this study to established journals for peer review. One article was submitted, accepted and presented in the IEEE RFID-TA 2019 conference in September 2019 [8]. This produced the opportunity to present the work done to industry professionals and receive feedback on the work done.

A second article will be submitted for peer review towards the IEEE journal of RFID Special Issue on the IEEE RFID-TA 2019 Conference. This journal will be published in September 2020, which means feedback will only be received after completion of this study. Both these articles are included in appendix A in support of the dissertation presented towards the achievement of this degree.

The first article will be found with the following reference:

- N. Bester and A. Hoffman, "Kalman Filter based RFID tag velocity estimation in the presence of frequency hopping," in *2019 IEEE International Conference on RFID Technology and Applications (RFID-TA)*, 2019, pp. 488–493.

The second article pending peer review will be submitted as:

- Hoffman and N. Bester, "RSS and phase Kalman filter fusion for improved velocity estimation and characterization of real-world factors on estimation accuracy," in *IEEE journal of RFID Special Issue on the IEEE RFID-TA 2019 Conference*, 2020

2. Literature Review

In this chapter a complete literature review is given on all the aspects that will contribute to solving the identified research problem.

2.1. Introduction

In this chapter the development of RFID technology, how it improved over the years and its applicable capabilities will be discussed. This chapter will give a broad overview of the different aspects that make up an RFID system. It will provide different options to consider regarding hardware and software, read setups, etc. Methods and approaches on how to use this hardware to determine the motion estimation of an RFID tag is discussed. This chapter will also provide the reader with the necessary background to form an idea of what possible solutions could look like and include.

2.2 Vision for RFID

Radio frequency identification (RFID) is a technology that, if fully utilised, has the potential to change every day living and completely revolutionise how technology interacts with people. There is still some way to go before this can be achieved but this technology along with Big Data management can fulfil the vision that people always had with wireless technology.

This technology can change asset and supply management completely, replacing current systems and save a lot of time if everything that is promised is delivered in this field [9].

The goal for RFID tags is that it would replace barcodes and be used to track every asset in a company. This means that all products can be inventoried and tracked without having to scan them by hand. The tag is placed directly on the packaging and the technology allows a reader to read all the items in range. If this becomes more reliable, it would be possible to apply them to products in a store, which means no more packing and unpacking at a till, this along with the Internet of Things movement can change the way we approach technology [10]. You will be able to simply walk through a portal and pay on the other side. This technology would allow companies to better track the movement of people and assets for security purposes. A person can wear a tag and a laptop assigned to that person would also have a tag. If the laptop moves without the person it can be seen as a possible theft.

One thing that the RFID system have lacked thus far is showing the direction of travel of the tag. It can tell you at which reader the tag was read and when, but not whether it was going through the door out of the building or into the building.

This is the area of focus for this thesis: how to accurately determine the direction and velocity of travel and apply it to existing systems. This can help factories track movement of items without the need to place readers every few hundred meters. The readers can be placed at key points such as gates and exits. Here it can be determined if the items went out the correct

door and at what estimated speed. This all means that there will be more information available to assist security and other management functions to track and optimise item movement.

2.3 Background Context

Systems that implement RFID have four basic elements that have to be present, namely: tags, readers, antennas and a computer or microcontroller that is used to interpret the readings from these items [11].

The tag is made up of an antenna and small chip, which includes a radio receiver, modulator, small amount of memory, power system and control logic [11]. The power system receives power from the RF signal applied by the RFID reader's antennas. Three types of tags exist, passive, semi-passive and active tags [12]. The main difference being that active tags have a battery that help power the circuitry. This also means that the tag is always on and the range of the signal is much bigger. Range can typically be around 50m. Passive tags do not have a battery and rely solely on the signal received from the reader antennas for power. This means that the range is less than 10m and more typically around 5m. One of the biggest advantages of the passive tag is that it has a low profile, allowing it to be applied to almost any surface without protruding and being in the way. It is also less expensive, meaning that it is more likely to be used at item level and as disposables. Semi-Passive RFID tags are also battery powered but do not transmit active signals, they are primarily used to monitor states such as temperature during transport. For this reason, the study will mostly focus on passive tags.

Certain parameters can be read on the reply signal of the RFID tag. These parameters include phase, RSSI, doppler, frequency, EPC, TID, etc. It is these parameters that can be used to uniquely identify each tag; it will also be used to determine the direction of tag movement. Each tag also contains a small amount of memory. This memory can be used to store information about the product on which the tag is applied. Standards enable companies that comply to the Gen 2 standards to be identifiable world-wide on a dedicated database. This means that information about a package is much more readily available and, in many cases, it won't be necessary to open the package to see what products are inside if the RFID tag is correctly configured.

The reader can send out a RF signal on different frequencies; depending on regional regulations this may consist of a specific frequency hopping sequence. The ETSI regulations determines that you are not allowed to broadcast a signal on a single frequency for more than 4 seconds if a tag is being read, and 1 second if no tag is being read[13].

RFID tags are unique and can be applied to assets or items in order to identify each one uniquely. RFID tags are becoming more cost effective and the hands-free advantages it brings make them one of the most exciting prospects available. Development over the years have

made it possible for these tags to be applied to metal surfaces and even with the correct setup on items containing fluids, something that has been a cause for concern in this field for a long time [14].

The applications for RFID are endless; with the Internet-of-Things gaining a lot of ground this is even more true since RFID will allow systems to track non-electronic items as well. This means that more applications can be developed and even more opportunities will arise to incorporate this technology in new fields. Localisation techniques have been developed using RFID readers and tags as the medium [15]i [17]. This is a result of the nature of the technology where at its core it is the send and receive of radio signals, meaning the same approach to signal localisation used with broadband radio signals can be used here. New techniques developed in this area fine-tuned the results and it is possible to track and locate RFID tags in a broad area using standard readers. The control in a business will be improved a great deal if all assets or even people can be located and tracked. This can however also lead to ethical questions and opens up an entire new field for debate

To conclude: RFID has developed a great deal since it was first introduced. As the technology become more sophisticated and reliable its applications will also increase with an already huge current client base. Every time a new approach is documented that extracts more useful information from the existing technology it is one step closer to the envisioned world where everything is connected, traceable and works together to make everyday living easier, more reliable and help people in all aspects.

2.4 World market for RFID

The world market for RFID is very big. IDTechEx found that in 2017 the total RFID market is estimated to be worth 11.2 Billion dollars [18]. The forecast shows that this number will grow to \$14.9 Billion in 2022. The market forecast is divided into four different categories. These categories and the trends they follow as well as the market share, they own is shown in the figure below. Passive RFID tags in the different markets make up the biggest part of the world market.

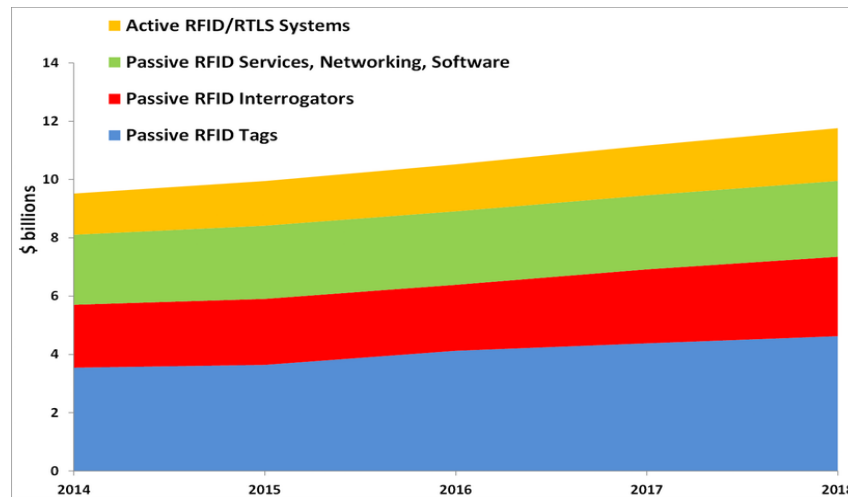


Figure 2-1: World market for RFID, reproduced from [18]

The study showed that RFID tags in clothing and apparel environments are by far the biggest, holding an estimated \$8 Billion on its own. These values show that the market for RFID is big and the applications where it can be used is endless. The vision of this technology becoming part of every household and everyday technology as part of the internet of things is a real possibility. Each day new innovations are created in this field. The current technology becomes more reliable and the usage of RFID tags are expanded. This all contributes to the technology growing over time and why more and bigger companies develop applications in this area.

Some of the most common reader providers in this market include Impinj, Motorola, GAO RFID, Applied Wireless RFID, Mojix, Caen RFID, Zebra, Smartrac, Alien Technology and Thingmagic. In the UHF field other participants such as NXP Semiconductors, Avery Dennison and Invengo also hold a respectable market share [19].

Each of these companies have a unique approach to their products. Impinj offers custom solutions and installation with a lot of their products, Zebra manufactures readers for most of the environments where this technology is implemented; others like Alien technology have been around for more than 20 years [20].

There are a lot of factors to consider when choosing technology. One of the things to consider is support in your own country. Other factors that can also influence technology selections are the pre-installed features of readers, the software interface between the reader and the computer system, compatibility between products, etc. Some manufacturers focus on a specific target market, like handheld readers, while others compete in most of the fields.

2.5 Challenges with RFID

The technology has specific inherent challenges and problems that have to be overcome. One of these challenges is interference. There are three main types of interference that can occur.

The three types are interference between tags, interference between readers and interference from an external source and the environment.

The interference between tags is where multiple tags that are present in the readers field interfere with each other; methods such as anti-collision protocol has been implemented to help prevent these types of problems. Gen 2 tags can be set so that only tags with an EPC that correlates to a software defined set of rules will respond. This means that in an area where the tag density is very high each tag will be read. The read rate is much slower with this setting, but at least all the tags will be readable. RFID has such a broad range of applications and settings that it is important to note that one of the biggest parts of implementing a new RFID system is to use the most effective and appropriate settings. Some settings will be more suitable than others. This includes settings such as read rate, type of sessions, etc. This is further discussed in a later section.

Interference between readers occurs when readers operate in the same range and at the same frequency. If two readers form part of the same system, interference can result in some tags not being read at all, if the signal from the one reader interferes with that of the other. This phenomenon is called reader collision [21]. To counteract this problem TDMA is used to allow two readers to read on the same frequency channel but at different times. One of the other problems that can happen when both the readers are able to read the same tags, are that the tag can be read more than once (by the different readers). This means that it can seem that the tag is at more than one access point or area which can lead to wrong assumptions made by the system. The software employed in cases where this is possible must account for these possibilities to prevent incorrect movement detection or incorrect stocktaking.

Another common type of interference is interference caused by other RF devices. Since the channels that are available to be used are not restricted to only RFID devices, some interference caused by other devices can occur. This is why thorough testing and characterization of the system is important before installing the final version. By doing this it is possible to determine which signals are from the system and which signals are caused by interference. Big steps have been made in the data processing area where if a system is thoroughly characterised, a fault in equipment or noisy data can immediately be identified. Interference as a result of the surroundings is very common in the RF field [22]. The tags are very prone to interference in the environment, such as metal and water in the surroundings, causing signals to be blocked or reflected. As the antenna designs as well as other techniques improve this will become less of a problem. For the moment, the best the developer can do is to use the available signal, strong or weak, as best as possible to identify the parameters that are required.

According to Deloitte the four major RFID challenges are determining the value of the tag (estimation of the cost of implanting the technology and how its application improves the value of a system or company), mastering the technology, integration and planning to scale [23]. The problem of finding the value is discussed in the part above since interference and accuracy of readers is still not 100% solved. The main reasons that mastering the technology is not straight forward is because improvements in tags are still being made, meaning that it is not a set technology yet and that costs are still higher on the tags than it is on barcodes. Integration is a huge process since it is a completely new system that has to be joined with the current system. There may be a period where the two are integrated but where everything will not work correctly yet. This takes time and effort to solve and is thus a major element to consider, especially in big corporations and factories. If integration is successful on the initial system, the future scaling must be accounted for as well. This means tagging more items, if the corporation grows more it will mean more items and maybe more installation sites. It is thus clear that it is not just a simple task to convert from barcodes and the current systems that are in place to a hands-free system where everything is managed by RFID tags and readers. The vision for a system that has completely integrated RFID has a lot of advantages and will definitely improve the control for a company but there is still a way to go before this can be achieved.

One more thing that can prove challenging is that the RF signal does not penetrate a surface very well, for instance if a human body is in between the reader and the signal it is possible that this signal will not be measured [24]. On the other hand, the signals reflect really well, which means that if there are items surrounding the tag it is possible that a better and stronger signal can be achieved as a result of having these items, or possibly people in the surrounding area. This also means that the signal will not necessarily improve as a person comes closer to the reader and decrease as a person carrying the tag moves away. It can mean that the signal will have a less predictable strong point somewhere in between as a result of reflections and weak points closer due to impenetrability. This effect is due to the fact that the RF signals are electromagnetic (EM) waves, and just as sound waves and other types of waves can experience reflection, refraction, diffraction and absorption [25]. As such the RFID will experience a multipath environment. This means that there are several different signals that will arrive at the reader from different reflection and diffraction points. This ensures that RFID tags will be read but makes it difficult to determine the exact source of the signal. Reflections occur from metallic surfaces as well as dielectric surfaces. This also means that each surface will reflect a different portion which is dependent on the attributes of the items. The reflectiveness of the signal is part of the environment where RFID is applied and must be considered when implementing the system.

2.6 Localization mapping systems

Localization systems are used to locate a tag in a certain environment. Even though this application doesn't necessarily track the movement of a tag some of the techniques used in this application can give a good insight into the tag's signal response. Localization techniques use phase and RSS signals to locate the tag and overcome certain flaws in the RFID technology, such as unwanted signal response from stray tags. Thus, these applications provide a valuable insight into techniques that can be used with other goals in mind such as motion estimation.

Phase-based near-field source localization (NFSL) is based on Direction of Arrival (DOA) estimation [26]. Algorithms that are suitable for use in backscatter environments are discussed in literature. Parr A. et al. [23] mentions 5 different techniques that can be applied. These are conventional Beamformer, Capon's Beamformer, MUSIC algorithm, calibrated Beamformer and 180° Beamformer.

All of these techniques use a stationary reader to locate stationary tags. The beamformer technique changes the path of the signal in order to gain more information from the setup. The conventional beamformer algorithm aims or steers the beam to a specific location. This is done with signal processing, applying phase shifts to measurement paths. The relative position of the tag is then calculated by maximizing the target function [26].

Capon's Beamformer [23] uses degrees of freedom and minimizes the output power of the array and maximizing the output power for the position the signal is aimed at. This delivers more information regarding the response than conventional beamformer technique.

The calibrated beamformer algorithm aims to get rid of differences in the phase measurements at the reader as a result of various factors, like cable length, shifts associated with send and receive electronics, antennas and phase introduced by tags. This technique then uses the real part of the norm, where it will be maximized if the differences between measurements tend to zero at all the antenna elements. The author claims that this will lead to an increase in localization accuracy if a very good calibration is achieved. This calibration is not always possible since the properties of all the tags are not always known.

The last technique, the 180° beamformer technique is similar to the conventional beamformer. The difference being that the algorithm is adopted to work in the zero to 180° domain instead of the zero to 360° domain. This technique is designed to not be affected by phase errors of 180° since the algorithm wraps them. The spatial beam pattern is changed from the traditional in a similar way as it would be if the frequency was doubled according to Parr A. et al [27]. The disadvantage of this technique is that there is a penalty for the spacing of elements between antennas. In order to use this technique, the interelement spacing needs to be reduced by a factor 2 compared to conventional beamformer techniques.

When using radio frequency signals noise and multipath propagation are always present and thus represents another big challenge to overcome [25]. How multipath affect the signal response from the RFID tag is illustrated in the next figure. Here it is illustrated how the observed signal may vary depending on the reflections present.

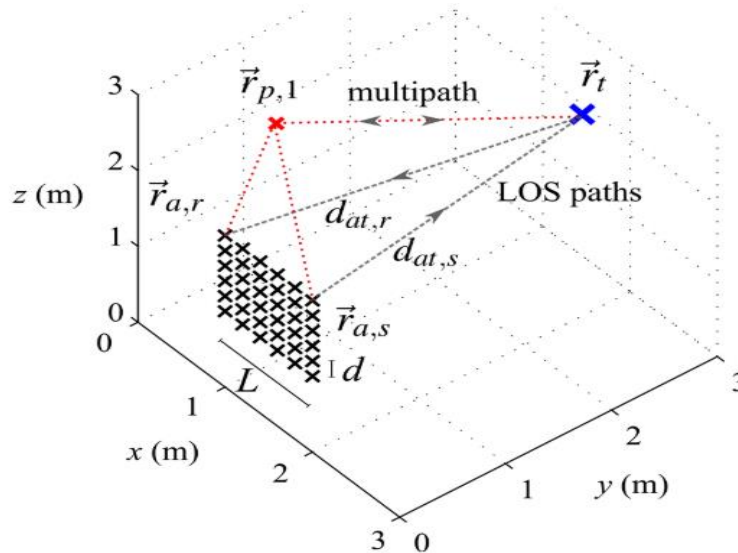


Figure 2-2: Multipath and line-of-sight difference illustration, reproduced from [25]

The figure above is a great illustration of how multipath makes the reading of accurate phase and RSSI values difficult. Reflections from metal and water are the main causes for multipath as well as constructive and destructive interference in the antenna array field. These factors influence results and great effort has been made to develop techniques to overcome this.

Impinj developed a localization system that locates tagged items on a floorspace. This product is known as the Xarray RAIN RFID gateway [5]. It uses roof mounted antennas to create a 2-D location map. The technology is able to track the movement of an item along the x and y axis. This means that it is possible to locate an item in the store as well as monitor theft in a shop. The solution is claimed to be accurate within 1.5m and when correctly installed has a field of view of 139 square meters, which shows what is possible with this technology. If the cost of such systems can be reduced it can be implemented within a much wider range of possibilities.

In conclusion, the techniques and technology mentioned in this section gives some insight into the behaviour of signals and the techniques used to overcome certain location and movement detection problems. This proves to be helpful in understanding the behaviour of Radio Frequency signal propagation and RFID behaviour in general, highlighting certain challenges. These techniques do however require very specific knowledge of the tags and setup in order to function correctly. This means that the scenarios where this can be applied are limited but does exist.

2.7 Passive RFID tags

This study will mainly focus on the movement tracking of passive RFID tags. It is important to understand how the technology works on a lower level in order to explain phenomena that might occur later on. For this reason, more detail is given on passive RFID tags.

2.7.1 Components of a passive tag

Tags consists of three different components. These are an integrated circuit (IC) RFID chip, an antenna and a substrate [28]. Often a manufacturer will outsource the manufacturing of some of these parts. For example, the IC will be designed and made by another manufacturer that focus on semiconductor technology. One of the most important parts of the tag is their antennas and thus these parts are made by a tag manufacturer and designed by them as well. The antennas normally determine a lot of the characteristics of the tags and can be designed with a specific purpose in mind. The size, shape and form factor determine the attributes of the tag response. Some tags are designed to be worn on the body while other tags are applied to boxes. Some are even mounted on metal surfaces. Different challenges exist with each surface and have to be considered in the design process. The most important thing manufacturers will consider is that the tag will give a signal response on the surface it was designed for. A lot of tags are mass produced and are seen as standard tags, these will work in a lot of applications and most of the time it won't be necessary to get other custom tags. In the figure below a typical RFID tag is displayed. The layers are a barcode with some information on top, then the antenna and IC inlay and finally a base surface. A lot of passive RFID tags are designed to be stickers for easy application on to items. Some however have a hard, base surface in order to be more durable; this can also influence the reflection of the signal.

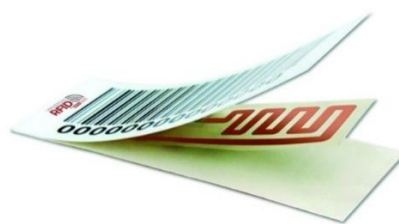


Figure 2-3: Passive RFID tag, reproduced from [24]

Most tags will have a barcode printed on top. This is included to help with stock tracking and make sure that an item is identifiable without an RFID reader. Different passive RFID tags are designed with 3 main frequency band in mind [29]. These are:

- 125 ÷ 134 KHz (Low Frequency) ÷ these tags have a very short read range (1-10cm) and is broadly used for animal tracking and tagging

- 13.56 MHz (High Frequency and NFC) i read range vary from 1cm to 1 meter. This frequency is used in access control devices and normally only used for data transmission applications.
- 865-960 MHz (Ultra High Frequency) i These are the most common tags and have a typical reading range of about 5-6 meters. More recent technology shows result in the range of 15 meters (from independent testing). The applications for this vary from supply chain management and file tracking to race timing.

Higher frequencies have longer read distances but are also more susceptible to reflections and interferences.

The final part of the tag is the label. Depending on the application this can be a label as presented by the manufacturers or a custom barcode label from the user end company.

2.7.2 Signal response of a passive tag

Passive RFID tags have no power source of their own. The tags rely on the power from the reader in order to function. There are two types of modes used to emit energy to tags. One is inductive coupling and the other capacitive coupling [30]. Inductive coupling uses a magnetic field that is emitted from the reader as power source. This technology is short range since the magnetic field's strength decreases significantly as the tag moves further away. High Frequency applications use this type of mode.

The other method, capacitive coupling, uses the electromagnetic wave emitted from the reader to power the chip and then respond with the same power obtained in the form of a RF signal. The response is known as a backscatter response since the tag uses the same energy to power up and respond to the reader output signal. The reader then listens for the tag response. The tag response is achieved by using a modulated backscatter process, done by a micro-circuit altering the antenna load to portray the information it needs to reply [31]. This is the case most of the time since the receiver and transmitter of the reader are on the same device and uses the same antenna. By using this method of communication, the tag is able to send/receive information on the same frequency as the reader. The transmitter and receiver can use TDMA to send and receive information. Multiple access can then be applied to allow each tag to communicate with the reader, ensuring the best chance to read all the tags and also enhance the throughput. The tag modifies the antenna cross section in order to change the power of the backscattered signal, thus allowing the information stored to be detected by the reader.

Where several tags are near each other in the RF field the tags can influence each other when transmitting a response to the reader. This signal interference can result in reduced

performance [32]. Tag collision can occur if more than one tag sends a response at the same time, resulting in mis- or unread tags. This will happen since the reader is not able to successfully demodulate two different tag signals at the exact same time. This is something that can happen very easily if there isn't a method in place to manage the response from different tags. There are different methods available that can manage these types of responses, which mainly focus on the setting of the reader to ensure that the tags respond in a manner that the scenario permits.

Tag collision and uncontrolled, overwhelming response from tags were the biggest problem that existed with different tags that are near each other. An overwhelming response can occur in a weakly implemented system, where no form of response control is implemented [21]. If there is a lot of tags in the vicinity and each one responds, or try and respond, to the reader at the same time it can cause the reader to wrongfully read or fail to read each individual tag. Most systems do however have protocols to ensure that this do not happen. A lot of tags near each other can also cause interference in the sense that the signal can be jammed as such because with more tags there will also be more noise. A phenomenon known as shadowing can occur when tags are placed directly behind each other. In this case the first tag absorbs most of the electromagnetic energy and replies while the tag behind do not have sufficient energy to respond successfully to the reader [33].

Since tags use the energy obtained from the reader to reply this is not as strong as the initial signal. This factor along with the nature of UHF means that the signal is vulnerable to interference and reflections. This influences the read reliability caused by the weaker. Some of the main causes are obstruction and/or interference between the tag and the reader. Big enough disturbance will result in the tag not being read by the reader. The distance from the reader and as a result signal strength will also influence the rate at which the tags can be read. In ideal conditions with a strong signal from all the tags there are other parameters that will influence the reading rate as well. Tag orientation with regards to the reader can also influence the reading rate. A good tag orientation will also increase the reading rate of the system[34]. If the reader has a certain polarization the tag antenna has to be aligned with this polarization (discussed in chapter 2.8.2) in order to receive the maximum power. It is possible that the tag will still work efficiently if it is not perfectly aligned since the reflected signal will turn the polarization. Ideally one would like the tag to be in line-of-sight and perfectly aligned resulting in the strongest possible signal response from the tag, every time.

One last thing that can influence the response signal of tags a great deal is the presence of metal. Metal can detune the antenna, causing reading failures that will ultimately cause the read rate of the antenna to decrease since the tag will have to be re-read several times.

This section showed some of the variables, that influence the functionality of this technology to consider when implementing RFID systems.

2.7.3 Gen 2 passive tags

This is the most common UHF tag being used today. The Gen 2 is the name given for the EPCglobal (governing body for EPC) class 1 Gen 2 tags. This is the requirements for the passive-backscatter both for the physical and logical aspects of the tag [35].

The requirements state that the Gen 2 operates in the UHF band mentioned above and also uses Frequency Hopping Spread Spectrum (FHSS). This is done to read the tag at different frequencies to get the best possible read as well as to allow different readers to operate in the same region.

Gen 2 tags have the following basic memory features:

- 96-bit EPC number
- 32 i 64-bit tag identifier (TID)
- 32-bit kill password
- 32-bit access password
- User memory

The EPC class 2 and 3 are already under development and the features still need to be defined. The Gen 2 tags allow the reader to read different signal parameters from the tags as well. These parameters include RSSI (Received Signal Strength Indicator), Phase values of the signal and many readers also use the Low Level Read data to calculate an inherent Doppler frequency of the tag. The accuracy of this is dependant the tags used as well as the setup configuration and it must be noted that this is a derived value. This means that the doppler is derived from the different phase values and time stamp values and is not a unique parameter measurement [36].

2.7.4 Importance of EPC and TID for unique identification of tags

Each RFID tag has an Electronic Product Code (EPC). This is a unique code that is generated by EPCglobal. This helps to ensure that each tag applied to an item can be identified and thus linked to a specific asset. Once the EPC code is scanned a system running Savant can look up the code in an ONS database. The ONS database acts like a telephone directory but in the opposite direction. The system matches the EPC number to an online address which contains a lot of data about the product. Any Savant system can access this data. The EPC number consists of a header and 3 sets of data. These data sets are for the EPC manager, which is linked to a specific company that uses the EPC code, an object class which identifies the exact type of product and lastly the serial number which is unique to every item [37].

EPCglobal is a GS1 initiative and the body behind industry standards for the EPC. The drive behind the standards are to ensure that the use of RFID is maintained and to drive the global visibility of items with the EPC Information Services (EPCIS) [38]. The standards developed

for the EPC helps maintain the uniqueness of tag identification and help developers work together to enhance the system.

Part of the parameters used to identify a tag and consequently an item is the TID. This stands for Tag Identifier Memory. Every RFID tag has a unique TID and the TID is not editable by end users [32]. This means that every item in the world that is tagged can be uniquely identified if the tag and its details are registered in a database. This also means that no two tags can be identified as the same tag. This is only true for companies manufacturing tags that adhere to these standards. Private manufacturing of tags can be done where the TID and EPC code is open to employment by this company. This is very important in security scenarios. The TID consists of an 8-bit ISO allocation class identifier (EPCglobal tags are 0xE2), 12-bit Tag mask-designer ID and a 12-bit Tag model number. If the manufacturer wants to add a tag serial number this would be the area where this is added [32].

As can be deduced from the details mentioned above, if all the processes are followed in the manufacturing and implementation of the tags it would be possible to uniquely identify each and every tag ever produced. Bodies like EPCglobal with their standards and parameter that are included in the tag memory like the TID enables companies to tag their assets with the certainty that the tag is unique and has the best chance possible to be tracked by readers and be linked back to the correct owner.

2.8 RFID Readers

One of the most important parts and one of the most expensive parts (along with antennas) in any RFID system is the reader. It is even more influential in the performance of the entire system than the tags. In this chapter different components and functionalities of RFID readers are discussed.

2.8.1 Components of RFID readers

A RFID reader is used in RFID systems for producing and reading radio signals [39]. One reader is designed to work on several frequency bands. The range of frequencies and ability to interpret these frequencies depend on the manufacturer. Most modern readers have anti-collision algorithms built in that are used for detecting several tags in quick succession to seem that they are being read at the same time. The reader is the part of the system that communicates with the tag and the computer software. It deduces the information from the tag and presents it in a format the computer program will understand. Most readers can connect to the computer using RS-232, RS485, USB, RJ45 or WI-FI. RFID readers have built in functions and components that assist the software in many respects. The following figure shows these components.



Figure 2-4: Functions of a RFID reader, reproduced from [33]

At a lower level a reader has a modulator/demodulator that is connected to the antenna, this connects with a coder/decoder which communicates with the controller, which in turn provide the interface to communicate with the software application.

Antennas connect to the reader via co-axial cable. There can be anything between two to 4+ antennas connected to the reader. Most readers handle multiplexing between antennas with its onboard controller. The figure below shows an image of a typical RFID reader with available connections for 4 antennas.



Figure 2-5: Typical RFID reader and IO connections (Impinj Speedway reader)

Readers are a sophisticated technology with a lot of functionality, but fortunately manufacturers have gone a great distance to make the interface between the reader and computer software more user friendly. Low-Level Read Protocols (LLRP) have been developed to help set up the reader to user specification via software. This is discussed in a later section. Effective use and interaction with the RFID reader are crucial parts of any operation regarding RFID and it is important to note what functions are available with the chosen reader, what is the range of frequencies and hopping method. Correct configuration is one of the most important parts of installation in any RFID setup and the reader is where this is best seen.

2.8.2 Types of antennas

Antennas can be classified by different attributes. One of the classifications of antennas are the polarization of the antennas. The two main classes are linear polarized and circular polarized antennas. The circular polarized can either be left-hand circular polarized (LHCP) or right-hand circular polarized (RHCP).

Both of these types of antennas have advantages and disadvantages over the other and it depends on the applications which would be better. Circular polarized antennas overcome

interference by generating a more efficient multipath signal. This means that with this type of polarization there will be more than one path to the tag and back to the antenna. This will result in a cleaner signal with less noise since the chances for the signal to arrive without interference is better. A reflected signal will not interfere with the original signal because of the change in orientation of the signal when reflected. One of the disadvantages is that this polarization can result in a shorter reading range since more energy is sent in different directions than straight ahead, and taking into consideration that the total reader signal must be limited below a specified power level [40]. They lose roughly 3dB dividing the power into different planes. A representation of how a circular antenna broadcasts its signal is shown below.

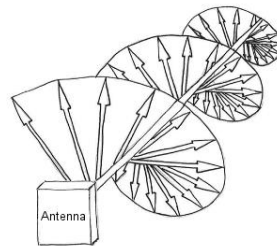


Figure 2-6: Illustration of circular polarized antenna radiation, reproduced from [40]

For linear polarization the electromagnetic waves are on only one plane. This can be either horizontal or vertical. When using these antennae, the orientation must be known and the tag antennas must have the same orientation as the reader antenna polarization in order to be read accurately and consistently. The advantage is however that the reading range is greater than for the circular polarized antenna.

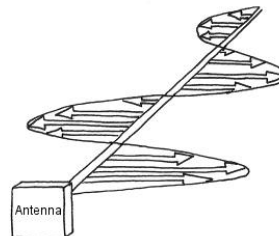


Figure 2-7: Illustration of linear polarized antenna radiation, reproduced from [40]

The question then is how to choose linear or circular polarized antennae. The answer depends on the application, if the tags will all be roughly the height of the linear polarized antenna and in the same plane then that would be the option. If the tag orientation and position is inconsistent and unpredictable then the circular polarized antenna will provide more advantages than disadvantages.

As mentioned above circular polarized antennas can either be left hand or right hand. The direction of the polarization is the only difference with the one being clockwise polarization and the other being anti-clockwise. It is important to note that the transmitter and the receiver should have the same orientation [41]. Since most RFID readers use one antenna for both read and transmit, this is normally the case. In an area where there is a lot of antennas and

they are circular polarized, using a different polarization than the other antennas can help decrease interference and enhance signal reads. Normally one system would use the same antenna polarization for the entire setup unless it is important to have reads in the same dense area and this is one way to overcome interference.

From the above it can be seen that the signals from other antennas can interfere with each other and certain protocols need to be implemented to ensure that this do not happen. This problem is called reader collision. The reason why readers can influence each other is because normally the frequencies on which they broadcast are close to each other and the signal being relatively strong, typically many orders of magnitude stronger than tag signals to be received, then result in the readers influencing each other. One proposed method and implemented by most readers is to use time-division multiple access (TDMA) [42]. With this technique each reader gets a chance (time slot) to broadcast and read before it is the other reader or antenna's turn. If the readers are on the same system it means that the tag can be read more than once. Thus, provision in the software need to be made to ignore undesired multiple reads if this is the case in a system with several readers in close proximity to each other.

2.8.3 Antenna Radiation pattern

Most antennas in the RFID industry uses directional antennas. Directional antennas have a certain radiation pattern in the specific read area. A radiation pattern of an antenna is very important since it tells the user where the weak spots in the reading range is, how the reading range looks like and what type of attenuation one can expect at different points in the reading range [43]. An ideal radiation pattern would be one that has an isotropic pattern throughout the entire reading range. This means that the same signal strength can be measured everywhere in the reading range. Unfortunately, this is cannot be achieved fully. The next figure shows a typical radiation pattern for an antenna by Poynting, one in the vertical plane and one in the horizontal plane [44]:

Radiation Patterns

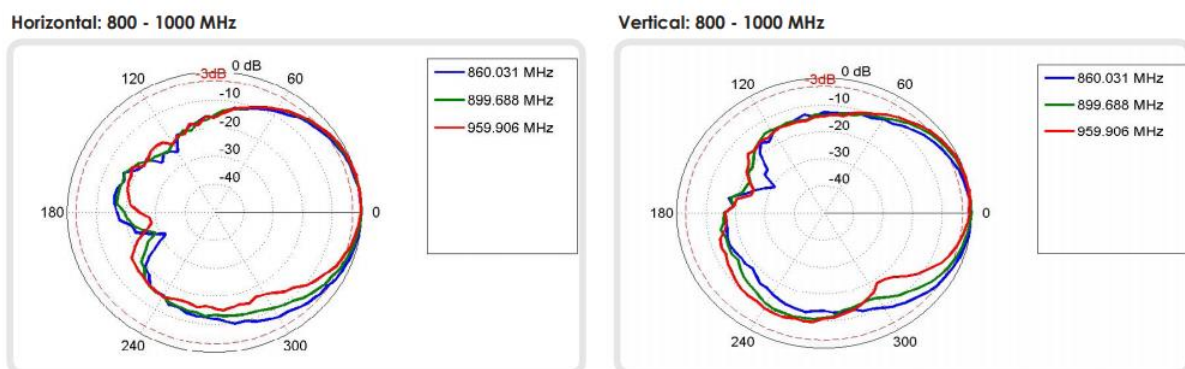


Figure 2-8: Radiation pattern for a Poynting Patch-25 Antenna, reproduced from [42]

In these figures it can be seen that the radiation pattern for the antenna is dependent on the frequency band it is radiating at. This also shows that at 0 degrees in line with the antenna the strongest signal can be read but that there is a lowering in power to the sides of the radiation pattern. This shows that an antenna does not radiate a signal in straight lines from the centre of the antenna, but rather in a concave pattern outward. This can affect phase readings of a moving tag, depending on the direction of travel. If the direction of travel is perpendicular with the 0-degree radiation then the change in phase directly correlates to the change in distance based on the wavelength, but if the tag moves at an angle this means that the wavelength measured and the change in phase is not a perfect correlation resulting in an erroneous offset. How the phase change and the distance travelled correlates is discussed in chapter 2.10.4

2.8.4 Reader settings that are important and how they influence results

RFID systems must be very versatile in terms of specific goals to be achieved by the system in different environments. To allow for one device to be able to adapt to the different environments, manufacturers added settings that change some of the characteristics of the readers and thus the system, each setting having a specific type of application in mind. One of the most important settings to select is which session to use. The session will determine how often a tag will respond to requests from the reader. The sessions can be set up to allow a tag to be read multiple times by different readers for different inventories. A Gen 2 tag has 2 different states. The states are referred to as state A (default state) and state B (time out state) [36].

Session 0 instructs the tag to reset its state every time it was inventoried to state A. This means that all the tags are always on and will always try and respond to the reader. This session is good to read a few tags a lot of times, but is not suited for an instance where a lot of tags have to be read.

Session 1 will instruct the tag to switch from state B for a maximum of 5 seconds and a minimum of half a second when it is inventoried. This will ultimately reduce the time that a tag is read and is suitable for an environment where a lot of tags are read and it is not necessary to continuously monitor the same tag.

In sessions 2 and 3 all tags are instructed to stay in state B for at least 2 seconds. This session is optimal for reading a larger number of tags, when you want to keep them quiet once they have responded to the inventory.

Session 2 and 3 can be used together on two different readers to inventory items and check the control [36].

Along with these sessions, specific search modes are also employed to accommodate different scenarios that might exist. The search modes are dual target, single target and single

target with suppression. These search modes also handle the tags differently. With single target mode the reader will only read tags that are in one state, typically state ϕ_A . With dual target mode the reader will select tags that are in both states. With dual target mode the session does not significantly influence the reader because all tags will be pushed to a different state each time it is read and then it will be read again. Single target with suppression can be used along with session 2 and 3 which allows extra versatility in how the tags will respond to the reader.

2.9 How readers and tags produce phase measurements

The phase difference between a tag signal and the reader signal is a function of the distance between the tag and the reader as well as the carrier frequency. The relation between the wavelength and the frequency is given by the following equation:

$$\lambda = \frac{c}{f} \text{ (meters)} \quad (2.1)$$

The phase measured in radians is composed of the following parameters as seen in the equation [45]:

$$\theta = 2\pi \left(\frac{2R}{\lambda} \right) + \theta_T + \theta_R + \theta_{TAG} \quad (2.2)$$

Where R is the distance between the tag and the reader, λ is the wavelength, θ_T is the phase component added by the radio frequency transmitter, θ_R is the phase component added by the radio frequency receiver and θ_{TAG} is the phase component added by the tag circuitry.

The reader that sends out a carrier wave and the tag that responds using this signal to backscatter a response are shown in the figure below. The effect of the phase added by the transmitter, receiver and tag can also be observed.

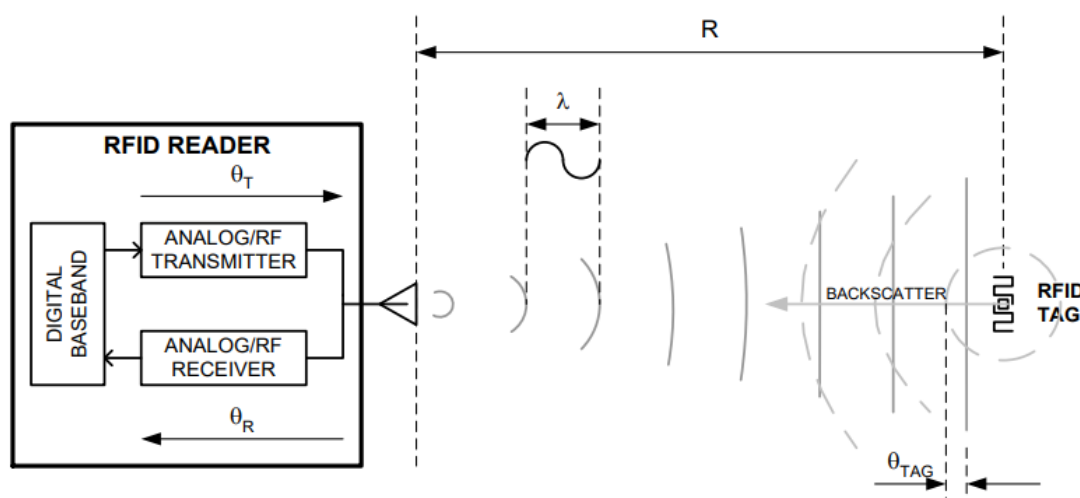


Figure 2-9: Diagram depicting the concept of radio wave propagation between RFID reader and tag by Impinj, reproduced from [45]

Here it can be seen how the wavelength λ , distance between the reader and tag R and the phase of the different components in the tag all contribute to the final phase measured at the reader side. Although the phase added by the transmitter, receiver and tag is small compared to the influence of the carrier wave and the distance, it still influences the result. As such the way the reader measures phase is by using a differential approach. It has a phase base band and the difference in phase measured is recorded. This means that the phase added due to the transmitter, receiver and tag are the same with both cases and the only parameters that are left to influence the phase are the distance and frequency. This approach simplifies the process a great deal. An explanation of the lower level phase calculations is given below.

One way to produce phase readings is if the RFID reader has I-Q channel capability. This is the in-phase and quadrature parameters present in a signal [46]. This can be represented by the real and imaginary parts of a signal. The reader will produce a signal that is either clockwise or anticlockwise (reader dependant). This describes the way the reading is represented and does not have an impact on the reading that the end user or even further development will perceive. The most common type is the CW signal; the Impinj Speedway reader uses an anticlockwise approach. The phase value is represented by a 12-bit value. This means that each step/rotation has an interval of 0.088°

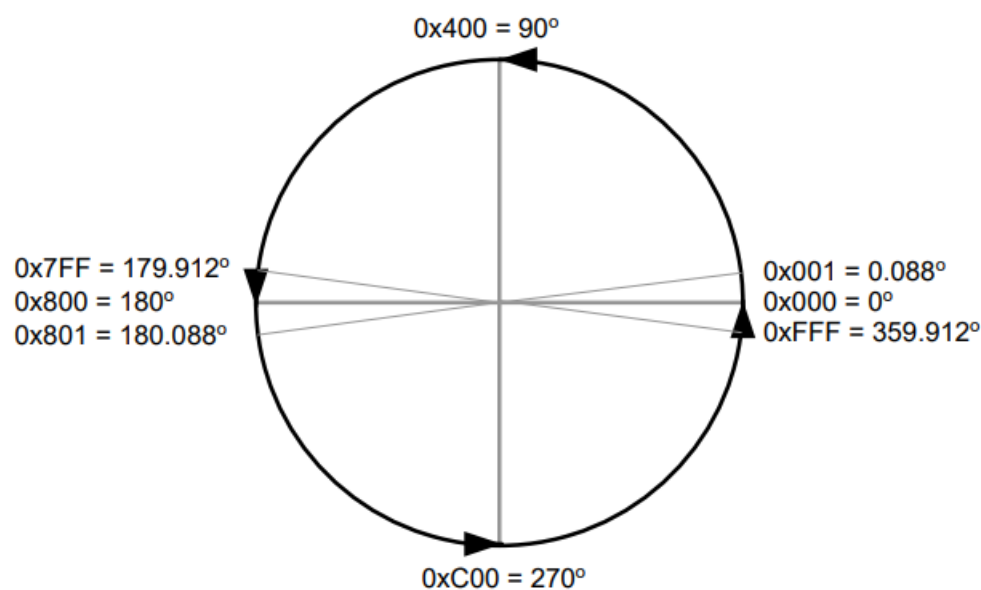


Figure 2-10: Mapping of phase to the 12-bit reported value by Impinj, reproduced from [44]

After modulating the signal, the tag will then respond to the reader's signal. At the receiving end of the reader the signal is then split into two paths. The Real and Imaginary parts or otherwise known as the I-channel and Q-channel paths. These channels are mixed with the reader's broadcast signal. To arrive at the phase delay, the reader takes the multiple sampled I-Q pairs, as sampled by the Analog to Digital converter, and averages them over several

samples. This means that a Q and I pair is produced by the reader during each tag read. Inside the reader the received signal is processed by a quadrature homodyne splitter which delivers an output of an in-phase signal (0-degree shift) and in-quadrature (90-degree shift) version of the carrier wave. When this stage is completed the signals are fed through a low-pass filter and sampled by A/D converters producing the Q and I values. The phase delay is calculated by the following equation according to Carrick, J. C. et al. [47]:

$$\Delta\phi = \tan_{-1} \left(\frac{Q}{I} \right) \quad (2.3)$$

The final phase delay value is produced to the processor which averages the result over several I-Q pairs. The reason why these values are averaged over several samples is to get rid of some noise that may creep into these measurements and thus compromising certain measurements.

2.10 Previous work on motion estimation of RFID tags

This section discusses previous work done on direction determination with RFID technology.

2.10.1 Phase based spatial identification

Most UHF RFID readers can read the power and phase of Gen 2 tag signals. By using these parameters, it is possible to use three different approaches for spatial identification and motion estimation. These three approaches are Frequency Domain Phase Difference On Arrival (FD-PDOA), Spatial Domain Phase Difference On Arrival (SD-PDOA) and Time Domain Phase Difference On Arrival (TD-PDOA) [48].

When determining the spatial difference of a tag one can also derive the direction and relative speed of the tag. If the speed is calculated one also knows the direction of the travel since the speed is derived from the velocity which inherently has direction. With the TD-PDOA technique one measures the phase of the tag at two different points in the tag's movement and the change in the phase is then used to calculate the radial velocity. The phase change over time which is used to calculate the velocity is also a form of Doppler shift. V. Pavel et al. shows this in the figure below [48].

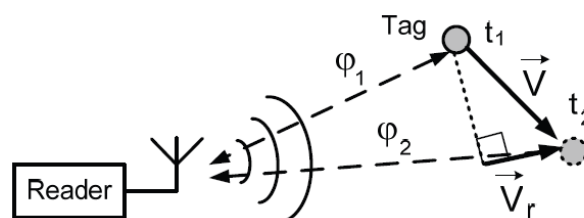


Figure 2-11: TD-PDOA illustration, reproduced from [48]

In this example it is assumed that the phase offset and the tags backscatter phase stay constant. The difference in these two phases should be negligible. The phase difference must

be calculated at a fixed frequency. By computing the derivative of these phase changes with respect to time the instantaneous radial velocity can be determined. The formula below shows this.

$$V_r = -\frac{c}{4\pi f} \frac{\delta\phi}{\delta t} \quad (2.4)$$

Here V_r is the relative velocity, f is the current frequency band, c is the speed of light, $\delta\phi$ is the change in phase measured and δt is the change in time.

The FD-PDOA is primarily used to estimate the distance to the tag. This is done by taking phase samples at different frequencies. For this technique to work it is assumed that the frequency change is such that it can either be calibrated out or do not change significantly. Pavel V et al. also notes that the tag must move significantly less than a wavelength otherwise this technique would not work. By then measuring the change in phase and using the formula showed below it is possible to determine the range to the tag. This is one technique to determine the range. This is suitable for a still standing tag and reader.

$$d = -\frac{c}{4\pi} \frac{\delta\phi}{\delta f} \quad (2.5)$$

Where d is the estimated distance to the tag, c is the speed of light (electromagnetic wave) $\delta\phi$ is the change in phase and δf is the change in frequency. Other methods to determine the distance to the tags do exist such as using Friis free space equation which will be discussed later on.

The PDOA technique of note is the spatial domain phase difference of arrival technique. The SD-PDOA technique is used to estimate the direction towards the tag from a point of reference. This point of reference will typically be the receiver antenna. This technique entails that the phase of one tag be measured by more than one receiver antennas. Pavel V. et al. notes that this is based on a form of direction-of-arrival technique. This technique is illustrated in the figure below.

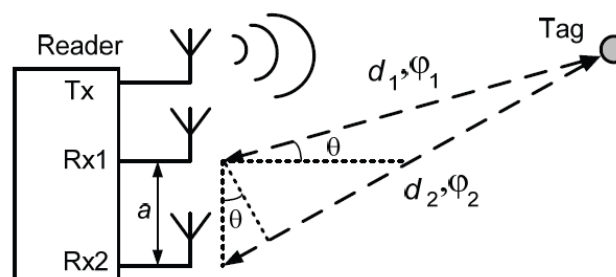


Figure 2-12 SD-PDOA illustration, reproduced from [10]

For this technique to work the phase difference must be measured at two different antennas using a fixed frequency. The phase difference measured at the two antennas can then be contributed to the path difference. A form of calibration is necessary since each receiver antenna has a different impedance depending on its internal characteristics, manufacturing

tolerance and length of cable. This difference causes a difference in phase when the tag is the same distance from the readers. The tag bearing given the illustration above can then be determined using the following formula:

$$\theta \approx \arcsin \left[-\frac{c}{2\pi f} \frac{\phi_2 - \phi_1}{a} \right] \quad (2.6)$$

In this equation θ is the relative angle towards the tag, c is the speed of light, a is the distance between the two receiving antennas, f is the current channel frequency and $\phi_2 - \phi_1$ is the calibrated difference in phase measured by the two antennas.

Using these three techniques it is possible to detect the relative speed, distance and angle of travel of the tag. There are certain challenges with these methods. These challenges include multipath propagation of the tag response signal, regulations regarding the time that a reader is allowed to transmit on the same frequency and other tags in the perimeter can cause a bigger delay in between readings of the same tag. Each of these techniques also requires their own specific setup. Combinations can exist but not all three of these techniques can work on the same setup all the time. The experiments that were performed provided evidence of the robustness of the TD-PDOA technique to multipath. The other two techniques suffered as a result of the lack of bandwidth available in the UHF ISM band. The reason why these techniques struggle in these environments is because the narrow band do not allow for a broad analysis of the signals over several frequencies. This means that multipath effects and destructive signal interference can cause tags to not be accurately read and measured. A broader range of available frequencies can directly solve this since the area where the destructive interference occur will move along with the wavelength. The frequency hopping however can result in the phase change being too big, which means that the estimation will also be faulty or not possible to make. This is however a very useful combination of techniques. One other problem that exists is that this type of setup where there is a transmit antenna and two reader antennas is also not always practically possible. A more common RFID setup is one where one antenna is both a transmitter and receiver. This of course means that the calculations will differ since the tag responds to two different transmitted signals. This also makes these techniques more challenging.

To conclude, the techniques illustrated works well and for the type of setup illustrated in the figure it is possible to accurately track the movement of the tag within local standards. The shortcomings are that this technique is not reproducible in all scenarios and will have to be combined with other techniques that are available to distinguish between external tags and the tag that is of concern.

2.10.2 A received signal strength RFID-based indoor location system

Indoor location systems (ILS) mainly use three types of techniques namely, Time-of-Flight (ToF), Angle-of-Arrival (AoA) and Received Signal Strength (RSS). Research found that the first two techniques (ToF and AoA) were more accurate. The RSS however is less expensive since it does not require specialist equipment [49]. The main advantage of using the RSS is that it can use existing equipment that is common in indoor environments. Current Gen 2 RFID systems already deliver the RSSI in the tag signal response. This means that the information for this technique is already available to be used. A limitation of this technique is that it requires a specific setup and thus limits the application environment.

The technique used to detect the angle of arrival consists of using two antennas. Firstly, the antennas are tilted with respect to the y axis. This is shown in the figure below.

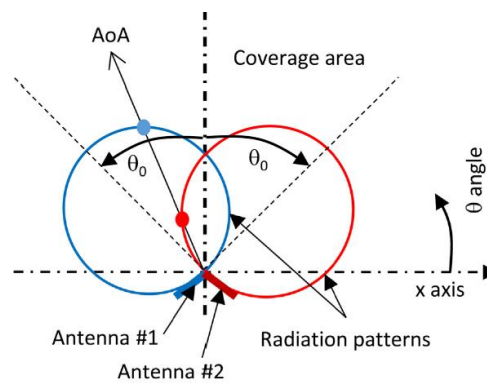


Figure 2-13: Illustration of angled antenna reading range, reproduced from [49]

By tilting the antennas, the field of view is also increased. The antennas used in these tests is a pair of broad beam antennas. By using this setup, the limitation of using switched beam antennas that are capable of a predetermined set of beams according to Lopez Y. et al. is overcome (this would otherwise be necessary) [49]. The technique was designed with the use of switched beam antennas in mind but because these antennas are not capable of reading short time signals it increases the complexity of the setup by a great deal. The broad beam antennas allow the same predetermined beams to be generated but with the added advantage of reading short-time signals. The way that these antennas are tilted and their fields overlap means that the AoA is related to the ratio of the RSS values between these antennas assuming that they have similar radiation patterns. In order for this technique to work successfully each RSS ratio value should correspond to a certain angle. The RSS ratio and angle of arrival is not linear with respect to each other. To overcome this the authors suggested a quasi linear expression, which will relate the non-linear behaviour to a linear range of values.

Lopez Y. et al. used antennas having a $\cos(90^\circ - \theta_0 + \theta^2)$ and $\cos(\theta_0 + \theta^2)$ radiation patterns. Using these patterns, the author then showed that it is possible to calculate the angle of arrival as follows[49]:

$$\theta_{AoA} = K(20 \log_{10} \cos(90^\circ - \theta_0 + \theta^2) - 20 \log_{10} \cos(\theta_0 + \theta^2)) \quad (2.7)$$

$$\theta_{AoA} = K(RSS_A[dB] - RSS_B[dB]) \quad (2.8)$$

An adjustment value exists, depending on the angle, represented by K.

Using these equations, it is possible to determine the AoA within a certain range. The region of angles where the AoA can be determined is dependent on the overlapping region. The range for the AoA where the overlapping signals will not result in an ambiguous reading is shown by the green regions in the figure. The following figure illustrates theoretical data were the region of confidence is located for the AoA determination in this setup [49].

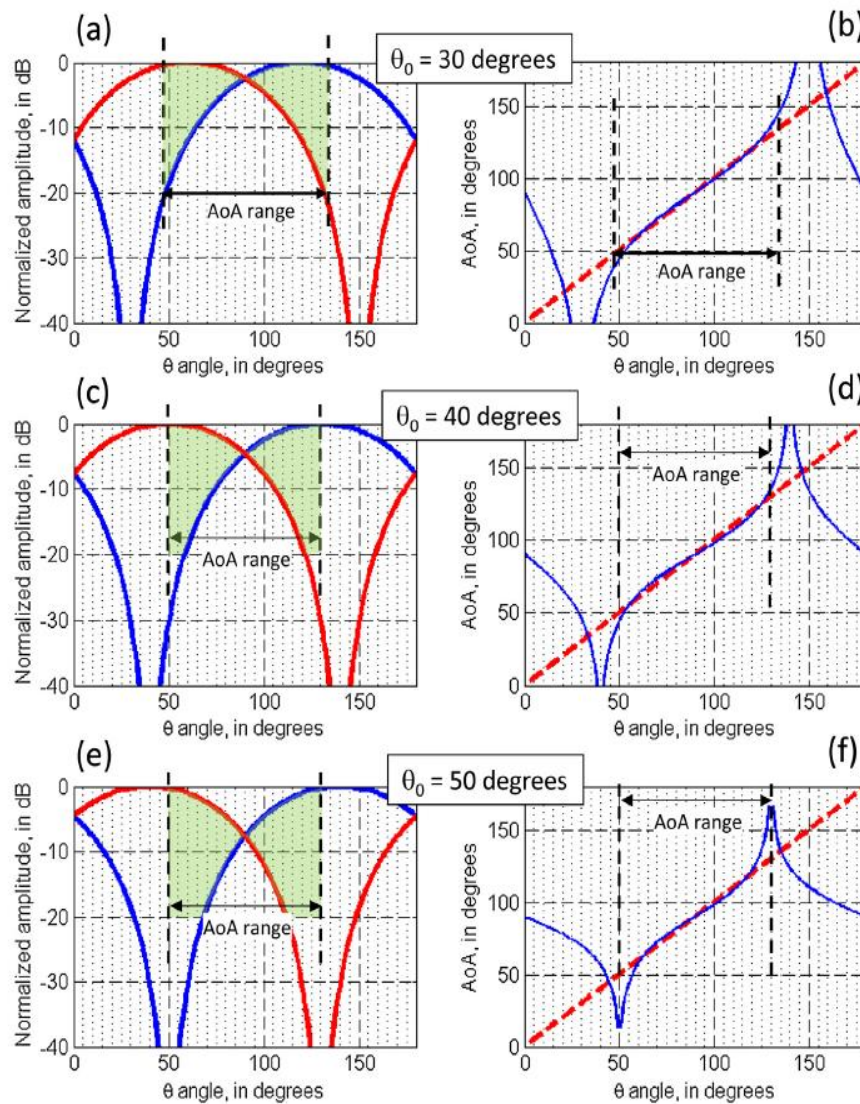


Figure 2-14: Theoretical antenna radiation patterns (left), Reference AoA and theoretical AoA (right), reproduced from [49]

In this figure θ illustrates the difference in angle that the antennas are facing. The blue and red solid line represents the theoretical radiation patterns of each antenna. The figures on the left shows the RSS and angle of detection and the figures on the right shows the reference Angle of Arrival (the dashed red line) and theoretical Angle of Arrival (the solid blue line), both as a function of the offset angle.

During experimentation the authors used an offset angle between the directions that the antennas are facing of 40 degrees, the reason being that this maximizes the AoA. The experiments showed the following results:

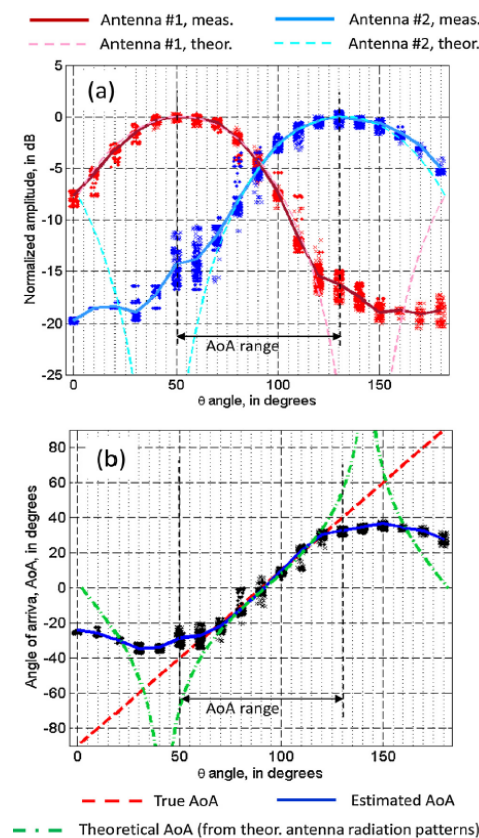


Figure 2-15: Experimental results of antenna radiation patterns and AoA determination, reproduced from [48]

From these figures one can see that the pattern followed that which was expected from the theory. It is visible from these graphs that the AoA could be determined. Further results depicted in this study also showed that the direction finding was less sensitive towards multipath signals than another algorithm will be. This is as a result of the ratio of RSS values. The results showed up to an 85% confidence level on the 80-degree sector. This shows that for precise movement this is not the most suitable detection system but for relative position calculation this works fairly accurate. The results are promising. The author also aimed to implement an RSS based range estimation algorithm. This algorithm failed due to multipath effects and could not meet the requirements. This in the end resulted in a big error count for the localisation technique. If this technique were to be used to determine the direction of travel

it would need to be adjusted to accommodate a real-world scenario; this might mean that more antennas have to be added to the setup they proposed. What the results do show though is that it is possible to get a relative AoA from just the RSSI data if the setup is known and the tag is within a 80-degree range.

The problem with using this technique is that it is not possible to always set up the antennas in this fashion if the antenna's main purpose is to monitor for example supply movement. This means that the types of scenarios where this system can be deployed might be limited, but that it will work effectively enough for rough calculation of the direction of travel. This technique can be used to derive a very accurate estimation for the angle of travel of tag if that is what the scenario requires.

2.10.3 Distance estimation technique using signal propagation characteristics

Looking at passive RFID tag propagation it can be seen that the signal model adheres to standard Radio Frequency signal propagation in free space [50]. This means that the waveform between the reader and the tag will produce a signal strength reading similar to other RF applications, where the signal is susceptible to reflection, constructive and destructive interference and absorption [51].

RFID antennas can be directional or omnidirectional. If a directional antenna is used it closely resembles a uniform radiation pattern [48]. There are certain inefficiencies where the antenna radiation, even though it was designed to be isotropic, results in peak signals or weaker areas also referred to as 'holes' in the radiation environment. If it is assumed that the antenna radiation and tag response is uniform it means that Friis's free space equation to calculate the measured signal attenuation as a function of distance can be applied [52]. This can be done since the error as a result of this is proven to be small enough [53]. Thus, this will enable the distance estimation in certain scenarios based on the RSSI signal received. One aspect to note is that if the environment is such that clear multipath effects or very strong reflections will cause ambiguous readings, this technique will not be accurate. This is ideally suited for an open space environment with as few reflections as possible, or reflections that will not result in perfect multipath signals.

Friis's transmission formula is related to the free space path loss, both antenna gains and wavelength of the transmitted signal to the transmit and receive power at the antenna [54]. This is given by the following equation:

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi R)^2} \quad (2.9)$$

Here P_T is the power transmitted in watts, G_T and G_R is the gain of the transmitter and receiver, λ is the wavelength of the transmitted signal and R is the distance between the two antennas. This shows that the frequency (wavelength) has a big impact on the power loss during

transmission. If the antennas are not polarly matched this also means that the equation can be multiplied with a loss factor and the relationship between the attributes will be maintained. Furthermore, the equation can be adjusted to also account for the environment and signal response of a backscatter signal. This applies to the RFID tag and antenna communication. This relationship can be expressed by the following equation [53]:

$$P_R = P_T G_T^2 G_R^2 PL \left(\frac{\lambda}{4\pi d} \right)^{2n} \quad (2.10)$$

Here PL represents the backscatter transmission efficiency if it exists, otherwise it has a value of 1, n is the path loss exponent. According to S. Subedi [53], if line-of-sight (LOS) is considered between the tags and the reader antenna, free space propagation can be assumed, which means that n will be 2 for these environments. This means that equation 2.10 can be rewritten to account for the distance as a function of the power received. This can be seen in the following equation:

$$d = \left(\frac{\lambda}{4\pi} \right) \left(\frac{P G_t^2 G_r^2}{P_R} \right)^{\frac{1}{4}} \quad (2.11)$$

Using this equation, it is possible to determine the distance between the tag and reader antenna. Some backscatter transmission efficiency constant can be present and should be added to equation 2.11 if this does exist.

The main concern with using this technique is that complete characterization is required for all aspects of the formula. That is the antenna gains for both the reader antenna and tag antenna should be defined. This can be determined empirically with measurements assuming one value for the transmitter gain. This means that with a known distance and a measured signal strength the value for the tag antenna gain can be determined. This requires a precise setup where the antennas for both the reader and tag are perfectly aligned. This means that the gain can then be determined with the following form of equation 10:

$$G_t^2 G_r^2 = \left(\frac{P_R^{0.25} d}{P_T^{0.25}} \frac{4\pi}{\lambda} \right) \quad (2.12)$$

With the definition of each parameter, the distance estimation is possible and but defined by each unique tag. What this means is that according to the equations above, each tag will have its own antenna gain. This means that for every tag the process of characterization should be repeated in order to produce accurate results. This technique cannot predict the distance in the presence of multipath effects since it assumes isotropic/directional uniform radiation. This limits the environment where this technique can be employed but for an ideal scenario this can be added as an extra parameter to indicate the change in distance over time in order to calculate the velocity and motion estimation of the tag.

2.10.4 Real time tag motion estimation based on PDOA techniques

As mentioned previously, tracking the speed and direction of a tag can have several advantages. Most common positioning techniques include Time of Arrival (TOA), Time Difference of Arrival (TDOA), Received Signal Strength (RSSI) and Phase difference on Arrival (PDOA). It has been shown that the TOA and TDOA are not well suited for RFID readers, because the required short pulse mode is not available with the technology [55].

The techniques best suited for this type of tag tracking is RSS and PDOA. The biggest problem with RSS however is multipath effects that can happen. This means that due to reflections in the environment more than one path towards the reader from the tag exists and this will be different for each frequency and change as objects in the environment change. For this reason, the technique is not suited to most indoor locations as there is a big error in the measurements. The PDOA is the preferred technique since it provides protection against multipath effects. The concept of PDOA is that the RFID reader transmits a signal with a certain carrier wave, the tag then responds on this signal. The received phase delay is then a result of the distance between the antenna and the tag as well as the carrier frequency, hence taking the difference between two phase measurements, a correlation of the movement of the tag can be found.

This phase delay is represented by the following function:

$$\phi = f(\text{frequency}, \text{distance}) \quad (2.13)$$

To determine the motion dynamics of a tag, the tag is interrogated at a fixed frequency several times. The phase of the tag as well as the time when the measurement was taken is known for each sample. This means that over the course of the movement of the tag several samples of the phase and time is taken. This allows the calculation of the velocity with the following equation:

$$V = \frac{c\Delta\phi}{4\pi f\Delta t} \quad (2.14)$$

$$\Delta\phi = \Phi_1 - \Phi_2 \quad (2.15)$$

$$\Delta t = t_1 - t_2. \quad (2.16)$$

Where C is the speed of the electromagnetic wave (speed of light), $\Delta\phi$ is the change in phase, f is the frequency of the carrier wave and Δt is the change in time. The direction is inherently part of the velocity. A positive velocity is in one direction and a negative velocity in the opposite. The change in phase is dependent on the RFID reader. Most reader's phase angle will rotate clockwise as the tag moves towards the reader, meaning a positive change in phase and anticlockwise as the tag moves away from the reader, resulting in a negative change in phase. This rotation is a representation of how the phase changes over time as the tag moves. The type of representation can be seen in figure 2.10, where the reader detects the offset of the

phase or the change in phase in relation to a base phase. This can then be represented by a radial change or movement on a circle. This can however differ between readers.

This technique and the related settings used are very dependent on the environment and type of measurement. If a tag is moving at a high speed it will have a different suitable setup than a tag moving at a slow pace. The reason for this is that a few assumptions are needed to accurately determine the velocity. One of the assumptions are that the maximum change in phase between consecutive measurements must be less than the measurable phase of the reader. This is reader dependant, some readers can measure a change in phase of π and others 2π [45][56]. This is because a bigger change means a phase ambiguity error will occur and the velocity will not be correct. This assumption means that there is a maximum velocity that the tag can travel at, depending on the sampling rate of the reader. The maximum velocity can be determined with the following equation:

$$v_{max} = (\pi \times 3 \times 10^8) / (4\pi \times f_i \times 10^6 \times \Delta t) \quad (2.17)$$

This will be different for each tag and reader combination, the amount of tags present and the range will also influence the speed since the polling rate will decrease. The opposite is also true, the equation expects a change in phase per sample. The time difference between successive phase readings at the frequency specified is dependent on the RFID reader and tag capabilities. It is for this reason that the maximum velocity can differ slightly between each reader. The protocols and setup of the system can also influence this greatly. This means that a slower moving tag requires a slower polling rate. For a fixed speed there will thus be a minimum velocity of the tag that can be measured accurately. This depends on the minimum change in phase that can be measured by a RFID reader. The reader used by R. Mittra et al.[55] had a minimum phase change interval of 0.087 radians. Thus, for simplicity 0.1 radians were chosen. Based on this accuracy the minimum velocity of the tag can then be calculated as follows:

$$v_{min} = (0.1 \times 3 \times 10^8) / (4\pi \times f_i \times 10^6 \times \Delta t) \quad (2.18)$$

For a tag that moves at a speed between these limits the velocity can then be relatively accurately determined. With this technique several samples are taken over time and then used to determine the velocity of the tag. This means that a tag traveling at a constant velocity will also be tracked more efficiently. If the system does not require real-time velocity estimation, samples can be taken and then after a certain period be simplified with linear or end-point regression. This will remove noise spikes and certain erroneous samples. For real-time application a different approach is necessary. One proven technique is Kalman filters which is discussed in a later section.

By using a Kalman filter it is possible to adjust the measurement per sample. An explanation of how Kalman filters work is discussed in a later chapter. A short description of how it was implemented in this use case follows.

The basic concept of a Kalman filter is that it creates a prediction of the next unwrapped phase value, using the previous values. This is done per sample where the time between the phase values are also considered. With each new measurement the predicted value and current value is adapted. This means that contrasting measurements are filtered out and their effect are minimised. For real time applications this works very effectively since it provides a good amount of filtering without causing a delay. Mittra et al. tested the application of a Kalman filter in the velocity estimation of a person moving around in front of a reader installed in a portal, without the person actually going through the portal. After a few seconds the filter averaged the estimated velocity to zero since the person was not going anywhere. The results are shown in the next figure.

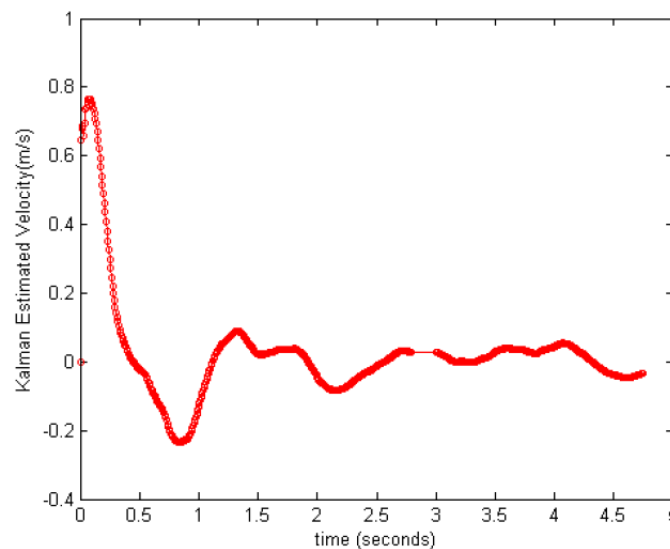


Figure 2-16: Kalman filtered estimated velocity, reproduced from [10]

In this figure, a positive velocity indicates movement towards the antenna and negative velocity is movement away from the antenna. A thorough explanation of how the Kalman filter works is discussed in a later section.

2.10.5 Direction finding method used in robot docking system

Another method for direction determination is similar to what was discussed in section 2.10.2 where two directional antennas are used to determine the location of the response signal. The difference being that this setup is attached to a moving robot. This means that the tag will be the stationary item and the reader is the moving item. Myungsik K. et al. proposed a robot docking system that uses the RFID signal to navigate to the dock station [57]. The direction of arrival system (DOA) system uses dual-directional antennas, where the ratio of the signal

strengths between the two antennas are calculated. These ratios are then used to calculate the DOA. To prevent multipath from influencing the direction of travel Myungsik K. et al. proposed a direction correction algorithm.

For the direction sensing with the dual antennas the setup proposed looks like the figure below, where the Azimuth angle of the signal is calculated using the ratio between the two signals. This is seen as a bearing-based approach to direction finding.

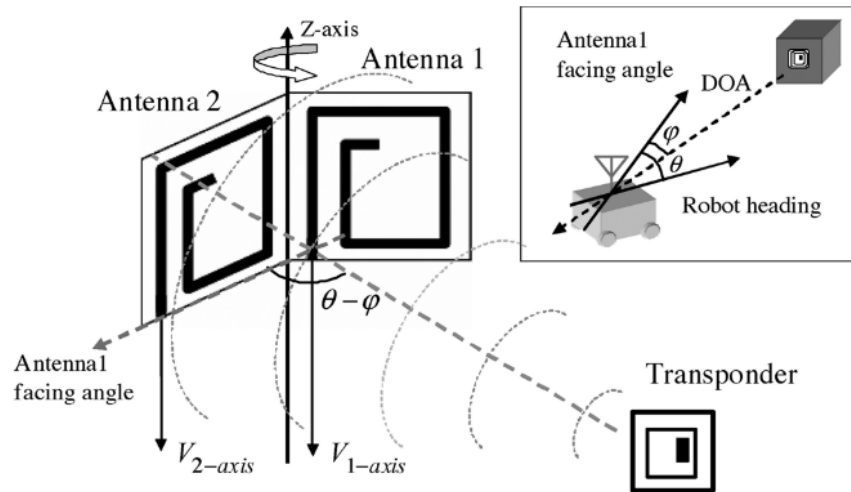


Figure 2-17: Dual antenna setup for direction finding, reproduced from, reproduced from [36]

The author further proposed an algorithm where the robot will move and adjust its movement by comparing its own position with that of the DOA signal. Then using an estimation by looking at the past few DOA it is able to determine when the signal is coming from the source and when environmental effects have caused multipath. This algorithm calculates the potential error in the DOA in order to change its direction of travel. The system assumes continuous movement of the robot so these calculations are done repeatedly until the robot reaches the docking station. The system also uses distance determination for error correction since it is expected that for every movement the robot gets closer to the antenna and do not move further away.

This system again showed promising results with regards to direction of arrival. In this approach where the reader is the item that is moving the same principles were applied and it was shown that this approach has a lot of promise. Multipath is a big problem in RF and this was again proved by Myungsik K. et al [57]. In order to overcome the impact of multipath creative and new ways have to be developed and often these techniques are very environment and scenario dependent. This means that a new technique might work exceptionally well in one scenario but fail miserably in the next. This has to be considered when developing and installing the final product. This technique showed some possibilities if the direction is the main area of concern and how to go about solving it.

In summary: direction finding of the source of a signal is a field that is relatively well known and was investigated on several levels. Moving targets complicate this process a great deal, but also provides more information on where the tag has been in order to predict the direction of movement.

2.11 Description of scenarios where motion estimation is important

This section describes 3 examples of where directionality and velocity information would be useful.

2.11.1 Personal asset security control

In most corporate companies a laptop and other devices are assigned to personnel. This equipment is often under threat of theft. Companies have started to add RFID tags to the devices in order to better control the movement of the equipment [58]. This same procedure is followed on some construction sites and other venues where Personal Protection Equipment (PPE) is important. The PPE is assigned to a person and each item in the PPE is tagged. If the person that this equipment is assigned to also has a specific ID tagged with an RFID tag, then it is possible to detect whether the equipment moved past antenna with the person it was assigned to. If this is not the case then it probably means that an unauthorised person is moving the device or equipment without consent. The problem with this is that if knowledge about the direction of movement is not available then it would mean that if a device or person moves into the field of the antenna without actually going through the gate, then it might sound false alarms. By adding the direction details to this analysis, it can add certainty to security and alarms and thus result in a more complete system. Some tags that are attached to equipment are equipped with a sensor that will alert the reader if the tag is removed from the item. Adding velocity to these scenarios, means that further anomalies or irregular behaviour can be detected.

2.11.2 Supply chain management

Passive tags have gained a lot of ground in supply chain management applications [59]. RFID tags have replaced barcodes in a many applications and are widely used to track the movement of objects and stock items [60]. A common flaw that is present within these systems is that if an item is read by a reader without information on the direction of movement of the tag there is uncertainty about the outcome of the relevant supply chain activity. E.g. if tagged items are taken out of a truck, read by the antenna reader and then placed back on the truck, it will appear to the system as if the goods arrived at the destination when in fact it never did. Adding direction of movement data to the system however will allow the system to provide a measure of certainty that the item came in through the door and if it went out it will also show

that the tag moved away from the antenna again. This method will improve security and prevent some of the ways to fool the system.

2.11.3 People tracking

Tracking people is of great importance for certain companies. Organizations that require a high level of internal security around the movement of people on their premises will typically provide visitors with RFID tags that are used to track their movements and access through certain parts of the building. If directionality and velocity is added it would improve the security greatly, meaning that visitors and possibly criminals can be more accurately monitored without any extra cost.

Another example of where this technology is used is in conferences [7]. People wear tags on their body and the information is used for analysis of people behaviour as well as access control. If this is used in conjunction with video processing of footage from security cameras, it would be possible to track the exact movements of a large number of people. Directionality of movement would also provide data mining companies an insight to the behaviour of people. This can result in the optimization of placement of usable items and layout of a building.

2.12 Kalman filter

The Kalman filter is a proven data processing technique that is used in many scenarios where a dynamic system observes a series of measurements over time, which contains certain variabilities and noise, and produce an improved estimation of these variables based on a model of the system [61]. The noise can be measurement noise or system noise. Another name for the Filter is a Linear Quadratic Estimator or LQE. The Kalman filter uses correlation between states and data to predict and adapt to uncertain information. This filter is applied in various applications where measurements can be unpredictable; examples include positioning, guidance, control of aircraft and trajectory optimization [62][63]. In the RFID field the Kalman Filter is also widely used for indoor localization techniques, robot navigation, vehicle tracking and state estimation [64] [67].

The Kalman filter uses samples measured over time which include a certain amount of noise and/or inaccuracies to produce an estimate value. These values are closer to the actual values based on the relationship between key states in the system [46]. By doing this, errors in reading can be corrected and a better result obtained. This can be done in real-time, allowing for run-time application. One major benefit of using Kalman Filters in these applications is that it does not add a lot of overhead to the algorithm or uses a lot of memory in the process. It only stores the current states and predicted state and not every measurement throughout.

Kalman filters uses a state to represent the system. The state is comprised of a discrete time-controlled process and uses the following linear stochastic difference equation to represent the system according to Pujare, R. [37]:

$$x_k = Ax_{k-1} + Bu_{k-1} + W_{k-1} \quad (2.19)$$

Where A is the state transition matrix, B is a possible control input matrix, U is the input to the matrix and W is a random variable which represents process noise. The state transition matrix provides a relationship between the previous state and the current state.

A measurement is represented by z_k which is given by:

$$z_k = Hx_k + v_k \quad (2.20)$$

H is the observation matrix. This provides a relationship between the measurement and the state. V_k is the measurement noise present in most devices.

The measurement noise variable and process noise variable, also known as the process variability, are assumed to be independent of the system. The normal probability distribution can be represented as follows:

$$p(w) \sim N(0, Q) \quad (2.21)$$

$$p(v) \sim N(0, R) \quad (2.22)$$

Here Q is the process noise covariance and R is the measurement noise covariance.

The matrices mentioned above are not time-indexed, even though they might change with time. The assumption is that these values are constant, but in practice certain environments or conditions can lead to a different variability.

The Kalman filter estimates the state of the filter based on the terms of two matrices recursively and continuously as new measurements are taken. These two matrices are the estimation matrix and the error covariance matrix. They are denoted by $x_{k/k}$ and $p_{k/k}$ and are known as a posteriori matrix. This refers to a state and conclusion drawn from an effect to determine the cause. The $x_{k/k}$ state is the mean of the state distribution, which includes observations up to the certain time k. The $p_{k/k}$ is a measure of the estimated accuracy of the state estimated according to Pujare, U. [37]. This means this state is used to determine how accurate a prediction the estimation is based upon previously known knowledge.

The state of the system can have multiple variables with some relation to each other. In the case of predicting the velocity of a tag based upon its phase, the velocity and phase will be variables of the system [62].

The Kalman filter uses the different states defined, which includes the noise and measurement model variables, and the measurements taken to alternate between the predict phase and update phase (also known as the time update phase and measurement phase).

The predict phase will project the next state parameters by using the state estimate and covariance matrix from the previous time step.

The predicted state estimate is given below and is similar to the equation stated above.

$$x_{k/(k-1)} = Ax_{k/(k-1)} + Bu_{k-1} \quad (2.23)$$

The predicted covariance estimate is then:

$$P_{k/(k-1)} = AP_{k-1/(k-1)}A^T + Q \quad (2.24)$$

Both of the equations mentioned above are *a priori*, meaning they are derived from theoretical knowledge and reasoning, instead of experience, measurements or observations. They are modelled to produce the best estimate and the matrix will look as follows:

$$x_k = \begin{bmatrix} \text{Parameter 1} \\ \text{Parameter 2} \end{bmatrix} \quad (2.25)$$

Where Parameter 1 and 2 denotes the parameters of the system, this can be distance and velocity in the case of object tracking, coordinates for navigation or phase and velocity for tag tracking.

$$P_k = \begin{bmatrix} \Sigma_{pp} & \Sigma_{pv} \\ \Sigma_{vp} & \Sigma_{vv} \end{bmatrix} \quad (2.26)$$

This is based on the explanation given in [38], where x_k is the best estimate and P_k is the covariance matrix. The covariance matrix consists of four elements each of which is the degree of correlation between different elements. For example, the term Σ_{pv} is the covariance between the p th and v th state variables and so forth for all other elements in this matrix.

Next the update phase will execute. The update phase then follows the prediction phase. During the update phase the estimation phase is combined with the latest measurement data to produce a refinement of the estimate. By doing this the measurement serves as feedback in the system to provide a more accurate estimation. This new state is then called the posteriori state estimate. The updated state is calculated by using the following matrix manipulating equations [37]:

$$K_k = P_{k/k-1}H^T(HP_{k/k-1}H^T + R)^{-1} \quad (2.27)$$

$$x_{k/k} = x_{k/(k-1)} + K_k(Z_k - Hx_{k/(k-1)}) \quad (2.28)$$

$$P_{k/k} = (I - K_kH)(P_{k/(k-1)}) \quad (2.29)$$

During this phase the posteriori estimate $x_{k/k}$ is obtained. As seen above this is done by combining the current measurement Z_k with the estimate state. As mentioned above there will be a difference between the prediction and the actual measurement. This is due to error factors, not perfect model parameters and a possible time difference between uniform measurements. The residual of the difference between the predicted and actual measurements is given in the second equation by the term $[Z_k - Hx_{k/(k-1)}]$. The K_k term in this equation is used to give this residual a weighting factor, this means that the difference between actual and estimation measurements can have a big impact on the estimate state $x_{k/k}$ or it can have a small impact, depending on the scenario. The same is true for the error

covariance, which is also influenced by this factor in the last of the three equations. It is of great importance to define this parameter as accurate as possible in order to improve the reliability and precision of the system estimation.

By this explanation it can be seen that the Kalman filter switches constantly between the predict and update phase. With every measurement the state estimate is changed and updated to a value that should be closest to the actual value. This process minimizes the mean squared error according to Lacy, Tony [68]. The different states can be represented by the following diagram:

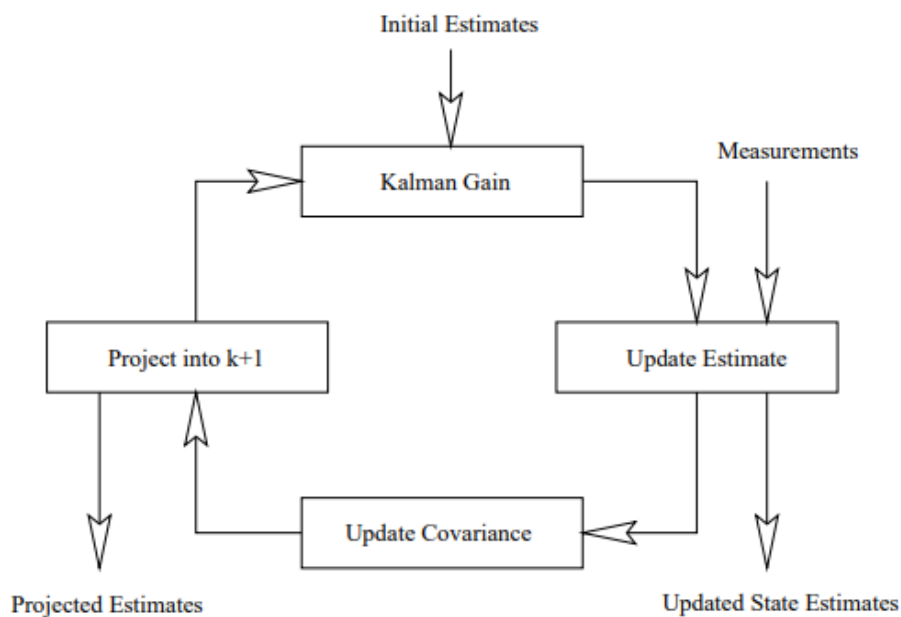


Figure 2-18: Flow diagram of Kalman filter process, reproduced from [68]

Here it can be seen more clearly how the estimation and the measurements interact to generate a projected estimate and current estimate. The application of this filter to predict real-world movement is discussed in a later chapter.

2.13 Phase Unwrapping

Phase wrapping is something that occurs as a result of a bigger change in the variable than what the system can measure. For example, with the phase measurements, the change in phase can be measured between 0 and 2π radians for an Impinj Speedway reader or 0 and π for Thingmagic mercury 6e reader [56][45]. This is as a result of the demodulation hardware used in the readers. If a change in phase results in a measurement outside the 0 and π range, wrapping will occur where the π radians will be added or subtracted, depending on the direction of change in phase. Meaning that if the change in phase is such that it exceeds the π limit then the next reading will still show between 0 and π since that is what the reader is capable of measuring. For example, if the first phase measurement is $\pi/2$ radians and the phase changes with π radians, the measurement will be wrapped and the next phase

measurement will still be $\pi/2$ radians. Thus, when comparing phase measurements and specifically the change in phase, this wrapping effect will lead to misrepresentation and ambiguity of the signal data. The process to unwrap a signal is essential in order to use the phase change data. This is possible, as long as the system can determine in which direction the phase changed, in other words if the phase increased or decreased. This is true for most applications, problems can occur if the change in phase is much bigger than the parameters, resulting in a big wrap around effect, for instance where the phase changes by 8π radians between consecutive measurements, meaning that there is a very big difference. This can cause false measurements if the system does not provide additional capabilities to deal with such events. This is also part of the limitations of the technique and should also be included when implementing such a technique.

A wrapped signal may cause errors in the direction detection not to mention ambiguity in the velocity calculations. For this reason, techniques on how to unwrap the phase measurement are needed.

Unwrapping of phase in its simplest form is portrayed by the following equation [69]:

$$\phi_{\text{unwrap}} = \phi_{\text{wrap}} \pm \pi \quad (2.30)$$

This is true if the wrapping is done between 0 and π radians. This allows the profile to be continuous, allowing comparison between consecutive samples taken even if the phase changes more than the π radian value.

The effects of unwrapping can be seen in the next two set of figures. The first is an example of sinusoidal wave that was unwrapped [70], the second is phase measurements taken while a tag was moving away from a reader [46].

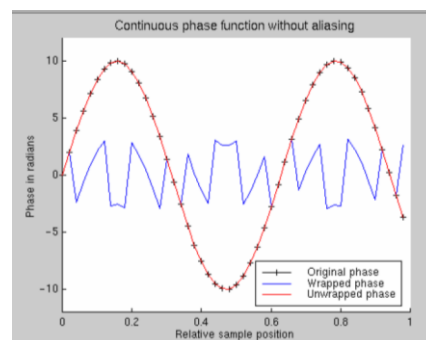


Figure 2-19: Unwrapping of a sinusoidal wave, reproduced from [70]

Here it can be seen that without the unwrapping no real estimation can be made on the behaviour of the signal and its parameters, showing the importance of accurate wrapping.

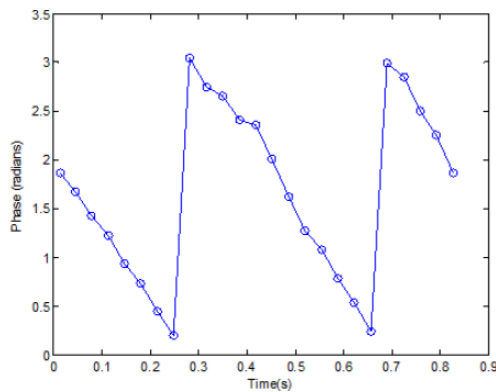


Figure 2-20: Wrapped phase measurement of a tag moving away, reproduced from [42]

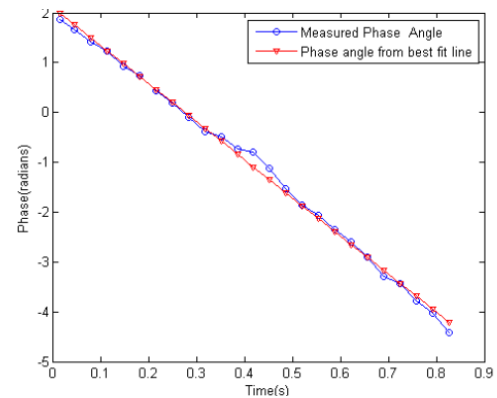


Figure 2-21: Unwrapped phase measurement with a best fit line, reproduced from [42]

These two figures show the conclusions that can be drawn from unwrapping the signal to get the real analysis of what is happening with the measurements. This also illustrates the necessity of such a technique and its application in real-world scenarios

2.14 Software language used for product development

The two main software languages that are used in the production of RFID solutions are Visual Basic (VB+), C# and more recently python. All offer different advantages and disadvantages. All of these languages have a multitude of libraries available with different pre-programmed functions that can be incorporated into the final solution. Visual Studio which is one of the most common Integrated Development Environments (IDE) in this field, supports both these languages as well as C++. Other IDEs that also has this support includes SharpDevelop, Zeus, MonoDevelop, etc. Thus, there are several IDE options available for the different programming languages and this should not influence the decision on which language to use. Both languages offer the possibility to use multithreading. This is a capability that is necessary for most applications developed for real-time use. Both these languages are part of the .NET environment which integrates several of these advantages into the programming environment and language. C# and VB can interoperate with any other language on the .NET platform, which means compatibility is not an issue. Personal preference and programming background will carry the most weight in this decision-making process. The time spent to learn a new language or language that is the furthest away from current knowledge can be time better spent somewhere else.

Advantages of C# coming from a C++ background is that the language is very familiar. It is seen as the rapid development which VB offers to C++ developers according to C. Uteley of TechRepublic [71]. New functions and variables are added to C# from C++, the syntax is much more simplified. C# uses the .NET environment; this include advantages such as memory

management systems like the .NET's garbage management scheme. Other advantages of this language include type-safety, memory leak solution, good support and that it runs CLR. This stands for Common Language Runtime (CLR). This is the virtual machine part of the .NET framework, which manages the execution of these programs.

Some disadvantages of the C# environment is that C# is seen as less flexible than C++ because it depends on the .NET framework. It is difficult to determine the exact memory usage of a large application because it uses a garbage collector scheme. This make it less precise than other languages such as C++.

The biggest advantage of the VB language is that it allows very fast programming, due to added features such as the My namespace, which brings along other functionality. Other advantages are that VB allows the user to invoke shared methods on an object instance and that the GUI of the VB-IDE is easy to use.

Some disadvantages with VB are that it offers a lot of work behind the scenes, meaning you cannot be as precise and explicit as you can be with C#. Programs written in VB is also difficult to convert to other operating systems, since the .NET framework was designed by Microsoft. In the end both of these languages are part of the .NET framework and the choice about which program to use comes down to the user, which environment is the most comfortable based on previous knowledge. Both of these languages offer great and similar functionality and at a lower level is very similar. This means that the biggest factor is the preference of the user.

2.15 Important protocols to consider during development

Several protocols have been created to help developers with implementing software associated with RFID systems. One of the key protocols is known as the low-level reader protocol (LLRP). This is a protocol to aid the user convey instructions between software and the reader [72]. This was designed with the intent to allow developers to be able to control the operation of the reader, regardless of the reader manufacturer, and thus standardizing several commands. This protocol gives fine control over a single reader. This protocol is compiled of almost 100 commands as well as providing the interface for low level functionality. It is common practice for manufacturers to support the LLRP as well as their own vendor-specific interface. This improves adaptation between different systems using different readers, but the same logic.

The protocol that defines most tags and system being used in the RFID environment is the GS1 UHF Gen 2 protocol. What the tags and readers are able to do and how they communicate with each other is defined in this protocol. According to the ITU regulations for UHF RFID a reader is not allowed to stay on the same frequency for a period longer than the set amount of time defined by local standards. According to local broadcasting standards in

South Africa this is set at 0.4 seconds for RFID reader frequency channels, meaning that every 0.4 seconds or less a frequency hop has to be made by the reader to another channel within the allowed range [73]. The allowed frequency channels are the following for UHF RFID applications:

- 865MHz ÷ 868MHz for common RFID applications
- 915.4MHz ÷ 919MHz for RFID applications including passive tags and vehicle localization

The standard that defines most of the protocols and procedures for the RFID system is the ISO/IEC 18000-63 standard, which is also known as EPC class1 Gen2 standard. This includes the air interface for RFID devices, the physical and logical requirements for passive tags using backscatter techniques, interrogator and tag operating procedures and commands to name a few [74]. There are two main bands in South Africa, one is set a subset of FCC which is the 915.4MHz to 919MHz range and the other range is set by ETSI and states a longer time between frequency hops. During this dissertation the focus will be on the use of the subset FCC band.

This chapter outlined very briefly some of the standards worth mentioning. Other standards that will directly impact or influence the limitations, challenges or outlining of certain techniques will be mentioned during method description. This served as an informative section to note that there are certain regulations that have to be adhered to when implementing solutions in real-world scenarios.

2.16 Antenna setup

The setup of the antennas can greatly influence the final solution. This forms the basis from which an algorithm work to determine the directionality and velocity of movement. Different antenna setups can provide different advantages for different scenarios. Some may be suited for most applications while other setups can be goal specific. It is important to consider the options that are available and choosing the correct one based on the given setup scenario where such a system will be implemented. The most important aspect of the setup of the antenna is the direction of the antenna's radiation pattern, since directional antennas are the most common in the RFID industry. Secondly it is their relative position with respect to each

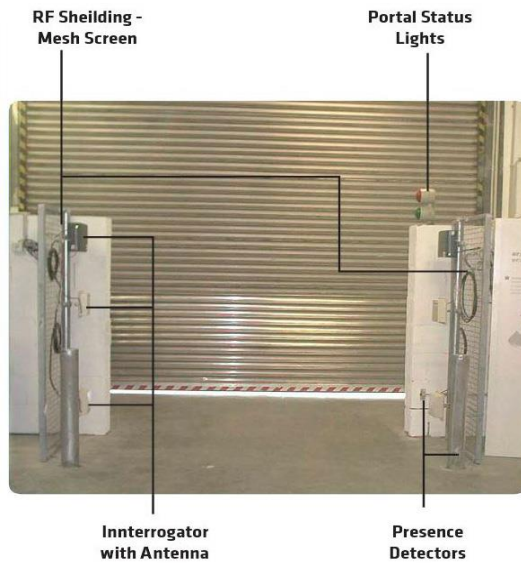


Figure 2-22: Antennas on both sides of an entrance with a shield on the outside, reproduced from [74]



Figure 2-24: Antennas placed on one side of a series of entrances, reproduced from [74]



Figure 2-23: Typical 3 antenna setup inside a bay door, reproduced from [74]

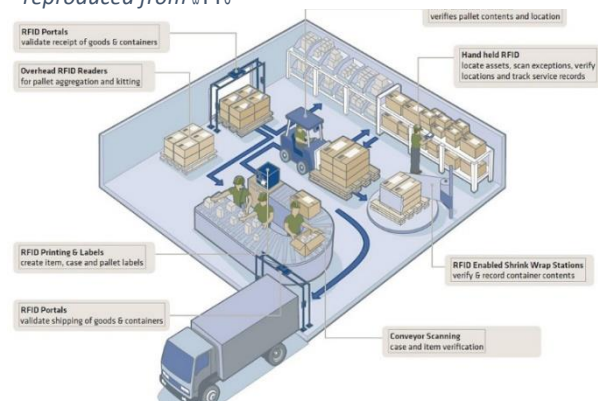


Figure 2-25: Antenna setup design in a factory setup, reproduced from [74]

other and with respect to the expected direction of travel that a tag can undergo that has to be determined. Antennas are placed to help achieve the main goal and in the most applications this would mean to read the tags that pass within range of the antennas as best as possible. To illustrate this the figures above shows a couple of examples where antennas are typically placed to read the tags in their path as best as possible without reading any stray tag [75] [77].

During the testing phase, individual testing will be done to provide improved insight into the real-world behaviour of these setups and to better understand how the setups mentioned above influence the readings that are required in order to determine the directionality of the tag movement. The antennas will be placed in such a way that it will produce the most complete set of readings for the tags moving past it. The best angle will be determined with different tests and experimentation. The antenna setups portrayed in this section were designed to read tags moving through the portals and absorb the signal otherwise. If the phase and signal strength can be used to track the movement of the tags the definition of stray tag changes and the setup will change accordingly.

2.17 Conclusion

This chapter showed that it is possible to create an algorithm that will track the motion estimation of a moving RFID tag based on previous knowledge and techniques. Challenges in the RFID environment as well as specific challenges towards a solution for this problem were mentioned. The different possible techniques, that can be used to solve this problem were discussed. This chapter serves as the background and basis for all the techniques developed and mentioned in the following chapters.

3 Experimental learning and initial testing

This section is included to show the process of learning through practical experimentation. Each time a new technology has to be mastered and the measurements understood it is good practice to learn how the equipment works in a practical environment, trying to achieve set outcomes. This is exactly what was done in this section.

3.1 Antenna setup and its influence on phase and RSSI response

As outlined in sections 2.8.2 and 2.8.3 the directionality of antennas, radiation patterns and movement in relation to the setup greatly influences the measurements. To see the effects in a practical environment with real-world reflections, different antenna setups will be used to test the phase and RSSI response from each of these setups. This will provide knowledge on the signal response and how this can be utilized to track the motion of a moving tag. Each setup has its own advantages for different applications in different scenarios.

The antenna setups were chosen based on real-world application examples. Similarities exist between the examples in 2.16 and the setups chosen for these experiments. It is known that the radiation pattern of an antenna is outwards in the direction it is pointing at. The radiation pattern will propagate, as viewed from above, in convex waves outwards. This means that movement directly towards the centre of the antenna from a 0-degree angle (head-on) will produce the most accurate correspondence between a change in phase and a change in distance, as illustrated in the figure below.

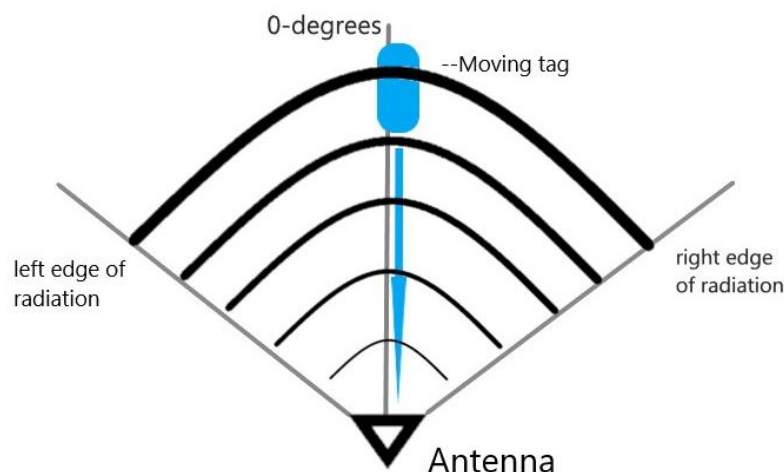


Figure 3-1: Antenna radiation illustration with moving tag as reference

Since it is impossible for a tag to move past an antenna and straight towards the centre point of the antenna at the same time there will be a slight angle error depending on the line of movement.

The offset between the line of movement and the line towards the centre of the antenna results in a change in the correlation between the distance travelled and the change in phase. There will need to be a tangent calculation with the unknown angle in order to determine the correct correlation. These angles are illustrated in the figure below.

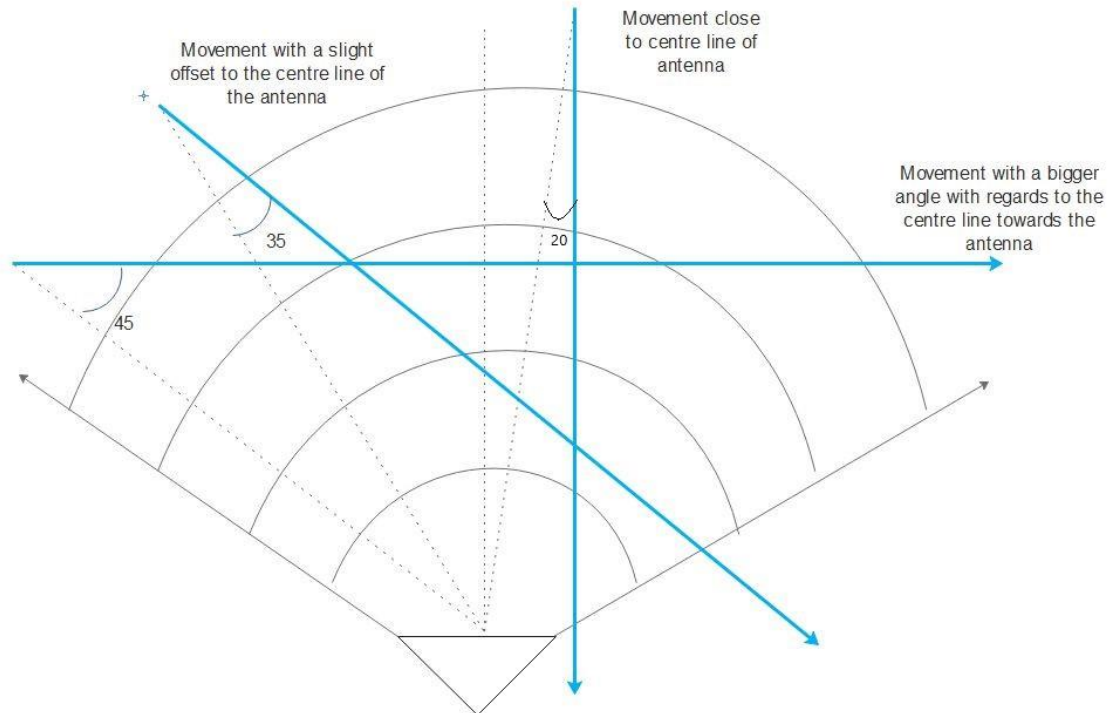


Figure 3-2: Illustration of the offset in the angle of movement with regards to the centre line of the antenna

In this figure the line of movement is represented by the blue lines. It can be seen that there are different offset angles for each line of movement shown with regards to the centre line of the antenna. To simplify the motion estimation, it is assumed that the offset angle is close to zero to negate the effects that this offset will have on the velocity estimation. It does mean however that if the angles that the antennas are facing changes, it can influence these offset angles as well. This change is due to the fact that the line of movement can naturally change since the antenna might obstruct more of the angle of movement if it is tilted towards or away from the line of movement. If this is the case it will be mentioned in that specific experiment to explain the resulting phase pattern that is observed. If the angle of movement in reference to the centre line of the antenna stays the same for all changes in the angle that the antennas are facing, then the only observable difference will be the signal strength that is measured for this type of movement.

This does not mean however that other setups and configurations are completely erroneous. The different setups will effectively change the incoming angle of the tag towards the antenna and it is this resulting phase change that will be measured. The first setup chosen for this experiment is based on antennas placed in door frames for inventory control as illustrated by figure 3-3 and 3-4, where the antennas face inwards towards each other with a 90-degree angle to the direction of movement. This means that the tag will move horizontally across the radiation pattern illustrated in figure 3-2.

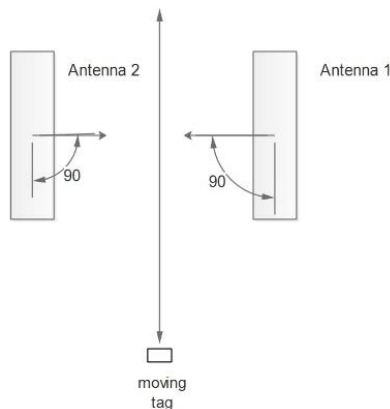


Figure 3-3: Antennas facing the expected movement direction with a 90-degree angle (2D-View)

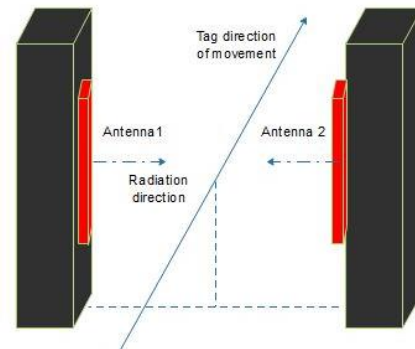


Figure 3-4: Antennas facing the expected movement direction with a 90-degree angle (3D-representation)

This setup is similar to figure 2-22 where the tags unloaded in a warehouse is monitored. This is also similar to that found in shops that use this as a means of theft control.

The next setup is concerned with tracking moving tags from a front angle. The antennas are directed at a 45-degree angle towards the expected movement direction, facing the oncoming tag. This setup is sometimes used, if the tag placement is uncertain and it might be that the tag is either placed on the front or the sides of the package. This corresponds to a tag moving with a 45-degree angle towards the antenna with regard to the radiation pattern. From section 2.8.3 it can be seen that the radiation pattern is not equally strong in all directions, which may lead to a weaker edge signal response directed at an angle towards the antenna. This setup is illustrated in figure 3-5.

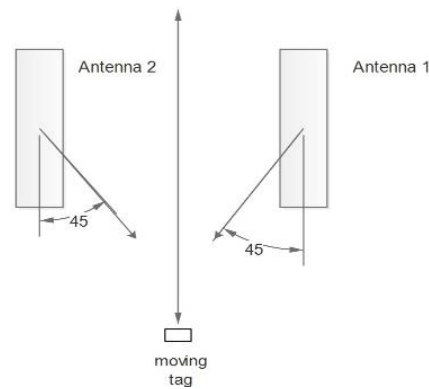


Figure 3-5: Antennas facing the expected direction of movement with a 45-degree angle

The final two setups will be more suited towards tracking the velocity of the moving tag for longer periods, based on the knowledge provided in section 2.8.3, because the angle of arrival is the closest to 0-degrees towards the antennas out of all the setups. The one setup will have both antennas facing straightforward parallel in the estimated direction of travel, while the other setup will have one antenna facing towards the tag and the other in the opposite direction away from the tag, meaning it will also track the tag in the opposite direction as it moves away from the antenna. Both these setups can be used in the real-world, where the expected placement of the tags is in the front or back of the object (first and second of these setups). These setups can be seen in figures 3-6 and 3-7.

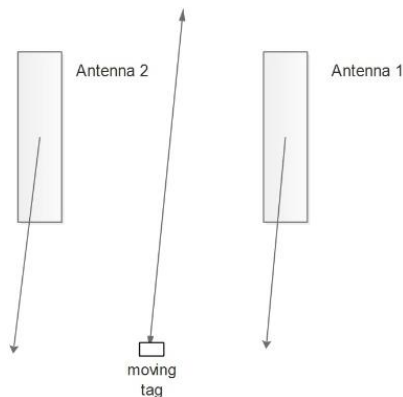


Figure 3-6: Both antennas facing towards one side parallel to expected movement

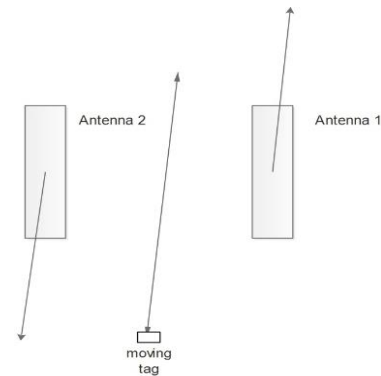


Figure 3-7: Antennas facing opposite direction parallel to the expected direction of movement

From figure 3-6 and 3-7 it can be seen that the tag will not move directly towards the centre point of the radiation signal but rather with an angle past it. This is a practical challenge that will always be present since an object cannot pass through the antenna. This is however a practical setup that allows travel with the least amount of deviation from that centre line towards the antenna and were chosen as a result of this. A short description of the experimental setup follows.

For all the tests done in this section the tags will travel in a straight line, past the two antennas, as illustrated in the figures above. The speed at which the tag is traveling will be regulated

with a bicycle speed sensor and the tags will be attached to flat surface on the front of the bicycle. This allows for better experimental control since different speeds can also result in different readings, as discussed later. The bicycle speed is monitored by a wheel speedometer. This speedometer works by measuring the number of times a wheel rotates per minute. This is more accurate than a person judging their own walking/running speed, but variation due to the imperfect control capabilities of a person does still exist.

To see the effect of the antenna setup the tags were moved at three different speeds. Each of the set of measurements were repeated 3 times for each different antenna orientation. The speeds chosen for this experiment will represent the speed at which a person can walk. This is to test a scenario that can be used for access control as well as security purposes. The antennas are placed in an asymmetrical environment with one side having a wall and the other not. These types of environmental dissimilarities effect the behaviour of the readings, but can be explained due to the reflections of the signals. These types of setups occur in practice, in environments where the system is deployed without having enough space to accommodate the ideal circumstances.

The placement of the tags and relative position with regards to the antennas can be seen in the figures below, where the tags are attached to a flat surface on the front of the bicycle and the antennas installed on both sides of a passageway.

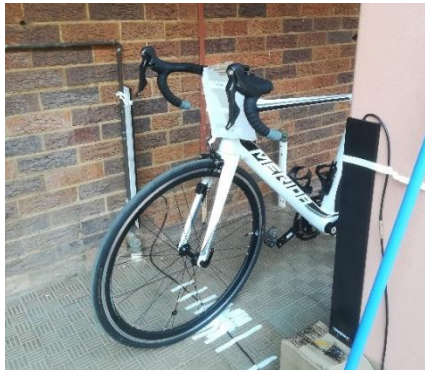


Figure 3-8: RFID tag attached to front of bicycle during testing



Figure 3-9: Antenna installation on both sides of a passageway

The main tag was mounted at a height of 68cm, while the top most part of the antenna is at 82cm high, with the effect that the tag will definitely be in the antennas propagation range. A description of the equipment and reader settings used during the experiment is described next.

The following table is a summary of the equipment used and standardized settings during the experiment

Table 3-1: Testing equipment used for experimental learning on antenna setup

Equipment	Description
RFID Reader	Impinj Speedway R420
RFID tags	Alien G-tags H3 tags used by Techsolutions
RFID Antenna	2x Times-7 Door frame Antenna FCC
Antenna rated Frequency	902-928 MHz
Antenna 1 cable length	132 cm (including links and connectors)
Antenna 2 cable length	210 cm (including links and connectors)
Hopping rate	Standard (150ms)
Channels	Set by software (915.6 MHz-918.8MHz) for SA band
Software version	Own reading program that converts reads into a csv file for study at a later stage
Speed of moving tag (kmph)	3,5,7

The setting for the reader determines the read rate as well as the characteristics of the setup.

For this experiment the following important settings were used:

- Max throughput mode
- Transmit power 30dB
- Tari 0 (default)
- Session 0
- Tag Population 32 (default)
- Tag transit Time is set to 0
- Low duty cycle mode is disabled
- Tag inventory state aware is set to false

One concern is that, as a result of the speed of movement and the setup of the antenna, the tag might not be read a sufficient number of times (i.e. there may not be enough measurements to provide data regarding phase and RSSI to be able to provide a verdict on the movement of the tag). The test described above was conducted with a proposed reader setting to see whether this setup will be able to provide sufficient data in order to make intelligent predictions and an analysis of the movement of tags. To be able to make a preliminary conclusion on whether or not the tag is moving in a certain direction as well at what speed the tag is traveling, there needs to be at least two phase and RSSI measurement samples of the tag per frequency hop on a specific antenna. The more consecutive instances of more than two successful measurements of these parameters, the more certain a verdict on the movement of a tag can be reached. A successful measurement is thus one where two or more measurements of phase and RSSI are made per frequency channel hop per antenna. It can happen that only one antenna successfully measures consecutive samples; in this case

it will still be seen as a successful measurement, since adding additional antennas broadens the field view. As long as sufficient data is provided, the antenna it is measured on will not change the result for this application. This does however illustrate the importance of successful, successive measurements during the direction and velocity tracking process. The figures showed in this section only includes data from one antenna. This exclusion is done to remove ambiguity and confusion since different antennae will produce different RSSI and phase readings depending on the characteristics of the antennas. The length of the cables used with the corresponding antenna will also influence these readings. Thus, in some cases half the data of the moving tag is filtered out to only include the readings from one antenna and make the data more presentable.

The software used to record this data is a basic program that was written in C# using the LLRP, along with the toolkit provided by Impinj, to store the samples received from the reader in a csv file. The functionality for basic reading using this program was compared to the standard reader software provided by Impinj and showed the same sample rate recorded, thus justifying the reliability of the software.

The results from the different experimental setups and what this means with regard to the motion estimation of a tag is discussed next.

3.1.1 Experimental setup 1: Antennas angled at 90-degrees in relation to the direction of the tag movement

This setup is illustrated above by figure 3-3 and 3-4. This setup has the advantage that the tag must pass in between the two antennas and thus it is certain that the tag will at one stage be in the field of view. Unfortunately, this also narrows the field of view since the antennas are placed relatively close to each other. What one expects to see is that the phase will increase constantly up to a cross over state and then decrease until the tag is outside the field of view. This was proven to be true in the samples taken. This is shown in the two figures below that shows how the phase increases first and then decreases. The same is true for the signal strength. It will increase steadily and then decrease again. This is as close to ideal data as one can get with these types of scenarios. The tag is monitored for a reasonable period and never defers from the behaviour that is expected. One aspect that has to be monitored is the number of samples per pass of the antenna. For lower speeds this will not have such a big impact but at higher speeds the influence will be very big. Another problem when using this setup, is to define the relationship between the phase change detected and the change in distance of the tag.

The graph illustrates the distribution of syllable types (Kl) across different syllable counts (t) in the RŠSŭ language. The y-axis represents the number of syllables (t) from 1 to 11. The x-axis represents the syllable types (Kl) from m to tr. The graph shows a fluctuating pattern with peaks at t=11 and t=10, and troughs at t=1 and t=2.

The data portrayed in the figures above clearly shows the pattern for the change in phase but also shows the problem with RSSI. Due to the reflections present in the setup, there are no clear patterns in the behaviour of the tag, that can be deduced from the data. Multipath effects of the RF signal influence these readings. For a slower speed, this setup will be able to track the movement direction of a tag, but has a large uncertainty in regards to the velocity estimation of the tags.

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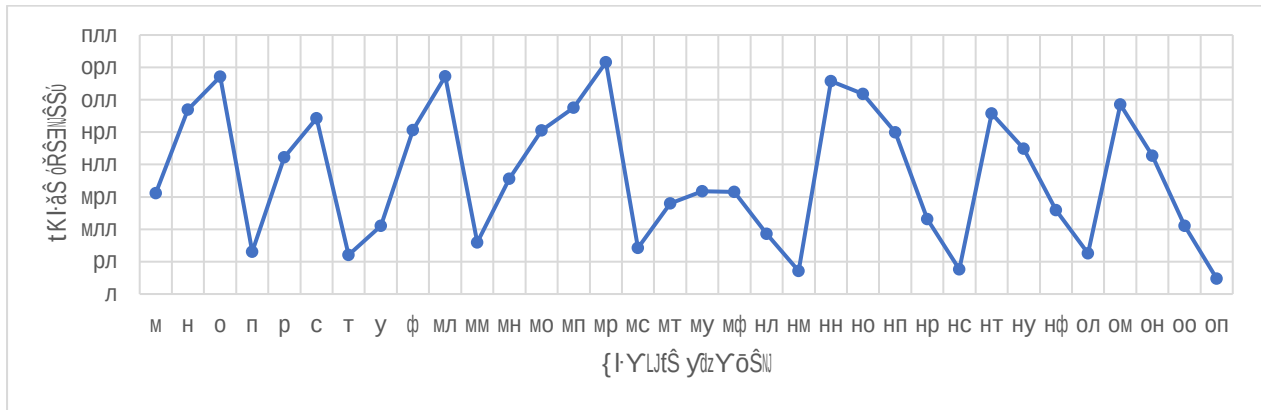


Figure 3-12: Phase measurement for tag moving at 5kmph produced by antennas facing each other (door frame scenario)

The figure above shows that the amount of data available almost halved with the increase in speed. The next figure also shows the same trend for the change in RSSI. This again shows the lack of change in signal strength measurement for this setup and outlines the problem with using RSSI to detect the motion estimation of a tag.

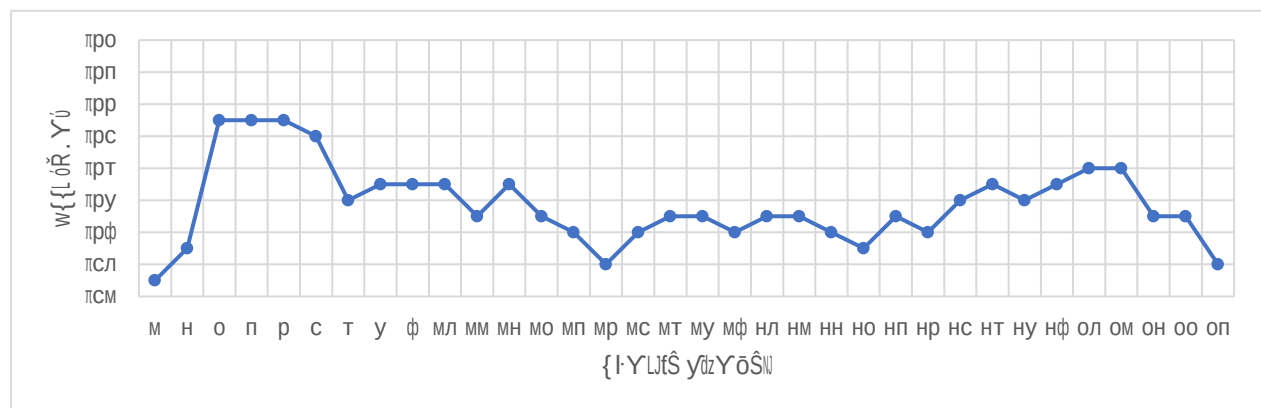


Figure 3-13: RSSI measurement for a tag moving at 5kmph produced by antennas facing each other (door frame scenario)

The next two figures show the phase and RSSI data for a tag traveling at 7kmph. Here it can be seen that the number of samples decreases further, highlighting the problem at hand. As the speed increases this effect gets increasingly worse.

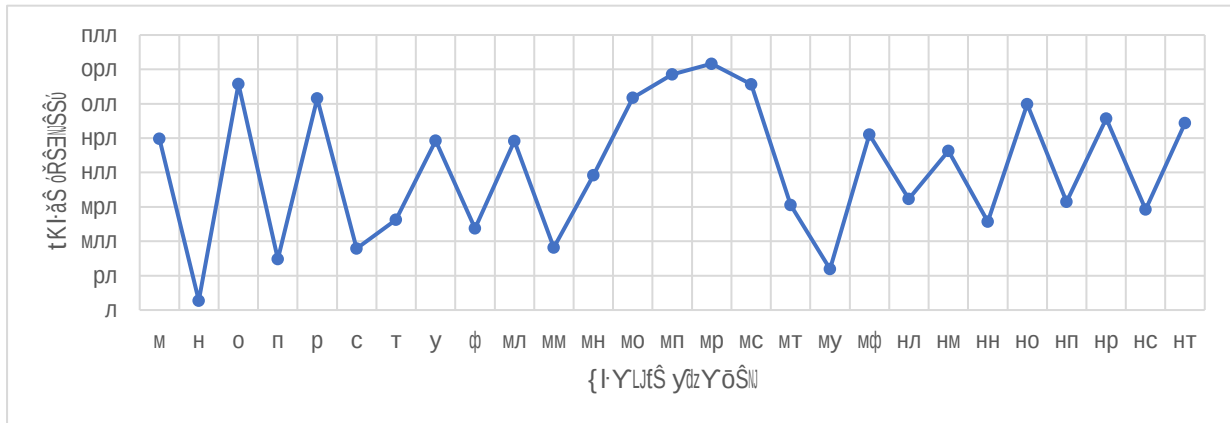


Figure 3-14: Phase measurement for tag moving at 7kmph produced by antennas facing each other (door frame scenario)

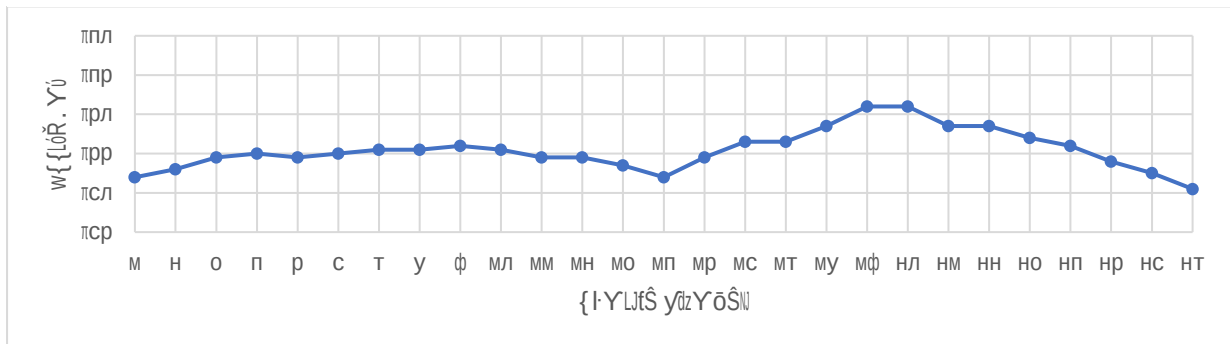


Figure 3-15: RSSI measurement for a tag moving at 7kmph produced by antennas facing each other (door frame scenario)

From the figures above, it can be seen that the same trend in phase change is observed but at slower speeds there are more data samples to track the movement than at faster speeds. From the data for the higher speeds, it is noticeable that the RSSI values do not reach the same value as one would expect. This is due to the relative position and orientation of the tags with regards to the antenna, resulting in less samples and lower RSSI readings. This setup does however still provide good enough signal strength and readings to determine in which direction the tag travels. Phase wrapping is very clear for the few samples that were taken for each passing of the tag. This along with the challenge in calculating the correlation between a change in phase and a change in distance means that it is not ideal to calculate the velocity of a moving tag but can certainly detect the direction of movement as long as the tag is not traveling at a very high speed.

3.1.2 Experimental setup 2: Antennas angled at 45-degrees in relation to the direction of the tag movement

This experimental setup is illustrated by figure 3-5. This is typically installed in a scenario where the tags can either be on the front or the sides of an object and the object passes through a terminal. This is done to ensure that the best possible read of the tag is ensured and is not designed with motion estimation in mind. This presents the possible shortcoming of the environment in that the direction of motion of the tag will always be at an angle with regards to the antenna. This means that the signal strength will be lower for a longer period of the movement and if the line of movement moves slightly, it will also increase the difference in angle between the line of movement and line towards the centre of the antenna. This also means that if the direction of travel is constant, the reading range will be shortened since the angle does not directly point to the area where the tag is coming from. The following two figures shows the change in phase and change in RSSI for the movement past the antenna setup mentioned above.

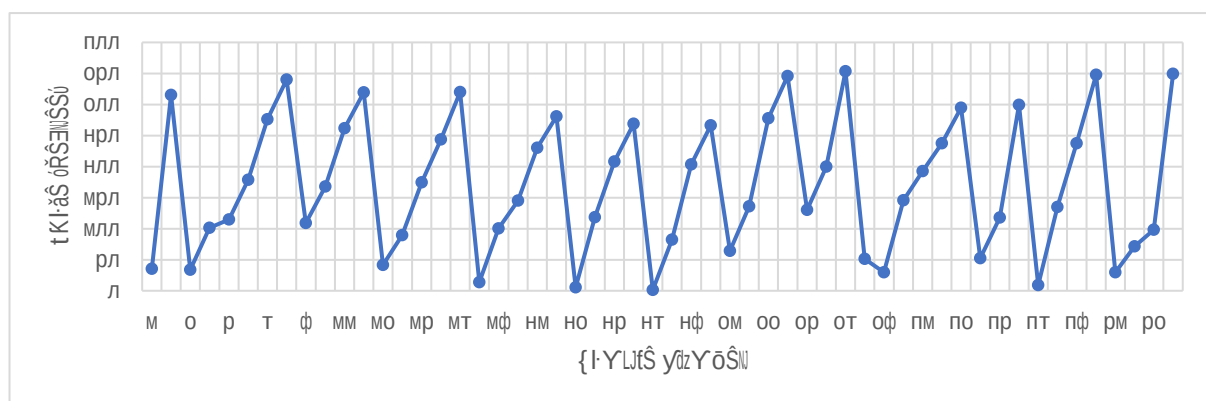


Figure 3-16: Phase measurement for tag moving at 3kmph produced by antennas facing the direction of travel with a 45-degree angle

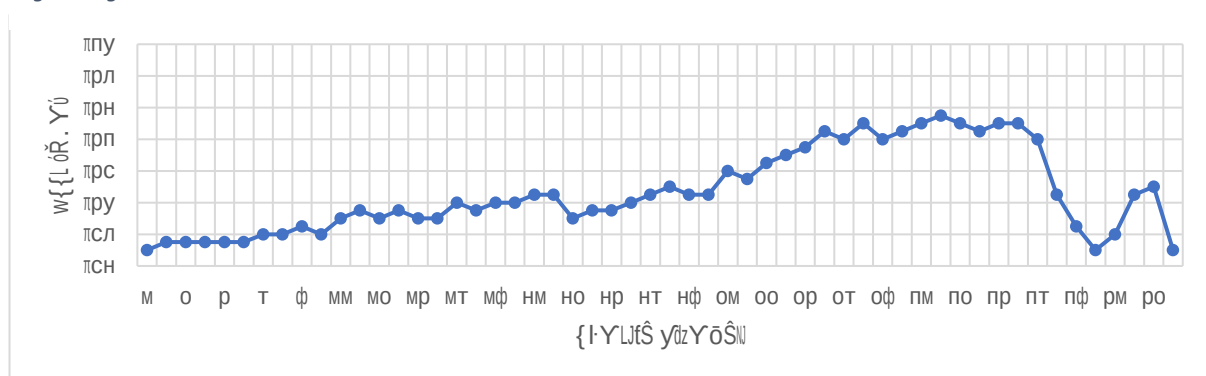


Figure 3-17: RSSI measurement for tag moving at 3kmph produced by antennas facing the direction of travel with a 45-degree angle

Looking at the data from the figures above, it can be seen that the wrapped phase increases as the tag moves closer to the antennas. This shows that direction determination is definitely possible. The RSSI data shows a trend that can be expected; a steady increase as the tag moves towards the antenna. It is observable that the resolution of this change in phase is not

very high, resulting in a jagged line. The multipath effects can be observed as certain areas results in a decrease in RSSI when one would expect an increase. The same effects that occurred in the first scenario, where the number of samples decrease as the speed increase can be seen here but, on average there is a higher number of samples recorder with this setup. This increase in the number of samples is because the antenna angle is such that the tag is in the reading range for a longer period of time. This effect is limited since the antennas used for this experiment is more suitable for a door frame installation and thus do not have such a big reading range as other antennas would have. These effects could however still be observed. The figures below show how the phase and the RSSI values change. The phase value again shows an increase up to the phase wrapping point before the process is repeated, meaning that a clear pattern that can be used to determine the velocity and direction of travel is present. The RSSI again shows an increase as the tag approaches the reader but lack resolution, or in other words big enough changes between samples to determine a clear behaviour.

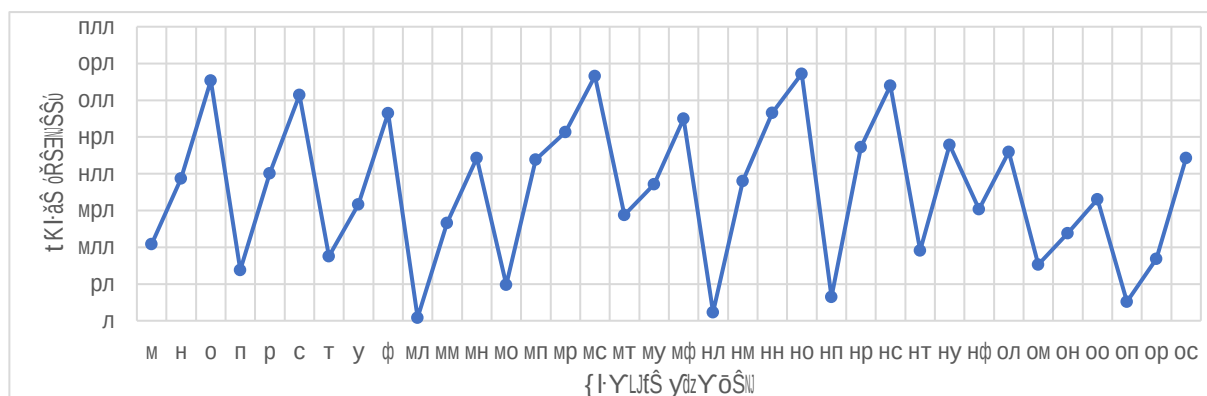


Figure 3-18: Phase measurement for tag moving at 5kmph produced by antennas facing the direction of travel with a 45-degree angle

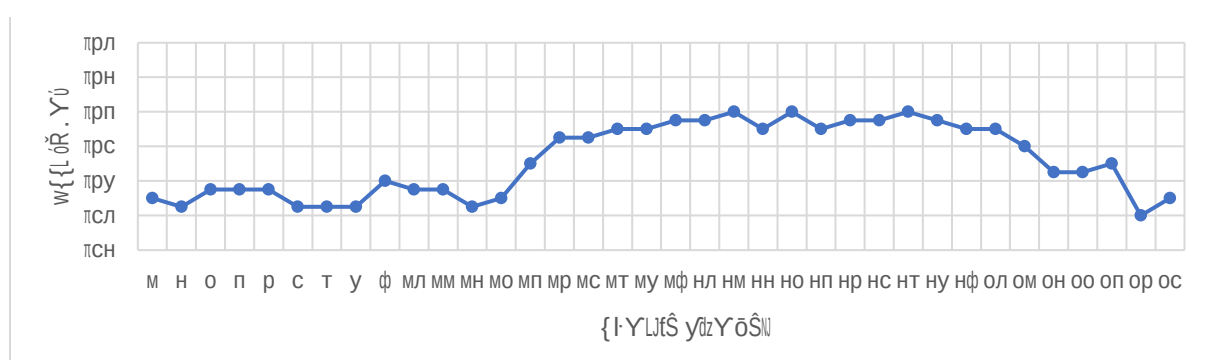


Figure 3-19: RSSI measurement for tag moving at 5kmph produced by antennas facing the direction of travel with a 45-degree angle

Already similarities can be seen between the first setup and this one. Looking at the faster speeds, again it becomes more difficult to determine the behaviour of the moving tagged item. The phase data in the first figure below shows that there is still a constant increase in phase as the tag approaches the antenna, but due to less samples before wrapping occurs this pattern is more obscured. In the data for the tag traveling at 7kmph the direction of movement

is almost indiscernible as there are now in most cases only two measured samples before phase wrapping occurs.

The same is true for the RSSI data where it is unclear how the data correlates to the movement of the tag. There is an initial increase in the signal strength but after this there is too much variation to draw any conclusions from this data.

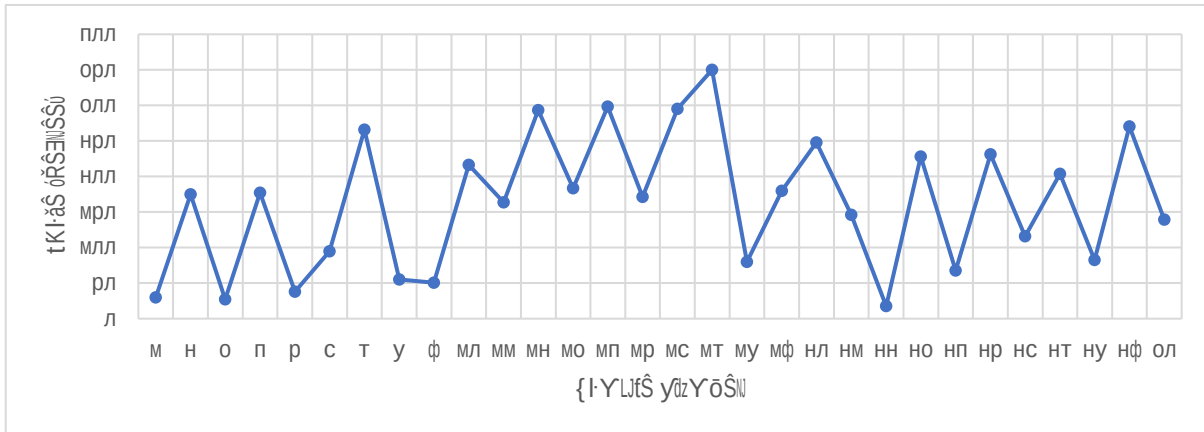


Figure 3-20: Phase measurement for tag moving at 7kmph produced by antennas facing the direction of travel with a 45-degree angle

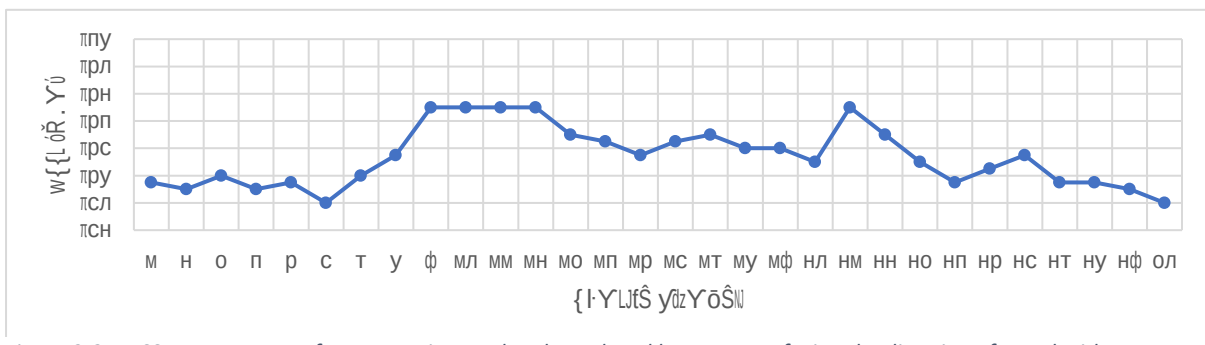


Figure 3-21: RSSI measurement for tag moving at 7kmph produced by antennas facing the direction of travel with a 45-degree angle

From these samples it can be seen that more data per passing of the tag exist in the first setup, there is also a more consistent relationship between the data seen and the expected behaviour of the signal response. Multipath effects and the non-ideal travel angle with regards to the antenna, means that velocity estimation based on the data for experimental setup 2 will be troublesome.

3.1.3 Experimental setup 3: Antennas angled parallel towards the oncoming direction of the tag movement.

The setup, illustrated by figure 3-6, is typically used to ensure that a tag, that is attached to the front of an oncoming object, is read. This ensures a good reading in one direction and can even, in a narrow field, be reduced to only one antenna on one side of the passageway. Theoretically in an open field where there are no reflections this type of setup will be suitable for motion estimation due to the angle of travel with regards to the antenna, where the tagged object moves close to the line towards the centre of the antenna for a greater period of time. Reflections and interference are constant obstacles and their influence will also be investigated here. Looking at the tag moving at 3kmph, there is a clear increase in phase with wrapping at the 360-degree mark throughout the movement of the tag. From the RSSI data it is unclear whether any pattern exist. An initial increase in signal strength followed by a tapering off near the end of the reading can be as a result of the tag moving from the main antenna radiation lobe to one of the side lobes, but can also be caused by the asymmetrical setup. This illustrates how the phase measurement is less affected by reflections and multipath than RSSI readings. Both the phase and RSSI data for one passing of the antennas are shown in the following two figures.

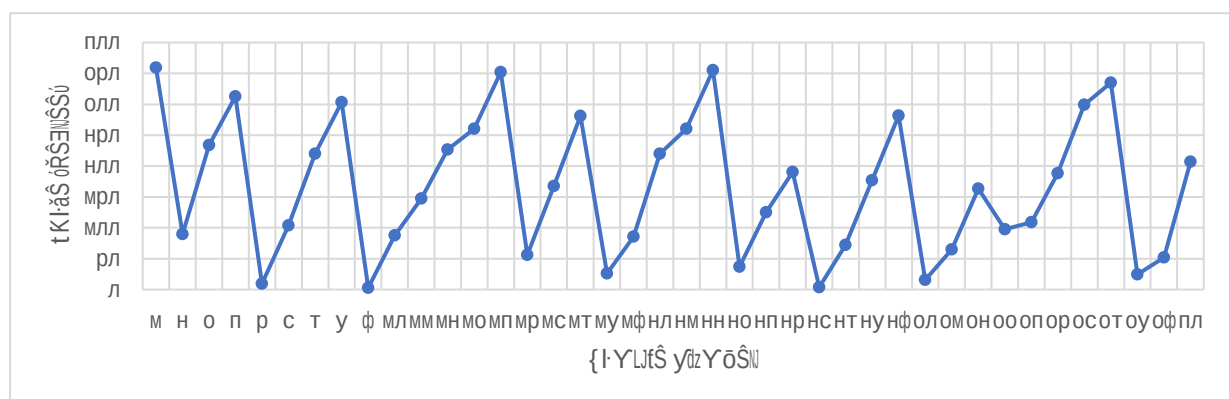


Figure 3-22: Phase measurement for tag moving at 3kmph produced by antennas pointing parallel towards the oncoming direction of travel of the tag

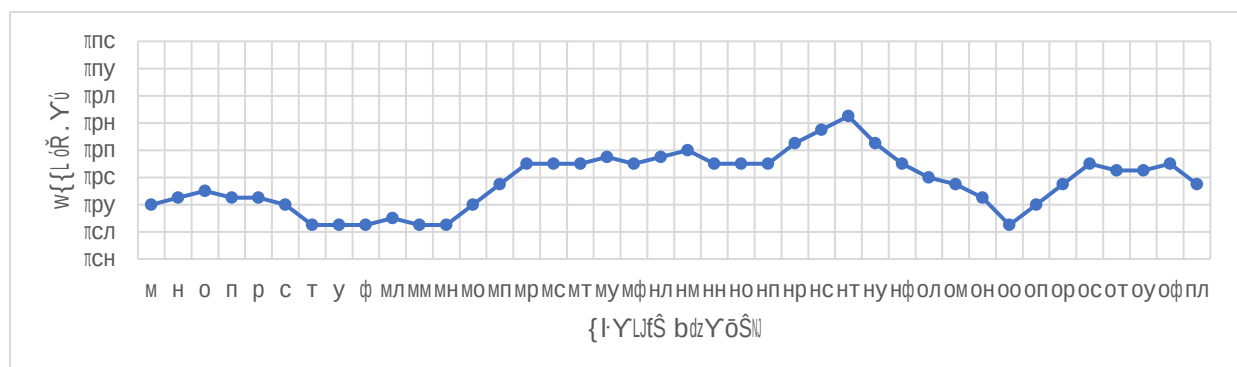


Figure 3-23: RSSI measurement for tag moving at 3kmph produced by antennas pointing parallel towards the oncoming direction of travel of the tag

Observing the data from the faster moving objects the same pattern is true, where the number of samples decrease, the wrapping effect in the phase reading is more prominent which will make it more difficult to use the data produced. This also results in the RSSI data becoming irregular and less consecutive samples per antenna channel is produced. To avoid repetition only the figures showing the phase and RSSI data for the 7kmph experiment are shown below.

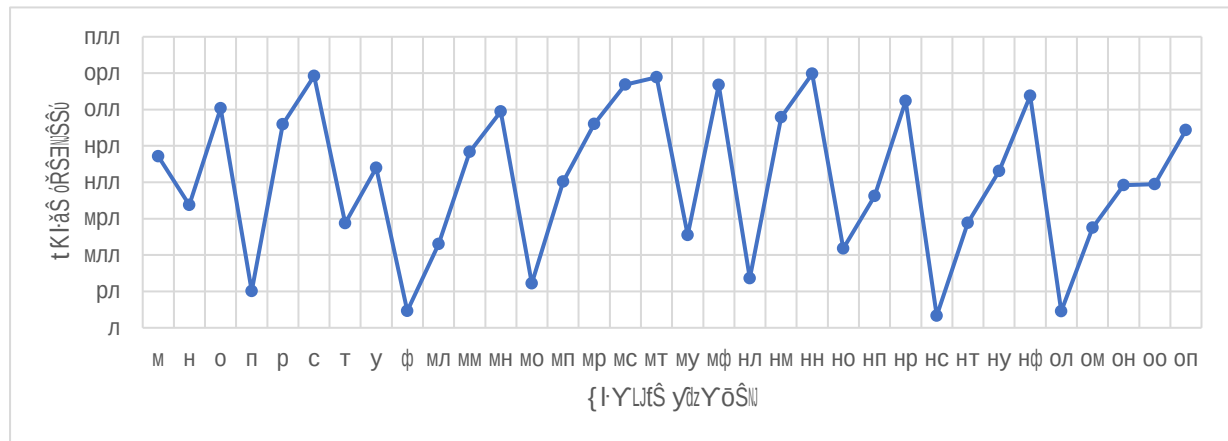


Figure 3-24: Phase measurement for tag moving at 7kmph produced by antennas pointing parallel towards the oncoming direction of travel of the tag

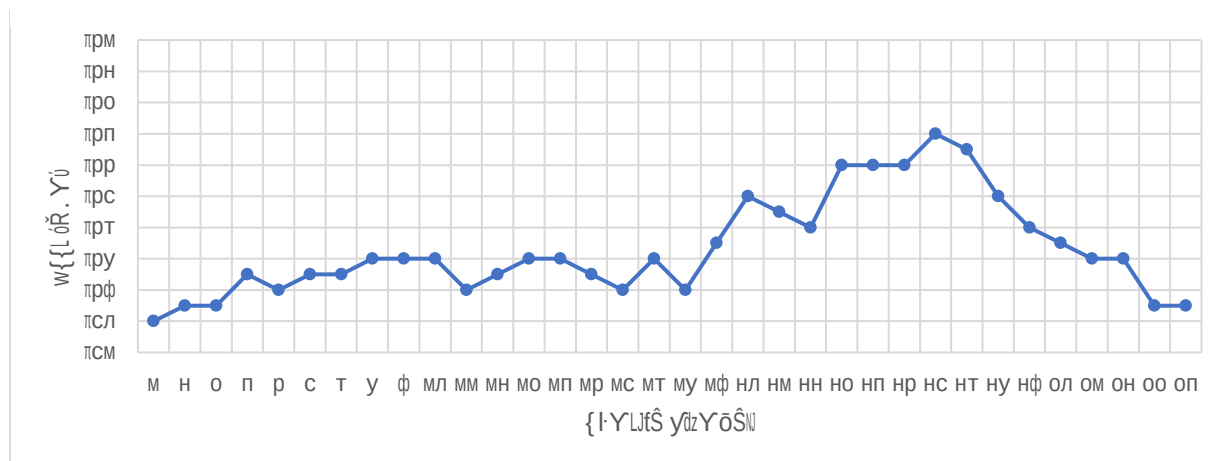


Figure 3-25: RSSI measurement for tag moving at 7kmph produced by antennas pointing parallel towards the oncoming direction of travel of the tag

Since only data from one antenna is shown, there exists a need to include the number of samples per passing of the tag. For this reason, a table is included in section 3.1.5. that shows the different number of samples recorded per instance of the experiment for each setup.

From the data above it can be seen that there is a clear wrap around effect where the phase constantly increases from a certain starting point. Per frequency band and antenna channel, one can clearly see a definitive increase in the phase. One aspect that was not accounted for is the lack of RSSI change. For an entire frequency band hop, there were no change in RSS. It was first believed that this will clearly increase incrementally as the tag travels closer to the antenna, but from this data it can be seen that from the samples this is not as clear. There is even a slight decrease in RSSI for certain samples even though the tag travelled closer to the antenna with a relative constant speed. This shows that due to multipath reflections and

standing wave patterns of the signal there can be certain 'dead spots' in the antenna range where there is destructive interference. Other parts might experience a stronger signal further away from the antenna and will result in a stronger RSSI. This finding means that comparing the RSSI is not an effective method in a lot of instances. By comparing the data, it shows that the phase increases constantly per frequency hop, although the RSSI might stay the same. This can be seen throughout the different speeds but is more prominent in the slower runs. First impressions show that this setup is an improvement on the previous ones and without reflections this setup will be even better for motion estimation. All setups included in this study has proven their advantages and for only direction estimation all can be considered possible candidates for implementation in real-world scenarios. Velocity estimation will need a more precise setup and will be chosen based on the controlled direction of travel.

3.1.4 Experimental setup 4: Antenna 1 facing towards the direction of travel and antenna 2 facing in the opposite direction

This setup effectively divides the movement of the tag into two parts, one where the tag is moving toward an antenna and one where the tag is moving away. The movement away from the antenna is a bit more challenging to accurately detect and separate from the movement towards the antenna. Since the tag is not necessarily in the line of sight of the antennas reflected signals can power the tag, as a result of the tagged object being between the tag and the antenna. This means that the phase will react different than a tag that moves away from the antenna with direct line of sight. The phase still changed as expected, but the RSSI is constantly lower in the area where the object moves away from the antenna, compared to the part of the movement where the object is moving towards the antenna. One of the advantages of this setup is that directionality determination is already incorporated, since detecting a tag first on the one antenna and then on the other shows in what direction the tag is traveling. This is not definitive since the placement of the tag on the object can mean that it might not be read by one antenna but will be read by the other. The phase and RSSI data for the tag moving at 3kmph can be seen in the next two figures, with the results for each antenna shown separately to simplify the graph. Antenna 1 is used to track the oncoming movement and antenna 2 the movement away.

The phase change seen in figure 3-26 shows a steady increase in phase as the tag approaches the antenna, followed by a short period of variable data and then a steady decrease in phase measurement as the tag moves away from the reader. The RSSI measurement is more discernible, where there is a period of increase in signal strength as the tag approaches antenna 1 but, for the movement away from antenna 2 the signal strength is constantly low.

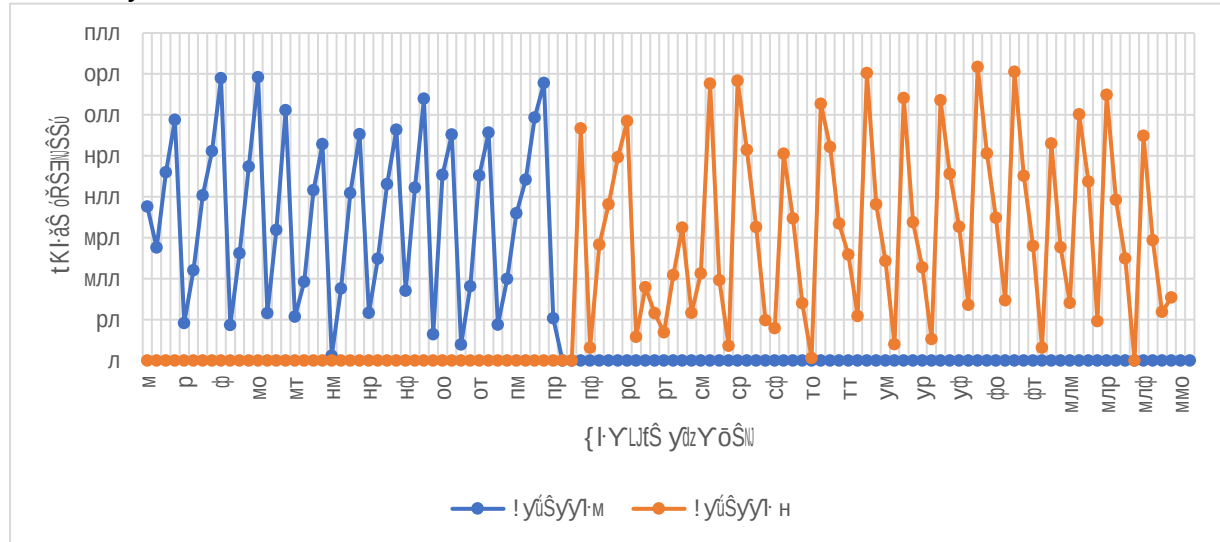


Figure 3-26: Phase measurement for tag moving at 3kmph produced by an antenna facing parallel towards the oncoming direction of travel and the other in the opposite direction away

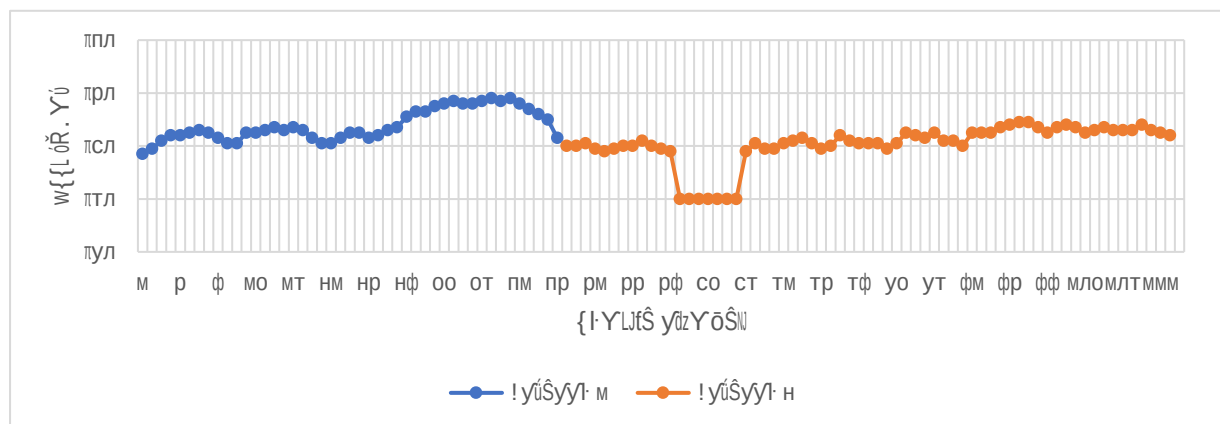


Figure 3-27: RSSI measurement for tag moving at 3kmph produced by an antenna facing parallel towards the oncoming direction of travel and the other in the opposite direction away

From the data of the tags traveling at higher speeds, the difference in phase per reading is bigger for consecutive reads. This is to be expected since the distance travelled is bigger. As mentioned in the literature as long as the speed at which the tag is traveling is less than the maximum speed that can be tracked, it will still be possible to fairly accurately determine the velocity of the tag. The only concern is the unwrapping algorithm will need to be better for faster speeds, since less data between wrapping points is available. This setup shows exactly what was expected from the theory, which is that the phase will increase along with the RSSI from one side and decrease going away from the antenna on the other side. This setup

provides data in such a way that the tag can be sampled for a longer period of time and thus provides additional advantages above the other setups. The most important thing to keep in mind with this setup is to place the antennas in such a fashion that it will have a good enough field of view to sample tags that needs to be read. This setup is very directional and would not be suited for all applications. In a corridor or narrow pass-through this will however be a very good setup, since the tags can be tracked for a long time. The figures for the tag traveling at 7kmph is included next, this shows certain problematic areas, where the phase wrapping is more frequent as a result of bigger changes in phase, it illustrates the decrease in available samples to draw conclusions from and also the lack of resolution and variability in the RSSI response. The 5kmph data is a good middle point between the effects seen with the 3kmph data and the 7kmph data and was omitted as it shows the same pattern that was seen in the previous setups.

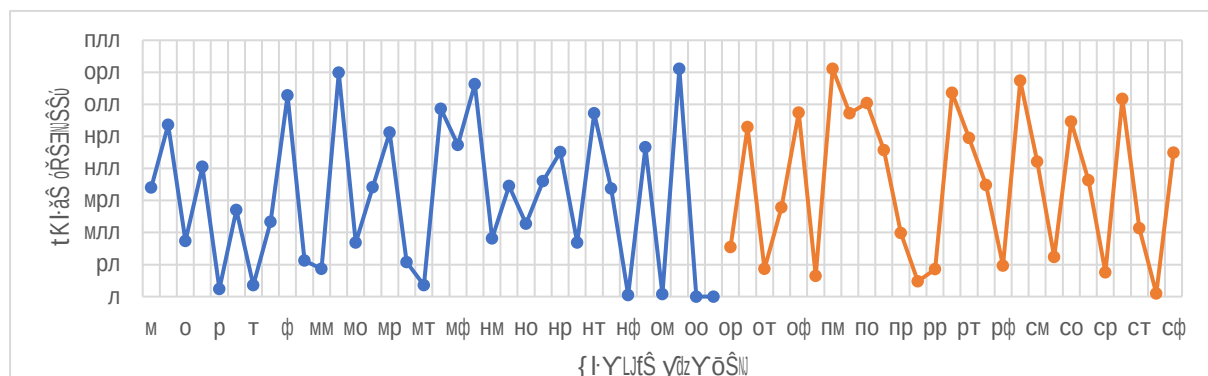


Figure 3-28: Phase measurement for tag moving at 7kmph produced by an antenna facing parallel towards the oncoming direction of travel and the other in the opposite direction away

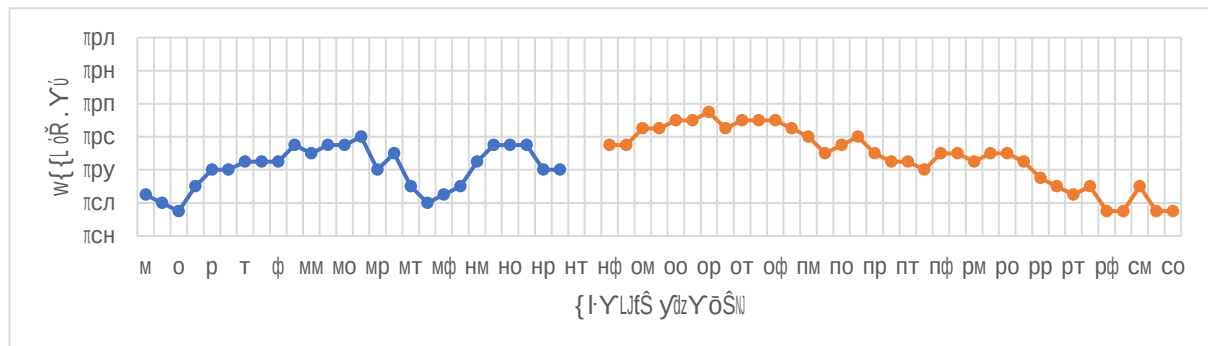


Figure 3-29: RSSI measurement for tag moving at 7kmph produced by an antenna facing parallel towards the oncoming direction of travel and the other in the opposite direction away

At the faster speed measurements, the data is not as clear as with the slower speed. Phase values still show the increase as the tag approaches and decrease as it moves away from the antenna. The RSSI shows a slight, irregular increase towards the antenna and slight decrease away from the antenna, but the changes are not very big.

Considering the propagation area of the RF antenna, this setup should be most ideal for motion estimation of a tag since it provides the longest observation time of the tag movement

as well as being the most centred towards the line of movement, increasing the correlation between a change in phase and a change in distance.

3.1.5 Summary of experiments

From these experiments it is clear that antennas that are more suited to close range reads in a door frame type of scenario, produce a lower signal strength than what can be expected from long range readers. The equipment was used based on availability and was sufficient for the goal set out for these measurements.

One aspect that will increase the reliability of the motion estimation is the number of samples taken per passing of the antennas. The following table shows the average number of samples recorded at 5kmph for each of the different setups per single passing of the antennas along the straight line of movement.

Table 3-2: Average number of successful reads per tag, per passing of the antenna

Experimental setup	AVG number of samples measured
М	НП
Н	НУ
О	ОЛ
П	ПН

From this table it can be seen that the setup with the most reads is setup 4. This is as expected since this setup records data on both sides of the centre point of movement. The next best setup is also as expected since this setup is angled more towards the initial position of the moving tag, meaning that it tracks the tag for a longer period. This will be even more true in a scenario where there are less reflections, since the reflections present in the environment aided setup number 1 and 2 to produce more successful reads in this space.

These experiments provided valuable insights into how the different antenna setups can influence the signal response from the tags. This also provided more information on the effects of multipath and reflections for the setups where the antennas were angled more towards the wall, producing more reads than expected but also having more variability in the signal strength as a result. The last 2 setups provided the most reads and the least amount of variability in the signal strength and phase responses.

All the setups have their advantages and disadvantages and from this test it seems that it will be possible to use any one of the setups to determine the direction of travel. The difference in measured phase patterns is clearly different for the direction of travel for each setup supporting this statement. With some setups these phase patterns are clearer than other, but for velocity estimation the number of samples available has a big impact. Thus, the setup with the clearest phase pattern does not necessarily have the highest number of samples of the movement.

This means that one of the aforementioned setups will be more suited to velocity estimation, but that the direction estimation will be possible with anyone of these setups.

The patterns produced by the data and samples during these tests provide a clearer understanding of how the tag parameters changes when moving in a certain direction at a constant speed. In experiments further in the study, tags moving at varying speeds and multiple tags in the field of view will be tested. This would enable the final product to function in a real-world scenario.

3.2 Antenna setup design suitable for real-world applications and motion estimation

Section 3.1 provided valuable insight into the effect that different antenna setups will have on the tag response of the RFID system. The ideal system to detect motion estimation in real-world applications will be one that produces sufficient samples per frequency hop on an antenna channel, limiting the direction of movement of the item, as close to the centre of the antenna along the movement path as possible, while ensuring that it is reproducible every time. The placement of the tags on the tagged object also influences this ideal setup. For the purpose of this study, it will be assumed that the tag placement is always on the front of the object or hanging from the front of the object meaning that antennas looking toward the oncoming direction of travel will be able to read these tags.

From the theoretical understanding of antenna signal propagation, as well as the practical measurements in 3.1, a system capable of producing reliable and sufficient velocity estimation will have at least one antenna facing in the direction of the theoretical start of the straight line of movement. Another antenna can face either in the opposite direction along the line of movement or also towards the start. The optimal choice will depend on the area where this is implemented, if the tagged object can move in a straight line for this distance and if antennas can face both directions.

Practically the placement of the antenna can be either on the sides of the line of movement as seen in figures 3-6 and 3-7 or it can be placed above the line of movement. This can typically be deployed if the tagged object passes through a door frame and the antenna can be placed on the door frame. For this scenario to be more suitable the tag(s) should also be placed as high as possible to come closer to the height of the antenna. This type of setup is illustrated in figure 3-30, the antennas will face in a direction that is closer to parallel to the ground.

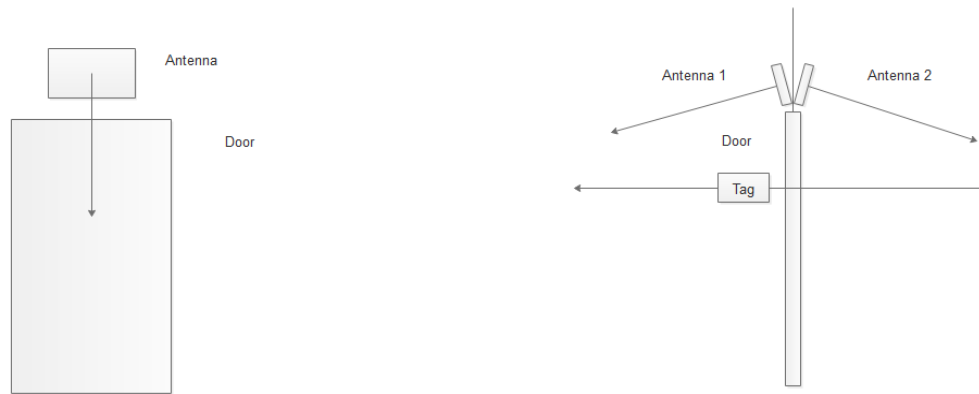


Figure 3-30: Antenna setup on top of a door frame (Left: View from the front; Right: View from the side)

This setup is limited to specific scenarios since the optimal tag placement and placement of antennas from the perspective of direction detection is not often practical based on other considerations.

For this study the scenarios that will be used in the investigation of motion estimation will be the setup seen in figure 3-6 and 3-7 and can be reduced to only include 1 antenna facing towards the oncoming tag. These two setups can be implemented in most inventory or item tracking systems in practice and will also provide the best platform to perform a velocity and direction estimation. This setup also simplifies the testing environment contributing to the final decision.

3.3 Challenges posed by phase wrapping in practice

Phase wrapping, as discussed in 2.13, is something that occurs when the phase increases or decreases beyond the range of the reader. For the Impinj reader used in 3.1 this range is between 0 and 360 degrees. The impact this has on measurements in a practical environment, when the movement of an RFID tag is tracked, can be seen in figure 3-10 and 3-16. In figure 3-10 it can be seen that for the first part of the signal analysis, phase wrapping occurs at the top of the range, at the 360-degree mark. This is for the part of the signal where the tag approaches the antenna. For the second part of the signal the phase wrapping occurs at the bottom of the range, at the 0-degree mark, as the tag moves away from the antenna. For this slower moving speed there exists a clear increase and decrease in phase for the different stages where up to 5 samples are between the lower and upper limit before the wrapping occurs. The same is true for figure 3-16 where there is an increase in phase for more than 3 samples before the wrapping occurs in the upper limit of the signal. Both of these illustrates an ideal case where sufficient data and read rate allows good tracking of the behaviour of the tag. For a worse case example one can look at figure 3-20, where the speed is increased and less samples exist between wrapping points. A slight increase in phase can be seen, but because of the big difference in phase readings it is troublesome to determine whether the

phase is increasing or decreasing. This is one of the biggest difficulties besides ambiguity that an unwrapping algorithm face.

This illustration shows what logic operation is needed to determine whether wrapping has occurred and whether the wrapping was as a result of the phase increasing over the top limit or decreasing to a value below the lowest limit. Some historical data or initial estimation can help with this where the phase behaviour of a few samples is taken to determine whether the phase is increasing or decreasing and when a wrapping event occurs this can then be rectified by adding or subtracting a multiple of the upper limit of the readers range. These examples provide a good overview of how the expected signal will look like in practice and what type of input an unwrapping algorithm will have to solve for these applications.

3.4 Conclusion

This chapter provided a crucial insight into the expected signal response received from an RFID tag when moving, how the different antenna setups influences these readings and provided good examples of challenges such as phase wrapping and line of movement of the tag that will have to be controlled in order to successfully implement motion estimation of a moving tag.

Constructing the different antenna setups based on real-world scenarios did not only prove valuable in determining the setup that will be used for further applications of motion estimation but also provided insight into how these setups can be used in different scenarios to improve the tracking of RFID tags.

4 Design

In this chapter the design of the different aspects of the motion estimation algorithm will be discussed. This will include the velocity and direction estimation algorithm designs, mathematical models for the different Kalman Filter implementations, reader settings and equipment choices used to design a possible practical solution and all other techniques used to improve the accuracy of the reading for different scenarios.

4.1 Reader settings and equipment chosen for measurements

The RFID reader equipment and the different settings chosen for the implementation of the motion estimation algorithm will have an impact on the results. The aim for this study is not to produce a complete solution to motion estimation, but rather develop techniques that can be applied to different scenarios using different equipment in the future. For this reason, the only constraints on the equipment choice are availability and it should be COTS available equipment that a user can buy from a retailer.

The first equipment choice is the RFID reader used. There are a lot of similarities between the different readers available on the market, which means that most readers with Gen 2 capabilities will be suitable for application of the motion estimation algorithm. The availability of readers provided by the university and industry partners were narrowed down to the Impinj Speedway R420 reader and the Thingmagic Mercury 6e reader. Both readers are used widely in the industry. The one advantage of using the Impinj reader for development above the Thingmagic reader is the LLRP protocol designed by Impinj specifically for their readers. This provides the developer with easier access to some features of the readers. The Thingmagic reader however is smaller in size, which means it can more easily be integrated into a complete system in real-world applications. The difference between the Thingmagic reader and the Impinj reader is very small. The Impinj reader is capable of reading phase data between 0 and 360-degrees while the Thingmagic reader limits this to between 0 and 180-degrees, any phase value bigger or smaller than this value will be wrapped to remain between these limits.

This difference in phase range can limit and reduce the effectiveness of the algorithm by requiring a wrapping occurrence more regularly. The small form factor of the Thingmagic makes it suitable for possibly more implementations in real-world scenarios where remote systems are deployed, or where there are power constraints. This is the reason, the Thingmagic reader was chosen for the implementation of the algorithm; to support the idea that the algorithm should work on most COTS equipment.

The other main equipment choice that will directly affect the readings is the antennas chosen for the measurement. This is also limited by availability. The two types of antennas available

are the Poynting Patch 25 antennas and the Times-7 A8060 Door Frame Antenna. The Times-7 antennas are mostly suited for reading tags in a short-range environment and would thus not be efficient in tracking the tags from a long distance. The choice for the antennas is therefore the Patch 25 antennas. They are also circularly polarized making the tracking of tags with different orientations easier. The antenna is optimized for the frequency range between 860MHz and 960MHz, ideally suited for the RFID band in South Africa.

Some settings can greatly influence the functionality of the algorithm and some settings cannot be managed without. In order to maintain a high sample rate, the session should be set to session 0 and the target needs to be set to both A and B. Some readers have a setting for this to set the states to BA which can result in even more reads per second. This means that even though a tag has already been read, the tag will still respond to the read requests. This combination of settings will result in maximum throughput for the number of samples recorded by the reader. The downside of using these settings is that if there are a lot of tags in the reading range, these settings will not ensure that all the different tags be read.

Other settings that influences the efficiency of the algorithm is the time between frequency hops. It is recommended that this is set to the maximum time allowed by the country's local standards. The maximum time allowed by the Thingmagic reader was just under 400ms. Thus, the hop time was set at 375m, which means every 375ms there will be a change in the carrier frequency to the next frequency in the hop table defined. The hop table is chosen to maintain the frequency inside the band defined for RFID in the local standards. Lastly, the power of the reader can be adjusted according to the scenario. For this application it was assumed that there will be open space to move in and thus this was set to the maximum power of 30db, defined by the reader and limited by standards.

This was a short summary of the most important settings used in these experiments and why this was chosen. With each experiment the different setups used in each case will also be explained.

The different models and algorithms explained in this chapter will be implemented using a standard computer, but will also be adjusted to run on a Raspberry pi 3. This means that it will also be able to run on typical external real-world scenarios where the system deployed does not necessarily have access to big computing capabilities.

4.2 Phase unwrapping algorithm design

Unwrapping forms a crucial part of the overall functionality of the velocity calculation and motion estimation of RFID tags. It is important to design and implement an unwrapping algorithm that adds a low amount of processing to the overall program but is still efficient in most cases of wrapping. The unwrapping algorithm forms the basis of the motion estimation

algorithm, since any error that creeps in here will be exaggerated in the following steps in the program. The unwrapping should be able to correct signals that have small phase changes as well as bigger phase changes within the limits.

The biggest difficulty is determining whether the signal pattern causes an increase or a decrease in phase. If this is known then determining when a wrapping event occurs becomes much easier. If a moving object has a velocity close to the maximum determinable velocity from the first time that it is detected, unwrapping that signal becomes extremely difficult since the change in phase is almost a complete phase cycle. What this means is that the change in phase is close to the limit of the reader capability. If the reader reads the phase of a signal between 0 and 180 degrees and a phase change of about 170 degrees is measured from the moment the tag is powered up, the logical decision based on this data would be that a phase change of 10 degrees occurred instead of the change of 170 degrees. This means that either some initial estimation of the system being measured should be known which can mean always taking the biggest possible phase change, or a parallel system needs to be implemented where other factors are used to determine whether the tag is traveling at the faster or slower speed. Some of these factors can be to take the time that the tag was in the reading range, the number of samples or to use the change in RSSI. All of these factors however add uncertainty to the solution and can be interpreted wrongly if excess noise, reflections or bad reads are present in the system.

The focus of this study is to determine whether motion estimation of a moving tag is possible in scenarios where all the requirements of a practical environment are adhered to. For this reason, a simpler approach to unwrapping is followed, where it is assumed that the system where this algorithm is applied will be characterizable. This means that there will be some information regarding the expected velocity of the tag. This means that the unwrapping algorithm can be adjusted to assume the biggest or smallest jump in phase depending on the scenario. It can also be assumed that for slower moving objects there will be sufficient data to determine whether the phase is increasing or decreasing. For this to be determined there needs to be at least two samples within the limits of the reader, before wrapping of the phase signal occurs. Figure 4-1 below illustrates the logical operation of the unwrapping algorithm design.

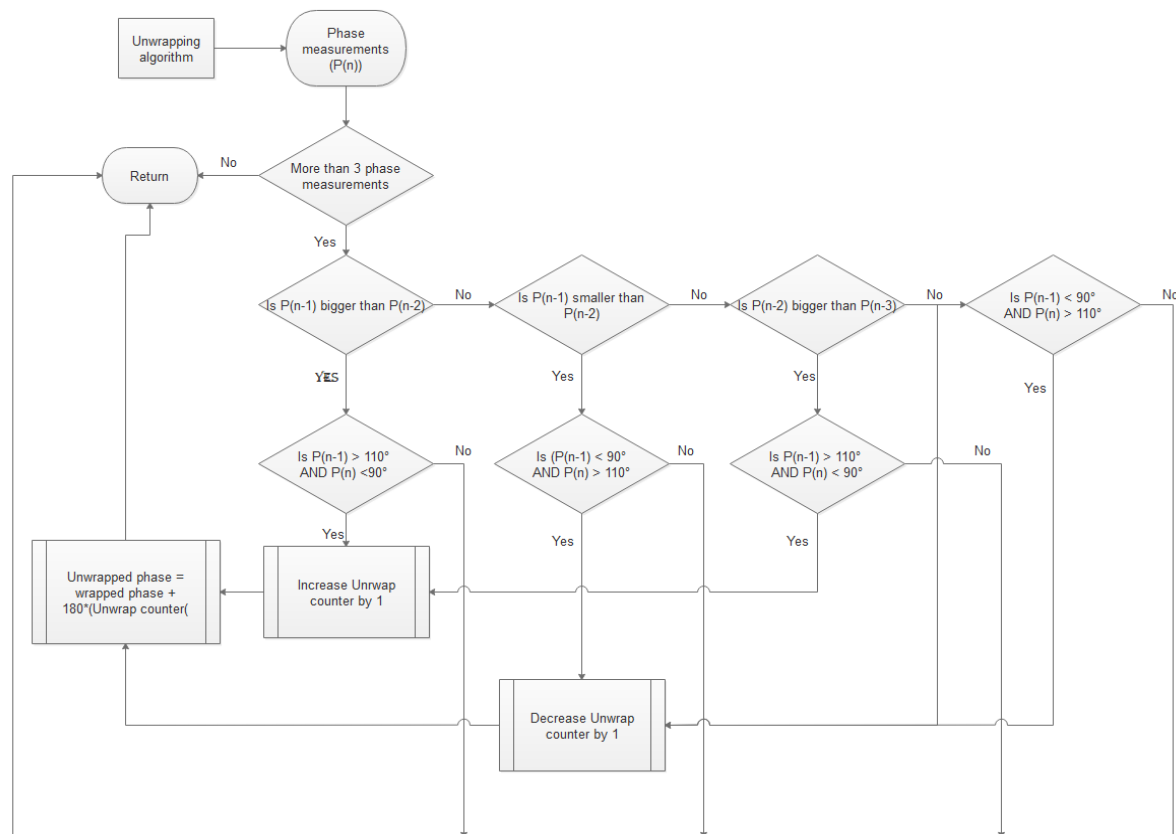


Figure 4-1: Unwrapping algorithm logical flow

In the figure above it can be seen that there are several logical gates and rules to determine the outcome of the wrapping event. Firstly it is monitored whether at least three phase samples have been recorded, if not the process will return and wait until it is true. If there are more than three samples the previous two samples are compared to see whether the phase increased or decreased. If it increased then the current phase sample and previous are compared to see whether a wrapping event occurred such that the latest sample is actually a bigger phase value. If wrapping occurred then one is added to the unwrap counter, otherwise no wrapping occurred and the process returns. If the previous two samples that were compared showed that the phase decreased then the current phase measurement and previous one are compared to determine if wrapping at the 0 limit occurred. If this happened the unwrap counter are reduced by 1. If the previous two phase samples are equal then the two samples before that are compared to determine whether the phase increased or decreased before checking if a wrapping event occurred. The unwrapped phase is then the summation between the current phase value and the product of the unwrap counter and 180. This will produce continuous phase values that can be compared to determine the velocity

For the unwrapping algorithm it is assumed that the phase measurements are already collected and in an array format that is easy to access and it is possible to access previous measurements. At the end of the operation, the unwrapped phase will be increased or decreased by 180 degrees times the number of wrappings that have occurred in a specific

direction. This value of 180 degrees is determined by the phase reading range of the reader used, as discussed further in section 4.8.

The unwrapping algorithm needs at least three phase samples to work effectively. This will determine firstly, whether the phase is increasing or decreasing and there after determine when a wrapping occurred, adjusting the phase value as described in the figure above.

The complexity added to the overall program is very little since the primary operation consists of if statements. This means that it will still be able to perform the process quickly and enabling it to run on a smaller form factor computer like a raspberry pi, if needed in the real-world scenario.

4.3 Velocity and direction estimation algorithm

Several techniques were discussed regarding motion estimation of an RFID tag. From the different techniques discussed in chapter 2 with relation to motion estimation, the most promising results came from the PDOA technique and especially the time domain technique. One study (made by Pujare et. al) proved that this technique can work efficiently to determine the velocity of several tags in the reading range. This technique however did not adhere to all the broadcasting standards, specifically frequency hopping. This is something that needs to be added to the technique in order to fully test the capability of such a method in a real-world scenario where these standards need to be conformed to at all times.

To calculate the velocity of a moving tag, successive readings on the same frequency channel from the same antenna are needed. The frequency and time between samples must be known. An assumption is made that the tag is traveling directly towards the centre of the antenna even though there might be a slight variation in the line of travel. It is also assumed that for these measurements the tag will be moving in a straight line. This is to prove the concept that it is possible to determine the velocity of a tag, while adhering to local standards. The change in phase can be converted to a change in distance using the frequency band the signal is sent over and converting it to a wavelength. This relationship is shown by equations 2.13-2.15 and repeated below for convenience.

$$V = \frac{c\Delta\phi}{4\pi f\Delta t} \quad (2.13)$$

$$\Delta\phi = \Phi_1 - \Phi_2 \quad (2.14)$$

$$\Delta t = t_1 - t_2. \quad (2.15)$$

The input to the velocity estimation algorithm is the unwrapped phase signal, the frequency band the samples were taken at as well as the times the samples were taken at. Frequency f is in hertz, the time difference, Δt is in seconds with a resolution of up to a microsecond scale and the phase difference $\Delta\phi$ is measured in radians.

This technique will be used to calculate the velocity of a moving item. Key aspects to be included in the software is storing at least the previous tag response sample, including the timestamp, phase, RSSI, and frequency band data. A proposed architecture will be to implement the system such that at least the five latest samples are stored in an updated array for each unique tag read. Every time a new sample is measured it will then replace the oldest sample data. In this way the overhead memory use of the algorithm is kept low, but enough data is available to keep applying the velocity estimation with possibilities to include smoothing and other filters to the data. Further implementation for correction algorithms/filters that will be applied to the velocity estimation is discussed later in this chapter. This velocity estimation will also include inherent direction data. This direction of movement will be using the movement towards or away from the antenna as reference. A positive estimated velocity is a result of the tagged object moving closer to the antenna and a negative estimated velocity is as a result of the tag moving away from the antenna. This can also be used in further filters to determine which tags are moving in through a portal and which tags are moving out of the portal.

As mentioned earlier, switching from one frequency channel to another will have an impact on the performance of this technique, because two samples from different frequency channels cannot be compared to determine the change in phase. This means that every time there is a change in frequency, one phase sample pair is lost. This will affect several characteristics of the system, including the maximum and minimum detectable velocities of the tagged object, the accuracy of the instantaneous detected velocity and as a result the reliability of the overall performance. The influence is mainly as a result of effectively reducing the sample rate, where roughly every 0.4 seconds two samples are lost. These 0.4 seconds is the limit in South Africa, for an RFID system, before an obligated frequency change is required in the FCC band.

Initially it was thought that by defining the change in phase due to the change in frequency for each individual tag, that a factor could be determined that could be used to estimate the effect. In other words, determining the effect of the frequency change on the change in phase and multiplying it with the measured values could result in a phase change purely as a result of the change in distance between the tag and the antenna. This was proven wrong by looking at the effect of the change in phase for a moving item. Below is a definition of a change in phase, where the change in phase is measured by subtracting two consecutive unwrapped phase measurements from each other. This phase changed is defined by equation 4.1

$$\theta_{2-1} = \Delta\theta = \theta_2 - \theta_1 \quad (4.1)$$

Two factors result in a measured change in phase, namely a relative change in distance between the antenna and the tag and the change in wavelength for each signal response as a result of the change in frequency between the two samples. Equation 4.2 shows this result.

$$\theta_{2-1} = 2\pi \left(\frac{2R_2}{\lambda_2} - \frac{2R_1}{\lambda_1} \right) \quad (4.2)$$

Where R_2 and R_1 is the distance between the antenna and tag for sample 2 and sample 1. λ_2 is the wavelength of the second carrier frequency and λ_1 is the wavelength of the first carrier frequency. The distance is multiplied by a factor of 2 since the RF signal have to travel the distance R towards the tag and then the same distance back to the antenna from the backscatter wave. Simplifying the equation to 4.3 shows that problem in solving this equation for each tag:

$$\theta_{2-1} = \frac{4\pi(R_2\lambda_1 - R_1\lambda_2)}{\lambda_1\lambda_2} \quad (4.3)$$

From equation 4.3, the wavelengths of both samples are known, but no distance information is measured. This means that there will always exist the two unknown variables in R_2 and R_1 with only one equation to solve them, thus resulting in an unknown effect between the change in phase and the change in distance. It is for this reason that adding frequency hopping to the algorithm increases the complexity of the solution and will lower the sample rate. If 7 to 10 samples on average for each frequency band are available, the decrease in the number of samples available for velocity estimation will be around 12.5% - 9%. If the number of samples per band increases the effect will also be decreased, but the reverse is also true, meaning that in less ideal conditions where the reading rate is low due to a high number of tags in the reading range or excessive noise, the effect of a loss in samples due to frequency hopping is also increased. This can be solved by installing a known RFID tag at a fixed location in the beam. By installing this reference point the phase shift due to a change in frequency can be measured which can be used to resolve the uncertainty in the phase unwrapping and reduce the samples lost.

Implementing the velocity estimation in equation 2.13, delivers an instantaneous velocity as a result of the change in distance. There are two approaches to overcome the effect of the loss of samples due to the frequency hopping. The first approach will work in a system where the velocity of the moving object is fairly constant. For this approach each time there is a frequency hop, the estimated velocity for that lost sample pair is replaced with the previous successfully calculated velocity estimation. This will help in smoothing out the velocity when these samples are lost. The downside to this approach is that if the previous velocity value is affected by high noise levels and as a result is very inaccurate, the effect is doubled by duplicating it into the next value. Further smoothing and correction filters/algorithms can help fight this effect but adding such a defect to the estimation is not ideal and should be avoided when the possibility for this happening is higher.

The second approach is more conservative and is the one that will be followed most of the time. Here the velocity estimation for the phase pairs between frequency hops is ignored. This

omission lowers the number of samples but prevents any inaccuracies from having a further impact on the overall performance of the system. In the scenarios where there are a high number of samples per frequency hop, this will have a very small impact. This can be influenced by limiting the freedom of the read environment by either setting up the antennas in such a way that only a limited number of tags can be measured with limited reflections at a time or by restricting the movement of the tagged object.

This section described the process of calculating the velocity and basic direction of a moving tagged object while adhering to local standards. The following sections in this chapter will discuss methods to improve on a possibly noisy outcome of this algorithm and later chapters will test the impact of different variables, that exist in real-world scenarios, on the reliability and variability of this technique.

4.4 Phase based Kalman Filter for velocity estimation

It is expected that the velocity estimation algorithm will not provide a reliable output in all scenarios, but rather an instantaneous velocity estimation that contains some noise. This noise will be as a result of reflections and external influence on the RF measurements. Tolerances in reading equipment, inaccuracies in the unwrapping algorithm, non-ideal movement from the tagged object veering from the suggested movement line and a bad sampling rate can all cause variance in the velocity estimation, which in turn can result in variability in the data for an object that is moving at a constant velocity. These uncontrollable variabilities create certain limitations on how accurate the velocity estimation can be, creating the need for another method to improve upon these readings by either adding knowledge about the system into the equation or adding another parameter that will give more information on the system.

To improve the readings obtained from the velocity estimation algorithm, a Kalman filter is proposed to improve the estimation, based on the measurements obtained as well as a model designed for the motion of a moving object. As mentioned in 2.12 Kalman Filters have been successfully used in improving the readings for object tracking which further motivates the decision to use this technique to improve upon the noisy readings in this environment. The method used for this application and explained below, is based on the method and model described by Pujare, et al. in [46]. The filter was explained in section 2.12.

In order to have a real improvement in the estimation, the Kalman Filter requires an accurate model of the scenario. The scenario defined in this study assumes predictable behaviour of an object. This predictable behaviour means that it can be assumed that the object is moving at a constant velocity in a certain direction. For another scenario it will be tested how well this solution will work for instances where the object is moving at a constant velocity and then

accelerates at a constant acceleration. Thus, the model of the moving object should be able to predict the constant instantaneous velocity at which the tagged object is moving.

Basic equations in science describing the distance, velocity and acceleration of a moving object, is known as the Kinematic equations of motion in physics. These equations shown below are well known and can be expanded to include other external influences on these variables. The equations, 4.4 to 4.7, show the relationship between the variables mentioned above.

$$v = v_0 + at \quad (4.4)$$

$$\Delta x = \left(\frac{v + v_0}{2} \right) t \quad (4.5)$$

$$\Delta x = v_0 t + \frac{1}{2} at^2 \quad (4.6)$$

$$v^2 = v_0^2 + 2a\Delta x \quad (4.7)$$

In these equations, v is the velocity, v_0 is the initial velocity measurement, a is acceleration, t is time and Δx is the change in distance of the tagged object.

The model will need to be adjusted for each scenario. If the acceleration is assumed to be zero for a tag traveling at a constant velocity, the estimation parameter will look slightly different to the one where constant acceleration is assumed. With the knowledge of the movement provided from the kinematic formulas a Kalman Filter model can be derived.

The first step to determine the Kalman Filter model for the velocity estimation of a moving object is to determine the state space model. For this scenario the velocity, estimated from the change in distance and the time between samples, and the phase measurement best describes the movement of the tag. The state space can thus be presented as follows.

$$x = \begin{bmatrix} \phi \\ \dot{x} \end{bmatrix} \quad (4.8)$$

Here ϕ is the phase in degrees and $\dot{x}$ is the velocity in meters per second.

Based on the change of the state space parameters as a result of the external effects of the system, the following equation can be used to represent the observed changes in the form of a Kalman filter model. This is based on the Kinematic formulas and Newton's Laws of motion.

$$x_n = Fx_{n-1} + Ga_n + w_k \quad (4.9)$$

Where the time between sample one and sample two is described by the step from $n-1$ to n . F is the function describing the effect that will lead to a change in the state parameters. G is the function that describes the effect of an acceleration on the state parameters and a_n is the acceleration at the given time. w_k is the process noise. For the scenario where a constant velocity is assumed G will have no impact on the measurement or prediction. It should also be noted that there are no control inputs into this system, since it is designed to only be an observation system.

The different parameters that influence the phase measurements and resulting velocity are the time between samples in seconds, the frequency of the backscatter carrier signal in Hertz and the speed of the electromagnetic wave. The effect that acceleration has on the measurements are multiplied by time, since it is the only factor limiting its effect. These influences are shown in the following equations.

$$F = \begin{bmatrix} \frac{4\pi\Delta t}{\lambda} & 1 \\ 1 & 0 \end{bmatrix} \quad (4.10)$$

$$G = \begin{bmatrix} \frac{\Delta t^2}{2} \\ \Delta t \end{bmatrix} \quad (4.11)$$

$$\lambda = \frac{c}{f} \quad (4.12)$$

Where, λ is the current wavelength derived from the frequency of the carrier wave, f is the current frequency, Δt is the change in time between the two measurements and c is the speed of the electromagnetic wave, rounded to 3×10^8 m/s. The state parameters are influenced by noise. Both process noise and observation noise have an impact. The process noise that is observed, is calculated from the covariance of the process noise. This is based on the model derived by Pujare [46] and shown below.

$$Q = (GG^T \quad \delta_a^2) \quad (4.13)$$

$$Q = \begin{bmatrix} \frac{1}{4}\Delta t^4 & \frac{1}{2}\Delta t^3 \\ \frac{1}{2}\Delta t^3 & \Delta t^2 \end{bmatrix} \times \delta_a^2 \quad (4.14)$$

Where, δ_a is derived from the possible variance in the velocity of the tagged item. Since it is known that a person walking, riding a bicycle or even a forklift can not maintain a perfect constant velocity, this is set to be at 0.2 m/s to adjust for imperfect movement. For the case where constant acceleration is a possibility this will be raised to accommodate to this behaviour to a value closer to 1 m/s.

The last noise parameter that needs to be taken into account is the measurement or observation noise. This is based the resolution of the measurements made by the reader. In this model the measurement made is the phase of the returned signal and the variance of this measurement is determined by the Thingmagic reader used. According to the manufacturers the amount of ambiguity that can exist in a measurement is 2π in the 180° range. This equates to a standard deviation of 0.052 radians. This variance does not take into account the added measurement deviation due to the environmental impacts such as reflections and multipath effects. To improve this estimation the standard deviation of the velocity measurements of a tag traveling at a constant velocity between 3 and 15km/h was calculated. This is based on the algorithm designed in 4.3 and takes into account any inaccuracies in the algorithm, or

environment and is thus a far better representation of the actual measurement error that can possibly occur. This value is set at 0.9 m/s. Thus, the standard deviation of the observation noise and the observation model is represented by the following two equations.

$$R = |0.9^2| \quad (4.15)$$

$$H = |0 \quad 1| \quad (4.16)$$

Where 0.9 m/s is the observation covariance δ_z and H is the observation model. The observation noise parameter and the process noise parameter are such that it gives more weight to either the predicted values (based on previous measurements) or to the new measurement value. If R is higher more weight will be given to the predicted value. If Q is higher more weight will be given to the measurement value. R and Q work in a ratio with each other and influences the amount of smoothing applied by the Kalman Filter to the measurements, based on the weight given to the measured values.

The initial covariance matrix is chosen such that after initialization it will converge to the estimate. Thus, it is shown below.

$$P_0 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (4.17)$$

Finally, the last parameters needed to complete the Kalman Filter model are the initialization values for the state vector and the process covariance matrix. The values for the state vector are chosen based on the expected scenario. The values can also be seen as empty and the first measured values can be used as the initialization values. For most cases a neutral value of 0 m/s were chosen since the velocity value can be either positive or negative depending on the direction. If it is known that most objects will travel at a set velocity this value can be chosen accordingly. The only downside is that if the tracked object has a velocity in the opposite direction it will take longer to adjust to the new value. The values for the process covariance matrix are chosen such that the value is in the range of the expected samples, what this means is that the time difference between samples for this type of reader is expected to be around 10 milliseconds. The frequency value is chosen in the middle of the band, namely 917Mhz. This means that the process covariance matrix Q can adjust quickly with the first few measurements, improving the conformity compared to for instance an arbitrary value of 1 for the different values in the matrix.

One area with this model application that is different than the standard implementation of the Kalman Filter for such a system is that not only must the state vector parameters be maintained, but also the parameters in the covariance matrix for the process noise. This is because the time between samples are not fixed but rather variable, resulting in a change in the model parameters between each measurement. This adds complexity to the system, but can't be ignored since it will introduce further inaccuracies to the system. The different values

that have to be maintained after each measurement is the phase and velocity values and the four parameters of the covariance matrix.

This Kalman Filter model need to be maintained for each unique tag that enters the reading range for the entire period that its motion is being estimated. This means that if there are 100 tags in the reading range, there will be 100 different Kalman Filters producing an estimation for each individual tag.

4.5 RSSI based distance estimation algorithm

A basic signal strength-based distance estimator can add additional data to the motion estimation algorithm. Depending on the accuracy this data can be useful for several different scenarios. The method used to calculate the distance estimation is based on the method discussed in 2.10.3.

Adding distance estimation adds extra certainty to the direction estimation in that if the velocity is positive and the distance to the antenna is getting smaller the system can conclude with confidence that the tag is moving closer to the antenna. This distance estimation algorithm as discussed in the literature study can be applied using COTS RFID antennas and tags. The only drawback is that the tags and antennas have to be characterized in terms of the gain of their antennas. This also means that when the tag is not lined up perfectly with its antenna and the antenna of the RFID reader, then there will be an added error to the system.

The distance equation applied to the system is repeated below for convenience. This equation is based on the Friis transmission equation for RFID signals and then improved in a study by S. Subedi [53], to produce the equation below.

$$d = \left(\frac{\lambda}{4\pi} \right) \left(\frac{P G_t^2 G_r^2}{P_R} \right)^{\frac{1}{4}} \quad (2.11)$$

Here, the distance between the tag and the antenna is shown by d , λ is the wavelength of the carrier frequency signal, G_t and G_r are the gain of the tag and the reader antennas, P_R is the power received and P is the Power transmitted by the reader. The gain values are both constant values determined beforehand by characterizing the antenna of the tag and the reader. The values for the transmitted power and the frequency of the signal are known, since the reader defines it at the initialization of the reading software. The only value measured is the received signal strength.

This formula can be used because the Thingmagic reader provides the received signal strength reading in dBm. This can then be converted to watts to be compared to the signal strength propagated outwards by the reader.

The formula above in 2.10 can also be used to characterize the antenna gain of the tag. The gain of the antennas used are known. The gain is defined by the manufacturers of the

antennas. The tag gain can be estimated empirically by perfectly lining up the tag antenna with the reader antenna, measuring the RSSI at a known distance and then applying this to equation 2.10. This will produce a value for the tag gain. This should be repeated over several known distances in-order to get a good average value. It must be stated that this is just an estimation and cannot be completely accurate since there will be reflections in this environment. The reflections will be from the ground, any flat surface nearby, the object used to suspend the tag in front of the antennas and any other object in range, including the tag itself. This will however provide a good estimation with a low enough inaccuracy compared to the resolution of the reader so that this can be used to get a rough estimation of the distance between the antenna and the reader. This method will not be advised for a system where the distance estimation needs to be extremely accurate. The lack of access to an anechoic chamber and spectrum analyser motivated this method in determining the gain characteristic of the tag. Both of these two facilities can be used to improve the value and increase the accuracy of the system.

Even though this estimate is inaccurate it still gives a rough estimation of how far the tag is from the reader or even how well in line it is to the reader; for this reason it can still be used along with the phase to track the movement of the tag, since the phase data will be able to give a better estimation of the smaller incremental movements and the RSSI data can give a rough indication of how far the tag is initially from the antenna. To track the velocity and direction of the tag this data can be used in a Kalman Filter as another parameter. With a higher noise level this will have a smaller weight but it can still add value to the system. The Kalman Filter can also work well as a data fuser in this instance since it can use the two different measurements to give an indication of the distance travelled as well as the direction the tag is traveling in. The data that will be fused is the information received from the RSSI that delivers a reading for the distance from the reader and the change in phase data that gives a measurement on how far the tag moved in the time between samples. This implementation is described in section 4.7.

4.6 Kalman Filter for distance estimation

The tags used for most of the measurements have a reading range of up to 16 meters in an ideal environment. This, along with the knowledge that the tagged object will move in an expected straight-line path, means that a Kalman Filter model can be derived to determine the distance estimation and as a result the change in distance over time for the tagged object based on the measurement mentioned in section 4.5. The same process followed in section 4.4 will be applied here to determine the model. A short description of the model and the choice for the different parameters is given next.

Firstly, the state space model needs to be determined. The different states of the distance estimation are the distance x and the first derivative of x , contributing to the change in distance over time. This is shown in the following equation.

$$X = \begin{bmatrix} x \\ \dot{x} \end{bmatrix} \quad (4.18)$$

Where x is the distance between the antenna and the tag and $\dot{x}$ is the velocity of the tag at the moment of the measurement. The distance value is measured, but is also influenced by the velocity value. The state transition model and the model for the change in the state values due to acceleration, is shown next, where the relation between the states and how the states can change are described.

$$F = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix} \quad (4.19)$$

$$G = \begin{bmatrix} \frac{\Delta t^2}{2} \\ \Delta t \end{bmatrix} \quad (4.20)$$

This model is similar to a lot of different applications of Kalman Filters, where an object's position is being tracked. Key differences will be parameters specific to the system where it is applied. Here these parameters will be the observation and process noise. The process noise will be similar to the process noise for the velocity estimation model discussed earlier, with the key difference being that the covariance will describe the change in distance, not the change in velocity. The matrix for the process noise and the covariance for the process noise is shown below, where 4.22 is derived from 4.21.

$$Qn = (GG^T \delta_a^2) \quad (4.21)$$

$$Qn = \begin{bmatrix} \Delta t^2 & \frac{1}{2}\Delta t^3 \\ \frac{1}{2}\Delta t^3 & \frac{1}{4}\Delta t^4 \end{bmatrix} \times \delta_a^2 \quad (4.22)$$

The process covariance δ_a is determined by how much the distance typically can change between measurements. This again is scenario specific, since a fast-moving object will have a big change in distance and a slow-moving object, will have a small change in distance. For a typical scenario where the tag will be carried by a person or forklift the tag will move at a velocity between 3 km/h and 15 km/h which translates to a change of between 0.8 meters and 4.2 meters in a second. In crowded non-ideal case where the reader produces a reading only once every 100ms the biggest change in the distance is only 0.42 m. This means a value of 0.25 for the process covariance δ_a will be a good estimation for the different velocities. In practice this value can be tested and either increased or decreased depending on the performance of the Kalman Filter.

If most objects travel at a slower speed and the reading conditions are more ideal, producing a lot more reads per second, then this value should be lowered to accommodate for a smaller

possible change between readings. This thought process to determine the value for the covariances should always be repeated for each scenario and where possible, measurements should be taken to calculate this value. This will significantly increase the effectiveness of the Kalman Filter.

The observation covariance is determined by the resolution of the RSSI and how uncertain this value can be. The resolution of the RSSI in dBm is 1 dBm. This means that the RSSI is only measured in 1 dBm intervals. This does not even account for the ambiguity due to reflections from the ground that can exist in favourable condition. It was shown through experiments that the difference in RSSI measurement can differ within a range of about 4dBm. To determine the actual standard deviation of the measurement, the same test to determine the characterization was done, where the tag is placed at a known distance, the RSSI is measured and the difference in the estimated values is recorded. It was found that the standard deviation differs between 0.8m and 1.6m with the specific tags used. For simplicity δ_z is chosen as 1.5m for the measurement covariance value. This means that the worst-case scenario is also accounted for. This value can be adjusted for every scenario in order to have a custom value for the specific conditions. This will result in a more reliable prediction. The value for the R matrix and the observation model is shown below.

$$R = |1^2| \quad (4.23)$$

$$H = |1 \ 0| \quad (4.24)$$

Here it can be seen that the observation model notes that only the distance state is measured. The other state is only derived. The last part of creating the Kalman Filter model is to determine the initialization values for the system. Since it is expected that the tagged object will move along a specified path and the reading range for the tags used during these experiments are 15m when the tags are standing still, an initial value for x_0 of 14m meters is a good estimation. If the tag is read earlier the filter can adjust but based on the antenna propagation and tag response the tags should respond with frequent readings from 14 meters, further motivating this initialization value.

This Kalman Filter is unique for every tag being monitored and should be updated similar to the description given in section 4.4 for every tag for as long as the tag is in the reading range. This also means that if a tag has not been read for a specified time, the filter values should be reset, since historic data will not apply if a tag can moved out of the reading range for a period and then returned. New tracking data should be generated for these tags in such an instance. The Kalman Filter will help to smooth the irregular RSSI based distance estimation to produce values that will be more representative of a moving object's change in distance over time. The result of this is discussed in chapter 6.

4.7 Phase and RSSI Kalman Filter for velocity and distance estimation

The Kalman Filter can act as a very effective method for sensor data fusion. Normally you would have different sensors measuring the same variable and the Kalman Filter can be used to combine these measurements to produce a better value representative of both measurements as a result of the weight given to each. In this application both the phase and RSSI data comes from the sensor, but the data produced by them is different. To use both of these parameters to predict the change in distance and possibly improve the motion estimation of the tag, a Kalman Filter fusion technique is proposed, where the state space model will be represented with values from both these parameters.

This Kalman filter implementation uses the same kinematic formulas as the previous velocity estimation model, described in section 4.3, but differs in terms of the states used in the equation as well as the State transition model, observation model and covariances. The same generic Kalman Filter model is used, as described by equation 4.9, but because the parameter measured provides data for the distance between the tag and the antenna as well as the change in distance over time and as a result the velocity, the model will include other states in the object tracking as well.

This Kalman Filter model is a good combination of both the previously implemented Kalman Filters, namely, the Kalman Filter based on the phase data to produce a better velocity estimation and the filter used to improve the distance estimation calculated from the RSSI data.

Since the parameters provide all of the parameters used in object tracking, except acceleration data, the state space model will include the distance and the velocity of the moving object. The different states included in the model is shown below:

$$X = \begin{bmatrix} x \\ \dot{x} \\ \Phi \end{bmatrix} \quad (4.25)$$

where x is the estimated distance between the reader antenna and the tag, $\dot{x}$ is the velocity of the tag and Φ is the phase measurement. The RSSI data is incorporated as part of the distance estimation parameter and this simplifies the state transition model as well as the process noise matrix. The parameter can be added as part of another version of the Kalman Filter model to predict these values.

How the different states interact with each other to produce the estimation of the state parameters is shown in the state transition model. The state transition model given by the matrix F is shown below.

$$F = \begin{bmatrix} 1 & \Delta t & 0 \\ 0 & 1 & 0 \\ 0 & \Delta t \times \frac{1}{a} & 1 \end{bmatrix} \quad (4.26)$$

Where a is given by:

$$a = \frac{\lambda}{4\pi} \quad (4.27)$$

Here, λ is calculated exactly the same as in equation 4.12, by using the frequency of the carrier signal and the constant value of the speed of an electromagnetic wave. From equation 4.26 it can be seen that both the distance and the phase measurements have an impact on the velocity estimation. Both these parameters correspond to a change in distance over time. The phase has a much finer resolution, being able to track smaller incremental movements, while the RSSI will be able to track bigger movements, possibly even movements that are bigger than the limits set by using the phase only method.

The velocity, as a result of the phase and the change in distance, as a result of the RSSI measurement, is observed. This is shown by means of an observation matrix. The observation model H can then be defined as:

$$H = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \quad (4.28)$$

The reason this is defined as the observation model is because this is the only two elements that the system needs to track and predict during the process. The phase data is only measured and used in the calculations; thus, a prediction thereof is not necessary.

The next step is to define the effect of the unknown input G that applies to the state vector, this is any friction or external factors that will change the behaviour the tag during the movement. For the change in distance and the change in velocity, the main impact that can occur will be as a result of an acceleration experienced by the object. This is thus modelled as:

$$G = \begin{bmatrix} \frac{1}{2}\Delta t^2 \\ \Delta t \\ \frac{1}{2}\Delta t^2 \end{bmatrix} \quad (4.29)$$

It must be noted here that this will only be applied if the value for a possible acceleration is set to not be zero. Otherwise this value of G will only be multiplied by a zero-acceleration value and its impacted removed.

Finally using this model, the covariance of the process noise can be defined as:

$$Q = (GG^T \quad \delta_a^2) \quad (4.30)$$

$$Q = \begin{bmatrix} \frac{1}{4}\Delta t^4 & \frac{1}{2}\Delta t^3 & \frac{1}{4}\Delta t^4 \\ \frac{1}{2}\Delta t^3 & \Delta t^2 & \frac{1}{2}\Delta t^3 \\ \frac{1}{4}\Delta t^4 & \frac{1}{2}\Delta t^3 & \frac{1}{4}\Delta t^4 \end{bmatrix} \times \delta_a^2 \quad (4.31)$$

Where δ_a is the standard deviation of the process noise. Since the two different states, distance and velocity, will have different standard deviations, the weight of this value can be

different for the velocity parameter and the distance estimation, but the difference will also be incorporated into the matrix resulting from the GG^T operation. It can be seen in 4.31 that the first component in the matrix (row 1 and column 1) will result in a much lower value than the middle value (row 2 and column 2). This is true since the difference in time samples will be much lower than half a second.

To keep the operation for this Kalman Filter as simple as possible the standard deviation of the process noise, δ_a , was calculated as the average value between the process noise covariance for the Kalman Filter designed in 4.4 and the distance Kalman Filter in 4.6. This resulted in a value rounded up to 0.2. This will be tested in practice and adjusted accordingly. The advantage of determining these values is that there exists an underlying ratio between the value for Q and the value for R. To achieve the desired smoothing and prediction results from the Kalman Filter, both of these values should be calibrated. If one of these two values can be determined more easily, then the remaining value can be adjusted from the estimation to produce the desired results. Determining these values when they can not be measured is a skill that is developed over time and people more experienced in the relevant field, will be able to give an estimation for these values, purely based on the knowledge of how the states change and how accurate the measurements are.

The last step is to determine the measurement noise R. The possible variation in phase measurements is the same than the description given in the previous application, since the same Thingmagic reader will be used in the setup. This possible variation in phase measurements is identified as 2 degrees. This along with the standard deviation determined by the velocity estimation algorithm contributed to a standard deviation defined for this model at 0.8 meters per second for the velocity parameter. The distance estimation however from the literature can be set to a 1.3m standard deviation depending on the type of antenna and tag used, as explained in section 4.6. These values are identical to the models used in section 4.4 and 4.7, since this Kalman Filter model serves as a fusion technique for the parameters measured in those models. Thus, the matrix for the observation noise is defined by equation 4.32.

$$R = \begin{bmatrix} 1.3 & 0 \\ 0 & 0.8 \end{bmatrix} \quad (4.32)$$

Here the first row, first column value corresponds to the observation noise for the distance estimation and the second row, second column value is the observation noise for the velocity estimation. Since these states are not measured by other parameters the rest of the matrix will be set to zero, because they do not influence the other states' readings.

This Kalman Filter model can produce a better estimation for the motion based on different parameters measured by the RFID reader. In ideal conditions with limited reflections and multipath propagation this will be an improvement on the standard Kalman Filter model used

to estimate the velocity, but it is possible that this model using the RSSI data can reduce the accuracy of the velocity estimation in cases where there are a lot of reflections and a bad read rate. Because of the way the model is comprised with the different noise covariances chosen, more weight is given to the velocity estimation based on the phase measurements than the RSSI based change in distance estimation. This means that if there is erroneous phase data the result will be affected more than if there is erroneous RSSI data.

This filter was designed to add another layer of information to the motion estimation of an RFID tag and it can be used in specific scenarios, e.g. when there is uncertainty about the initial distance of the tag from the reader, to provide extra information to the user about the behaviour of tagged objects.

4.8 Conclusion

In this chapter the different algorithms and models needed to produce an accurate representation of the motion of a tagged object were derived. This is the basic building blocks of the entire system that will be tested against various influences on the system in the following chapters. The implementation of these algorithms will enable the RFID system to produce information on the direction, velocity and even distance between the reader and antenna. This information can be used as a filter for item tracking or in other localization algorithms.

5 Implementation and testing

This chapter will discuss the implementation of the designs of chapter 4 into a software solution as well as the experimental design process followed to verify the functionality and efficiency of the different algorithms. Different aspects that can influence the readings must be tested and the different methods to improve on the raw measurements will be compared. This include the comparison between the standard velocity measurement, an exponential smoothing algorithm applied to these measurements and the different variants of the Kalman Filter used to improve the standard readings. This chapter is designed to be read together with chapter 6, where the experiments discussed in this chapter produces the results in chapter 6.

This chapter will inform the reader of the different experimental designs used to test and verify the designed motion estimation techniques as well as determine the limitations of the system.

5.1 Software flow

In order to produce motion estimation parameters for a moving tag, different algorithms and features have to work together. In this section the flow of the sequential elements of the motion estimation solution is discussed. The motion estimation output can be seen as an extra parameter(s), given to an existing system to be used to improve the tracking of items. For instance, if a system needs to determine which items are moving and which items are standing still the motion estimation data can be used for this function. In a more basic system, the motion estimation can be used to track individual tags, with an accuracy dependent on the specific scenario. This means that the algorithm is designed to be part of a bigger software system.

Two separate software flow designs are presented, the first being the total motion estimation procedure with the phase based Kalman Filter used to improve the raw velocity estimation of the tag. The second includes the distance estimation algorithm, Kalman Filter to improve the distance estimation algorithm and the phase/RSSI fusion Kalman Filter to improve the velocity readings. These two techniques will also be compared to determine which one is more suitable and which one is preferred in most real-world applications.

The first design is shown in the figure below.

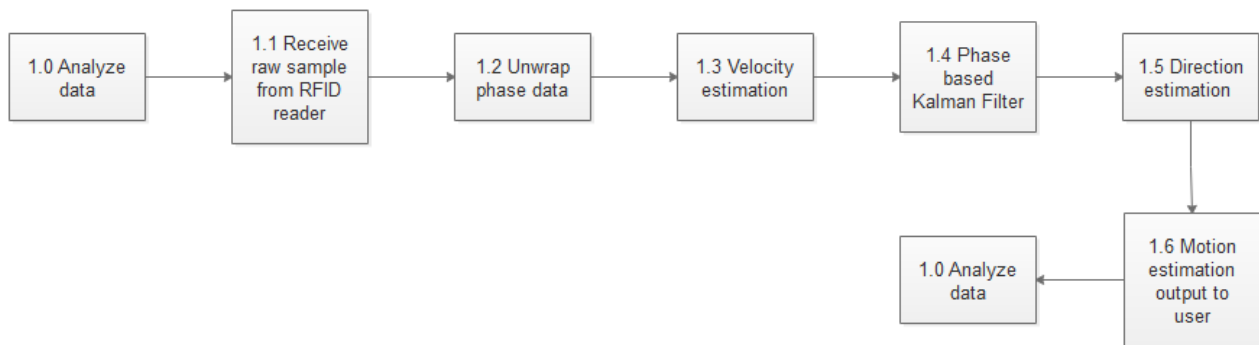


Figure 5-1: Software flow with phased based Kalman Filter implementation

The first block of the analysis of the data can be seen in block 1.1. The start of the analysis of the data will receive the raw data from the RFID reader. This data should then be converted to a format that can be used in the rest of the analysis. This entails the insertion of the different sample data in an organised array, where each entry corresponds to a unique sample number and EPC tag number. This organization enables the algorithms that follow to have access to each new reading and can adjust the motion estimation parameters accordingly. In practical environments this part can be adjusted to only store the latest samples, or for example the latest five samples for each unique tag. What this does is to free up memory space and reduce search time in the arrays for a specific entry. By storing the latest samples, all the data that is required for the velocity estimation and Kalman Filter is still present.

The second part of the process, represented by coding block 1.2, is unwrapping the raw phase data, allowing correct analysis of the different patterns of movement contained in this data. This is done by using the algorithm discussed in section 4.2. The output from this algorithm produces an unwrapped phase sample that can be used in the velocity estimation algorithm. The phase based Kalman Filter receives the velocity estimation, updates all the states and provides an estimate of the reading as output. This estimate is an improved velocity estimation based on the last measurement and the motion model. The model receives the velocity estimation and time values of each unique tag.

The direction can be derived from the velocity estimation; if the velocity estimation given by the Kalman Filter is positive the tag is moving towards the antenna. If the estimation is negative the tag is moving away from the antenna. This provides more data to the system on the type of movement made by the tagged object.

Finally, the direction and velocity estimation parameters are presented to the rest of the system from where decisions based on the specific application can be made, represented by block 1.6. If it is used for security purposes this data can be used to trigger an alarm, open a door or any other scenario specific application.

The second software design flow is discussed next. The figure below shows the implementation of this design in a schematic.

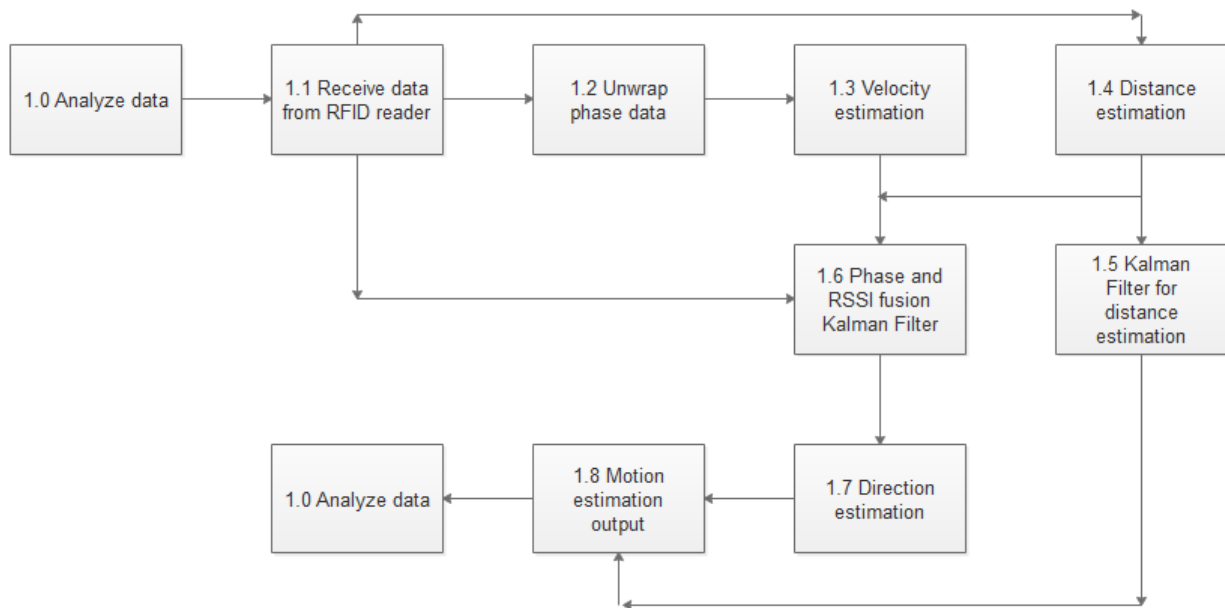


Figure 5-2: Software flow with phased and RSSI fusion Kalman Filter implementation

This design is similar to the first, with a few key differences. The differences can be seen at blocks 1.4, 1.5 and 1.6.

At coding block 1.4 the distance estimation algorithm is inserted. The distance estimation algorithm receives the RSSI data from the RFID reader. This is the algorithm discussed in section 4.5 and needs a detail characterization of the different tag gains used in the environment. This block of code produces an estimation for the distance between the tag and the reader antenna. This is then passed to a Kalman Filter designed to improve the rough and imprecise reading into a better change in distance estimation across all readings. This Kalman Filter for the improved distance estimation only is shown in block 1.5. This block will directly produce a value sent to the motion estimation output block, which delivers an additional parameter to the motion estimation output.

One key difference with this design is that from the velocity estimation produced by the algorithm, the data is sent to a Kalman Filter that combines the phase-based velocity estimation and the distance estimation as a result of the RSSI value. It will also receive the time stamp values from the reading blocks. This will produce a velocity estimation and distance estimation taking into account both parameters as discussed in section 4.7. The direction estimation based on this output is produced in block 1.7.

Finally, the distance estimation from both Kalman Filters, the improved velocity estimation and the direction estimation forms the motion estimation output. This software flow is repeated for every reading and every unique tag received by the RFID reader.

This section showed how all the different algorithms designed in chapter 4 work together to produce an estimate of the motion of the tag that can be used in a practical scenario to analyse the movement of the tagged object. Each step discussed in this program flow is repeated every time a new sample is read. This is done in real time, but can also be done after the different measurements are made. The goal is to use these estimations as an extra tool in a broader use case.

The next part of the chapter will discuss different tests completed to define the influences on the accuracy of the motion estimation parameters. At the end of these experiments, it will be possible to definitively determine whether or not the motion estimation can be applied to real-world scenarios and what the limitations of this technique will be.

5.2 Test 1: Influence of tag speed on velocity estimation accuracy

It has been established from the literature and experimental learning chapters, that there will be certain factors that influence the accuracy of the velocity estimation algorithm and as a result all of the motion estimation parameters. The primary source of a decrease in the estimation accuracy is a reduction in the number of samples available. This means that for the entire passing of the tag in the antenna propagation range there are less samples measured. A few factors can have an impact on the number of samples recorded for each unique tag even if the antenna and tag setup is such that there is little interference from other sources. These factors are the speed at which the tag is traveling and the number of tags present in the range of the RFID reader antenna. The reason why speed will have an impact on the number of samples present for each tag, is because the time that the tag will be in the reading range changes depending on the speed. A faster moving tag will move past the antenna in a shorter time, meaning there is also less time for the RFID reader to gather data from the tag and vice versa. How the difference in speed will impact the accuracy of the estimation will be tested with the experiment described in this section.

The goal of this experiment is to only test the influence of different speeds on the accuracy of the velocity estimation. This means that all other possible influences should be kept to a minimum. This means reflections, multipath effects, interference, unreliable tag orientation and other tags in the range should be avoided. To avoid erroneous readings as a result of these influences the setup environment was chosen such that the reflections will only be from the ground and no walls in the direct environment. The parking area was chosen as an ideal place, because of the big open space without any buildings in the proximity. Only one tag will be used at a time to ensure that other tag responses will not influence the result of this test. The speed of travel will be controlled with a bicycle, similar to a setup used in chapter 3, with a key difference being the placement of the tag. The tag will be placed on the front of the

bicycle such that it will be situated more to the front, reducing most reflections from the bicycle frame towards the tag and antenna. Finally, the line of travel will be in a straight a line, passing the antenna as close as possible.

This all means that the speed will be controlled, with a reference speed for every run, the reflections are significantly reduced to a point where the effect is negligible, the tag being monitored will be the only tag in the range, which only leaves the antenna setup. Based on the experiments the only two options viable for this test will be the setup discussed in section 3.1.3 and 3.1.4, where the antennas face the line of travel of the object as close as possible, either where both antennas face towards the oncoming tag or one antenna facing towards the line of travel and the other one in the opposite direction to also track the movement away from the tag. It would have been possible to only use one antenna facing towards the oncoming tag.

For this experiment the setup where both antennas face forward towards the oncoming tag was chosen. This setup is illustrated in chapter 3 by figure 3-6. This is to ensure that the tag will be read throughout movement; if an antenna has a certain area in the range with a bad signal response the other antenna will still record the sample. This setup will have antenna channel changes as well as frequency changes, which might have an effect on usable samples since this will also account for a loss of comparable samples, but the number of times where a switch in the antenna channel will not be associated with a change in frequency is very small, limiting the effect to near zero. The practical implementation of this setup and the tag placement at the front of the bicycle is shown in the figures below.

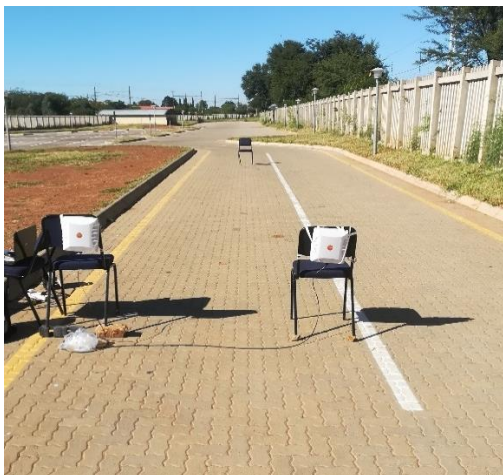


Figure 5-3: Antenna setup for experiment on the influence of different speeds on the accuracy of the velocity estimation in an environment with little reflections



Figure 5-4: Tag placement on bicycle for practical measurements, where the tag is oriented with the ideal angle in reference to the antennas

This basic setup is such that the main propagation direction of the antennas is parallel to the ground, to reduce reflections from the ground. If the antennas could be placed higher that would be more ideal, but due to the tag placement on the bicycle the ideal height for the

antennas were at the same height as the tags. The tag placement on the bicycle can be seen in the figure on the right, where the tag is attached to the cables sticking out in front of the bicycle frame, separating it from the frame of the bicycle and reflections from the frame as a result.

The equipment used for this experiment is listed in the following tables, where the first table is the tools used to move the tag at a controlled speed and the second table is the equipment needed to measure the phase change.

Table 5-1: Equipment used to move the tag at a controlled speed

Name of item	Amount	Purpose
Bicycle	1	Move the RFID tag smoothly
Rod	1	Surface to attach tag to the front of the bike
Speed sensor	1	Measure the speed at which the tag is moving (on the bicycle)

Table 5-2: Equipment used to measure the change in phase, to be used to estimate the velocity of the tag

Name of item	Amount	Purpose
Computer	1	Run program that process the data and collect the RFID reads.
Mini-USB cable	1	Connect computer to reader
USB type B cable	1	Provide power to the reader
RFID reader	1	Reads the RFID data from the antenna and sends it to the computer
Antenna	2	Measure the RFID signal
Cable	2	Connect the reader to the antenna
Tag	1-10	Broadcast phase data that will be used to calculate the velocity
Mount for antenna	2	Mount the antenna to a fixed position

It is important to note that a different bicycle is being used from this point on than what was used in section 3. The reason being that this bicycle makes it easier to attach tags and control the slower moving speed than the previously used bicycle.

The second table shows all the equipment and smaller details used to measure the signal responses. This is similar to the equipment and settings discussed in chapter 4 section 1.

At the end of this experiment it would be possible to relate the difference between the reference velocity set by the bicycle speed sensor, the velocity estimation produced by the RFID reader and algorithm and the improved velocity estimation after the Kalman Filter application, which will also be compared to a standard smoothing algorithm. This will enable

the determination of the correlation between the accuracy of the estimated speed and the measured speed at which the tag is traveling.

To ensure enough data is produced to deliver a verdict on the influence of the speed of the tag on the velocity estimation the following method will be used. The tag attached to the bicycle will move past the antennas at 4 different speeds. That is 3 km/h, 5 km/h, 10 km/h and 15km/h. The theoretical maximum velocity determined for this reader and setup is 22km/h, which means it all falls within the possible range of velocities. In meters per second these speeds are 0.83 m/s, 1.39 m/s, 2.78 m/s and 4.17 m/s. The aim is to produce a constant velocity throughout the reading range and to maintain that velocity from before the tag enters the reading range to avoid any detected accelerations. These measurements will be repeated 5 times at each speed to produce an average reading across all the different speeds.

It is expected that the velocity will have excellent accuracy at lower speeds. In other words, it will be within reasonable margin of error for lower traveling speeds of the tags. It is expected that the accuracy of the velocity calculations will be lower for higher speeds. The reason for this is that the higher the speed of the tag, the fewer number of samples for the same distance will be recorded. This means that there is less data to use to determine the nature of the movement of the tag. In order to produce an accurate velocity estimation, the phase unwrapping technique has to work very well in the circumstances, the time stamp values have to be accurate and the setup has to be such that unintentional changes in phase and signal strength do not occur frequently. If any one of these factors changes the accuracy will be reduced. The test will also be able to evaluate the functionality of the Kalman Filter. If the accuracy is good or bad a better understanding of the Kalman Filter in those circumstances will be gained.

From the test, knowledge on specific influences on the accuracy of the velocity estimation technique and the effectiveness of the Kalman Filter in those circumstances will be gained. The results of this experiment are discussed in chapter 6.1 relating to this section.

5.3 Test 2: Influence of the number of tags on velocity estimation accuracy

As mentioned above, two variables that influence the number of samples per tag are the speed at which the tag is traveling and the number of tags in range of the reader that have to be tracked. The number of tags present in the reading range will influence the number of samples per tag, because there are limitations on the speed at which the RFID reader can read backscatter signals. With the settings proposed for the motion estimation program, the main focus is to gather as many samples as possible, with the concept being that there will be

enough samples to produce an estimation of the motion from this data. This means however that the bandwidth of the RFID reader will not be spread equally between the different tags, which can mean that certain tags get read many times more than others. Other factors that also play a role is that the RFID reader will always read as fast as possible with these settings, which means that if only one tag is in the reading range that tag will be able to respond the maximum number of times. If the number of tags in the reading range increases, this maximum reading rate will be divided between the different tags, resulting in fewer reads per individual tag. The experiment described in this section will test this statement.

This experiment is very similar to the one discussed above, where all other factors that can influence the reading are minimized. The same equipment and antenna setup are used in this experiment that was used in the tables mentioned in section 5.2. In the previous experiment the speed at which the tag was moved through the antenna propagation range was varied. In this experiment the speed will be kept at a constant 5kmph for every run. This speed was chosen, because it is in the range where optimal velocity estimation accuracy is expected and it also represents the speed for normal walking pace.

To test the effect that the different number of tags have on the accuracy of the method, the velocity will be kept constant for each different iteration and the number of tags present will change. The velocity for each individual tag will be calculated. The result will include an average accuracy of the velocity estimation across all the different tags in the reading range. The different tags will be positioned at a similar height each time to ensure that non-ideal tag placement with regards to the antenna height will not influence the readings. What this means is that in cases where one tag has a perfect velocity estimation and another tag a highly inaccurate velocity estimation, the overall result will reflect the average between these results since the technique has to be based on the overall performance in the real-world. If such a technique is implemented the accuracy has to be known for different scenarios. The experiment will be repeated 5 times for each set number of tags. The technique will be tested for 1, 2, 5 and 7 tags in the reading range. This scenario is not ideal for the technique, since all the tags will move together, meaning the RFID reader has to sample all the different tags moving together at the same time. If this number of tags moved independent of each other it would be more ideal since the scenario will allow the RFID reader to collect readings from the tags closest to the reader or with the best signal response. If the same path is followed in this scenario it means that each tag will pass the ideal environment on its own at some point even though all of the tags are in the reading range at the same time. This experiment will thus produce more information on how the technique works in non-ideal circumstances, which can be used to characterize the capabilities of the technique.

The phase based Kalman Filter will also be applied to these readings. This will allow a comparison between the measured values, an exponential smoothing of the measured values

and the Kalman Filtered values. Based on these readings the Kalman Filter can be evaluated. From this data it will be possible to determine whether the Kalman Filter is able to improve the readings in these scenarios, acting as a goal for this experiment without changing the conditions of the main experiment, to test the effect of the different number of tags on the accuracy.

It is expected that the method will be able to calculate a velocity estimation for each of the different number of samples, but that fewer tags will produce less variability and higher accuracy in the velocity estimation. A higher number of tags is expected to produce a less accurate average velocity estimation for each individual tag with a higher variance in the readings. It is possible that the average velocity will still be within a reasonable range of the reference velocity but with an increased variance reducing the reliability of the measurements. The results and discussion of this experiment is presented in chapter 6 section 2. The results of the Kalman Filter are shown in the same section since this can be seen as second part of the same system.

5.4 Test 3: RSSI and phase fusion Kalman Filter impact on estimation accuracy

Adding another parameter to the motion estimation output in distance estimation is already a great advantage, but using this parameter to increase the accuracy of the velocity estimation as well would be very beneficial. This is the main intended advantage using a Kalman Filter to fuse the phase-based velocity estimation and the RSSI based distance estimation parameters into one. This section describes the experiment used to test the effectiveness of adding a distance estimation parameter to the Kalman Filter.

The experiment to test the effect of the different number of tags and the different velocities on the accuracy of the measurement is already described. To test the effectiveness of the added parameter to the Kalman Filter, similar aspects from these experiments have to be used. The fused Kalman Filter has to be compared to the original measurement, the exponential smoothing of the values as well as the basic Kalman Filter using only the phase-based velocity estimation parameter.

The aim for this experiment will be to firstly test the effectiveness of the RSSI and phase based Kalman Filter in comparison with the other Kalman Filter implementation, the exponential smoothing algorithm and the raw measurements. The second aim will be to test the effectiveness of tracking movement away from the tag, thus a tag moving closer towards and then specifically the movement away from the antenna once it passed the middle point.

The first step of using this technique is to determine the distance parameter. In order to be able to determine the distance, the tags used have to be characterized first, by taking the RSSI at different known distances. This enables the calculation of the gain of the tag in these circumstances using equation 2.10, adding some characterization of the environment into the effect as well. This was done by placing the tag at different distances in the reading range at the optimal height and orientation with relation to the antennas. This can be seen in the figures below.



Figure 5-5: Characterizing the RFID tag at a fixed distance (back view)



Figure 5-6: Characterizing the RFID tag at a fixed distance (Front view)

Using the same method, the limit of the reading range was determined. With the specific tags and setup used in this experiment the reading range was measured at 15m. This parameter can also be used as the starting distance for the distance estimation of the Kalman Filter.

The antenna setup chosen for this experiment is such that the antennas face in opposite directions, the reason being that the line of movement ensures that sufficient samples will be produced by only one antenna facing a direction. This allows the experiment to also serve as an opportunity to test the tracking of the away movement of the tag, which is a secondary aim of this experiment. The tags used in this experiment are more efficient than the tags used in the previous experiments. They are designed to work with metal pallets and have a very good signal response in the South African RFID spectrum range. The tags are provided by industry partners Techsolutions. A figure of the tag can be seen below.



Figure 5-7: On-metal tags used for experiment provided by Techsolutions

The tags will be attached to a wooden pole which will have negligible reflections in the antenna direction. The pole will be kept in front of the moving bicycle and person, thus ensuring less reflections from the person controlling the speed of movement and the bicycle frame itself.

The experiment will consist of multiple complete iterations where the tag is moved in a straight line past the antennas, until the tag is outside of the antenna propagation range. This means one complete iteration is where the tag enters the reading range of the one antenna at the furthest point. The tag will move in a straight line towards and past the two antennas, until the tag moves out of the second antenna's reading range that points in the opposite direction of the first, as seen in figure 5-8 above. This process will be repeated 5 times at 4 different speeds. The 4 speeds will be the same as the speeds chosen for the experiment in 5.2. This will test the effectiveness of the RSSI and phase based Kalman Filter technique in different circumstances. It will also be possible to produce an estimate of the effectiveness of tracking a moving tag that moves away from the antenna.

This setup used for the experiment is as close to an ideal scenario that can be replicated in a real-world scenario. There are very few reflections, no flat surfaces such as walls in the direct range of the antenna and the tags are separated from other items that can cause reflections. The antenna and the tags are kept at a similar height and the line of travel is ideal. If the RSSI and phase based Kalman Filter is only slightly better than the Kalman Filter with only phase-based data, then any constraint to the processing in the real-world application would support the decision to rather use the original filter with only phase data. This technique is less memory and processing intensive. Reflections and multipath readings can also cause the RSSI based distance estimation to be very inaccurate and varying, which can cause the RSSI and phase based Kalman Filter to produce a worse velocity estimation than the phase only based Kalman Filter. The phase measurement will be influenced less by these reflections.

It is expected that in this scenario the RSSI and phase based Kalman Filter will produce a velocity estimation slightly better than the phase only based Kalman Filter and much better than the standard estimation without any filters. It is also expected that the technique will be able to track the movement away from the antenna but that there will be a slight decrease in

accuracy due to obstruction from the tagged object and the nature of the measurement away from the antenna. Finally, it is expected that the distance estimation technique will be able to produce a distance estimation that is within a standard range as long as reflections are kept to a minimum. This estimation will be usable and even though it is not expected to be exactly correct, it is expected to be within a 1 to 2 range of the correct distance. This will still be usable in most practical environments.

5.5 Test 4: Influence of non-ideal variables on the accuracy of motion estimation techniques

The previous experiments described above all showed the effectiveness of the motion estimation technique in an ideal environment with low levels of reflections. The only non-ideal variables that were changed, were the speed of the tagged object and the number of tags in the reading range. Often in real-world scenarios the environment will be non-ideal. This means there might be differing levels of reflections, stray tags being read and other noise present in the environment. In an ideal scenario one would be able to control and reduce these effects but it is not possible all the time.

To define the capabilities of the current system and techniques for motion estimation in non-ideal environments, more experiments including these non-ideal variables must be performed. The first experiment will address stray tags in the reading environment, while the second experiment will include reflections.

5.5.1 Influence of stray tags on motion estimation technique

The goal for this first experiment will be to determine the accuracy of the motion estimation technique in an environment where there are stray tags in the reading range. The environment will consist of up to 20 stray tags in the reading range of the antennas. These stray tags will be stationary and then one tagged object will be moved through the reading range, with the goal to determine the velocity, distance and direction of the traveling tag. From this experiment it will be possible to determine how accurate the velocity estimation technique is, what the shortcomings of the technique is in non-ideal environments and where improvements can be made in the future.

The same setup described in 5.4 will be used for this experiment, where there are two antennas facing in opposite directions. The moving tagged object will move in a straight line passed the antennas, with the same movement described in the previous section. The speed at which the tagged object will be moved is at 5 km/h or 1.38 m/s which is a normal walking speed. This speed was chosen to enable the characterization of the effect of the stray tags without a higher or slower speed influencing the system. The difference with this experiment

is that the stray tags will be placed in the reading range of both antennas. This means that the possibility of these stray tags influencing the motion estimation of the moving tag is very big. The reason for this is that having tags on both sides, means that the RFID reader will switch between antenna channels in order to read the tags on both sides. This means that if the tagged object moves into the reading range of one antenna, it not only has to compete with other tags on that antenna channel for an opportunity to be read, but the RFID reader has to be reading on that channel for the time that the tag is in range. This can mean that a big portion of the movement is missed due to the fact that the RFID reader is reading on the opposite antenna channel for that time. The placement of the stray tags in the reading environment can be seen in the figure below.



Figure 5-8: Stray tags in the propagation range of the antennas

It can also happen that the tag will be read by both antennas through the movement which can decrease the effects of the stray tags and antenna switching.

It is expected that stray tags will influence the accuracy of the motion estimation a great deal, but that it will still produce a reading that can be used to some extent. Since the number of samples for each passing of the antenna will reduce drastically as a result of the tag being in a worse position than other stray tags for big portions of the reading range, it is expected that the accuracy of the velocity estimation will reduce drastically. The direction estimation will still be possible with these readings but the error in the velocity estimation can become very big. It is expected that in these scenarios the main focus would be to determine which tags are moving, filtering out the stationary tags and determine in which direction the moving tags went. It is expected that it will still be able to use the motion estimation parameters to determine direction of movement.

5.5.2 Influence of reflections on motion estimation technique

The second major influence on the different practical measurements is reflections and as a result multipath effect on these samples. This can happen when there is a solid structure in the range of the antenna. This can be a metal object or a wall - anything that will result in reflections from this object. The signal strength received from the tag response will be influenced the most by these objects. From the literature it is clear that the RSSI response is influenced more by reflections than the phase. Designing an experiment that will test the performance of the motion estimation techniques will provide valuable insight into the limitations of the current system and possibly how to overcome these effects in the future.

The aim for this experiment will be to test the accuracy and variance of the motion estimation techniques in the presence of deliberate reflections placed in the antenna and tag signal response range. The outcome will compare the measurements obtained from the scenario with reflections with those without reflections. The two implementations of the Kalman Filter for the velocity estimation and the Kalman Filter for distance estimation will also be compared to each other and the samples obtained without any reflections. The goal for this experiment is to be able to define the performance of the techniques in a real-world scenario where this might be used. This means to identify the possible errors in the technique and highlight the capabilities. This can also be used to identify areas that can be improved upon in the future.

In order to compare the scenario where reflections are present with those where there are no reflections, the same measurement conditions must exist with the exception of the added reflecting object. A similar method to the one discussed in section 5.4, to test the effect of the phase and RSSI based Kalman Filter on the samples recorded, will be used to analyse the effect of the reflections, the only difference being that only the one half of the reading range will be used, in other words only data from the movement towards the first antenna will be recorded. This means that a single tag will be moved through the reading range of the first antenna at a constant speed and direction, the reason for this being that the reflecting surface is only added to the environment in the first half of the movement. This experiment will be repeated 3 times at both 0.83 m/s and 1.38 m/s. The speeds will be identical to the speeds chosen in the previous experiments. The reflections added purposefully will be executed by parking a car parallel to the movement line in the antenna reading range. This will serve as a surface where both distortion and multipath can occur through the movement of the tag. The antenna setup used is also the same as described in section 5.4, where antennas face in opposite directions. This means that one side of the setup will have reflections from the car and the other will not. A figure of the experimental environment is shown below, where the line

of travel will be close to the white line, passing the antennas closely, providing opportunity for reflections to be produced by the object added to the reading environment.



Figure 5-9: Experimental setup to test the effect of reflections on the motion estimation techniques

It is expected that the motion estimation parameters will be slightly less accurate with an increased variability due to the reflections added to the environment. It is also expected that the RSSI and Phase based Kalman Filter will perform worse in these conditions as a result of the added inaccuracy to the distance estimation based on the variable RSSI measurement. The distance estimation will also be less accurate with much more variability if true multipath effects come into play. The velocity estimation will still be possible with reasonable accuracy; it is expected that it will be less accurate than the ideal condition but still usable for most practical environments where the precise velocity detected is not crucial to the operation. It is expected that the improvements from the RSSI and phase Kalman Filter over the standard phase informed Kalman Filter will be reduced and it can occur that the phase only Kalman Filter perform better than the other Filter. This is due to the relative immunity that the phase readings have to multipath effects.

This experiment will be useful to identify and characterize the strengths and weaknesses of the current motion estimation techniques, which will enable the definition of the limitations of the technique.

5.5.3 Influence of indoor environment with stray tags and reflections on estimation technique and other applications of motion estimation parameters

The final experiment will include measurements in an indoor environment. This adds multiple reflecting surfaces, multipath effects, stray tags in the range which also faces reflections and a short period of time where the movement of the tag can be reflected. This scenario describes one of the worst possible conditions for this technique.

The aim for this goal is to determine how well the motion estimation technique will work in completely non-ideal environments. This experiment will show the shortcomings of the techniques used and identify some use cases for these conditions. The secondary goal for this experiment is to identify if improvements to this technique will enable the system to detect motion even in these bad conditions or if a new approach will be needed to overcome these problems.

The experimental setup is installed next to the entrance into an office space. In this office space there are a lot of stray tags that will be detected by the RFID reader. The tag will move in a straight line past the antenna, through the entrance way. The detectable range for the antenna to read the moving tag is about 5m. Compared to the reading range of 15m in previous experiments this is a very short space to gather samples to detect the motion of the moving tag. Reflections from the roof, walls, floor and objects such as desks in the office will cause multipath reflections and a lot of noise in the readings. There are more than 60 stray tags in the range of the antenna of which about 20 will be detected for one iteration of the experiment.

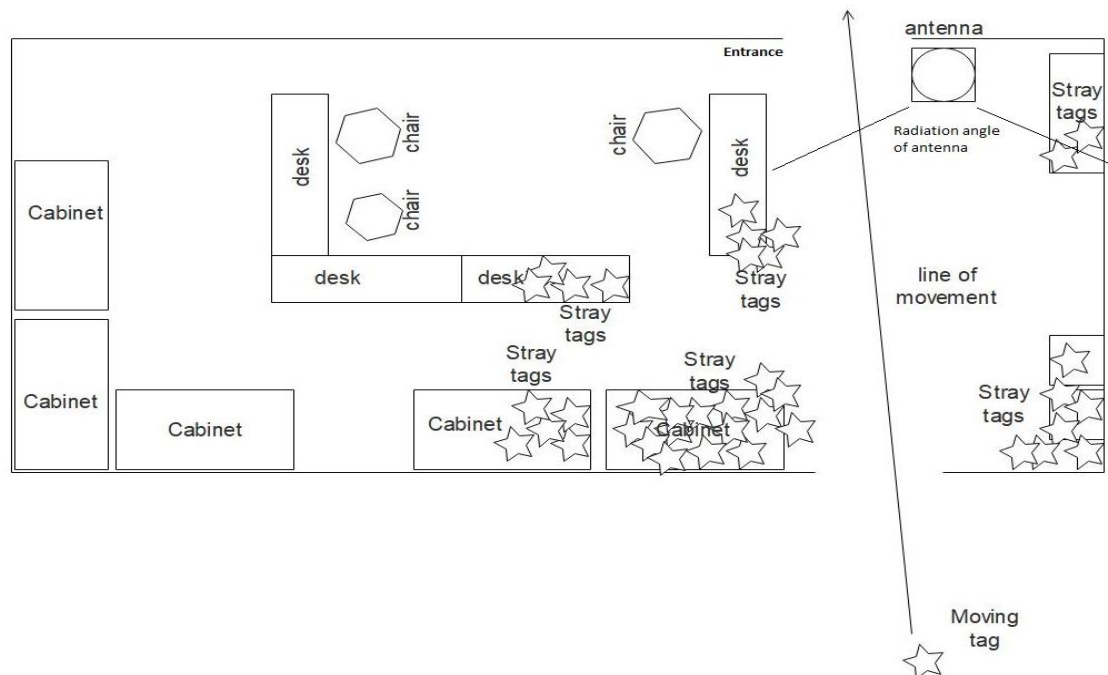


Figure 5-10: Schematic of the office used for the experiment in non-ideal conditions

The tag will be moved at walking speed past the antenna 5 times. A schematic of the reading environment is shown in the figure above, illustrating the placement of the antenna, the obstacles in the space as well as reflecting surfaces and the placement of most of the stray tags.

For this experiment only the velocity and direction will be determined. The variety of tags in the reading range as well as all the reflections makes the detection of the distance of the tags extremely difficult to characterize as well as inaccurate during measurements.

It is expected that the velocity estimation that will be produced will be inaccurate. The data gathered will possibly be varying significantly, with good motion estimation in some iterations and very poor performance in other. This is due to the influence of the noise on the system. It is expected that the data provided by the system will still be able to detect the direction but with less certainty than for the previous experiments.

This scenario opens up other opportunities for the motion estimation parameters to be used in a system. One use case will be to use this data as a movement detection filter, where it will be possible to determine which tags are moving and which tags are standing still. The results of this experiment are discussed in chapter 6 in section 4.3

5.6 Conclusion

The experiments described in this chapter will make it possible to determine what the impact of the different variables are on the accuracy, reliability and usability of the motion estimation techniques. Knowledge will be gained on the impact of the different variants of the Kalman Filter, how effective the filter is in improving the readings in different scenarios and which of the motion estimation outputs can be used in different applications.

It will be possible to describe the ideal environment that should be sought after when incorporating this technique in a practical scenario as well as what potential problems exist to be improved in the future. This chapter is a complete outline of all the experiments used to verify the functionality of the techniques discussed in chapter 4. The results of these experiments are discussed next in chapter 6, where after it will be possible to produce a verdict on the motion estimation technique for passive RFID tags.

6 Results and discussion

This chapter will be used to illustrate and discuss the results from the different experiments described in chapter 5. This will be used to draw conclusions on the effectiveness of the different motion estimation techniques used and the possibility to implement such an algorithm to add value to an RFID system in a real-world application. The tests performed in chapter 5 tested different possible influences on the accuracy of the velocity estimation technique and how the solution manages to compensate in the less ideal circumstances. Methods such as the different Kalman Filter implementations used to improve the basic estimations were evaluated. In this chapter the difference between each of these techniques with regards to the final motion estimation is analysed and discussed

At the end of the chapter the effectiveness of the proposed method in each of the different real-world scenarios will be known. It will be possible to draw conclusions on the shortcomings and stand out aspects of the velocity, direction and distance estimation technique. It will also be possible to determine where improvements can be made and what possible future research should include.

6.1 Influence of tag speed on velocity estimation accuracy

In this chapter the results of the experiment to determine the impact of the moving tag's speed on the velocity estimation will be discussed. The description of the experimental setup and the different factors influencing the results were discussed in chapter 5.2.

From this experiment it can be seen that the speed at which the tag is traveling will definitely impact the performance of the current system. The first speed that was tested, was 0.83 m/s. Thus, the tag was moved through the antenna propagation range at this speed. The velocity estimation, Kalman Filter estimation and exponential smoothing on the measured value, compared to the reference value can be seen in figure 6-1 below. The alpha smoothing value for the exponential smoothing algorithm is set at 0.2. This value was chosen since it would allow the smoothed line to still follow the changes in velocity estimation measured, but it would not be influenced as much by big erroneous reads in the velocity. The red line is the reference velocity of 0.83 m/s, the orange line the exponential smoothing, the green line the measured velocity and the blue line the Kalman Filter prediction. Each figure in the section represents one of the iterations of the experiment done at that specific speed, chosen to illustrate the effects observed at different speeds. It has to be noted that the Q values or the process variation value illustrated in these figures is the last Q value. The value is dependent on the time difference between samples and thus changes with each sample recorded. The R value stays constant.

During this experiment, every time there were an antenna or frequency change that value was ignored. For this reason, the measured velocity shows a few instances where the value is 0. The big negative velocity estimation is erroneous reads, where the tag moved through a bad patch in the signal response, causing a delay in the tag response and consequently resulting in a bigger than expected phase change. This can mean that an abnormally big jump in phase goes undetected as a wrapping event which would cause the erroneous read. From this data it can be seen that the Kalman Filter prediction values are a great improvement on the basic measured velocity estimation. The Kalman Filter value varies around the reference value with a slight margin and can be seen as extremely accurate. An analysis of the performance of each of the different estimations for each speed is given at the end of this chapter.

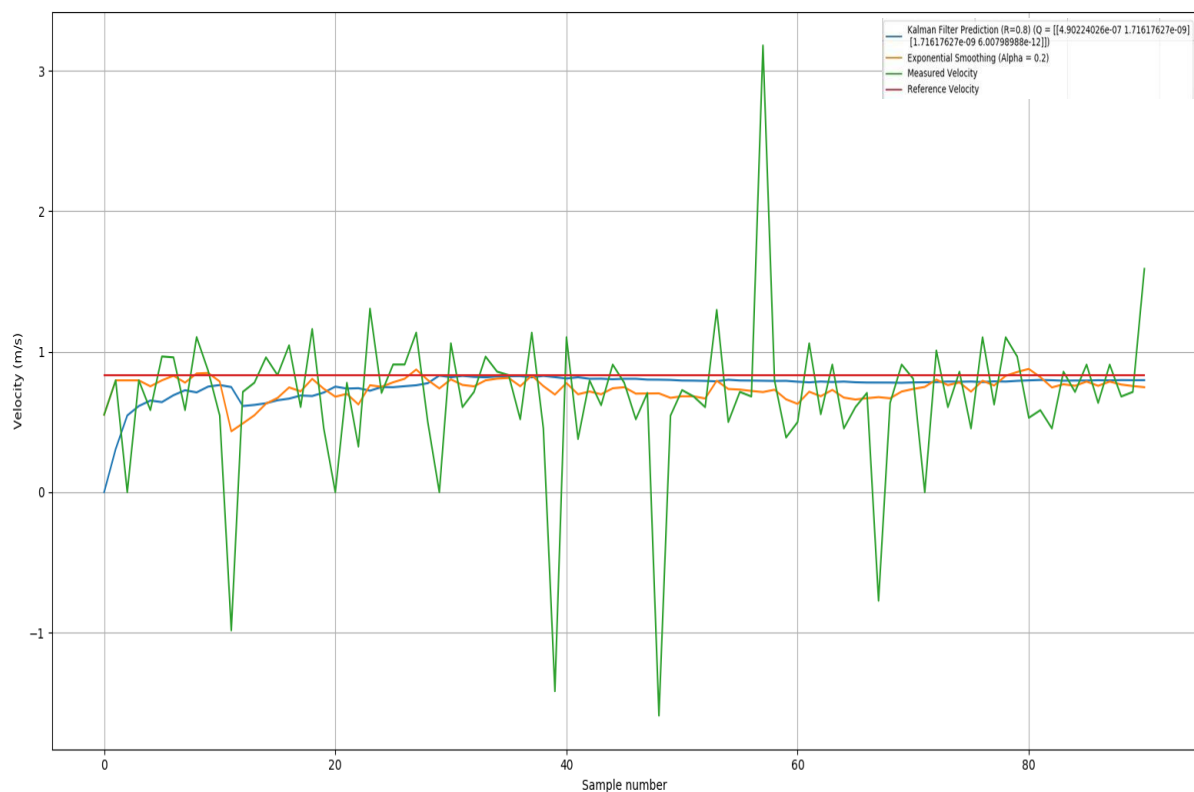


Figure 6-1: Velocity estimation comparison between TD-PDOA measurement, Exponential Smoothing prediction and Kalman Filter prediction for a tag moving at 0.83 m/s

From this figure it is clear that the need exists for a smoothing algorithm. Since the velocity estimation is an instantaneous estimation, in cases where any of the parameters, namely the time stamp or the phase value, are slightly inaccurate it is possible that this estimation will vary significantly. This supports the statement that a filter is needed to improve the reading and reduce the effects of the noise observed.

The figure above shows that the Kalman Filter provides a good estimation, improving on the accuracy of the raw measurement and on the exponentially smoothed value and reducing the variation substantially. This is at an ideal moving speed, allowing the RFID reader to gather many samples in the passing of the tag through the observation area. The next figure shown below is for a tag moving at a slightly faster speed, 1.38 m/s.

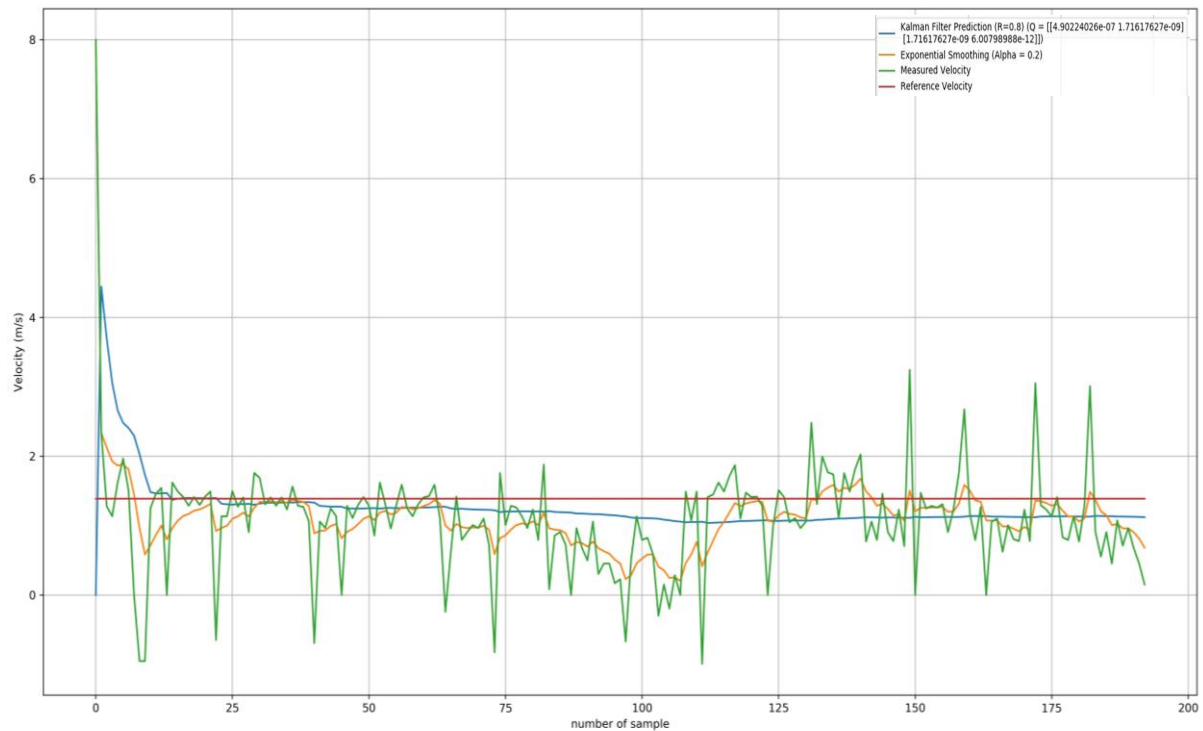


Figure 6-2: Velocity estimation comparison between TD-PDOA measurement, Exponential Smoothing prediction and Kalman Filter prediction for a tag moving at 1.38 m/s

From this figure it can be seen that there is slightly more variance than at the slower speed. An abnormal spike observed at the beginning meant that the Kalman filter took longer to settle. After that initial spike, both the measured values, the Kalman filter and the smoothing algorithm settled at a value very close to the reference until midway through the tracking of the samples. Here it can be seen that there is a visible reduction in the measured velocity estimation values. Looking more closely at the data revealed that at this part of the movement the measurements were done by antenna 2, whereas the initial part of the movement was recorded by antenna 1. It is possible that the movement of the tag passed closer to antenna 1 than antenna 2, resulting in a slight offset angle and producing a slower velocity estimation due to this angle than what is expected. This illustrates the importance of the movement line if accurate velocity estimation is required. From there the measured velocity estimation increases again to near the reference mark, with variation above and below this value. The Kalman Filter increases slightly, but since it has already settled, the change is not significant, showing that for the last part the exponential smoothing produced a value closer to the reference. This is as expected

since the Kalman Filter will only respond to a bigger change in velocity and in this case maintained the value it has settled on. This figure shows that the velocity estimation technique is working but also illustrates the big influence that a lot of different factors have on the accuracy of the technique. Again, the variation in the technique illustrates the need for the Kalman Filter or a similar correcting filter.

For the next two velocities measured it is expected that the measurements will vary with bigger margins, resulting in bigger offsets when an erroneous read occurs. The next figure shows the velocity estimations for a tag traveling at 2.78 m/s. This is faster than walking speed and can be a slow running speed for reference. The bigger variations due to erroneous read or erroneous phase unwrapping can be seen in the next figure where three big spikes in the negative range affects the velocity estimation.

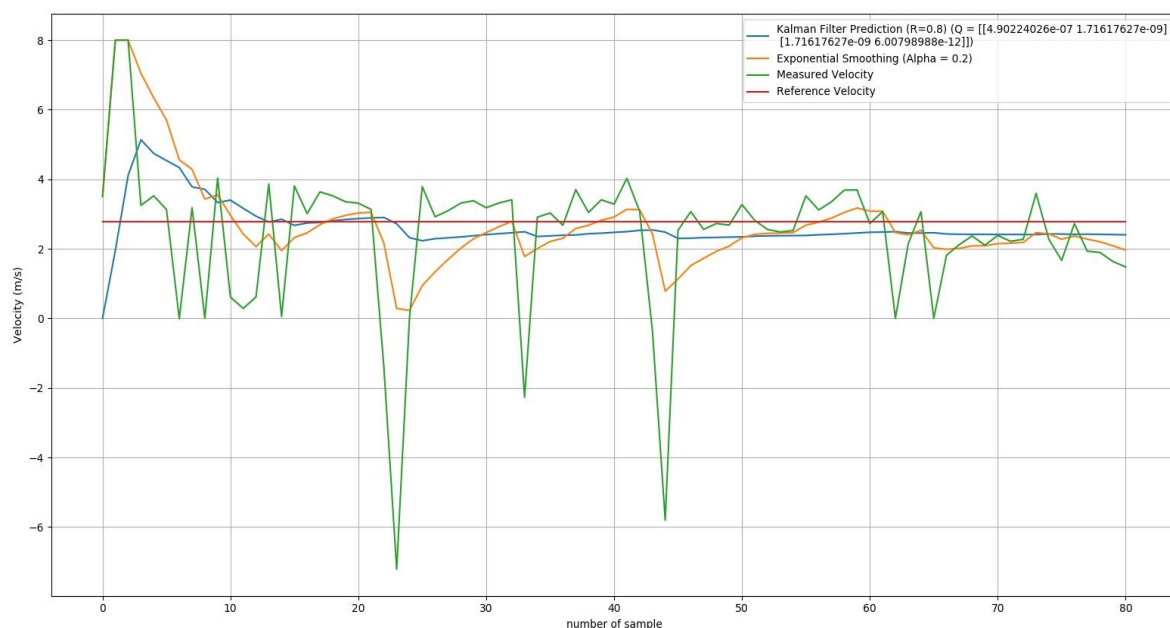


Figure 6-3: Velocity estimation comparison between TD-PDOA measurement, Exponential Smoothing prediction and Kalman Filter prediction for a tag moving at 2.78 m/s

In the figure for a tag traveling at 2.78 m/s it can be seen that again an initial spike in the velocity estimation occurs. This do not happen with every iteration but if the scenario allows for multiple measurements during the tag's motion estimation. A suggestion for an improvement to this version of the software would be to ignore the first 2 samples of the velocity estimation, until the measurement has settled and has a few phase measurements in a row that can be used for the estimation. The reason why this occurs is because of a big initial variance in the phase measurement as well as irregular timing of the measurements. This is as a result of the tag powering on initially and responding to the RFID reader's read requests. From there it can be seen that the measured velocity estimation has multiple values around the reference velocity mark, with three big spikes in the negative velocity range. This happened as a result of switching between antenna channels with a big delay in the tag

response. This increase in the time between samples meant that the phase change at this speed was too big to be detected as a wrapping of phase, resulting in the big negative spikes seen here. This imperfection in the solution is some aspect of the program that can be improved upon in the future.

A key observation to note is how well the Kalman filter smoothed over this jump in the measurement and settled closer to the reference value with the following measurements. This shows the value of such an algorithm, how even when imperfections in the measurements occur, the produced estimation is still close to the expected value.

The last iteration of this experiment was done at a speed of 4.1 m/s. This is still within the theoretical maximum velocity that can be detected, but already shows the limitations of this technique. The big variance in data as well as the inconsistent accuracy of measurements results in a bigger error for the estimation. The next figure illustrates how the velocity measurement changes between a value close to the reference point for multiple samples, followed by a big downward spike, several times.

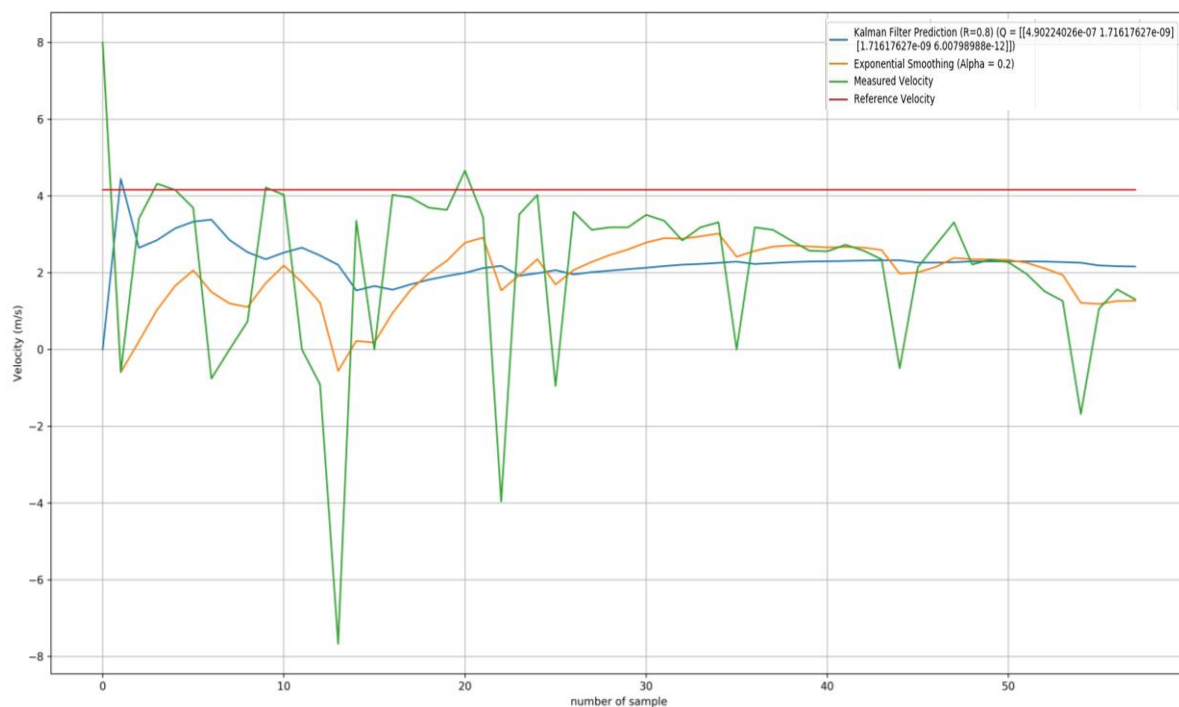


Figure 6-4: Velocity estimation comparison between TD-PDOA measurement, Exponential Smoothing prediction and Kalman Filter prediction for a tag moving at 4.1 m/s

As with the previous velocity, the big negative spikes occur as a result of erroneous phase wrapping, due to a bigger delay in time between measured responses. For a faster moving tag, a smaller delay in time between samples recorded can result in an error. This is because the distance travelled between samples is much bigger. It is possible to characterise these errors and adjust the wrapping algorithm accordingly. The algorithm can use the time between samples as a secondary input to determine whether a wrapping event occurred. The figure for

this fast-moving tag shows the potential of the motion estimation technique and also shows the importance of each aspect of the entire solution, such as the unwrapping algorithm and taking into account unforeseen delays between samples. It shows that there is a need to use more data from the tag response, such as the time values, as well as knowledge of the scenario to improve the motion estimation for a specific case.

From the figures above it can be seen that velocity estimation is possible and that it can be an accurate estimation to be used in several real-world applications. The limitations of the technique are also visible. To illustrate the effect that the different speeds of travel has on the velocity estimation technique as it is, the following figures are included. The first figure below shows the average estimated speed compared to the reference speed for all the iterations.

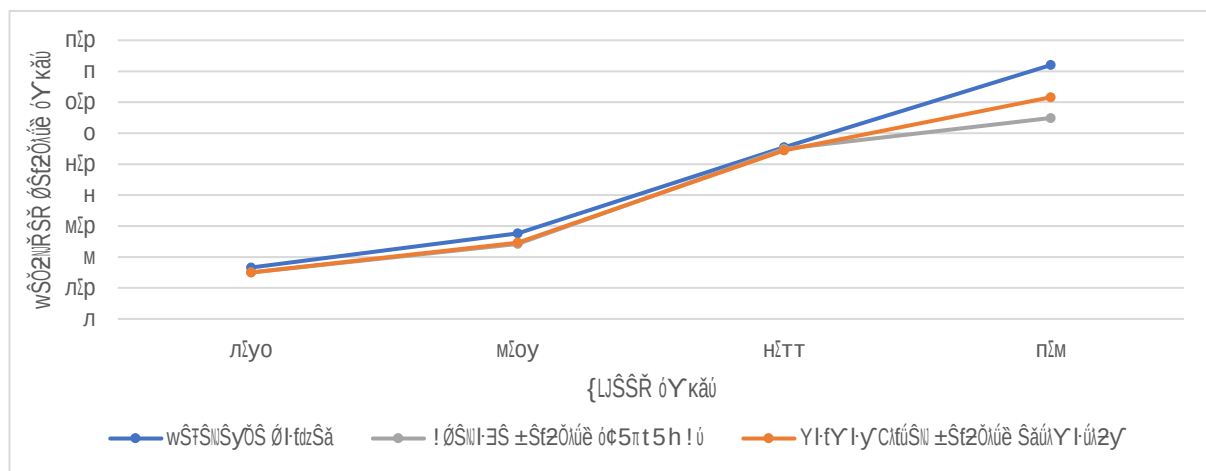


Figure 6-5: Average recorded velocity estimation compared to the reference value and Kalman Filter value for all iterations of the experiment

This figure clearly illustrates that the average measured velocity for the first three speeds recorded is very close to the reference value. It also shows the error in the reads for the 4.1 m/s recordings. This shows the capabilities of the velocity estimation technique and the improvement that the Kalman Filter offers. Providing more stability.

The biggest problem in the instantaneous velocity estimation, that were showed for the individual speeds in figure 6-5, is the variability in the estimation. To show how much the measurement varies, figure 6-6 below, of the average Root Mean Square (RMS) error for each individual measurement is included. The RMS error is calculated between the estimated value and the reference value for each estimation.

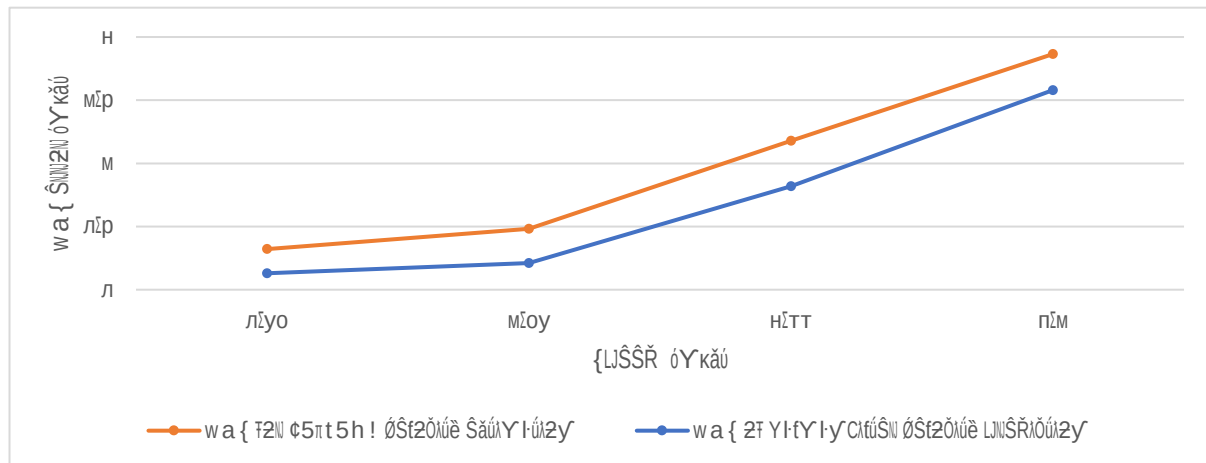


Figure 6-6: Average RMS error recorded between each estimated velocity, Kalman Filter prediction and the reference value, for each iteration of the experiment across the different speeds

In this figure it is observed that the variation between the estimated velocity and the reference velocity increases as the speed of the moving tag increases. This shows that even though the average velocity estimation is a good approximation of the actual speed at which the tag was traveling, the instantaneous variation is too big. This motivates the choice to include a Kalman filter into the solution, which decreases the variation and thus improves the instantaneous velocity estimation.

It is needed to show the effects and improvements of the Kalman filter implementation on the velocity estimation output. To show these improvements the average Mean Absolute Error, Mean Absolute Percentage Error and the Root mean Square error were calculated between the reference speed value and the measured velocity estimation, Exponential Smoothing value and the Kalman Filter prediction value.

The Mean Absolute error shows by how much each measurement differs from the reference value. The table below shows the average value for each estimation at the different speeds recorded.

Table 6-1: MAE comparison between different estimation techniques for different speeds

Speed (m/s)	Mean Absolute Error		
	Measurement	Exponential Smoothing	Kalman Filter
0,83	0,2111	0,1179	0,0449
1,38	0,3314	0,2570	0,1634
2,78	0,7913	0,5588	0,4143
4,17	0,9536	0,9434	0,8401

Two main observations can be made from this table. The first being the improvement that the phase based Kalman Filter offers compared to the standard measurements. For each speed there is a decrease in the error of the estimation and this value is a significant improvement. The Exponential smoothing values also offers an improvement since the variability of the measurements are decreased by using the formula.

The second observation of note is the increase in the error as the speed increases. This supports the claims made earlier that the bigger distance covered by the moving tag, resulting in a bigger phase change and more errors in the unwrapping of this phase causes a decrease in the accuracy of the technique.

The Mean Absolute Percentage error is showed in the table below. The Kalman Filter shows the smallest percentage error across the different values but interestingly shows that the percentage difference is smaller at the 2.78 m/s iteration than the 1.38 m/s, showing that variation in the instantaneous velocity estimation is an obstacle to overcome. The Kalman Filter and Exponential smoothing techniques again shows their worth with a much-improved analysis value across all the different speed measurements.

Table 6-2: MAPE comparison between different estimation techniques for different speeds

Speed (m/s)	Mean Absolute Percentage Error		
	Measurement	Exponential Smoothing	Kalman Filter
0,83	25,4442	14,2055	5,4082
1,38	30,6008	24,5528	18,9178
2,78	28,5670	20,1733	14,9599
4,17	22,8880	22,6415	20,1629

The analysis illustrated by this table shows that the average estimated value of the Kalman Filter varies by less than 20.5% for all the different speeds, providing a clear indication of the potential of the technique and its capabilities.

The last table in this section is included to show the difference in variance between the measured value and the filtered values. The Kalman Filter has far less variance, improving the consistency of the measurement and providing an estimation that can trusted more than the raw estimation value.

Table 6-3: RMSE comparison between different estimation techniques for different speeds

Speed (m/s)	Root Mean Square Error		
	Measurement	Exponential Smoothing	Kalman Filter prediction
0,83	0,2895	0,1561	0,0945
1,38	0,4914	0,40861	0,2914
2,78	1,0844	0,7191	0,6534
4,17	1,4112	1,2274	1,1323

In this section it was seen that the speed at which the tag is traveling influences the unwrapping of the phase and as a result the velocity estimation. It also provided clear evidence that it is possible to track the velocity of a moving tag by using the RFID phase backscatter

parameter and the TD-PDOA technique. Lastly, this section proved that the phase based Kalman Filter design provides an improved velocity estimation by using the motion model designed and the measurements as input.

6.2 Influence of the number of tags on velocity estimation accuracy

In this section, the results of the experiment to determine the influence of the number of tags to be tracked on the accuracy of the estimation, will be discussed.

The number of tags, for which a motion estimation is calculated, will influence the average accuracy of these estimations because of the variance in the number of samples available for the motion estimation. The next figure included shows the motion estimation for 2 tags being tracked simultaneously, which is attached to the same object, adding to the complexity. The Kalman Filter for each of these tags is also displayed.

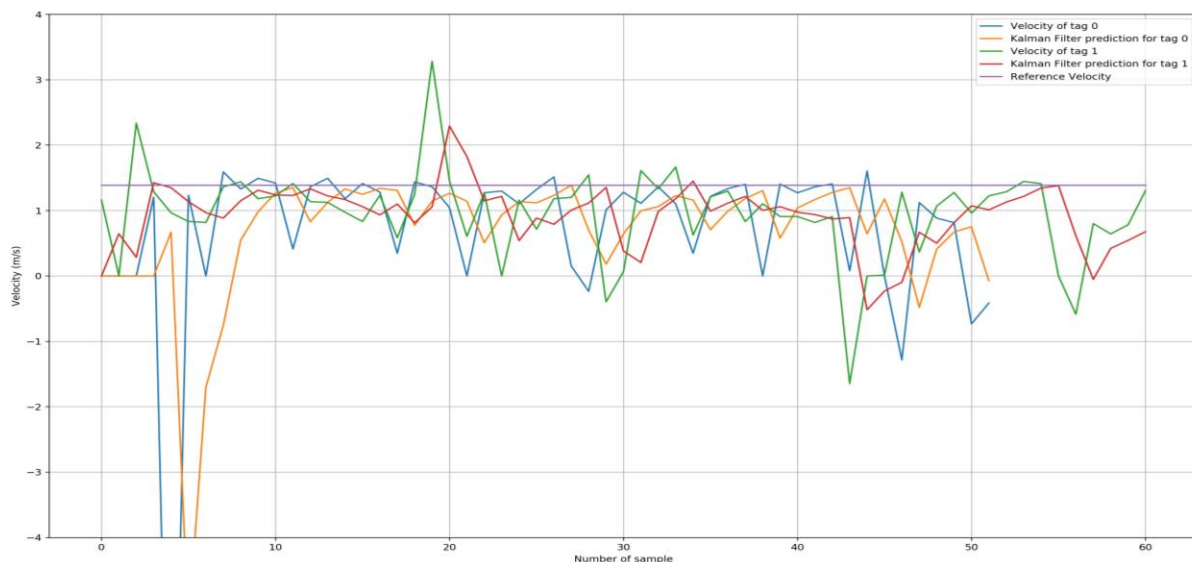


Figure 6-7: Velocity estimation and Kalman Filter prediction for two tags moving at 1.38 m/s

Here it can be seen that the motion estimation technique is capable of determining the velocity of two tags moving together through the propagation range. The same Kalman Filter parameters is used here as was used in the previous section. If it is known what the relative number of tags in the range will be, the measurement noise and process noise values can be adjusted to increase the smoothing effect of the prediction. Adding more tags increases the measurement variance parameter and this parameter can be adjusted accordingly. It was chosen to show the impact of the different number of samples on the technique as is, for cases where the number will not be known and a base value for these parameters have been chosen beforehand. In the figure it can be seen how the Kalman Filter improved the measurements by not allowing such big variation in velocity. Initially there were a big error in the velocity estimation for one of the tags showing a negative spike. The data showed the same time delay

that caused the spikes in the previous section, illustrating a problematic area in the solution. Already with just two tags being monitored, the reduction in number of samples per tag is evident. Where the number of samples for one tag was about 100 samples, here it can be seen that it is reduced to between 50 and 60 samples per tag for this iteration of the experiment.

The next figure shows the velocity estimation for 5 different tags being monitored at the same time, passing through the antenna range. All five tags traveling at the same speed is detected, some delivers a lot more samples, with less variation in phase, than the others.

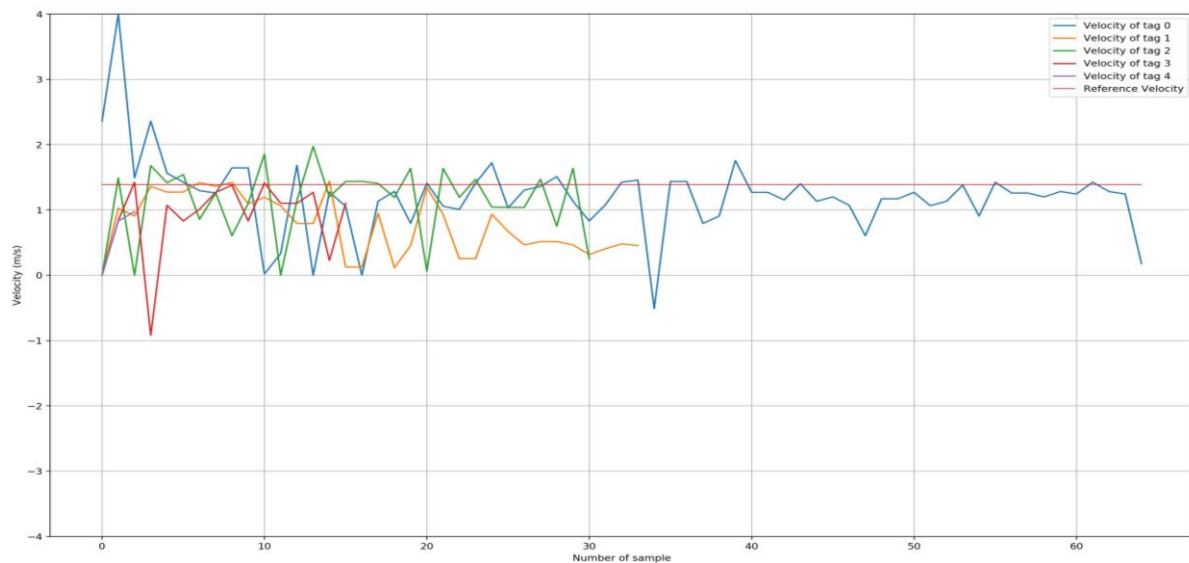


Figure 6-8: Velocity estimation for five tags moving at 1.38 m/s

It can be seen here that from all the tags a velocity estimation can be produced, but that the velocity accuracy varies between the tags. In the figure tag 0 shows the most consistency and is also the tag that produced the most samples. All the tags show the correct direction. This is shown by the sign of the velocity, a positive velocity is towards the antenna and a negative velocity is away from the antenna. In both the green and blue line, a consistent variation around the reference value is observed, but some of the other tags shows a lot lower detected velocity with more variation.

The next figure illustrates the Kalman Filter prediction for these measurements. This figure clearly illustrates the improved velocity estimation, removing a lot of the variation and resulting in an estimation that is more stable and comparable to the reference value. These values can be used to track the individual tags, with a slight deviation in accuracy between them, but the direction estimation using these values can be used with confidence and if it is known that these tags are in a batch a clear indication of the velocity can be deduced. The accuracy varies definitively between tag 0 and tag 1 for instance, where tag 0 seen in the graph show consistent values close to the reference while tag 1 near the end shows values almost a full 1m/s slower.

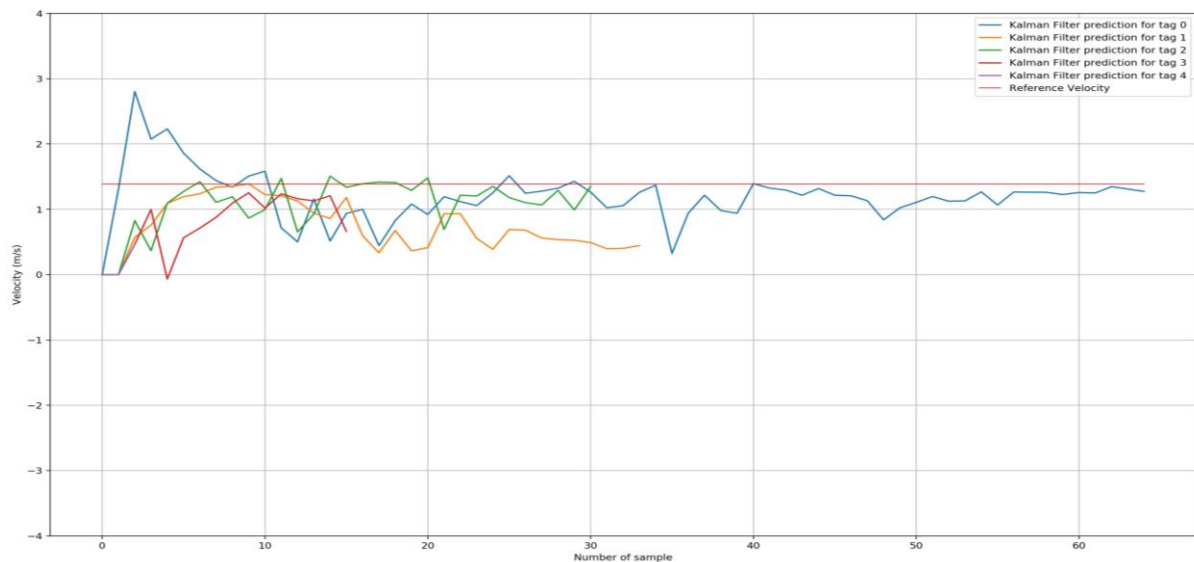


Figure 6-9: Kalman Filter velocity prediction for five tags moving at 1.38 m/s

Comparing the two previous figures, the advantage of the Kalman Filter shines through and the implication in real-world scenarios are illustrated. Using the Kalman Filter values that seem to be unusable are converted in to values that can be used to track the motion of moving tags. The velocity estimation for highest number of tags tracked simultaneously during this experiment, namely 7 tags, is discussed next. The trend of a decrease in the number of samples resulting in an increase in variability of the velocity estimation continuous with the increase in tags. The figure below shows the velocity estimation for each individual tag throughout the movement across the antenna propagation range.

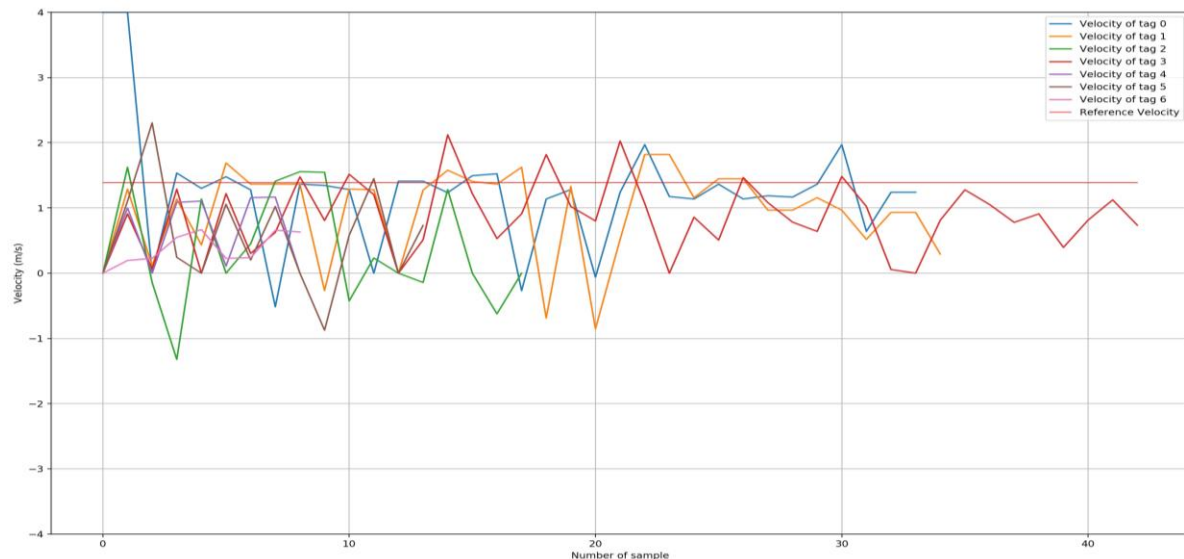


Figure 6-10: Velocity estimation for seven tags moving at 1.38 m/s

The decrease in consistent, consecutive samples from an individual tag contributes to the variability seen in the figure above where the velocity estimation changes constantly. By looking at the data it can be seen that for an individual tag there are periods where the tag is

not read for a substantial period. This means that the motion estimation throughout the movement, lacks data for periods at a time. Each time new, consecutive measurements are received, after a period of time has passed, from a specific tag there is ambiguity with the first measurement and the last measurement from the previous grouping of samples. In other words, if a sample is taken and there is a lack of received data for a big period of time, the next sample received will not accurately track the change in distance performed by the moving tag. This is because the phase change will not show this big of a change in distance. If this happen 5 to 10 times and only 35 samples are received from one tag there is a lot of inconsistent data. This all contribute to the increase in inaccuracy that is a result from the increase in tags in the reading range.

The next figure shows the improved velocity estimation produced by the Kalman Filter for each of the seven tags present. It shows a much smoother velocity estimation throughout, producing values that are easier to interpret and use in a real-world scenario.

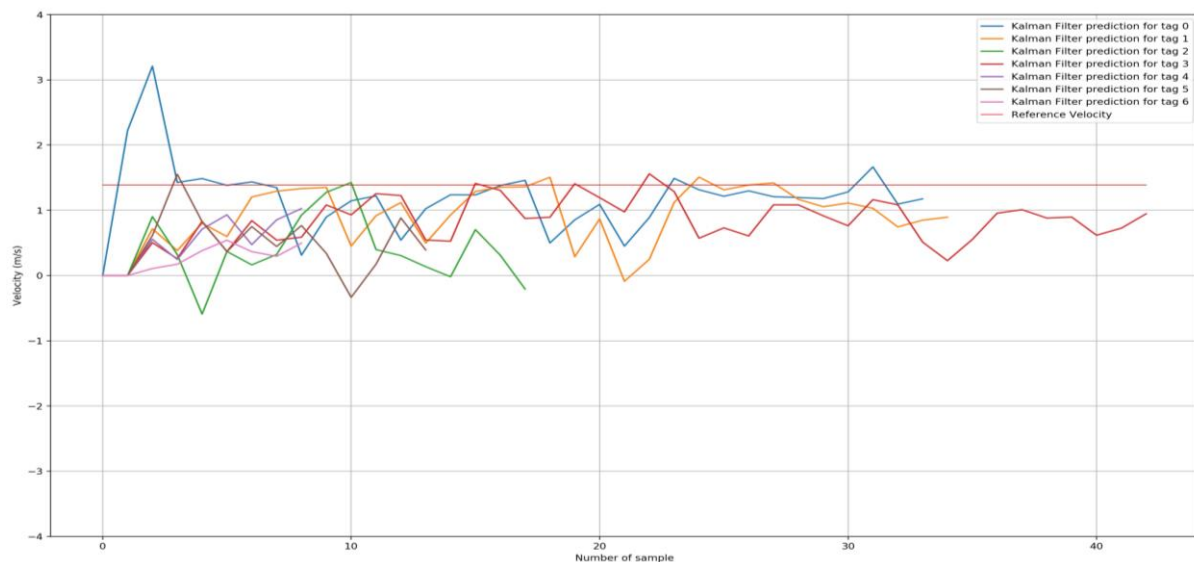


Figure 6-11: Kalman Filter velocity prediction for seven tags moving at 1.38 m/s

In the figure above it is clear that some tags's velocity estimation was done very successful. Looking at the orange, red and blue line it shows a good estimation for those three tags. The green, brown, pink and purple lines however show a lack of samples and consequently a lack of accurate estimations. From this less than ideal condition the direction estimation is still calculated with ease where it can be seen that all the tags moved in the same direction towards the antennas. This means that for safety purposes where it is needed to determine whether the tags moved in the direction of the antennas or away from the antennas, there is adequate information.

From the figures for each of the different number of tags that were tracked during this experiment it can be seen that with each iteration some tags are producing very good velocity estimation while others do not. Calculating the average velocity for each iteration of the experiment for each individual tag produced the following figure.

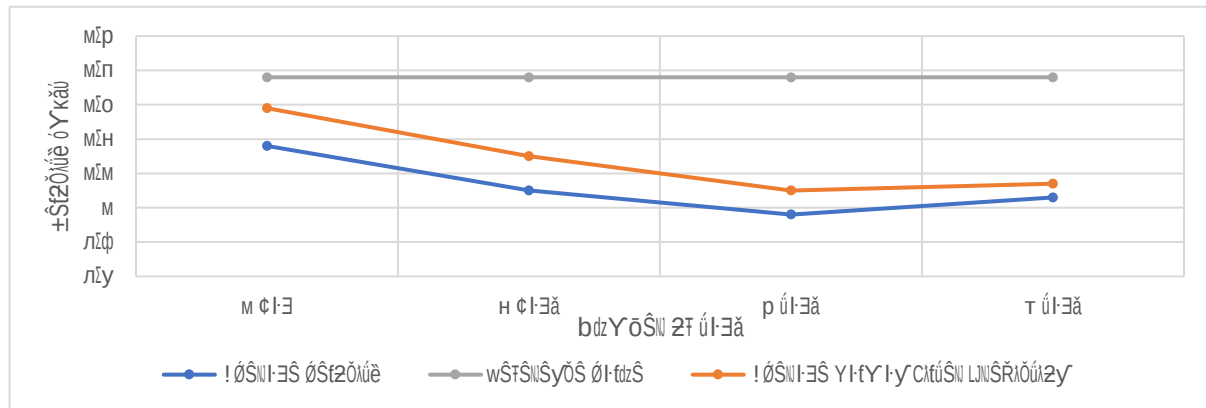


Figure 6-12: Average velocity per tag for each iteration of a different number of tags being monitored

It can be seen in this figure that difference in average velocity per tag across the different iterations is small. This figure does not show erroneous reads that is bigger than the reference velocity that can cause the average velocity estimation across the different tags to stay within a certain range, while the individual estimation is in reality far from the reference values. What it does show however is that if the average value across all the different tags are taken it is possible to get a good estimation of the real velocity that the tags maintained. It also shows that the Kalman filter provides a slight improvement on the accuracy of the velocity estimation but as the number of tags increase the improvement gets less due to an added irregularity in the samples

To show the variation of the individual velocity estimation the following figure is included that illustrates the average RMS error for each individual tag's velocity estimation for each iteration of the experiment.

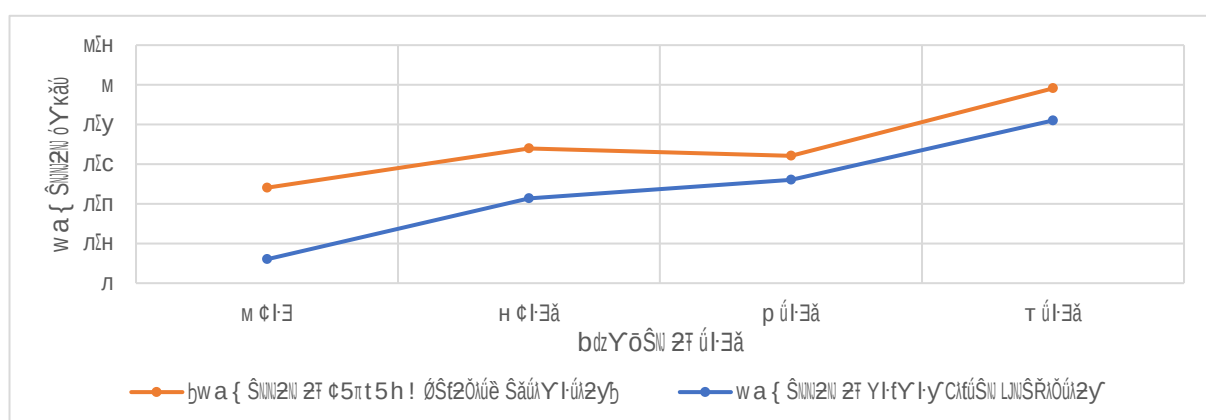


Figure 6-13: Average RMS error of the velocity estimation for each individual tag present for each iteration of the experiment

Here it can be seen that as the number of tags increases, the average RMS error increases as well. This shows that the variation in velocity estimation from the reference value increases. An added variability means that the instantaneous velocity estimation is less trustworthy, since the margin where the precise value is increases. Looking at the data produced for each iteration of the experiment, it is evident that as the number of tags increases, the number of samples per individual tag decreases.

As mentioned earlier, the decrease in number of samples means that a tag is tracked for a short period of the movement. This also adds to the increase in time between samples that contributes to the lack of coherent samples. This is the main reason why an increase in the number of tags results in a decrease in the accuracy of the velocity estimation. The table below has been created to show how the number of samples per tag changes as the number of tags in the reading range being tracked changes.

Table 6-4: Number of samples per tag in each scenario

Number of tags in range	Average number of samples per unique tag		Average number of samples for a tag	Average number of samples per frequency hop per tag
1	A	110	110	10,6
2	A	53	75	5.4
	B	97		
5	A	26	30.26	2.94
	B	73		
	C	14		
	D	8		
	E	29		
7	A	9	23.13	2.39
	B	9		
	C	43		
	D	34		
	E	35		
	F	14		
	G	18		

This table is a good illustration of the trend observed of how the number of samples changes with a change in the number of tags present. In the first row, as expected the individual tag responds to the RFID reader on average with a very high number of samples. In the second row it can be seen that both tags respond on average with a decent number of samples and it means that for both these tags the velocity estimation can still be determined accurately. With the jump to 5 tags there is also a big jump in inconsistency with the number of samples per tag. One tag has an average of 73 samples per iteration while tag D only has an average of 8 samples per iteration. This clearly shows the problem at hand. The technique requires that the highest number of samples be read, but it cannot control an even distribution of

responses across all the tags. As a result, the motion estimation will be extremely accurate for one tag and for another it will vary greatly with a low accuracy. The column second from right shows how the average number of samples per tag decreases as the number of tags in the reading range increases. Importantly, the average number of samples per frequency hop is shown in the column to the right. This clearly illustrates the problem with having multiple tags in the antenna range and adhering to frequency hopping standards. With 7 tags in the range the average number of samples recorded per frequency band is barely the minimum of 2 samples, illustrating the difficulty of the problem at hand.

This experiment perfectly showed that the number of tags for which motion estimation is being calculated at a time significantly influences the accuracy of the estimation. It was showed that the increase in the number of tags caused a decrease in the accuracy of the velocity estimation and an increase in the variation of this parameter. Finally, it was also shown that even though the accuracy of the motion estimation per tag decreases, it is still possible to track multiple tags at a time and that the direction estimation will be accurate despite this decrease.

6.3 RSSI and phase fusion, Kalman Filter impact on estimation accuracy

In the previous sections it was shown that it is possible to determine velocity and the direction of travel of a moving tag. The need for a filter that can improve the varying signal was pointed out and the influence of the phase based Kalman Filter was shown. In this section the results of adding a distance estimation parameter and incorporating it into a second Kalman Filter to improve on the velocity estimation is discussed. The advantage of adding this parameter is that the distance estimation adds another description to the motion estimation of an RFID tag.

As described in section 5.4, the setup used for this experiment has two antennas facing opposite directions. As a result, the expected change in distance will be a tag starting at the farthest signal range mark, in this case around 14m from the antenna, then it will steadily decrease the distance to the antenna until a midway point. Here the tag passes the antennas and from there the detected distance will increase up to the edge of the signal range. It is also expected that during the middle point there will be a lot of noise as the tag moves through the sidelobes of the antennas, as well as out of and into the different antennas's signal ranges. This will result in big variations in distance measurements for that part of the movement since the RSSI will directly be affected by this behaviour and the RSSI is the main input into the distance estimation equation.

The next figure shows the distance estimation for a tag moving at 0.83 m/s through the detectable area. In this figure the basic distance estimation, an exponential smoothing equation, a distance only Kalman Filter prediction, the phase and RSSI based Kalman Filter's distance estimation and a reference distance estimation is included. The reference distance estimation is calculated by using the time between samples and the reference speed as an estimate to the change in distance.

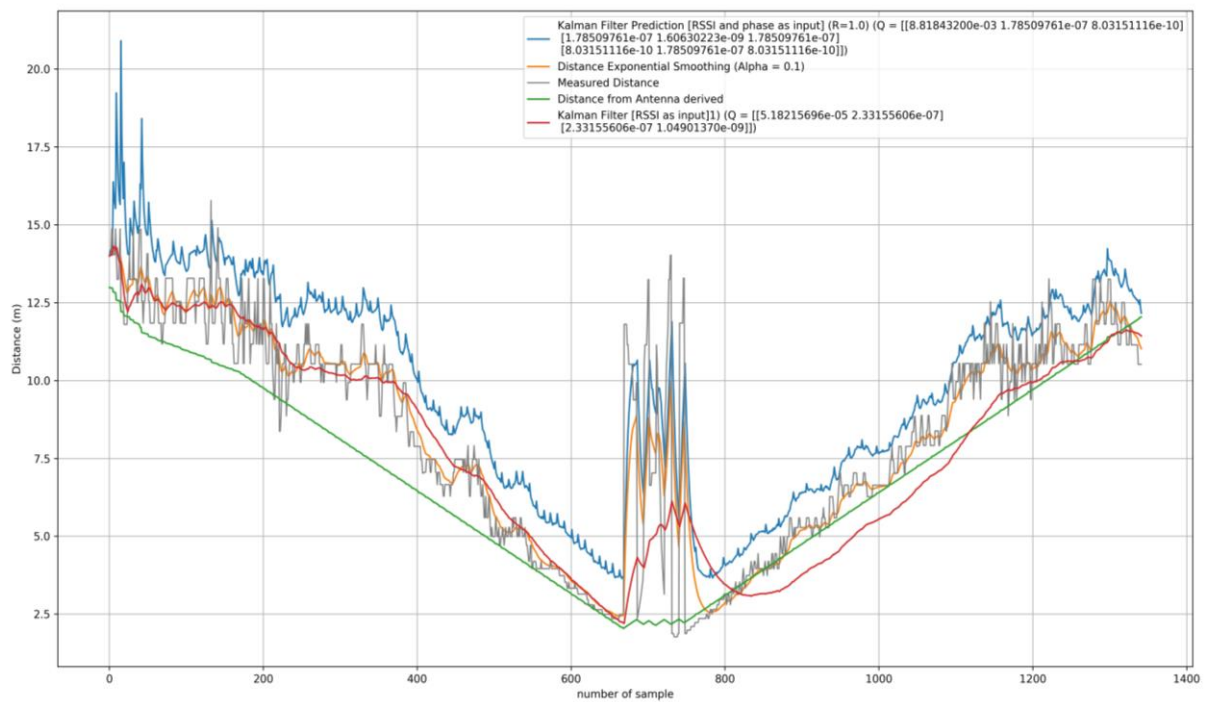


Figure 6-14: Distance estimation parameters for a tag moving at 0.83 m/s

In this figure the green line represents the reference value for the change in distance, calculated by multiplying the reference velocity and the time between samples. This shows a smooth change in distance as expected throughout. The grey line is the measured distance, the orange line is the exponential smoothing of the measurements, the red line is the Kalman Filter that only has the distance estimation calculated by the change in RSSI as input and finally the blue line is the distance estimation based on the phase and RSSI values. The reason for the irregular values produced by the RSSI and phase Kalman Filter's distance estimation is because of the combination of velocity and distance estimation values as input. The RSSI informed distance estimation does not have a high resolution, but the phase informed velocity estimation does. Due to this fact as the phase changes the Kalman Filter is expecting a change in RSSI to accompany this change to indicate the change in distance. Since this does not happen as regularly as the phase change it results in this jagged line each time there is a change. In other words, the constant velocity estimation results in an expected change in distance, the lack of change in RSSI however causes the Kalman Filter to adjust the distance estimation slightly. Every time there is a change in RSSI however this again results in a big

instantaneous change in the estimated distance. This do not correspond with the continuous change in velocity.

Every time a single increase or decrease is measured in the signal strength this would correlate to a very high instantaneous velocity and change in distance, followed by periods where there is no change at all. This effect is negated in the cases where the tag moves at a faster speed (discussed later in section 6.3), because the change in distance occurs more regularly. This happens since the distance covered by the tag between measurements are higher and as a result the change in signal strength is more regular. This also results in a much smoother distance estimation and aids in increasing the velocity estimation accuracy compared to the other estimation techniques.

The irregular distance estimation observed from the combined Kalman filter can be improved by using a moving average filter for the signal strength measurement before calculating the corresponding distance. This will result in a more constant change in distance with smaller intervals between changes, which will aid the Kalman filter prediction and increase the correspondence between the change in distance estimated from the phase parameter and the signal strength parameter. To increase the continuity even further a similar smoothing filter can be used on the output of the Kalman filter as well as for the input, it would be suggested that the smoothing be done on the input however, since this would also aid the velocity estimation prediction. This was not included in this study due to time constraints and it is important to illustrate the raw effects on the combined Kalman filter for future use.

The increase in velocity estimation prediction from the combined Kalman filter is as a result of the range limitations of the phase-based velocity estimation, where a faster moving tag is closer to the detectable change in phase. This can cause possible unwrapping errors due to some ambiguity. The distance estimation from the signal strength however is more constant, which means that the values can be trusted more in the faster moving scenarios and can reliably be used to increase the accuracy of the velocity estimation. In an ideal scenario one would characterize the possible velocities of the moving tags and adjust the Q and R values of the Kalman filter accordingly. In this study constant Q and R values for a wide range of velocities were used to illustrate the different effects observed.

It can be seen that the combined Kalman filter estimation, in figure 6-14, has a big spike in the beginning due to a slight decrease in the RSSI measured initially for the following samples. This would indicate an increase in distance but it is in reality just part of the RFID tag responds, due to some variation in the antenna propagation signal. From there it can be seen that most of the estimations follow the expected trend where there is a big increase in the estimated distance close to the middle of the movement as the tag moves past the antennas and in and

out of the antennas side radiation lobes. If this technique is installed as part of a monitoring system this behaviour will have to be interpreted as such.

Despite the big errors in the middle section the technique functions well in determining a rough distance estimation for a moving tag. The exponential smoothing technique aids in smoothing out the rough irregular changes in distance while following the measurement values closely. For this iteration of the experiment the Kalman Filter using only the RSSI informed distance estimation and kinematic equations as reference produced the best estimate. This estimate follows the change in distance closely and filters out a big part of the erroneous detection in the middle part.

This figure shows that in an environment where multipath effects are minimized it is possible to use the RSSI parameter to estimate the tag's distance from the antenna within a certain margin.

By using this distance estimation parameter and the phase informed velocity estimation as an input to the Kalman Filter it is possible to produce a secondary Kalman Filter prediction of the velocity of a moving tag. The next figure shows the comparison between the measured velocity estimation, phase only informed Kalman Filter estimation, the phase and RSSI informed Kalman Filter estimation and the exponential smoothing estimation.

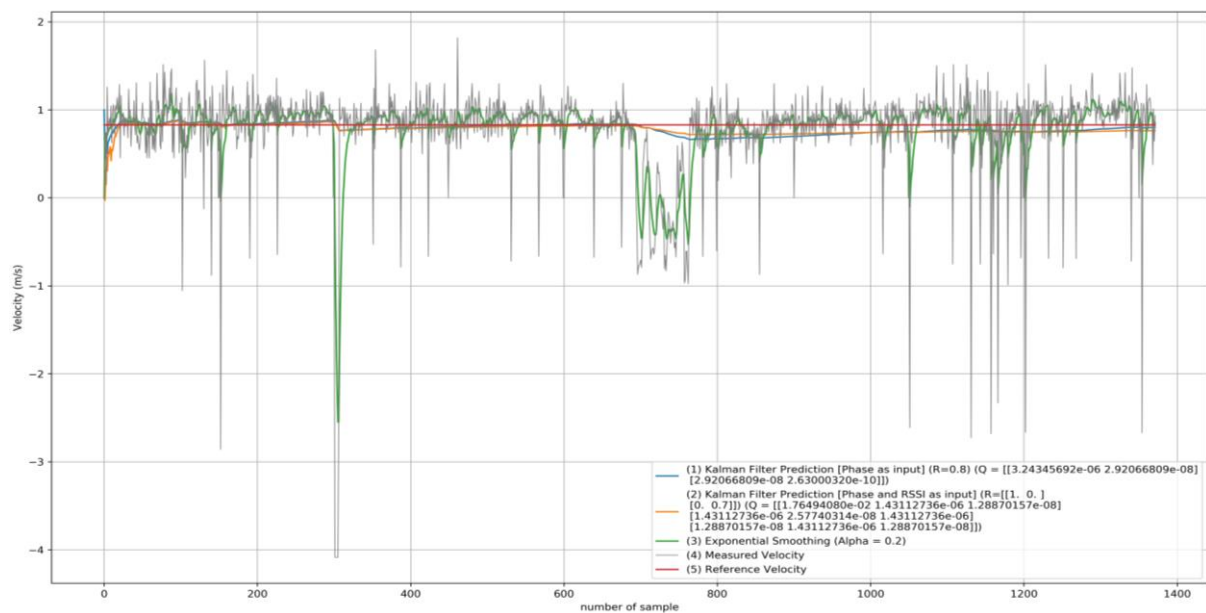


Figure 6-15: Velocity estimation comparison of the different techniques used for a tag moving at 0.83 m/s

For simplification the second part of this velocity estimation was converted to show a positive velocity. In the data the velocity will show as a negative velocity since a tag moving away from the antenna will produce a negative value. Here it can be seen that the same irregular velocity estimation exists in the middle part of the movement as a result of the tag moving from the one antenna range to the other. Both the Kalman Filter predictions have an observably good correlation to the reference velocity throughout the movement and especially in the first part.

As a result of the lower resolution of change in distance the phase and RSSI informed Kalman Filter converges more slowly to the reference velocity but is less susceptible to sudden detected changes in velocity. This shows in the middle part of the movement where the phase only Kalman Filter moves farther away from the reference velocity while the phase and RSSI informed velocities stays relatively constant. Finally, looking at the number of samples, the advantage of using tags that has a better signal response and thus produces samples from a bigger distance, can be seen. More than 1000 samples were recorded for this iteration of the tag moving at 3km/h. During this experiment it became evident that the tag and antenna combination used for the measurement provided a very consistent number of recorded samples per frequency band across the different velocities. The average time between samples changed however. Refer to table 6-5 for a further explanation at the end of this section.

This iteration of the experiment proved that it is possible to determine the velocity estimation for a moving tag very accurately, whether the tag is moving towards or away from the antenna. It also showed that there is an improvement in the estimation when the distance parameter is incorporated into the Kalman Filter prediction in ideal scenarios.

As the speed increases the RSSI values will also change more often, resulting in a smoother change in distance measured. The next figure shows the distance estimation for a tag traveling at 1.38 m/s.

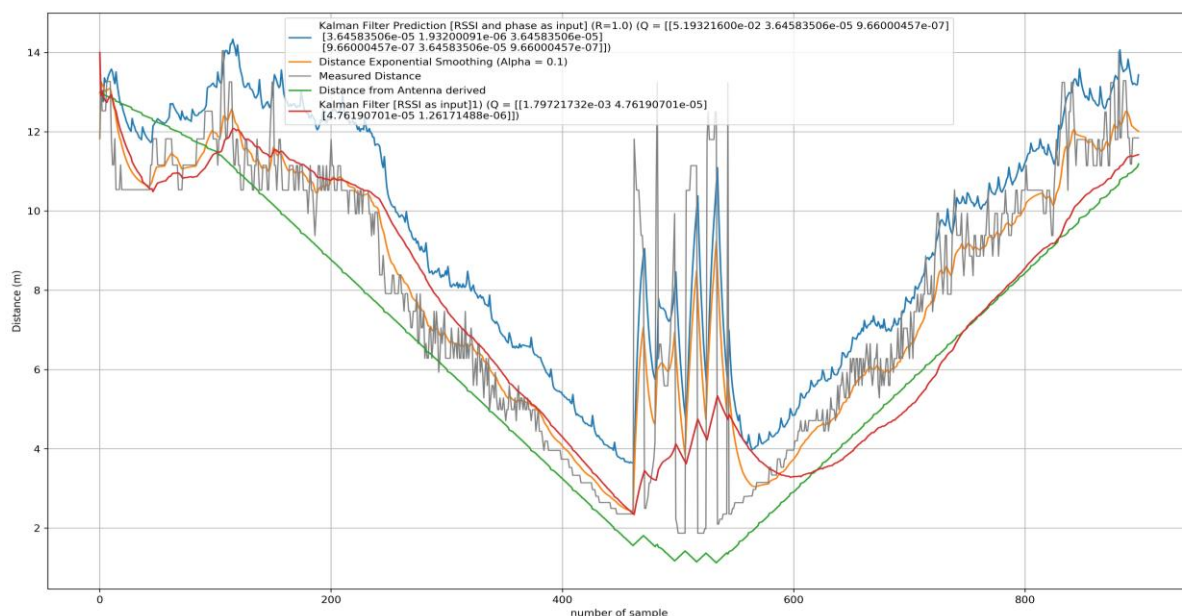


Figure 6-16: Distance estimation parameters for a tag moving at 1.38 m/s

The same trends observed for the tag traveling at 0.83 m/s is observed here as well. The increase in velocity is actually advantageous to minimize the lack of resolution in RSSI measurements. The middle part of the movement causes big erroneous reads again, but for the rest of the movement the distance estimation closely follows the reference values. The

same correlation between the different Kalman Filters, exponential smoothing, measured values and reference value is observed here. This figure supports the statement that a rough distance estimation is possible for an RFID tag if the reflections in the environment is controlled.

The next figure shows the velocity estimation for the entire movement of the tag traveling at 1.38 m/s.

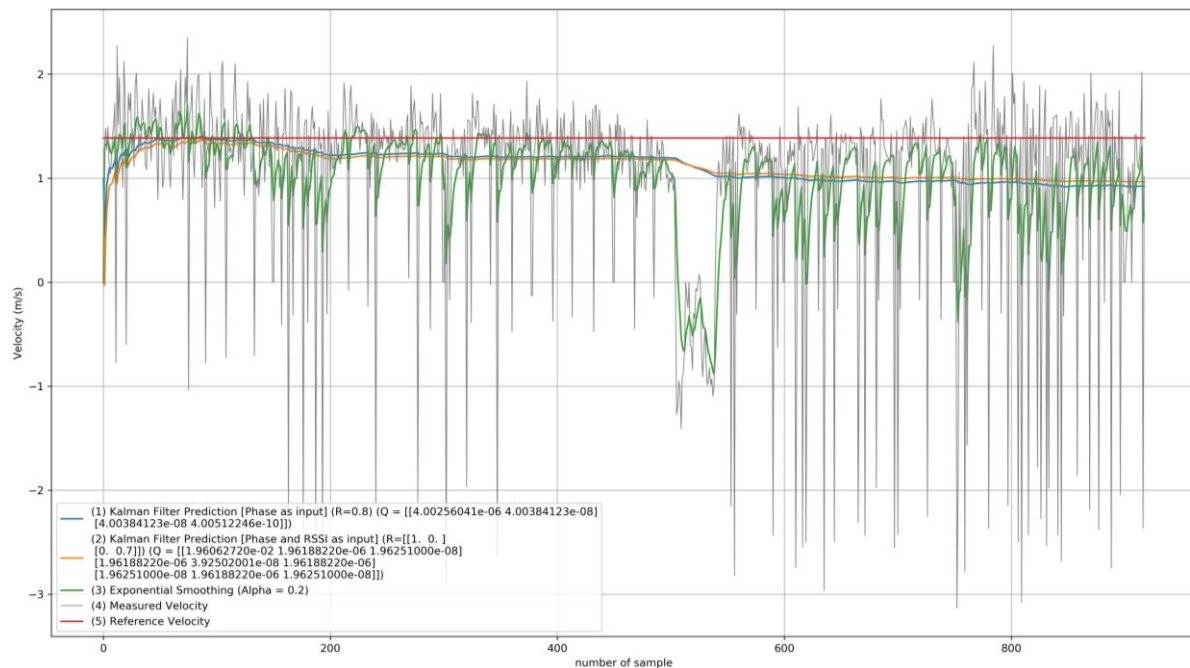


Figure 6-17: Velocity estimation comparison of the different techniques used for a tag moving at 1.38 m/s

In this figure the slight difference between the two Kalman Filters is observable. The Phase and RSSI based Kalman Filter is slower to react than phase only one resulting in a smoother prediction. This also makes it less susceptible to noise. The bad patch in the middle of the prediction causes an offset for the prediction in the second half, but as a whole the velocity estimation is accurate enough. If the middle part can be taken out during calculation then both sides of the antennas produce a good velocity estimation. It can also be seen here that the velocity estimation is slightly less accurate for the second half as the tag moves away from the antenna. This is due to the fact that the object that the tag is attached to, is between the tag and the antenna, resulting in a worse signal response.

The two different Kalman Filters produced very similar results in this iteration. Both these values are a better approximation of the velocity than the measurements and exponential smoothing as shown in the table later in this section.

The experiment is repeated for two more speeds to show how well the RSSI and phase Kalman Filter handles faster speeds. The next figure shows the distance estimation for a tag moving at 2.78 m/s. As with the previous increase in velocity, the change in distance estimation is smoother since the low resolution of the RSSI measurements is less noticeable.

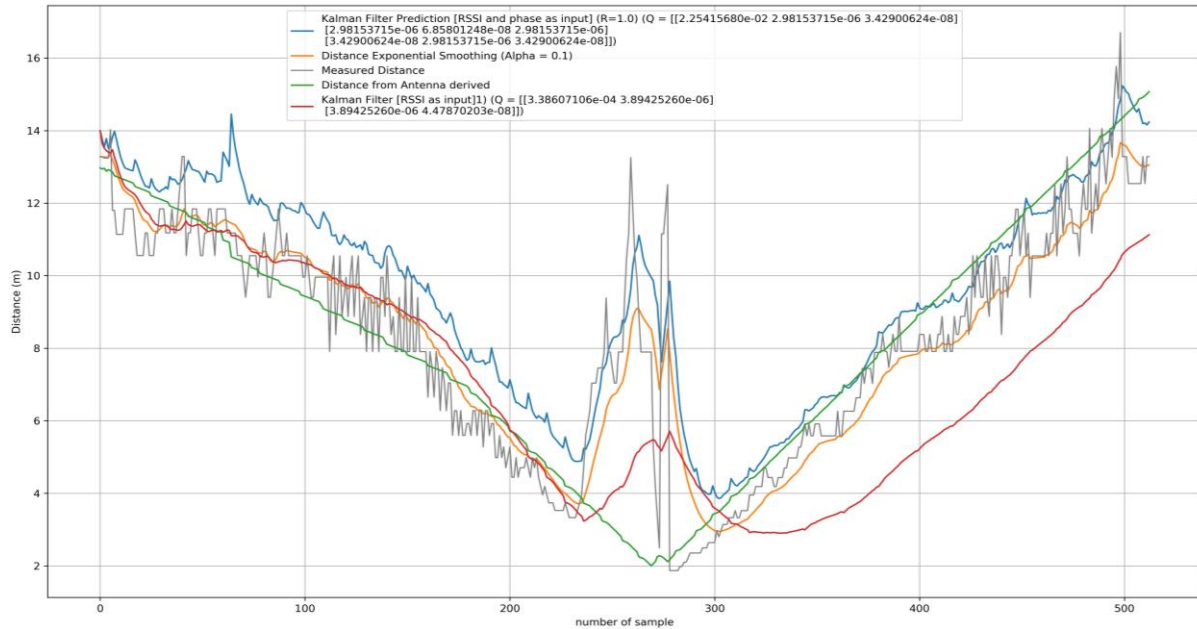


Figure 6-18: Distance estimation parameters for a tag moving at 2.78 m/s

Here it can be seen that the trend continues where the distance estimation has a big variation near the middle point of the figure. For each increase in speed the time spent in the side lobes of the antennas are shorter and thus the number of samples that produces these erroneous reads are less. In the figure it can be seen that due to the increase in speed, there is a bigger change in distance with less samples recorded. This causes the Kalman Filter prediction that only uses the RSSI as input to lag behind in the second half of the prediction. With this higher speed the Kalman Filter that uses the phase as well for input has a better correlation to the actual distance in the second part of the movement. This shows how the different models react differently to specific scenarios. For this reason, the model chosen for a scenario should be based on the exact conditions of the application environment. This also shows that the distance estimation technique functions well for faster moving speeds, but any future iterations should address the inconsistent period in the middle.

The next figure shows the velocity estimation for the tag moving at 2.78 m/s. At this speed the technique initially delivers a good estimation but when the tag neared the cross over point from one antenna to the other, the accuracy and consistency reduces drastically. From here the estimation never recovers fully the same estimation point. This shows some of the limitations of tracking the velocity of a moving tag for the movement away from the antenna when there is some kind of obstruction between the tag and the antenna. The slight difference

between the Kalman Filters is evident here as well. The filter with both the RSSI and phase as input reaches the reference value slower but then also stays slightly closer to the reference value for longer when the estimation accuracy reduces. It can be observed in this figure that the accuracy reduces before the tag reaches the cross over mark between the antennas. Closer inspection of the raw measurement revealed two main causes for this initial reduction in accuracy. Firstly, from sample 130 there is a sudden constant increase in the time between samples taken and secondly, the number of samples per frequency band is reduced from the high 20 samples per band to the 10 sample per frequency band region. The increase in time between samples means that the tag moves a bigger distance between consecutive samples. This increase in time between samples resulted in erroneous phase unwrapping, directly causing the reduction in accuracy of the velocity estimation. This increase can be caused by an area of weaker signal propagation of the antenna used and would not have had such a big impact on the slower moving tag due to the fact that the tag distance changed less per sample pair. The average number of samples per frequency hop and average time between samples are shown in a table at the end of this section.

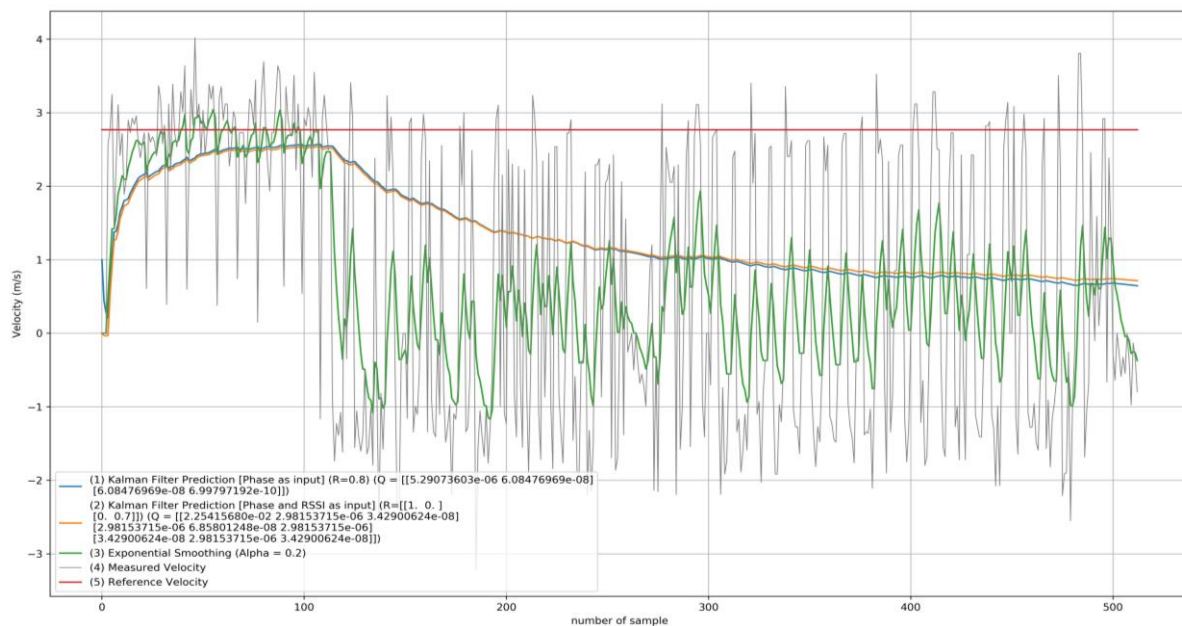


Figure 6-19: Velocity estimation comparison of the different techniques used for a tag moving at 2.78 m/s

It is important to note from this figure that both the Kalman Filters were designed to work for a variety of velocity estimations and expects a constant input. For this reason, it does not follow the pattern of the measurement immediately after it has settled on a certain value. The measurement values can be improved if the unwrapping technique is improved.

The main aim of illustrating that it is possible to detect the motion of a moving tag in different practical scenarios was achieved in this experiment. The advantage of the Kalman Filter over the exponential smoothing technique or just the normal measurements is clear looking at the

correlation between the estimations and the reference values. The tables later in these sections shows by how much the filters improved the values.

The next two figures show the distance estimation and the velocity estimation for a tag traveling at 4.1 m/s. The distance estimation technique shows that the system handles faster moving tags just as well, if not better than slower moving tags. The distance estimation is more regular compared to the slower moving tags and the exponential smoothing as well as the Kalman Filter with RSSI and phase as input follows the reference values much closer.

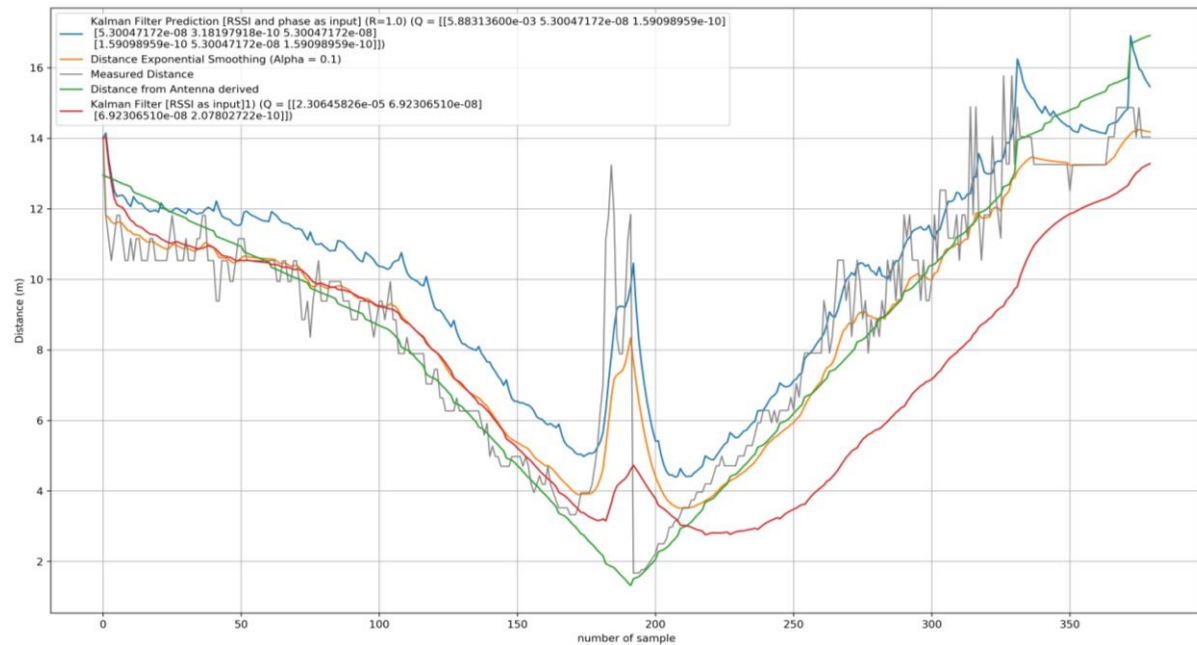


Figure 6-20: Distance estimation parameters for a tag moving at 4.11 m/s

The limitations of the velocity estimation technique are evident. For the first part of the movement the estimation almost reaches the reference velocity. Both the Kalman Filter estimation takes several samples to increase the velocity prediction and the advantage of the good distance estimation is seen in the Kalman Filter prediction that uses both the phase and RSSI as input, presented by the orange line. The technique struggles to detect the velocity for the away movement as a result of the irregular receiving of samples due to the obstructed line of sight. This means that the phase changes are too big to detect when wrapping occurs, resulting in a varying velocity estimation far worse than the part of the movement towards the antenna.

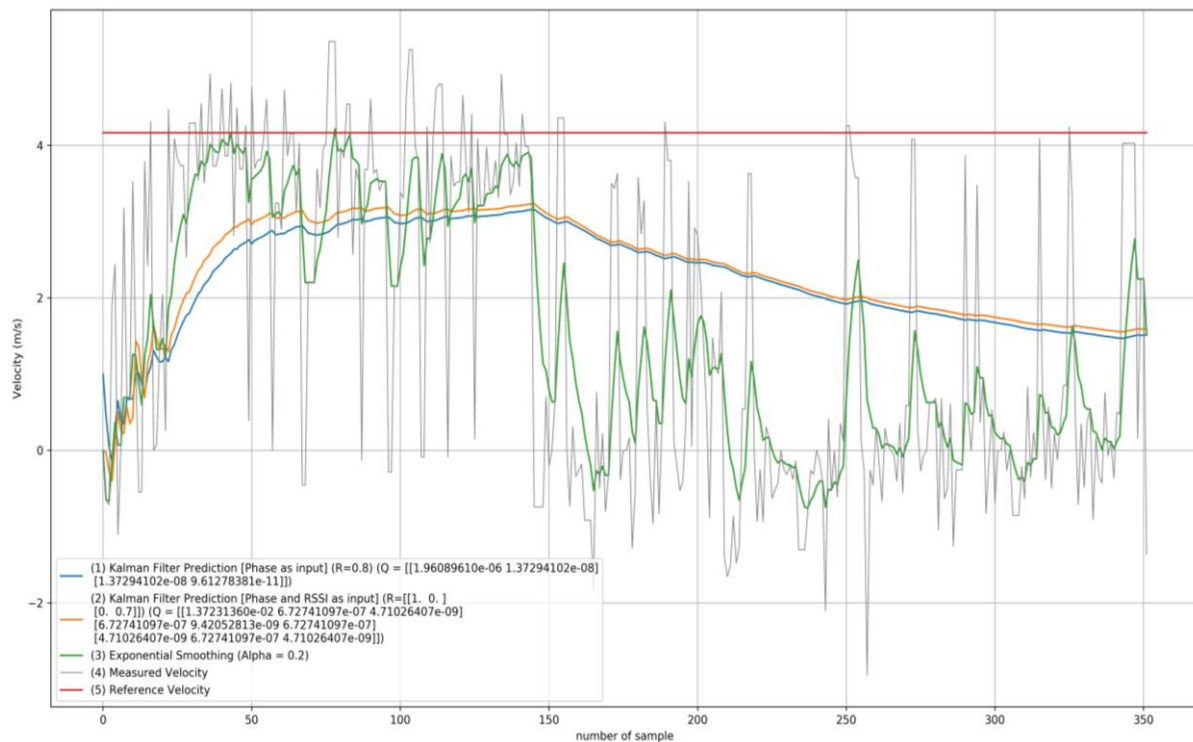


Figure 6-21: Velocity estimation comparison of the different techniques used for a tag moving at 4.1 m/s

Using the parameters above the direction of travel is clearly calculated. This shows that it is possible to calculate the velocity, distance and direction of a moving tag and also illustrates the advantage of adding the distance estimation parameter to the Kalman Filter to improve the velocity estimation. Distance estimation figures for tags traveling at 5, 5.5 and 6.9 m/s is included in appendix B. At this speed it is not possible to calculate the velocity of the tag, showing the value of the distance estimation.

As mentioned earlier in this section the number of samples per frequency band produced during these experiments stayed relatively constant. Some change was observed, but because of the nature of the scenario, where the tag is monitored for a very long distance, as well as the excellent signal response of the tags used, these changes in the number of samples are not as big as expected. One area that did have a big impact on these experiments are the time between samples accompanying these slight changes. A big increase in time between samples measured along with a slight decrease in the number of samples per frequency band produced measurements that are very difficult to unwrap effectively at higher speeds, resulting in some of the inaccurate measurements seen above. The next table is included to show the average number of samples per frequency band at the different speeds as well as the difference in time between samples recorded and the total number of samples per iteration of the experiment. Here it is evident that these parameters affect the accuracy of the estimation techniques directly.

Table 6-5: Analysis of signal response for each different speed

Speed (m/s)	Average number of samples per frequency band	Average time between samples (s)	Average total number of samples recorded for each iteration
0,83	18,56	0,0185	1442,31
1,38	16,98	0,0194	955,48
2,78	14,74	0,0342	540,29
4,17	12,85	0,0387	397,62

To determine the improvement the Kalman Filter with the RSSI and Phase as input compared to the phase only Kalman Filter, standard measurement and exponential smoothing the three tables below are included. These tables show the MAE, MAPE and RMSE for the velocity estimation of all the different tags. This analysis was not done for the distance estimation since during the experiment there were no access to a distance measuring device that can serve as a precise distance reference.

The first table included is the table showing the MAE values for the different velocity estimation parameters compared to the reference value, for the entire movement. This includes the erroneous section near the middle point of the tag movement, that increases these values significantly from the experiment discussed in section 6.1.

Table 6-6: MAE of the different estimation techniques for the entire tag movement at different speeds

Speed (m/s)	Mean Absolute Error			
	Measurement	Exponential Smoothing	Kalman Filter (Phase)	Kalman Filter (Phase and RSSI)
0,83	0,2839	0,1819	0,0776	0,0681
1,38	0,6376	0,5147	0,3562	0,3500
2,78	2,1896	2,0790	1,4980	1,4852
4,17	2,9286	2,8364	2,1203	2,1019

In the table above it can be seen that the Phase and RSSI Kalman Filter produces the lowest MAE of all the estimation techniques. Both the Kalman Filters improve on the standard measurement substantially. If only the velocity estimation for the part of the movement where

the tag is moving away from the antennas is included, the Kalman Filter using the Phase and RSSI will have an even lower MAE compared to the other techniques.

The next table included is the RMSE, to illustrate further the difference between the techniques. Again, bearing in mind that the extremely inaccurate middle portion is included these values are higher than it would be if only the main part of the movement was analysed. Here enhancing the differences, it is clear that the two Kalman Filters produce standout values for the velocity estimation and that the RSSI and phase fusion Kalman Filter technique is an improvement on the phase only based Kalman Filter.

Table 6-7: RMSE of the different estimation techniques for the entire tag movement at different speeds

Speed (m/s)	Root Mean Square Error			
	<i>Measurement</i>	<i>Exponential Smoothing</i>	<i>Kalman Filter (Phase)</i>	<i>Kalman Filter (Phase and RSSI)</i>
0,83	0,5645	0,3534	0,1002	0,0924
1,38	1,2037	0,7217	0,3950	0,3826
2,78	2,8081	2,3278	1,6248	1,6068
4,17	3,5927	3,2681	2,2633	2,2510

The last table included in this section shows the MAE error for the part of the movement where the tag is approaching the antenna. This was generally far more accurate than the second part of the movement and show cases the ideal real-world scenario of detecting the motion of a tag.

Table 6-8: MAE of the different estimation techniques for the section of tag movement towards the antenna at different speeds

Speed (m/s)	Mean Absolute Error			
	<i>Measurement</i>	<i>Exponential Smoothing</i>	<i>Kalman Filter (Phase)</i>	<i>Kalman Filter (Phase and RSSI)</i>
0,83	0,2123	0,1079	0,0419	0,0417
1,38	0,4044	0,2576	0,21970	0,2181
2,78	1,4640	1,2931	1,041	1,0841
4,17	2,6669	2,4313	1,6304	1,6041

In the table above for the first part of the movement it can be seen that the estimation is a lot more accurate. It also shows that the Phase and RSSI Kalman Filter as well as the Phase only filter produces excellent velocity estimations that can be used in specific applications.

In this section it was proven that a rough distance estimation is possible. It was shown that this distance estimation can then be used to also improve the velocity estimation by incorporating it into the Kalman Filter model. The experiment proved that it is possible to determine the motion estimation parameters using only one tag for the towards movement. The difficulties in determining the motion estimation parameters for the tag moving away from the antenna, with some kind of obstruction between the tag and the antenna, was shown. It was illustrated that for direction estimation there is several accurate measurements at all the different speeds available that can be used for this purpose. Finally, it was shown that the improved Kalman Filter is more effective compared to the phase based Kalman Filter at higher speeds, but that this will change if multipath effects are incorporated since this will increase the variability in the distance estimation.

6.4 Influence of non-ideal variables on the accuracy of motion estimation techniques

In this section several effects from real-world scenarios are characterized. The impact of different parameters that cannot always be contained is shown.

6.4.1 Influence of stray tags on motion estimation technique results

This section adds to the experiment done in section 6.2 where the number of tags being tracked were increased. For this instance, several stray, stationary tags were placed in the range of both antennas. This adds to the complexity since more frequent antenna channel changes will occur to read the stray tags on both sides. This means that the tag that is moving towards the antenna will be read far less than the previous instances.

The figure below shows the velocity estimation for a tag moving at 1.38 m/s. Only the first half of the part of the movement towards the antennas are included since the away movement did not produce consecutive samples regularly, resulting in instantaneous velocities without any correlation to the previous measurements, and to show an enhanced image of the irregular velocity estimation. The combined Kalman Filter is lower with this estimation because it normally takes more samples to converge to the same reference value. This is one downside of the technique, but with these parameters chosen it also provides a better smoothing effect. Here only 35 samples are recorded resulting in the lack of conformity observed.

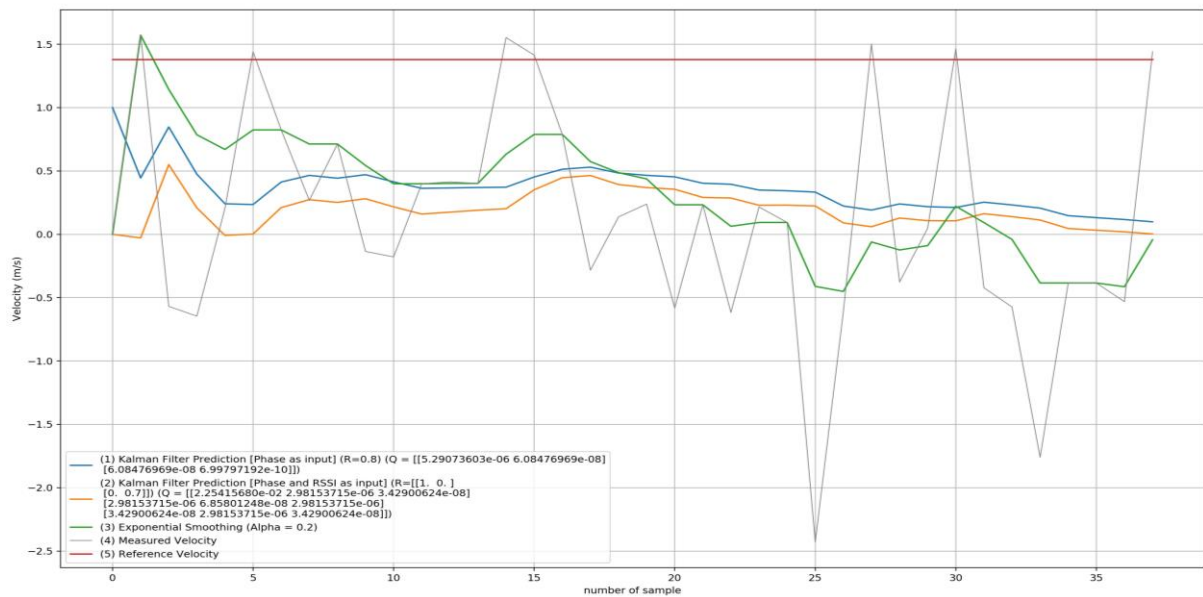


Figure 6-22: Velocity estimation of a tag moving at 1.38 m/s, in the presence of several stray tags.

The irregular sampling rate, due to the samples measured from the stray tags, results in inconsistent velocity estimation. Initially the velocity estimation seems to be accurate but a steady decline in consistent measurement adds to the troublesome detection. The accuracy decreases due to the lack of consecutive samples recorded. This means that a big distance is covered by the tag before another consecutive pair of samples are recorded. This results in erroneous unwrapping due to the ambiguity of the scenario and very inconsistent estimations. It is clear that adding this amount of stray tags in this setup where both antennas read samples, creates a lot of complexity. Using only one antenna per reader or restricting the stray tags to only one side will reduce these effects since it will also reduce the reading of samples on the opposite channel of the one where the moving tag is being monitored. This shows that the stray tags, using a maximum throughput reading mode, has the biggest impact on the current motion estimation technique. Both the Kalman Filters maintain the estimated velocity for longer but the lack of data causes a steady decrease. This also shows that the Kalman Filter with this added distance estimation parameter is not suited to all scenarios. This figure shows

that there is sufficient data to determine the direction of the traveling tag, but that there will be a big margin of error on the velocity accuracy.

The following figure shows the distance estimation for the first part of the movement.

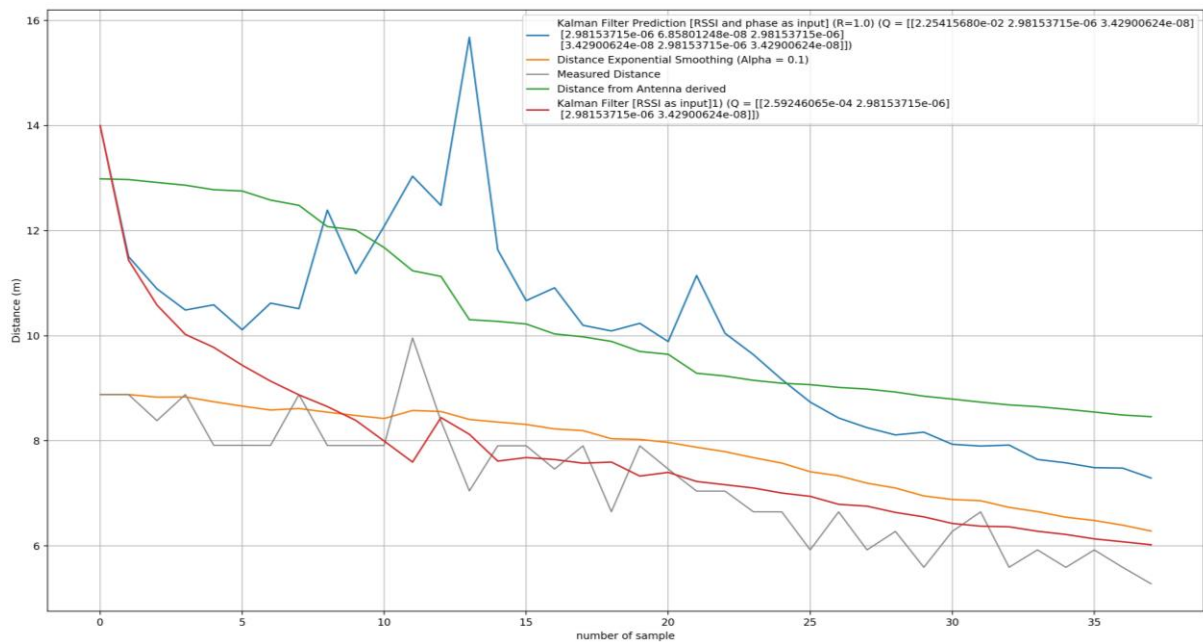


Figure 6-23: Distance estimation of a tag moving at 1.38 m/s, in the presence of several stray tags.

In this figure it can be seen that the tag was first read with an estimated distance of 9m from the antenna. This is 6m closer to the antenna than the theoretical maximum reading range. In the figure the lack of change in measured distance is also clear. It is evident from this observation that the tag is only read when it has a relatively strong signal strength and that the lack of successive samples on the same frequency band contribute to very poor motion estimation.

The next two figures show all the samples recorded of this iteration of the experiment to illustrate the lack of samples in this scenario. The first figure showing the TD-PDOA velocity estimation.

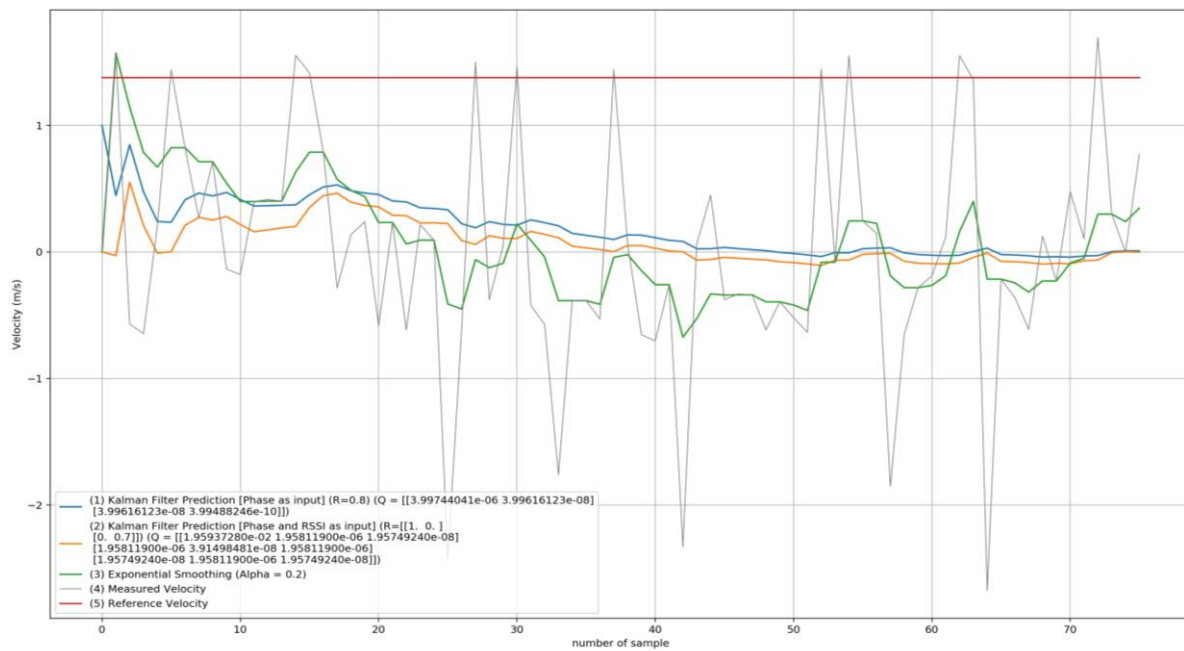


Figure 6-24: Velocity estimation of a tag moving at 1.38 m/s, in the presence of several stray tags including all samples collected.

The figure above shows that the last half of the samples had almost no consistency in the velocity estimation. This is all as a result of the increase in time between samples. The increase in time between samples causes irregular phase unwrapping and faulty phase unwrapping which in turn produces erroneous velocity estimations. The technique used to determine the velocity estimation relies on consistent correlation between samples, which lacks completely here. In these types of scenarios, it would be better to observe the samples in batches and ignore any previous phase measurements if the time difference between samples are above a certain point. This is a feature that can be added to the technique for specific scenarios and was not pursued due to a lack of time. From the figure above it can be seen that the number of samples is drastically less than that seen in the velocity estimation section 6.1 and 6.2, there the number of samples, on the first half of the movement as the tag approaches the antenna, are above 450 samples. Here it is less than 90 samples, illustrating the big difference.

The average time between samples for this experiment is calculated as 0.202 seconds, while the average time between samples for the experiment in 6.1 for a tag traveling at the same speed but without any stray tags is calculated as 0.0283 seconds. This shows how irregular the collection of samples was during this experiment.

The next figure shows the distance estimation and illustrates exactly where the last sample was taken. This is at the halfway mark through the movement, showing that no data was collected for the part of the movement away from the second antenna.

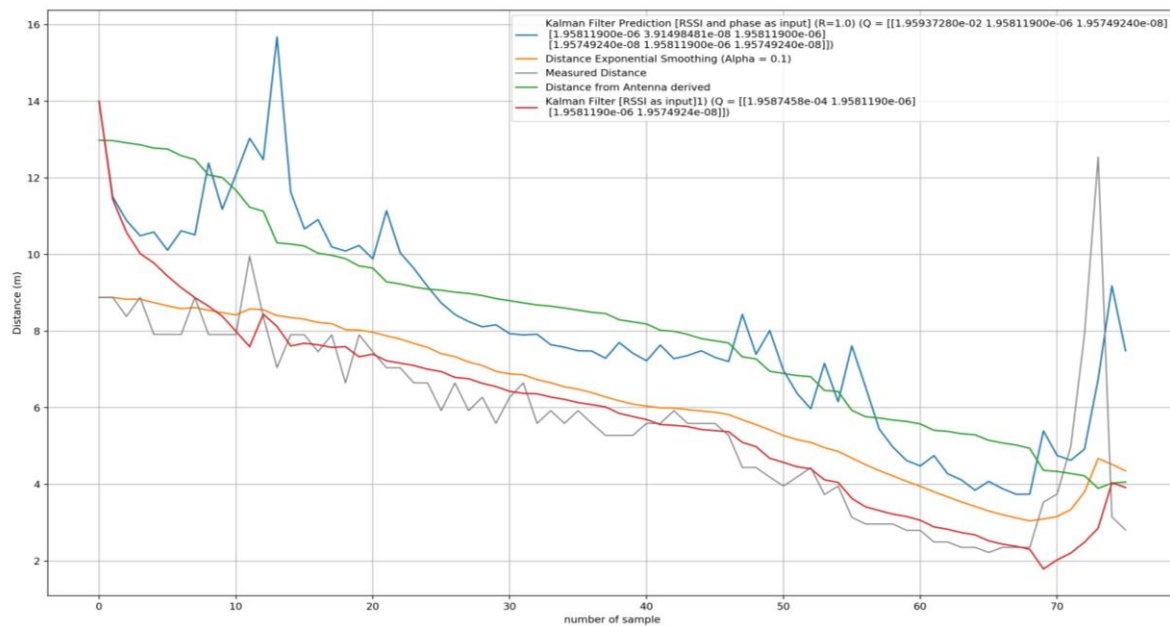


Figure 6-25: Distance estimation of a tag moving at 1.38 m/s, in the presence of several stray tags including all samples collected.

From the figure above it can be seen that the tag was monitored from 9m out up until the middle part of the movement where the tag moves past the two antennas. This shows that since there were no multipath effects and reflections were kept to a minimum the distance estimation that was produced was relatively accurate.

The number of samples produced for the moving tag in this experiment is about a tenth of the samples recorded with no stray tags in the environment. This accompanied by the irregular sampling rate is the main causes for the imperfect motion estimation. The distance estimation can still be seen as relatively successful for the one side of the movement but the velocity estimation was poor in these conditions.

This experiment highlighted one of the biggest problems with motion estimation in real-world scenarios. It showed that an adjustment to the technique is necessary in order to be able to accurately determine the velocity of a moving tag in these conditions. This experiment showed that even if the conditions are not ideal it is still possible to accurately determine the direction of travel and as long as reflections are minimized a rough distance estimation is still possible. Using batches of reads instead of looking at all the data as a continuous flow can definitely improve on these readings since the phase unwrapping technique will not compare samples that were taken from a previous batch. This theory will involve examining the time difference between samples and the frequency band of the recorded consecutive samples. Based on this correlation it can be determined whether the current sample can be compared to the previous one, allowing a more successful unwrapping of the phase measurement and

consistent velocity estimation. If it is determined that the time between the current sample and the previous one is too big, the current sample and following samples can be examined as a separate pair, providing an instantaneous velocity from these phase measurements without the influence of the previous measurements on the unwrapped phase value. Time constraints prevented the testing of this theory.

6.4.2 Influence of reflections on motion estimation technique results

It is well known that RFID signals are very susceptible to multipath effects and reflections. In this section the results to characterize the effect of some multipath signals on the motion estimation parameters are discussed.

The experimental setup is such that the first part of the movement will be affected by multipath if the tag gets influenced by the reflecting surface. It is important to inspect both the effects on the velocity estimation and the distance estimation, since it is expected that the RSSI signal will be more susceptible to the reflections than the phase values, which will show more clearly in the distance estimation.

The figure below shows the velocity estimation for a tagged object moving at just over 0.83 m/s.

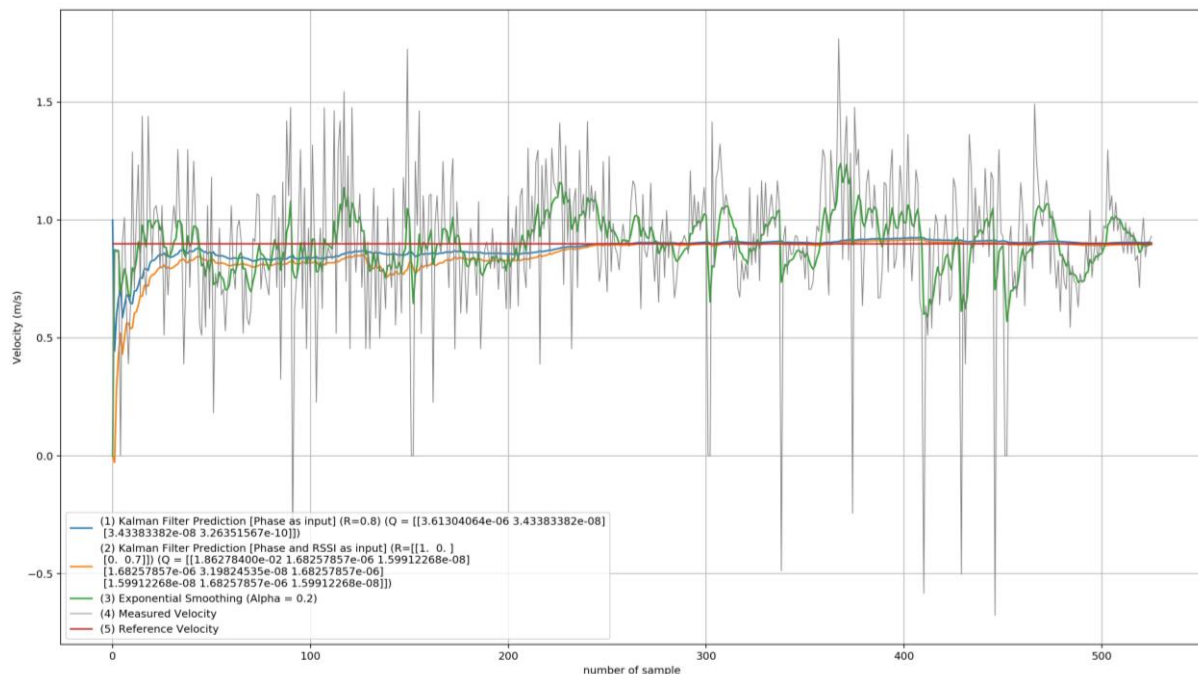


Figure 6-26: Velocity estimation of a tag moving at 0.86 m/s, in the presence of a reflecting surface

In the figure above it can be seen that the initial velocity estimation is not as accurate as expected, due to the reflections. Up until sample 200 the estimation is lower than expected. Looking at the blue and orange lines, which is the Kalman Filter using only phase as input and

the Kalman Filter with both the RSSI and phase as input (discussed in section 6.3), it can be seen that there is some difference in the conformation between the two. The orange line increases the velocity prediction at a slower rate than the blue line. Around sample number 150 there is a sudden, excessive drop in the velocity estimation compared to the other velocity estimations. Beyond this point the estimations converge to the same point and the second half of the samples included in this figure shows a very good velocity estimation for both techniques.

The behaviour of the velocity prediction from the Kalman Filter with both phase and RSSI as input can be explained by looking at the distance estimation for this movement. The figure below shows the distance estimation for this tag's movement.

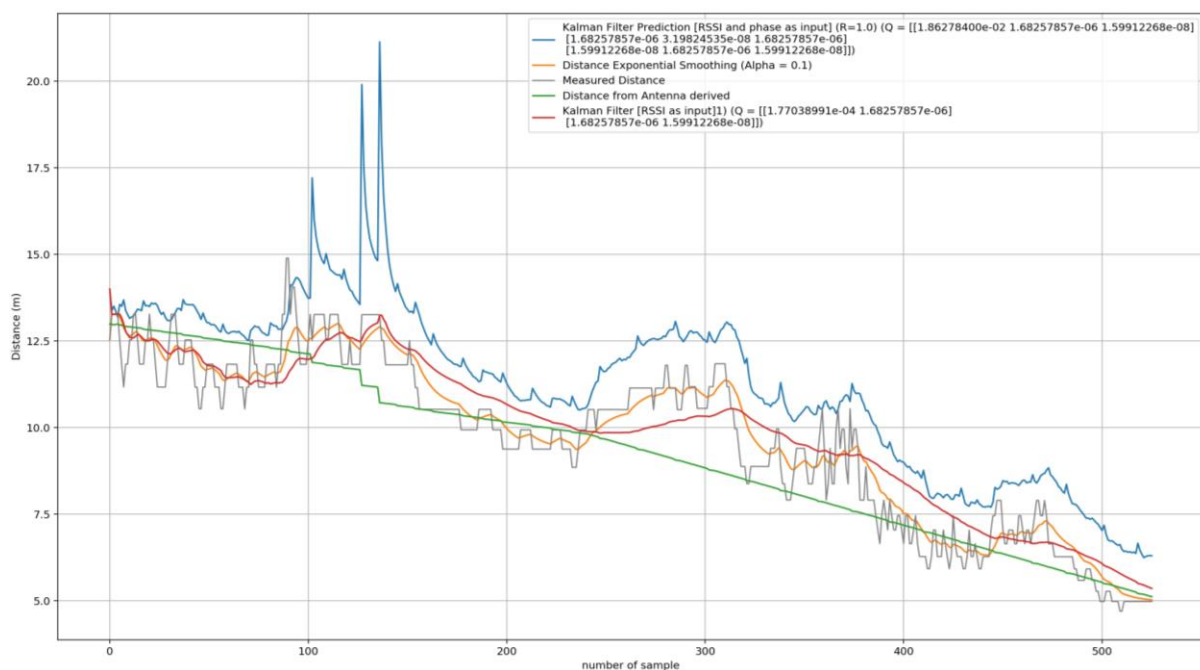


Figure 6-27: Distance estimation of a tag moving at 0.86 m/s, in the presence of a reflecting surface

In the figure above it can be seen that the distance estimation starts at the expected distance between 13 and 14 meters from the antenna. After the initial decrease in distance there is a sudden increase in the estimation at sample 100. This increase accompanied by the increase in velocity estimation results in a big change in the predicted distance estimation, away from the antenna by the Kalman Filter represented by the blue line. Two big spikes in distance can be observed between samples 120 and 150 on this blue line. This increase corresponds to the sudden decrease in the velocity estimation observed in the velocity estimation above. There after there is more instability up until sample 300 before a steady decrease in distance is observed. The biggest spikes were observed between samples 120 and 150 and explains the behaviour observed in the velocity estimation. This supports the claim that the RSSI signal will be more susceptible to reflections and multipath effects. The distance estimation predictions based on the RSSI parameters were more unstable, while the velocity estimation

remained more constant. As a result, the Kalman Filter using only phase produced a more constant velocity prediction compared to the Kalman Filter that uses both RSSI and phase together.

For a tag moving slightly faster the same type of behaviour is expected, at a slightly earlier point in the sampling process since the tag will reach the reflective area faster. The velocity estimation for a tag moving at 1.38 m/s is shown in the figure below.

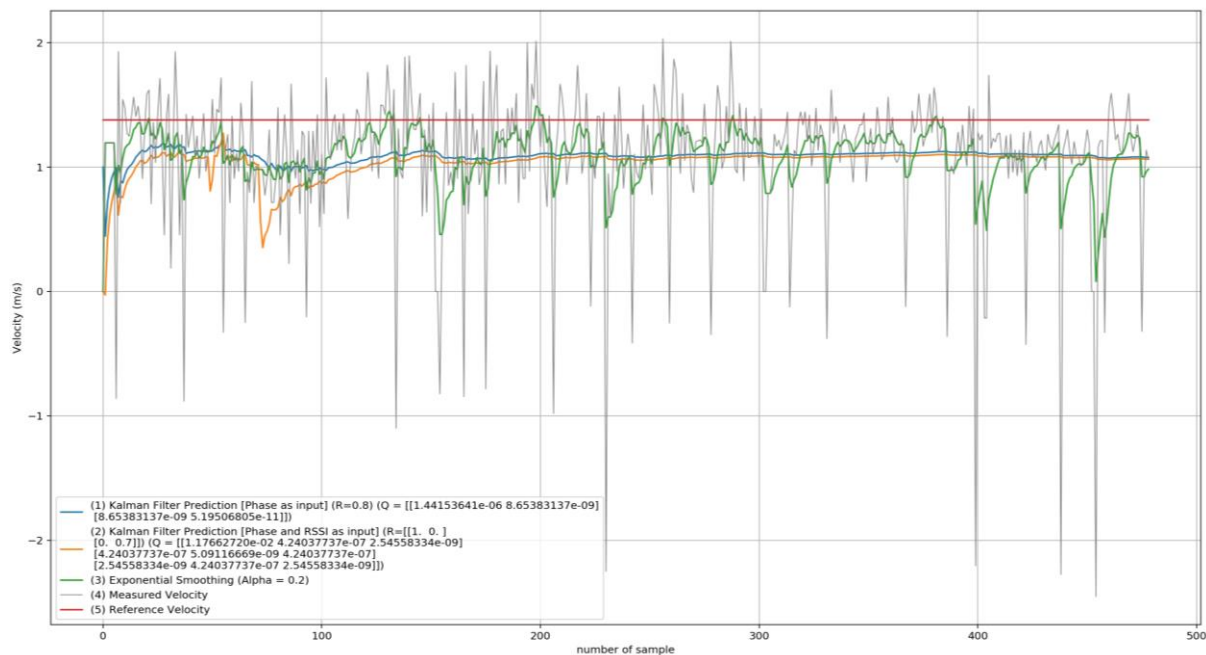


Figure 6-28: Velocity estimation of a tag moving at 1.38 m/s, in the presence of a reflecting surface

From the figure above it can be seen that the velocity estimation is slightly lower than that of the expected reference value. This can be due to the weaker signal response or to variation in the actual speed during the experiment. The most important observation here is the similar drop in velocity estimation around the 80th sample produced by the Kalman Filter prediction which have both the RSSI and phase as input (orange line).

Further velocity estimations after that point are very similar for all the different estimations with both the Kalman Filter predictions producing the most constant values. The next figure shows the distance estimation for this movement of the tag, with the focus on the earlier part.

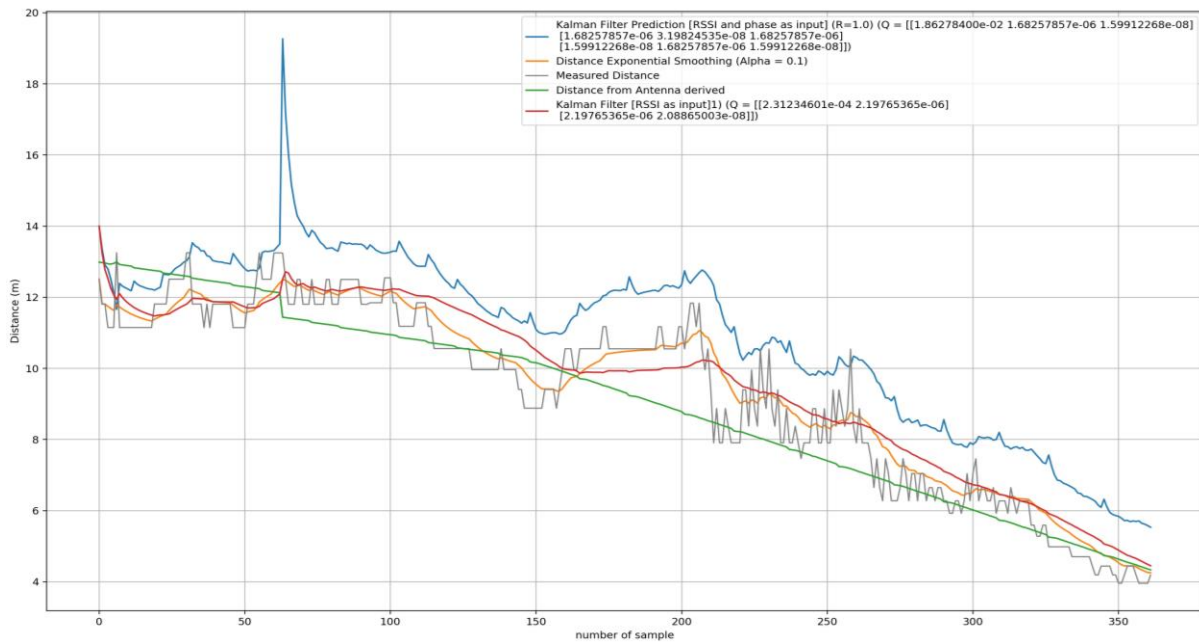


Figure 6-29: Distance estimation of a tag moving at 1.38 m/s, in the presence of a reflecting surface

From the figure 6-29 it can be seen that a similar spike to the slower moving tag estimation exists at around the 60th sample. This increases the expected distance between the tag and the antenna and causes the reduction in velocity prediction seen in the previous velocity estimation figure. Similar inconsistent distance estimation is observed for this distance estimation compared to the slower moving tag's distance estimation.

All the figures illustrate the effect that the reflective surface has on the motion estimation parameters, with the direction estimation influenced the least. The distance estimation experience increased variability due to the susceptibility of RSSI to multipath effects. This also affects the Kalman Filter velocity prediction that uses this value.

This shows the potential hurdles with using this specific distance estimation technique as well as using the parameter as input to improve the velocity estimation. The table below shows the analysis of the different estimation techniques for the tag moving at 1.38 m/s.

Table 6-9: Average error analysis of the different velocity estimation techniques for a tag moving at 1.38 m/s

Analysis method	Estimation techniques			
	Measurement	Exponential Smoothing	Kalman Filter (Phase)	Kalman Filter (Phase and RSSI)
MAE	0,3831	0,2934	0,29146	0,3424
MAPE	27,76	21,1907	21,1207	21,12078
RMSE	0,6394	0,35366045	0,2973	0,3665

This table clearly shows the reduction in accuracy for the phase and RSSI based Kalman Filter. It is important to note that the standard Kalman Filter still produced the most consistent estimation and that it can still be used to produce a reliable velocity estimation in the presence of reflections.

This section illustrated the effects that multipath and reflections have on the motion estimation parameters. This section also proved that the phase-based velocity estimation technique will work with limited multipath signals and reflections. This type of non-ideal conditions is something that can be found in most real-world scenarios and is an important consideration when the final velocity estimation and distance estimation techniques are chosen for implementation.

6.4.3 Influence of indoor environment with stray tags on estimation technique results

To show how the velocity estimation technique functions in a non-ideal condition the experiment is performed inside a building with many stray tags in the environment, as well as a short distance that the reader can track the movement of the tag.

If accurate velocity estimation is not possible in these conditions other suggestions on how to use this data in real-world scenarios will be presented.

The first few iterations of the experiment moved only one tag through the antenna reading range as described in section 5.5.3. The figure below shows the Kalman Filter of the velocity estimation for each tag that were recorded in the reading range.

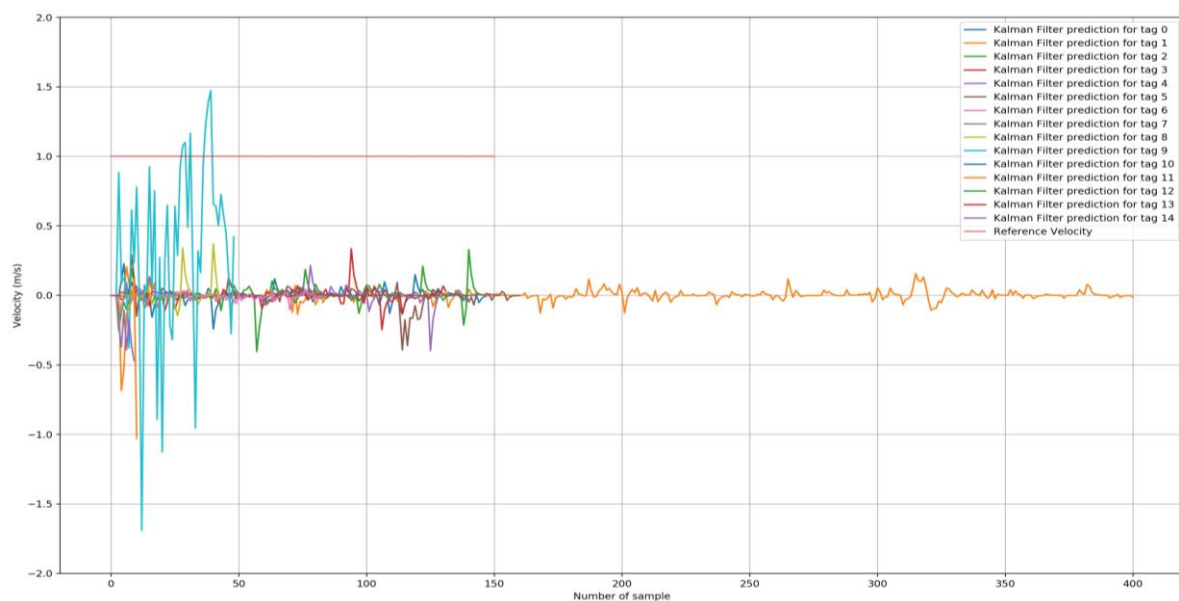


Figure 6-30: Velocity estimations of all the tags in the reading range, with one tag moving at 1 m/s and the others acting as still standing stray tags (Iteration 1)

In the figure above it can be seen that one tag clearly stands out as the moving tag in this scenario while all the other tags averages out with a zero velocity estimation. It can also be seen that only a few samples were recorded for the moving tag. The samples that were recorded for the moving tag, tag number 9, have a lot of variation and a clear velocity estimation is difficult to determine. The average velocity estimation of the moving tag in this scenario was recorded as 0.26 m/s. The next highest velocity estimation recorded is 0.09 m/s, clearly showing the difference between the moving tag and the stationary tags. Accurate velocity estimation however was unsuccessful in this scenario. The direction estimation was still accurate showing that the tag moved through the entrance, in the direction towards the antenna.

The next figure shows another iteration of this experiment with similar results recorded.

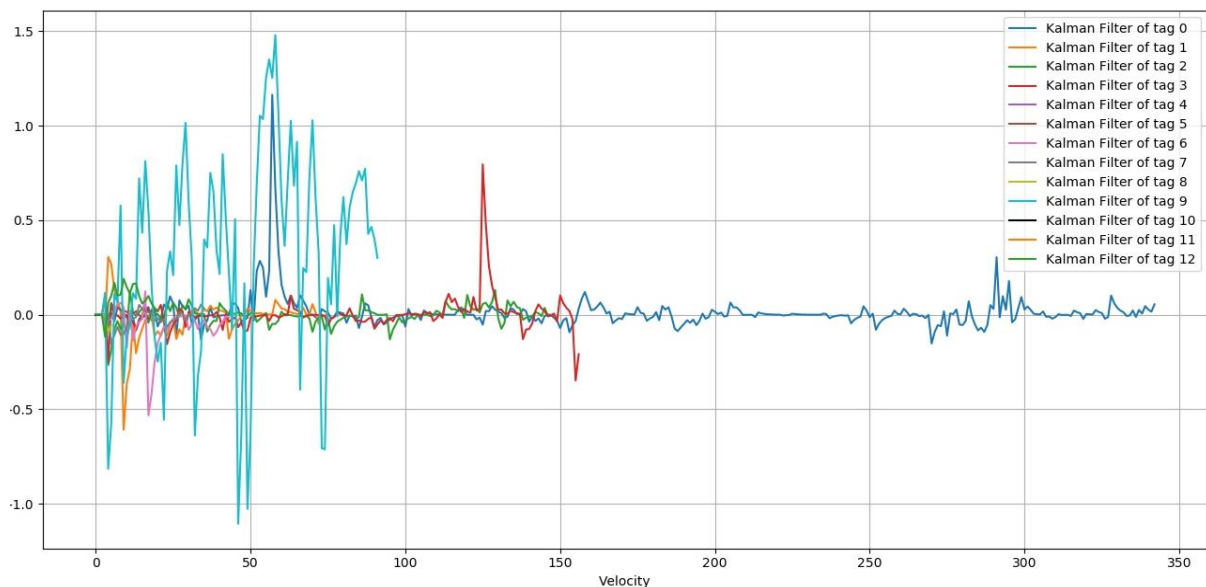


Figure 6-31: Velocity estimations of all the tags in the reading range, with one tag moving at 1 m/s and the others acting as still standing stray tags (Iteration 2)

In the figure above tag number 9, represented by the light blue line, again stands out clearly as the moving tag. The average Kalman Filter velocity estimation for this tag was calculated as 0.318 m/s with the closest other tag's velocity estimation being 0.086 m/s. In the figure above two spikes in the estimation can be seen, one on the red line and one on the blue line. These were both erroneous reads produced by the stationary tags and shows the importance of looking at a wider range of data when determining which tags are moving and which are stationary.

The next figure shows that the trend observed by the previous figures continues, where one tag clearly stands out as the moving tag but that the velocity estimation is not accurate. Here tag number 8 is the moving tag.

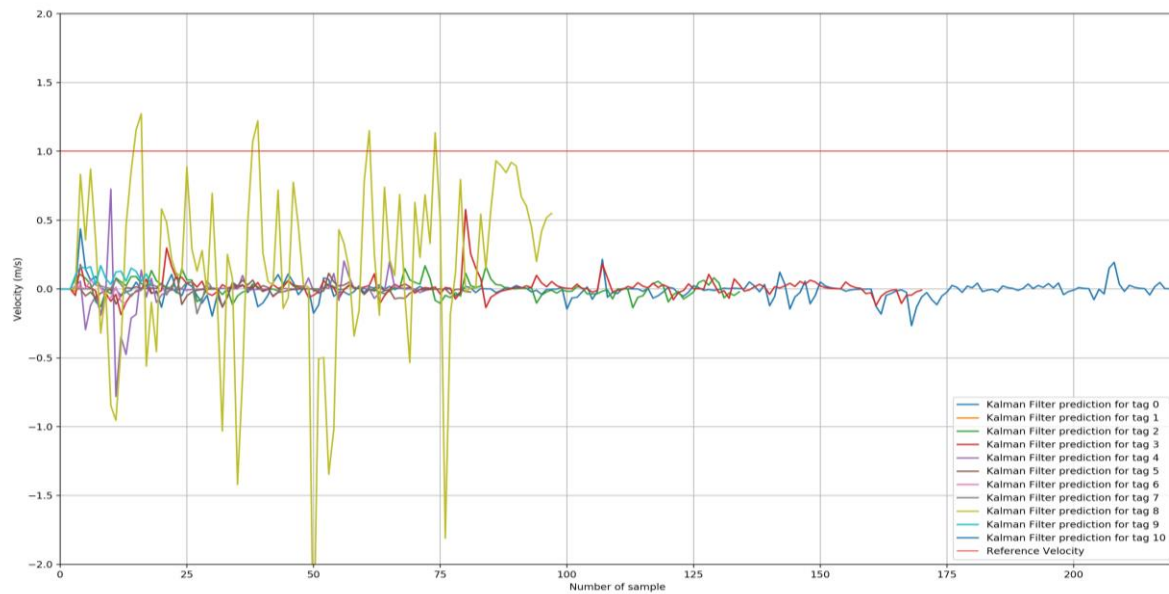


Figure 6-32: Velocity estimations of all the tags in the reading range, with one tag moving at 1 m/s and the others acting as still standing stray tags (Iteration 3)

The average velocity of the moving tag in the figure above is only 0.19 m/s, while the closest other velocity estimation for the still standing tags is calculated at 0.091 m/s. This again clearly illustrates the problems associated with calculating the motion estimation of a moving tag in very poor conditions.

The next two figures are included to show the results in the same experimental conditions, but where two tags are moved together through the antenna reading range. Similar results can be seen here to that illustrated with only one tag moving through the range.

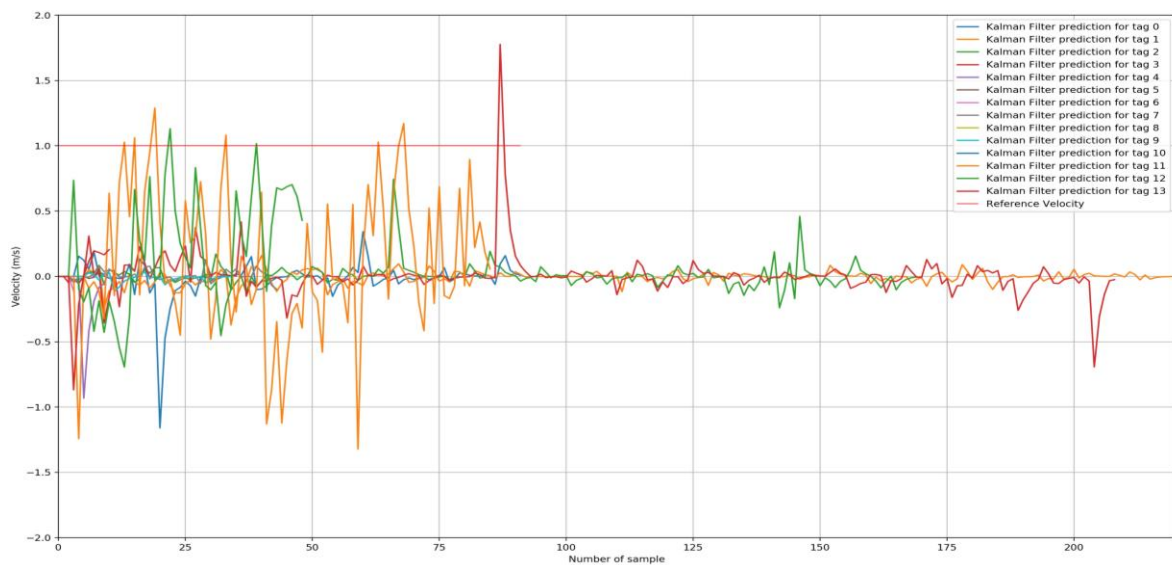


Figure 6-33: Velocity estimations of all the tags in the reading range, with two tag moving at 1 m/s and the others acting as still standing stray tags (Iteration 1)

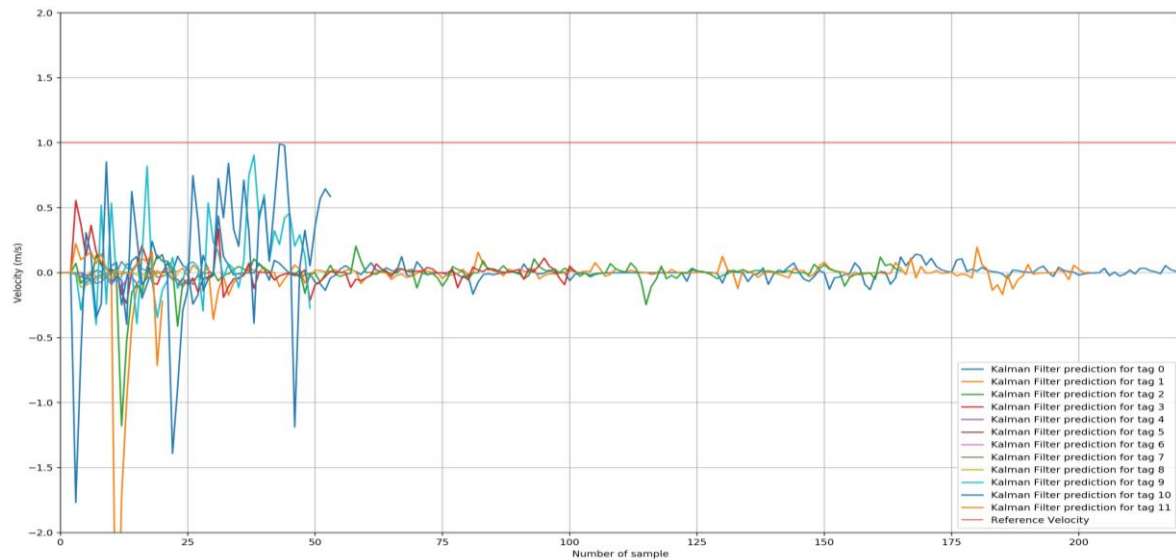


Figure 6-34: Velocity estimations of all the tags in the reading range, with two tag moving at 1 m/s and the others acting as still standing stray tags (Iteration 2)

In the figures above it can be seen that two tags show a varying velocity estimation with more consistency than the stationary tags. In the first figure the two moving tags are illustrated by the orange and green lines (tag 11 and 12) and in the second figure by the light blue and dark blue lines (tag 9 and 10). Erroneous peaks in the velocity estimation of stationary tags can be seen in both figures, but with no consistency in the peaks. The average velocity estimation of the moving tags in the first image are 0.1208 m/s and 0.198 m/s, with the closest stationary tag velocity being 0.017 m/s. In the second figure the two moving tags's Kalman Filter velocity estimation are calculated as 0.11 m/s and 0.122 m/s with the biggest velocity for a still standing tag being 0.02m/s.

The distance estimation was omitted from this section because of big variations in the RSSI signal. From the literature it was known that the distance estimation technique, used earlier in this chapter, is not suited to these conditions. It was thus decided that the testing will only focus on the direction and velocity estimation.

In this non-ideal environment the Kalman Filter can not improve the estimation by much, only managing to smooth out some of the variability. This is as a result of the lack of consecutive phase measurements within a certain time period. The next table is included to compare the raw velocity estimation, the exponential smoothing and the Kalman Filter predicted velocity against the estimated reference value for the experimentations performed in this section. Here the case where two tags are moved together is compared with the scenario where only one tag is moved through the signal range. It is expected that the MAE for these parameters will be very high since the velocity estimation never established a good estimation. The different techniques can however still be compared in this non-ideal condition. These results are shown in the following table.

Table 6-10: Mean Absolute Error of the velocity estimation techniques for a tag moving through the non-ideal environment

Number of moving tags	Estimation techniques		
	MAE Measurement	MAE Exponential Smoothing	MAE Kalman Filter (Phase)
1	0,8321	0,79215	0,7851
2	0,9215	0,8544	0,8427

From this table it is clear that the overall velocity estimation for the moving tag, in this non-ideal environment where there are a lot of reflections as well as several stray tags, is not accurate. It is not recommended to use this technique if an accurate measurement is required. The Kalman Filter managed to remove some of the negative peaks affecting the overall measurement accuracy, but the improvement is negligible. A small difference between the single moving tag and the scenario where two tags are moved simultaneously can be observed. These results do however show that direction estimation is possible and that a clear difference exist between the still standing and the moving tags velocity estimation.

The results in this section showed that in these types of conditions an accurate velocity estimation using the current estimation technique is still not possible. It did however show that the direction determination was still possible and that a clear difference in the velocity estimation between the still standing tags and moving tags is present. This means that the velocity estimation technique can be used to determine which tags are moving in which direction and which tags are standing still. This can then be used as a filter to only focus on the moving tags or to track the movement of the tags in non-ideal conditions.

6.5 Conclusion

In this chapter the results of various experiments described in chapter 5 were shown and discussed. It was illustrated that it is possible to determine the velocity, direction and distance from the antenna of a moving RFID tag in real-world scenarios. Different impacts of non-ideal circumstances that can be present in real-world applications were characterized and discussed. Finally, the functionality of the motion estimation techniques used, in non-ideal conditions were illustrated and a possible application of the less accurate estimations were given.

This chapter proved that by limiting non-ideal conditions that reduce the accuracy of measurements in real-world scenarios, it is possible to determine the motion estimation parameters accurately using the techniques described in chapter 4.

Finally, in this chapter the advantage of using techniques such as a Kalman Filter to improve measurements were illustrated. It was shown how different input parameters can influence the accuracy of the predictions and in the end a viable solution using this technique to determine the motion of moving tag was illustrated.

7 Concluding remarks

This dissertation investigated different RFID motion estimation techniques that adhere to local standards and can be applied in real-world scenarios. This chapter concludes the dissertation by describing how the different research questions were answered. A short summary of the completed research and recommendations for future research will be provided.

7.1 Research questions answered

Three primary research questions were identified in Chapter 1. This section discusses how these questions were answered.

7.1.1 Is RFID tag motion estimation in real-world scenarios possible?

This question was posed to determine if it would still be possible to determine the motion (direction/velocity/distance) of a tag in certain real-world scenarios. This means that all standards and regulations have to be adhered to for such a system to be implementable. This includes frequency hopping which will have a direct impact on the motion estimation algorithm and using COTS equipment. Previous research excluded frequency hopping from tests and removed real-world effects, such as reflections, multiple tags and stray tags in the reading range. The literature review in section 2.10 identified possible techniques that can be implemented to determine the distance, velocity and as a result the direction of a moving tag. By combining the distance estimation and velocity estimation techniques, adding frequency hopping to the algorithm and defining the most suitable antenna setup that can be implemented in several real-world scenarios (Chapter 3), it was proven that motion estimation of a moving tag is possible. The velocity estimation can be determined over a range of different speeds. The direction estimation as a result will produce information on whether the tag moved towards or away from the antenna, regardless of the accuracy of the velocity estimation. Distance estimation was proven to be possible in scenarios that limit specific reflections and can be applied in certain real-world applications. This distance estimation can also be used to improve the other motion estimation parameters, especially if the speed of the moving tag is above a set limit. The motion estimation of a RFID tag can thus be used in real-world scenarios as part of a system or as a stand-alone feature.

7.1.2 How accurate are the motion estimation techniques for different scenarios?

The question follows the main research question discussed above; it is added to determine the suitability of these techniques for different scenarios and also identify shortcomings of the techniques used. To answer this question several possible influences were identified that can have an impact on the accuracy of these techniques. In Chapter 5.2-5.5 the different experimental designs that will help answer this question is described. The results from these

experiments are presented in Chapter 6.1-6.4. It was found that the direction estimation deduced from the velocity estimation remains accurate even for non-ideal scenarios. The accuracy of the velocity estimation and distance estimation are dependent on several factors. The velocity estimation can be very accurate if the tag moves at a speed slower than the maximum detectable velocity, the line of movement is such that it passes close to the centre line of the antenna, the number of consecutive samples produced are enough, given the number of stray tags present and number of samples being tracked, and excessive reflections are controlled. The accuracy can be influenced by all of these factors but can still produce an accurate estimation if the effects are isolated (discussed in Chapter 6). The distance estimation is accurate if multipath effects and reflections are kept to a minimum. Therefore, an accurate motion estimation adhering to all standards, in real-world scenarios are possible and the different scenarios where the accuracy is reduced were described.

7.1.3 What factors will influence the accuracy of motion estimation and are there any ways to improve the standard estimation?

The previous question touched on the subject that different scenarios will influence the accuracy of the estimation techniques. How the estimation techniques are influenced is discussed in Chapter 6. The final question on whether any methods can be deployed to improve the estimation will indicate whether these techniques can be added to an application or not. The accuracy of the motion estimation techniques can be influenced by several factors that either influence the number of successive measured samples on the same frequency channel that are collected or the signal response parameters (signal strength, phase reading, number of samples and time between samples) received in these samples. The factors that will influence the number of samples collected are the number of tags being tracked, the number and placement of stray tags in the region, the antenna setup, the speed at which the tag is traveling and any obstructions between the tag and the antenna. Factors that influence the signal response parameters are multipath effects, reflections, placement of tag on the tagged object, antenna setup and objects in the reading range. The motion estimation parameters can be improved by using specific filter values. In Chapter 6 the results produced by the Kalman Filter implementations designed in Chapter 4.4, 4.6 and 4.7 are discussed. Here it is proven that by using the Kalman Filter, studied in Chapter 2.12, the accuracy of the motion estimation can be increased significantly. The improvement produced by the Kalman filter is compared to an exponential smoothing technique and the raw measurement. We demonstrate that it is possible to increase the motion estimation accuracy significantly if some prior knowledge to the system and behavioural patterns are known.

7.2 Practical verification of technique

In this study it was important to provide practical evidence that the motion estimation technique functions as intended, while adhering to the conditions and standards mentioned. This section briefly describes how this was implemented in this study.

Firstly, the work described in the literature study (Chapter 2) provided the foundation of the design and implementation described in Chapter 4 and 5. Chapter 2.10.1 showed a similar technique used to determine the velocity of a moving tag and Chapter 2.10.3 provided insight into a distance estimation technique. This showed previous implementations and shortcomings of these techniques in those scenarios. This illustrated the feasibility of the solution to the research question.

We showed that this technique is suitable for real-world use under local regulations by adding the necessary changes to motion estimation techniques previously implemented. The different factors present in a real-world scenarios were defined in cooperation with industry partners and were based on the literature review. To verify the accuracy of the techniques being investigated during experimentation, the motion estimation results were always compared to a reference value that were recorded with each experiment. By maintaining a reference velocity in a known direction both the distance covered and the velocity of that experiment is known. This meant that all estimations from the signal response can be compared to known values. This leaves no room for speculation on whether the estimation is acceptable or not, providing evidence of the functionality of the technique.

The experimental results closely resembled the expected values and behavioural patterns, supporting the analysis produced. All deviations from expected results could be explained based on the presence of different factors that were influencing the results. The different experiments conducted provided practical results for a broad array of scenarios where the technique will produce a satisfactory outcome, illustrating the functionality of the technique practically.

To conclude, the results obtained from practical implementation and experimentation, all compared to known values in experimentation, supported the objectives set out in the beginning of the dissertation, which in turn validate and verify the solution provided.

7.3 Summary

This section shortly recapitulates the different chapters presented in this dissertation.

At the beginning an introduction and background into RFID systems and tag response is provided. Here the shortcomings of current systems were identified, resulting in the research problem. The three primary research questions concerning motion estimation in real-world scenarios are presented. This defined the scope of this study. This chapter also included

certain definitions into what real-world scenarios entail and what the limitations are surrounding this terminology. The work presented for peer review during this study were described here.

Chapter 2 provided a literature study on key areas surrounding RFID and motion estimation. The main subjects discussed were the components of RFID systems, how the signal response parameters are produced in these systems, previous work on motion estimation of RFID tags, phase unwrapping, Kalman Filtering, applicable scenarios and antenna setups. These sections formed the primary source of knowledge towards solving the research problem. It was important to consider the previous work done in order to improve the techniques to function in the desired conditions.

In Chapter 3 an experimental learning approach was described. Here the phase and signal strength response for different antenna setups are explored and compared to the literature regarding this subject. From this a clear concept is formed on the expected signal response parameters, the suitability of different antenna setups for motion estimation and possible challenges towards the suggested solution.

The design of the different aspects of the solution were described in Chapter 4. Here the reader settings and equipment used during implementation were discussed, the approach followed for phase unwrapping were described and the motion estimation algorithm was presented in detail. The motion estimation algorithms include the velocity estimation equations, deriving the direction from the motion estimation and the design that would be implemented to determine the distance between the antenna and the tag. Also included in this chapter were the three different Kalman Filter designs that were used to improve the motion estimation parameters and to ensure a more reliable prediction of the movement of the tag.

It was very important in this dissertation to practically test the implementation of the different aspects of the motion estimation techniques, as well as the impact from different factors on these techniques. Chapter 5 described the implemented flow of the software, produced for the motion estimation, as well as 4 main experiments that were conducted to verify the functionality of the techniques, as well as to determine whether and how the motion estimation was influenced by the determined factors. Here the setups, aims and expected results of each experiment were discussed, providing the reader with a clear vision of what were to come in the results chapter.

The experimental results were shown in chapter 6. Here the functionality of the direction, velocity and distance estimation were presented. The velocity estimation in the different scenarios were compared to the reference velocity, highlighting certain effects from different factors, and an analysis on the performance of this technique as well as the Kalman Filtered prediction and exponential smoothing filter were provided. This chapter also includes the implemented results of the distance estimation and an analysis on the Kalman Filter fusion

technique for improving velocity estimation in certain scenarios, compared to the techniques mentioned above. This section provided proof of the functionality of the motion estimation techniques as well as valuable insight into the factors that influence the result of these techniques. Here it was shown that motion estimation of a passive RFID tag in real-world scenarios are possible with the implemented techniques.

Finally, the work presented in this dissertation is concluded in this chapter with only future research recommendations remaining.

7.4 Future research

The research done for this dissertation continued on the work of previous research. The following suggestions are made for future research:

- The precise velocity estimation for a moving tag will be possible if the angle of movement can be determined with reference to the centre line of the antenna. This can be determined by firstly determining the AoA and then calculating the velocity. This will allow the estimation of velocity for tag moving at any angle through a portal of antennas.
- Some real-world scenarios will have an accelerating or decelerating object. An improved velocity estimation with a suitable Kalman Filter for such a system can broaden the application of these techniques.
- Improved resistance to reflections and improving unreliable phase unwrapping can increase the accuracy of these motion estimation technique significantly. Adding these features will not only provide an improved final solution to the problem but may produce techniques that can also be used to improve existing RFID applications in the localization field.

7.5 Conclusion

In conclusion, a successful implementation and characterization of motion estimation techniques in real-world scenarios were presented. This can aid the RFID industry to broaden its applications and improve existing ones. All of the set outcomes have been achieved and this study can therefore be brought to an end.

The following quote hold true, even in research: *“Success is the sum of small efforts, repeated day in and day out”* Robert Collier

To God be all the glory, Amen.

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Appendix A: Publications and submissions for peer review

This appendix includes the work presented for peer review, in order to receive feedback from experts in the field, learn how the research can be used to improve current systems and interact with industry partners on the quality of the work done in this research.

The first article included is:

- N. Bester and A. Hoffman, "Kalman Filter based RFID tag velocity estimation in the presence of frequency hopping," in *2019 IEEE International Conference on RFID Technology and Applications (RFID-TA)*, 2019, pp. 488–493.

The second article included in this appendix, pending peer review will be submitted as:

- Hoffman and N. Bester, "RSS and phase Kalman filter fusion for improved velocity estimation and characterization of real-world factors on estimation accuracy," in *IEEE journal of RFID Special Issue on the IEEE RFID-TA 2019 Conference, 2020*



Kalman Filter based RFID tag velocity estimation in the presence of frequency hopping

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Abstract— This paper compares different techniques for estimating the velocity of UHF RFID tags within practical applications. We use COTS RFID equipment complying with ISO18000-6C standards, including the use of frequency hopping, to capture tag identification, phase angle and signal strength data. A Phase-Difference-of-Arrival technique is applied to calculate tag velocity. Different signal estimation techniques, including Kalman filtering and Exponential Smoothing, are used to improve the accuracy of the estimated velocity in noisy conditions. These techniques are evaluated and compared within different scenarios, including cases with a fixed speed, acceleration and deceleration. Shortcomings of the RFID backscatter signal parameters are shown, and the effects of the number of tags present and number of samples taken within one frequency hop cycle are investigated. Finally, the potential to use such techniques within practical applications and required improvements are discussed.

Keywords—RFID, Phase-Difference-on-Arrival, Kalman Filter, backscatter, velocity

I. INTRODUCTION

While the use of Radio Frequency Identification (RFID) has greatly expanded since it was first introduced, it also became clear that for some applications the simple identification of a tag is not always sufficient. One application area that is still lacking, is using passive UHF (ultra-high frequency) RFID operating within the allowed standards and regulations to perform accurate motion estimation of moving objects. The requirement is to detect the general direction of a tag as well as the speed at which the tag is traveling[1]. Adding these features to an RFID system will produce useful information that can help track items more accurately, as well as enable the optimization of existing system layouts. A relevant use case is the tracking of personal protective equipment (PPE) in industries such as mines where the direction of travel can help to determine whether tagged items that passed the antenna at a certain point are used appropriately within defined operational procedures [2]. Other examples include the tracking of goods in supply chain management, where it must e.g. be determined if goods moved into or out of a container, and people tracking in buildings, where it may be important to know if a person entered or left a building. Tag direction of movement data can be used to reduce the number of false reads, adding significant value to an existing RFID system.

II. LITERATURE ON RFID MOTION ESTIMATION TECHNIQUES

The velocity at which a UHF tag is travelling as well as the direction in which the tag is moving can be determined using proven techniques developed in the field of wireless signal theory. Tested methods include phase difference of arrival (PDOA) [3][4], angle of arrival (AOA) [5][6], time

difference on arrival (TDOA) [7] and received signal strength indicator (RSSI)[8]. The same techniques can be used in RFID with some being more suitable than others. ISO18000-6C (or Gen 2) RFID tags produce a phase measurement and RSSI measurement per sample taken. Phase measurements are less sensitive to reflections and multipath signals compared to signal strength measurements, and are therefore most suitable for accurate motion detection. This study will focus on creating a motion estimation solution that will comply with local RF broadcasting standards, specifically frequency hopping, by using proven techniques as basis.

Time difference techniques, that requires synchronization between the tags and reader, are not ideally suited for passive UHF RFID, since backscatter communication does not allow for the required synchronization. Angle of arrival techniques have been proven to work well to determine the direction of travel for an RFID tag, but require antennas to be exactly characterized to determine the precise radiation pattern, with the initial area of travel for the tag limited to a certain range[9]. This is not suited for most real-world scenarios due to the presence of multipath reflections that impact the magnitude of tag signals. Multipath effects happen when there is more than one path for the signal to travel along between the tag and the reader. This will vary depending on the frequency that is being broadcast as well as the environment.

A. Phase Difference of arrival

Phase difference of arrival offers several advantages for most RFID systems used commonly in industry. Phase delay is measured by comparing the backscatter modulated signal received from the tag and the baseband modulated carrier signal sent from the reader. The phase delay is a function of the distance traveled by the tag, the carrier frequency, and the phase delays caused by internal circuitry of the transmitter, receiver and the tag (1)[10]:

$$\theta = 2\pi \left(\frac{2R}{\lambda} \right) + \theta_T + \theta_R + \theta_{TAG} \quad (1)$$

The small phase delays caused by the transmitter, reader and tag are normally negligible compared to the phase delay caused by the distance R and the wavelength λ . These phase delays are also a constant for each tag and transceiver combination, and will therefore be identical for consecutive phase measurements applied to the same tag. Their contributions to phase delay differences, that are required to determine distance of movement, will therefore be zero.

The phase measurement is done by using the in-phase and quadrature channel capability of the reader to compare each component of the backscatter signal with the baseband signal. At the receiving end of the reader the signal is split into two

paths: the real and imaginary parts, otherwise known as the I-channel and Q-channel paths. These channels are mixed with the reader's continuous wave signal. To arrive at the phase delay, the reader takes the multiple sampled I-Q pairs, as sampled by the Analog to Digital converter, and averages them over several samples. The phase delay is calculated using the following equation according to Carrick, J. C. et al. [11]:

$$\Delta\phi = \tan^{-1} \left(\frac{Q}{I} \right) \quad (2)$$

B. Different PDOA techniques

Different PDOA techniques exist namely time domain PDOA (TD-PDOA), frequency domain PDOA (FD-PDOA) and spatial domain PDOA (SD-PDOA). Each of these techniques have been proven to be better at a specific task than the others. The FD-PDOA technique is used to estimate the distance to the tag by taking phase samples at different frequencies. Pavel V et al.[3] notes that the tag must move much less than a wavelength, otherwise this technique would not work as it will produce ambiguous results. By measuring the change in phase and using (3), it is possible to determine the range to the tag.

$$d = -\frac{c}{4\pi} \frac{\delta\phi}{\delta f} \quad (3)$$

where d is the estimated distance to the tag, c is the speed of light, $\delta\phi$ is the change in phase and δf is the change in frequency. Since the reliability of this technique depends on the frequency not changing too much, this technique is not ideal for real world UHF RFID applications where the size of a frequency hop is required to be according to regulations.

The SD-PDOA technique can be used to calculate a much more accurate direction of travel of the tag, by calculating the angle of travel towards a specific reference point, normally an antenna or antennas. This technique requires a precise setup of the antennas with the phase being measured by more than one antenna, similar to direction of arrival technique, as can be seen in fig. 1[3]. From this figure it can be seen that a precise setup as well as calibration of the system is required. The advantage of such a system is that the angle of travel can be determined instead of just a general direction.

For this study only the general direction with respect to the reader (typically in or out) as well as the velocity is required. The technique ideally suited for this application is the TD-PDOA technique, as it allows the calculation of the velocity of moving tags as well as a basic direction of travel, as illustrated in fig. 2 [3].

When reading the backscatter signals from the RFID tags the phase measurement is accompanied by a timestamp that can be translated to Unix time. This allows for a very accurate measurement of when each sample was taken. To calculate the instantaneous velocity of a moving tag two phase measurements are compared; this can be seen in (4), where c is the speed of light, f is the frequency, $\Delta\phi$ is the change in phase and Δt is the change in time [12].

$$V_r = -\frac{c}{4\pi f} \frac{\Delta\phi}{\Delta t} \quad (4)$$

According to the GS1 regulations for UHF RFID, a RFID reader is not allowed to stay on the same frequency for longer than the set period defined by local standards (in South-Africa this is 0.4 seconds) before the frequency must hop inside the allowed band of frequencies. For TD-PDOA only the phase differences of samples taken at the same

frequency can be compared to each other, resulting in a smaller number of available samples, and thus less usable data, to calculate the velocity and direction of the moving tag. Previous published work on TD-PDOA based motion estimation did not include the impact of frequency hopping and the challenges presented by this [12].

Two samples from different frequencies taken at different times cannot be compared to each other because there is not enough information to predict the change in phase as a result of the change in frequency while the tag is moving. From (1) the phase difference can be derived as:

$$\theta_{2-1} = \Delta\theta = \theta_2 - \theta_1 \quad (5)$$

$$\theta_{2-1} = 2\pi \left(\frac{2R_2}{\lambda_2} - \frac{2R_1}{\lambda_1} \right) \quad (6)$$

$$\theta_{2-1} = \frac{4\pi(R_2\lambda_1 - R_1\lambda_2)}{\lambda_1\lambda_2} \quad (7)$$

Both θ_1 and θ_2 in (5) are measured; λ_1 and λ_2 are known since the frequency per measurement is known; both distances R_1 and R_2 are however unknown, as well as the phase change when hopping from one frequency to the next. From (7) it can be seen that it is not possible to derive a constant value that can relate the change in phase between each frequency hop without knowing the distance travelled. We will therefore limit ourselves to cases using signals received from the same tag during the same hopping cycle.

The TD-PDOA method have a few restrictions; one of these is the maximum and minimum speed at which a tag can travel. If a tag movement results in a bigger than π radial phase change, an ambiguity in phase value occurs that may cause erroneous detection. This means that the maximum velocity at which a tag can be detected is [13]:

$$v_{max} = (\pi \times 3 \times 10^8) / (4\pi \times f_i \times 10^6 \times \Delta t) \quad (8)$$

For accurate measurements, requiring at least 2 phase measurements between phase wrapping points, this will however be closer to half of this speed.

In the same way there are limitations to the accuracy at which the reader can read phase changes. The reader used has a minimum detectable change in phase of 0.052 radians. This means that the minimum velocity at which the tag can travel and for the change in location to still be detected is given by the following equation:

$$v_{min} = (0.052 \times 3 \times 10^8) / (4\pi \times f_i \times 10^6 \times \Delta t) \quad (9)$$

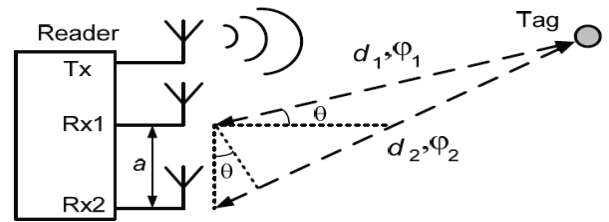


Fig. 1. SD-PDOA illustration [3]

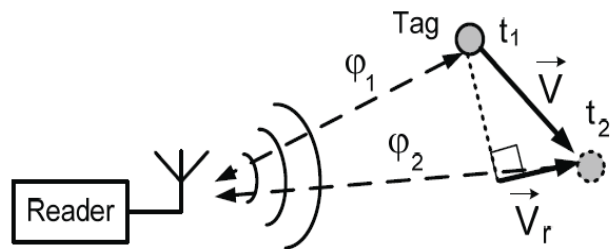


Fig. 2. TD-PDOA illustration [3]

Using (8) and (9) it is possible to determine the limitations of the motion estimation technique and consequently the type of movement that can be detected reliably. The minimum phase change in (9) is as a result of the sampling of the reader as well as the margin included to prevent ambiguity in the reads.

Due to noise in the signal and reflections it is possible for phantom movements to be detected, where it seems that a tag is moving around slightly when in fact it is standing still. It is possible to filter out these changes by averaging across multiple phase measurements, but for real time estimations this can result in slightly less accurate measurements. A tag traveling at a constant speed will be easier to detect because the change in phase will be almost uniform. For real time estimation previous studies have shown that a Kalman Filter is very efficient in removing erroneous spikes in the data[13].

III. PHASE UNWRAPPING

Phase wrapping is something that occurs as a result of a bigger change in the variable phase than what the system can measure unambiguously. To determine the difference in phase as needed for the TD-PDOA technique, the wrapped phase angle therefore needs to be adjusted in order to be continuous[14]. The reader has a π ambiguity and thus a range of π or 0-180 degrees. This means that an increasing phase measurement wraps around once it passes π and will show a reading of 0 plus any incremental radial difference in phase bigger than zero at the next measurement. Effective unwrapping is crucial to be able to accurately calculate the velocity of a moving tag for cases where the phase differences are not limited to $\pm \pi$. If the algorithm does not take this into account it means that the velocity measurement will show abrupt changes in direction and speed at the wrapping point which can be incorrectly interpreted; this is more likely to occur if a tag is moving at a fast speed. Fig. 3 shows the effects of wrapping on the measured phase angle. The samples were taken for a tag moving at 0.83 m/s towards the antenna, using a Thingmagic M6e reader with a range of 180 degrees. This means that wrapping will occur at the 0- and 180-degree points. Here it can be seen that as the phase increases and approaches 180-degrees it wraps around, resulting in the phase of the next sample being the difference in phase minus 180 degrees, while in actual fact the phase is constantly increasing. This demonstrates that velocity calculations using wrapped phase data will result in erroneous results at every wrapping point. Fig. 4 displays the unwrapped signal of the same data, showing a monotonous increase in phase throughout the measurement with slight noise still in the dataset. Velocity calculations using this data will obviously be more reliable.

The unwrapping technique used detects whether the phase is on average increasing or decreasing with every next measurement. Based on this status the algorithm adds or subtracts multiples of 180 degrees to the current measurement should a sudden change in the opposite direction be observed, to produce values similar to what is displayed in fig. 4. This technique however becomes increasingly less reliable, as the phase differences between successive measurements approach 180 degrees. One suggested method to overcome this problem is to calculate both possibilities, namely one where there is a big change in phase (close to the 180 degree limit) resulting in wrapping and the other where there is only a slight change in phase where there is no wrapping present,

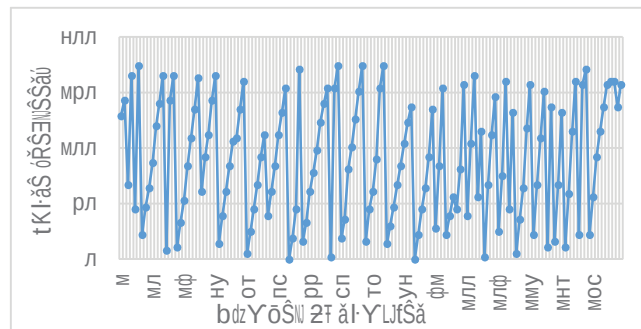


Fig. 3. Wrapped phase backscatter signal of a moving tagged object

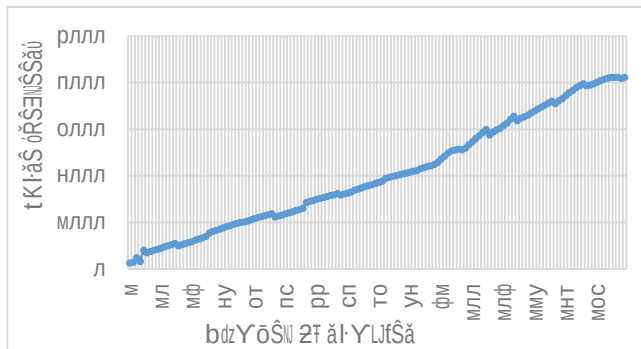


Fig. 4. Unwrapped phase backscatter signal of a moving tagged object

and then using the rate of change in RSSI to determine which scenario is more likely to be correct.

IV. TD-PDOA APPLIED WITH FREQUENCY HOPPING:

Different factors present in practical scenarios influence the effectiveness of the TD-PDOA technique. We investigate two of these, namely the speed at which the tag is traveling as well as the number of tags present in the reading range. Both factors influence the number of tag reads that the reader is capable of producing per tag, as well as the time between measurements, for the relevant reading range and the frequency hopping rate. This section proves that with frequency hopping included in the system, careful consideration has to be given to the influence from these factors.

A. The influence of speed on measurement accuracy

Measurements were performed for a single tag approaching and moving away from the reader, from a distance of 0m to about 7m. The speed was varied between different repetitions of the experiment to observe its effect on the measurements taken. Four different constant speeds were used; in each case the speed of the moving tag was measured using a speed sensor. The speed was also calculated using the phase data, based on (4) above. The actual and TD-PDOA measured speeds are compared in fig. 5. The values were obtained by averaging over different samples, normally between 60 and 180 samples, depending on the velocity of the tagged object. It was observed that measurements within a meter of the antenna produce irregular results, thus those samples were ignored, resulting in a more reliable speed estimation. From fig. 5 it can be seen that the standard TD-PDOA technique produced accurate results for the first three speeds but that measurement accuracy reduced for the fastest speed. This was as a result of erroneous unwrapping that sometimes occur at this higher speed as well as noisy measurements; this can be improved using the techniques

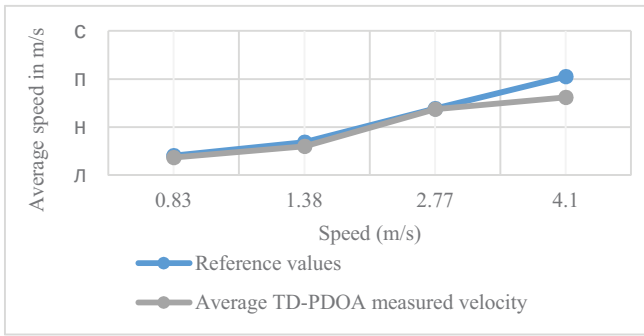


Fig. 5. Average velocity comparison between values measured with the TD-PDOA technique and the reference speed values

mentioned earlier. The extent of the noisy measurements is illustrated by calculating the root mean square (RMS) error across all measurements. Fig. 6 shows the average RMS error produced for the different speeds.

Larger distances travelled between measurements as a result of a faster moving tag also means that there are more opportunities for reflections and other elements to generate noise in the readings. The theoretical maximum velocity using (8) and the best average time between samples achieved in an experiment for this reader and setup is:

$$v_{0.013} = 6.301 \text{ m/s, for a frequency of 915.5Mhz}$$

$$v_{0.013} = 6.2791 \text{ m/s, for a frequency of 918.8Mhz}$$

B. Influence of number of tags on measurement accuracy

As more tags are added to the field, fewer samples are taken per tag within one frequency hopping cycle. This is as a result of the multiplexing done by the reader which is necessary to communicate with all the tags in the field. This means that the time between consecutive samples for an individual tag increases; as a result, the maximum and minimum measurable velocity are lower as calculated by (8) and (9). With increasing number of tags, a point will be reached where there will be too many tags to accurately measure the velocity of any one of them. If it is known that all tags move at the same velocity (e.g. where there are multiple tags on different tagged items moving on the same fork lift) some tags can be filtered out after detection, but the increased number of tags still increases the latency between measurements, resulting in fewer samples per second. In fig. 7 the average speed is compared to the reference measured speed for different numbers of tags moving together. It can be observed that the single tag produced the most reliable measurement, but that in most cases the system still managed to perform well with the addition of more tags, up until the last measurement where 7 tags were used and a bigger error is observed. This can however be improved using a Kalman Filter to predict the movement and remove noisy reads.

To show the difference in errors produced by irregular reading of the individual tag phase measurements, the average RMS error was calculated for each of the different number of tags present. Fig. 8 shows that the higher number of tags produced a higher RMS error. This provide evidence that if there are more reads per tag for the same distance travelled, the resulting velocity calculation is more accurate.

The results from these experiments proves that it is possible to calculate the velocity of a moving tag within a reasonable margin of error for different speeds and number of tags in range, but that improved accuracy is desirable for difficult scenarios.

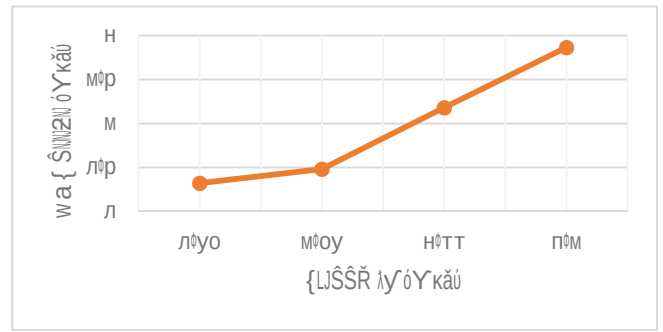


Fig. 8. Average RMS error calculated at different speeds

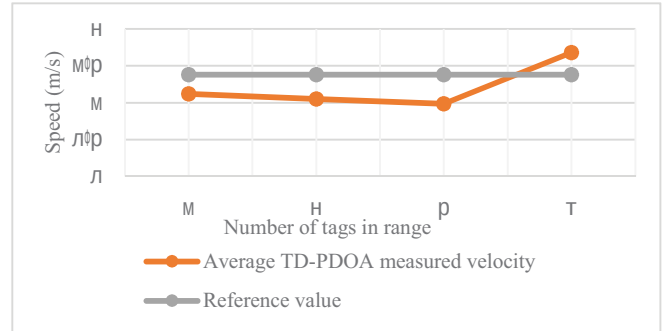


Fig. 6. Average velocity of different number of tags compared to the reference velocity

In the next section we develop estimation techniques to improve the accuracy of measurements for such cases.

V. KALMAN FILTER IMPLEMENTATION

The phase angle and signal strength extracted from RFID backscatter signals are inherently noisy. Thus, smoothing and prediction techniques are required to improve the accuracy of the readings. One such technique that have been shown to produce excellent results in this environment is the Kalman filter [4],[15][16]. To show the improvement of the Kalman filter, the predictions produced by this technique is compared to raw measurements as well as the predictions of an exponential smoothing algorithm applied to the measurements.

The Kalman filter provides more reliable results by using an accurate model of how current state variables can be predicted based on both previous estimates of state variables and current measurements. In this case a basic model can be derived using the standard movement equations used to calculate location based on speed and acceleration. These equations are then used to determine the state transition matrix required by the filter. The two state variables in this case is the velocity and the phase, where the velocity is dependent on the change in phase over time. Two other important variables that

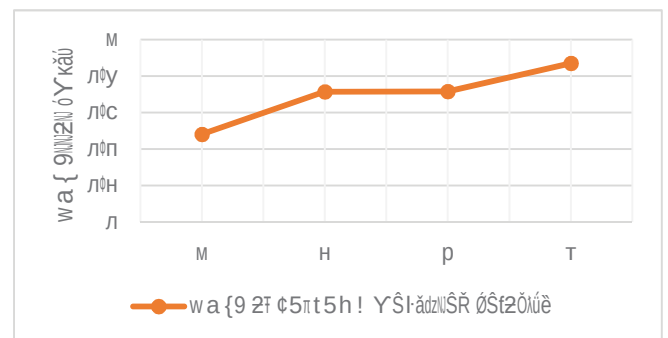


Fig. 7. Average RMS error produced when different number of tags are present in the reading range

will determine the efficiency of the Kalman filter is the process noise and the observation noise. These parameters determine how much smoothing will happen during the prediction. The accurate calculation of these variables is important: if the process noise estimate is too low the filter will smooth the data too much, resulting in a very big lag between filter output and actual measurement, resulting in no convergence if too high acceleration is introduced; on the other hand, if the observation noise estimate is too low the filter will follow the measurements too accurately and not filter out noise in the measurements. In scenarios where the nature of tag movement is well known the process noise is relatively small compared to observation noise; in our case a constant acceleration is assumed with a standard deviation in velocity of 0.3 m/s . It was clear that the measurements produced had significant noise due to the setup and tags used. The observation noise was determined by calculating the absolute mean difference between the TD-PDOA measured velocity and the known velocity. This was repeated for all the different speeds measured and the average taken to produce a standard deviation of 0.9 m/s . The process noise is dependent on the time between samples taken and was calculated as the squared time difference between samples timed by 0.1 m/s squared. 0.1 m/s is chosen since the deviation between consecutive measured velocity samples will be small. The process followed to determine the parameters for the Kalman filter is similar to what was used in [13]. As the observation noise is higher than the process noise, a relatively low α value was chosen for the exponential smoothing filter used, namely 0.2 . This means that the latest measurement has a lower weighted value than the estimate based on previous measurements. The exponential smoothing filter output is determined by (10), where S_t is the latest predicted value, v_t is the current velocity measurement and α is the smoothing factor:

$$S_t = \alpha \times v_t + (1 - \alpha) \times S_{t-1} \quad (10)$$

A. Application of Kalman filter

Two scenarios were tested, the first where the tag moved at different constant speeds and secondly a simulated scenario where the tag transitioned from moving at a constant speed to a constant acceleration. Fig. 9 shows that the Kalman filter prediction provides a significant increase in accuracy for a tag traveling at a constant speed. The filter allows for an initial estimation, but in a scenario where the direction of travel is not known before any measurement is taken, an initial

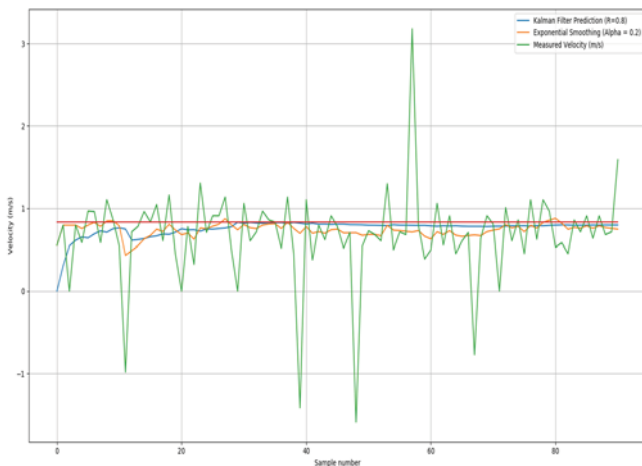


Fig. 9. Velocity estimation comparison between TD-PDOA measurement, Exponential Smoothing prediction and Kalman Filter prediction for a tag moving at 0.83 m/s

estimation of zero was chosen. From the figure it is clear that the filter needs a few measurements before settling if the initial estimate is not close to the measurement.

To measure the effectiveness of each technique separately, the mean absolute error (MAE), root mean square error (RMSE) and mean absolute percentage error (MAPE) were calculated for four different moving speeds of the tag. Each speed was repeated 3 times. The average of all the repetitions is taken and presented in tables 1-3.

The data provided in tables 1-3 shows that this basic Kalman filter using input parameters of limited accuracy already offers a big increase in reliability in measurements, resulting from the fact that the model correctly interpreted the relations between consecutive system states. This evidence also supports the claim that for a higher speed the velocity estimation errors will be bigger, however it also shows that the percentage error is not necessarily worse. Simpler smoothing algorithms also offer an advantage; this can be seen by observing the results for the exponential smoothing. This supports the statement that using a Kalman Filter with a basic, well-defined model can greatly improve the reliability of the system.

The second scenario was simulated by including constant acceleration while retaining noise levels as physically measured; this illustrates the behavior of the Kalman filter in more dynamic scenarios. When nonzero acceleration is introduced the covariance of the process noise and measurement noise changes; the effect of these changes can be seen in fig. 11.

TABLE I. MAE comparison between different estimation techniques for different speeds

Speed (m/s)	Mean Absolute Error		
	Measurement	Exponential Smoothing	Kalman Filter
0,83	0,2111	0,1179	0,0449
1,39	0,3314	0,2570	0,1634
2,77	0,7913	0,5588	0,4143
4,17	0,9536	0,9434	0,8401

TABLE II. MAPE comparison between different estimation techniques for different speeds

Speed (m/s)	Mean Absolute Percentage Error		
	Measurement	Exponential Smoothing	Kalman Filter
0,83	25,4442	14,2055	5,4082
1,39	30,6008	24,5528	18,9178
2,77	28,5670	20,1733	14,9599
4,17	22,8880	22,6415	20,1629

TABLE III. RMSE comparison between different estimation techniques for different speeds

Speed (m/s)	Root Mean Square Error		
	Measurement	Exponential Smoothing	Kalman Filter prediction
0,83	0,2895	0,1561	0,0945
1,39	0,4914	0,40861	0,2914
2,77	1,0844	0,7191	0,6534
4,17	1,4112	1,2274	1,1323

For this Kalman filter model it can be seen that there is no combination of filter parameters that will produce the most accurate result for both scenarios; the best possible solution that can be used in both scenarios must therefore be carefully selected. Fig. 10 shows that a suitable Kalman filter will smooth out a lot of the noise and still follow the measurement pattern when the acceleration is introduced, but with a slight lag. This means that in the case where there is no acceleration the Kalman filter will not produce results that are as good as was seen in the previous section; although it will still be an improvement on using the raw measurement.

Because there is no perfect solution for both scenarios, it would be beneficial to add another state variable with supporting measurements, such as location estimated based on RSSI measurements; the Kalman filter will then use both sets of measurements in parallel to predict the behavior of the tag more accurately.

VI. CONCLUSIONS AND FUTURE RESEARCH

In this article we provide evidence that accurate velocity determination of a moving tag is possible using COTS (custom off the shelf) RFID equipment while complying with RFID standards and frequency hopping regulations. The importance of the effects of the number of samples collected during the passing of a tag and within one frequency hop cycle is demonstrated. It is shown that the number of tags present as well as the speed of the tag influences the measurement accuracy. The value of a Kalman filter to produce accurate velocity measurement in the presence of noise is demonstrated

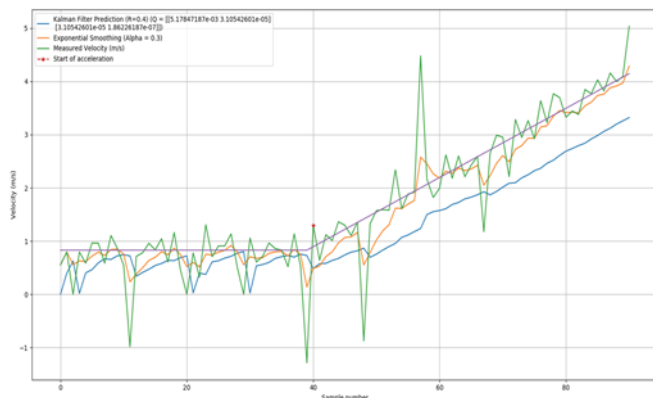


Fig. 10. Comparison between the TD-PDOA measurement, Exponential Smoothing prediction and Kalman Filter prediction of a moving tag with a constant acceleration introduced at sample 40

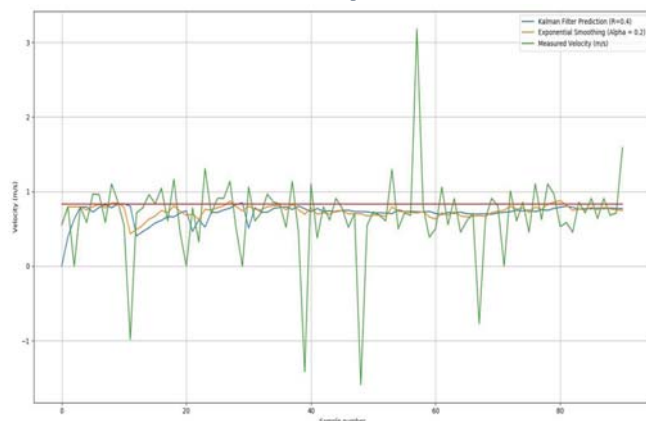


Fig. 11. Comparison between the measurement, Kalman Filter prediction and exponential smoothing of a moving tag with a constant velocity with a low measurement noise covariance

in several scenarios including different acceleration values. The impact of an accurate system model, including the estimated process and observation noise levels, is illustrated.

Even though velocity is the main required system state, it is possible to increase its measurement accuracy by adding other system states to the Kalman filter. As explained above the Kalman filter can be used as data fusion technique to combine the results of both phase and location measurements. A logical next step to ensure better results will be to use the RSSI signal as well as the phase signal in a Kalman filter that use both location and velocity as state variables. This is expected to produce a better velocity estimation as well as provide a rough position estimate (distance from antenna). Some sources such as in [17], have shown promising results using this approach in specific setups.

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RSS and phase Kalman filter fusion for improved velocity estimation in the presence of real-world factors

A.J. Hoffman and N. Bester

Abstract Motion estimation of RFID tags has been shown to be possible using phase information, while position estimation is possible using received signal strength (RSS). This paper combines phase and RSS information using a Kalman filter as sensor fusion technique. It compares the combined RSS and phase fusion Kalman filter technique for motion estimation with the phase only Kalman filter, exponential smoothing filter and raw phase motion estimation excluding a Kalman filter. These techniques are compared while adhering to frequency hopping broadcasting regulations. The primary factors found in real-world scenarios that influence motion estimation techniques are identified as reflections and the presence of multiple tags. The influence of these non-ideal environments are characterized and specific vulnerabilities of these techniques are investigated. Finally, the shortcoming of these techniques as well as advantages and possible environments where this technique can be successfully used are discussed.

Index Terms COTS, Kalman Filter, Motion Estimation, RFID, Real-World application, Sensor Fusion

I. INTRODUCTION

MOTION estimation of RFID tags has been proven to be feasible using phase information extracted from transponder signals [1]. Implementing this in a real-world scenarios opens up new possibilities for innovative RFID applications. For instance, this parameter can be used to improve theft control in a warehouse by monitoring the direction of movement of goods at an exit door portal. Reliable implementation of these techniques however requires a complete characterization of the performance of the motion estimation techniques in real-world scenarios. This includes the analysis of the effects of multipath propagation from reflective surfaces, stray tags and non-ideal line-of-movement.

The previous work on this topic explained how the estimation technique can be affected by the speed at which the tag is traveling as well as the number of tags present in the reading range [1]. By adding another measured parameter in the form of distance estimation based on received signal

strength index (RSSI) additional information about the motion of the tag will be available to assist the process of reliable movement estimation. In this paper we aim to compare the accuracy that can be achieved when combining phase and RSS information against the accuracy that is possible when using only phase information.

II. LITERATURE ON DISTANCE ESTIMATION AND SENSOR FUSION

RFID tags produce a signal strength reading, that can be measured in dBm, with every signal response. This allows the use of the RSS parameter to determine a rough distance estimation of the aforementioned RFID tag.

A. Distance estimation of RFID tags

When considering passive RFID tag signals it is evident that the signal propagation model adheres to standard Radio Frequency signal propagation in free space [2]. This means that the waveform between the reader and the tag will produce a signal strength reading similar to other RF

applications, where the signal is susceptible to reflection, constructive and destructive interference and absorption [3]. RFID antennas can be directional or omnidirectional. If an omnidirectional antenna is used it closely resembles a uniform radiation pattern [4]. If uniform antenna radiation and tag response are assumed it means that Friis free space equation can be applied to calculate the measured signal attenuation as a function of distance [5], as the resulting error has been proven to be small enough [6]. This will enable distance estimation in certain scenarios based on the RSS of signal received. One aspect to note is that if the environment is such that clear multipath effects or very strong reflections will cause ambiguous readings, this technique will not be accurate. The RSS technique is ideally suited for an open space environment with as few reflections as possible, or reflections that will not result in perfect multipath signals. Friis transmission formula relates the free space path loss, both antenna gains and wavelength of the transmitted signal to the transmit and receive power at the antenna [7]. Friis equation is given by the following [7]:

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi R)^2} \quad (6)$$

where P_T is the power transmitted in watts, G_T and G_R is the gain of the transmitter and receiver, λ is the wavelength of the transmitted signal and R is the distance between the two antennas. This shows that the frequency (or wavelength) has a big impact on the power loss during transmission. If the antennas are not polarly matched this also means that the equation can be multiplied with a loss factor and the relationship between the attributes will be maintained. Furthermore, the equation can be adjusted to account for the environment and signal response of a backscatter signal; this relationship can be expressed by the following equation [6]:

$$P_R = P_T G_T^2 G_R^2 PL \left(\frac{\lambda}{4\pi d} \right)^{2n} \quad (7)$$

where PL represents the backscatter transmission efficiency if it exists (otherwise it has a value of 1) and n is the path loss exponent. According to S. Subedi [6], if line-of-sight (LOS) is considered between the tag and the reader antennas, free space propagation can be assumed, which means that n will be 2 for these environments. This means that equation 2 can be rewritten to account for the distance as a function of the power received, shown by the following equation [6]:

$$d = \left(\frac{\lambda}{4\pi} \right) \left(\frac{P G_T^2 G_R^2}{P_R} \right)^{\frac{1}{4}} \quad (8)$$

Using this equation, it is possible to determine the distance between the tag and reader antenna. Some backscatter transmission efficiency constant can be present and should be added to equation 10 if this does exist.

The main concern with using this technique is that complete characterization is required for each parameter present in the formula, including the antenna gains for both the reader antenna and tag antenna. These gains can be determined empirically based on measurements assuming a specific value for the transmitter gain. This means that with a known distance and a measured signal strength the value for the tag antenna gain can be determined. This requires a

precise setup where the antennas for both the reader and tag are perfectly aligned. This means that the gain can then be determined with the following form of equation 3:

$$G_t^2 G_r^2 = \left(\frac{P_R^{0.25} d}{P_T^{0.25}} \frac{4\pi}{\lambda} \right)^2 \quad (9)$$

It is clear that in order to produce accurate results all tags must have the same antenna gain. The RSS technique cannot accurately predict distance in the presence of multipath effects since it assumes directional uniform radiation. For an ideal scenario this can however be added as an extra parameter to indicate the change in distance over time in order to calculate the velocity of the tag.

B. Kalman Filter for sensor Fusion

Sensor fusion consists of taking two or more sensor data inputs that measures the same parameter, and combining them to produce a more accurate measurement than a single one would produce [8]. This feature has been used extensively in the navigation and localization environments where typically the GPS data of a car and the distance measurement onboard are combined in patches where one would produce a less accurate signal.

In the scenario explored by this study sensor fusion can be used to improve the velocity estimation of a moving RFID tag in scenarios where there are very few reflections. The distance estimation can be used as a secondary input to track the change in distance over time, producing a secondary velocity estimation. The primary velocity estimation is produced by using the change in phase to determine a corresponding change in distance over time. The Kalman Filter is ideal to implement this sensor fusion, because it combines both the inputs into the motion estimation model, allowing an improvement of the estimation of the actual velocity of the moving tag [9]. The Kalman filter also allows the insertion of different measurement and process variances for each of the inputs in order to improve the estimation in noisy conditions, adding to its suitability for this purpose.

III. IMPLEMENTATION DESIGN

This paper has two main focal points. The first is to create and test a Kalman filter design that combines RSSI based distance estimation and phase-based change in distance estimation to produce improved distance and velocity estimations. The second focal point is to examine factors that influence the accuracy the velocity estimation in real-world scenarios, such as multipath effects and stray tags.

A. Kalman Filter design for parameter fusion

The modified Kalman filter implementation uses the same kinematic formulas as was used for the phase based Kalman filter [1], but differs in terms of the states used in the equation as well as the state transition model, observation model and covariances.

This Kalman Filter is based on a separate filter designed to use the phase data to produce a better velocity estimation and a filter used to improve the distance estimation calculated from the RSSI data. Since the measurements provide all of the parameters used in object tracking, except acceleration data, the state space model will include the distance and the

velocity of the moving object. The different states included in the model are shown below:

$$X = \begin{bmatrix} x \\ \dot{x} \\ \Phi \end{bmatrix} \quad (5)$$

where x is the estimated distance between the reader antenna and the tag, $\dot{x}$ is the velocity of the tag and Φ is the phase measurement. The RSSI data is incorporated as part of the distance estimation parameter which simplifies the state transition model as well as the process noise matrix. If one would like to predict changes in RSSI the same parameters with a slightly different model setup can be used to accomplish this.

How the different states interact with each other to produce the estimation of the state parameters is shown in the state transition model. The state transition model given by the matrix F is shown below.

$$F = \begin{bmatrix} 1 & \Delta t & 0 \\ 0 & 1 & 0 \\ 0 & \Delta t \times \frac{1}{a} & 1 \end{bmatrix} \quad (6)$$

where a is given by:

$$a = \frac{\lambda}{4\pi} \quad (7)$$

Here, λ is calculated by using the frequency of the carrier signal and the constant value of the speed of an electromagnetic wave. From the third column in the matrix in equation 6 it can be seen that both the distance and the phase measurements have an impact on the velocity estimation. Both these parameters correspond to a change in distance over time. The phase has a much finer resolution, being able to track smaller incremental movements, while the RSSI will be able to track bigger movements, possibly even movements that are bigger than the limits set by using the phase only method.

The velocity can be observed as a result of the phase change and the change in distance as reflected by the RSSI measurement. This is shown by means of an observation matrix. The observation model H can then be defined as:

$$H = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \quad (8)$$

The reason why the observation model is defined in this way is because distance and velocity are the only two variables that the system needs to track and predict during the process. The phase data is only measured and used in the calculations; thus, a prediction thereof is not necessary.

The next step is to define the effect of the unknown input G that applies to the state vector, this is any friction or external factors that will change the behavior the tag during the movement. For the change in distance and the change in velocity, the main impact that can occur will be as a result of an acceleration experienced by the object. This is thus modelled as:

$$G = \begin{bmatrix} \frac{1}{2}\Delta t^2 \\ \Delta t \\ \frac{1}{2}\Delta t^2 \end{bmatrix} \quad (9)$$

It must be noted here that this will only be applied if the value of the acceleration is known to be non-zero. Otherwise this value of G will be multiplied by a zero-acceleration value and its impact removed.

Finally, using this model the covariance of the process noise can be defined as:

$$Q = (GG^T + \delta_a^2) \quad (10)$$

$$Q = \begin{bmatrix} \frac{1}{4}\Delta t^4 & \frac{1}{2}\Delta t^3 & \frac{1}{4}\Delta t^4 \\ \frac{1}{2}\Delta t^3 & \Delta t^2 & \frac{1}{2}\Delta t^3 \\ \frac{1}{4}\Delta t^4 & \frac{1}{2}\Delta t^3 & \frac{1}{4}\Delta t^4 \end{bmatrix} \times \delta_a^2 \quad (11)$$

where δ_a is the standard deviation of the process noise. Since the two different system states, distance and velocity, will have different standard deviations, the weight of this value can be different for the velocity parameter and the distance estimation, but the difference will also be incorporated into the matrix resulting from the GG^T operation. It can be seen in eq. 11 that the first component in the matrix (row 1 and column 1) will result in a much lower value than the middle value (row 2 and column 2), as the difference between time samples will be much lower than half a second.

To keep the operation for this Kalman Filter as simple as possible the standard deviation of the process noise, δ_a , was calculated as the average value between the process noise covariance for the Kalman Filter designed to only use phase as input [1] and a separate Kalman Filter for distance estimation only (with only RSSI as input). This resulted in a value rounded up to 0.2. This will be tested in practice and adjusted accordingly. The advantage of determining these values is that there exists an underlying ratio between the value for the process noise Q and the value for the observation noise R . To achieve the desired smoothing and prediction results from the Kalman Filter, both of these values should be calibrated. If one of these two values can be determined more easily, then the remaining value can be adjusted from the estimation to produce the desired results.

The last step is to determine the measurement noise R . The possible variation in phase measurements is the same than the description given in the previous application, since the same Thingmagic reader will be used in the setup. This possible variation in phase measurements is identified as 2 degrees. This along with the standard deviation determined by the velocity estimation algorithm contributed to a standard deviation defined for this model at 0.8 meters per second for the velocity parameter. The distance estimation standard deviation is chosen as 1.3m, based on eq. 3 and the work done by S. Subedi [6], and this value was verified by practical measurements, accounting for slight variations in signal path as a result of reflections. This value also depends on the type of antenna and tag used. Thus, the matrix for the observation noise is defined by the following equation.

$$R = \begin{bmatrix} 1.3 & 0 \\ 0 & 0.8 \end{bmatrix} \quad (12)$$

Here the first row, first column value corresponds to the observation noise for the distance estimation and the second

row, second column value is the observation noise for the velocity estimation. Since these states are not measured by other parameters the rest of the matrix will be set to zero, because they do not influence the other states' readings.

In ideal conditions with limited reflections and multipath propagation this Kalman Filter model can produce a better estimation for the motion based on different parameters measured by the RFID reader compared to the Kalman Filter model using only phase data to estimate the velocity. It is however possible that the model using the RSSI data can reduce the accuracy of the velocity estimation in cases where there are a lot of reflections and a bad read rate. Because of the way the model is comprised with the different noise covariances chosen, more weight is given to the velocity estimation based on the phase measurements than the RSSI based change in distance estimation. This means that if there is erroneous phase data the result will be affected more than if there is erroneous RSSI data.

This filter was designed to add another layer of information to the motion estimation of an RFID tag and it can be used in specific scenarios, e.g. when there is uncertainty about the initial distance of the tag from the reader, to provide extra information to the user about the behavior of tagged objects.

B. Influence of real-world factors testing experimental design

In order to test the effects of factors in real-world scenarios an experimental design is discussed next. Three main factors that will influence the accuracy of the motion estimation techniques are stray tags in the reading range of the antenna, reflections that cause multipath reflections and a combination of the two.

The first two experiments consist of a two-antenna setup in an open space with controllable reflections. The placement of the antennas is described by the following figure. Here it can be seen that the antennas face opposite directions and the tag passes the antennas closely. This means that the tag will be tracked for both the incoming direction and where the tag moves away from the antenna, with a period in the antennas sidelobes in the middle where readings are inaccurate. For the first experiment stray tags will be placed on both sides of the antennas to ensure that the stray tags are present on both



Fig. 1: Antenna setup, facing opposite direction with the tag in the reading range.

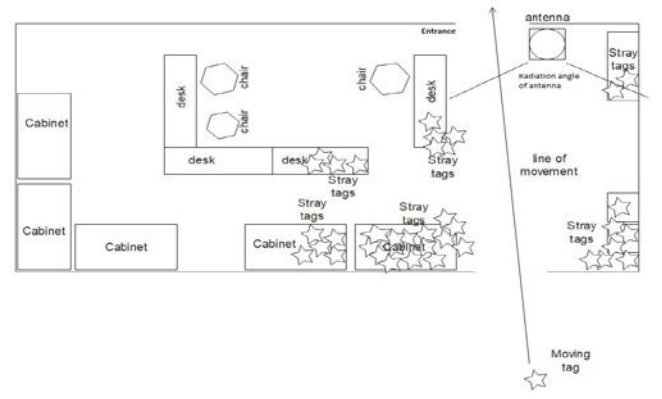


Fig. 2: Schematic of the office used for the experiment in non-ideal conditions

antenna channels.

The second experiment will control the reflection area by placing a big vehicle with flat side surfaces in the antenna range of one of the antennas. For this experiment only the data from one antenna channel (where the reflections are present), will be used in the analysis.

The last experiment is performed in an office scenario where the antennas are placed inside a building. Fig. 2 above shows a schematic of the experimental environment as well as the tag's line of movement. These experiments used a Thingmagic reader with a phase range of 180 degrees and on-metal tags. The speed of the tags' movement was controlled by a bicycle and the tags connected to a pole to ensure sufficient distance between the tags and the person holding the tags. The results from these experiments are discussed in the next section.

IV. RESULTS AND DISCUSSION

A. Kalman Filter fusion results

In previous studies it was shown that it is possible to determine velocity and the direction of travel of a moving tag [1]. The need for a filter that can improve the varying signal was pointed out and the influence of the phase based Kalman Filter was shown. The advantage of the added distance estimation is that another description of the motion estimation of an RFID tag is available.

Fig. 3 shows the distance estimation for a tag moving at 0.83 m/s through the detectable area. This figure compares the phase only distance estimation, distance estimation based on exponential smoothing, a distance only Kalman Filter prediction, the combined phase and RSSI based Kalman Filter distance estimation and a reference distance estimation. The reference distance estimation is calculated by using the time between samples and the reference speed as an estimate to the change in distance.

In fig. 3 the green line represents the reference value for the change in distance, calculated by multiplying the reference velocity and the time between samples. This shows a smooth change in distance as expected. The grey line is the distance based on phase measurements, the orange line is the exponential smoothing of the measurements, the red line is

the Kalman Filter that only has the distance estimation calculated by the change in RSSI as input and finally the blue line is the distance estimation based on the combined phase and RSSI values. The reason for the irregular values produced by the RSSI and phase Kalman Filter's distance estimation is because of the combination between velocity and distance estimation values as input. The RSSI informed distance estimation do not have a high resolution, but the phase informed velocity estimation does. Due to this fact as the phase changes the Kalman Filter is expecting a change in RSSI to accompany this change to indicate the change in distance. Since this do not happen as regularly as the phase change it results in this jagged line each time there is a change. In other words, while the constant velocity estimation results in an expected change in distance, the lack of change in RSSI however causes the Kalman Filter to adjust the distance estimation slightly. Every time there is a change in RSSI however this again results in a big instantaneous change in RSSI together with the continuous change in velocity. It can be seen that this estimation has a big spike in the beginning due to a slight decrease in the RSSI measured initially for the following samples. This would indicate an increase in distance but it is in reality just as a result of how the RFID tag responds, possibly due to multipath reflections. From there it can be seen that most of the estimations follow the expected trend where there is a big increase in the estimated distance close to the middle of the movement as the tag moves past the antennas and in and out of the antennas' side radiation lobes. If this technique is implemented as part of a monitoring system this behavior will have to be interpreted as such. Note that for this slower moving tag the distance estimation is not smooth as a result of the lack of resolution in the RSSI measurement. The faster moving tag (fig. 6) has a smoother response showing the advantage of this technique at higher speeds.

Fig. 4 shows the velocity estimation produced by the combined filter and other estimation techniques.

For simplification the second part of this velocity estimation was converted to show a positive velocity. In the data the velocity will show as a negative velocity since a tag moving away from the antenna will produce a negative value. Here it can be seen that the same irregular velocity estimation exists in the middle part of the movement as a

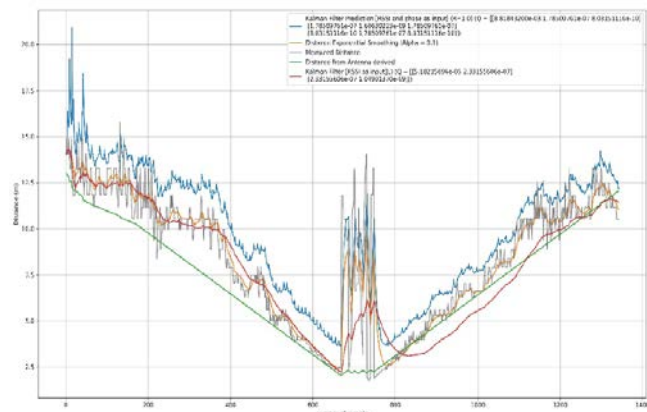


Fig. 4: Distance estimation parameters for a tag moving at 0.83 m/s

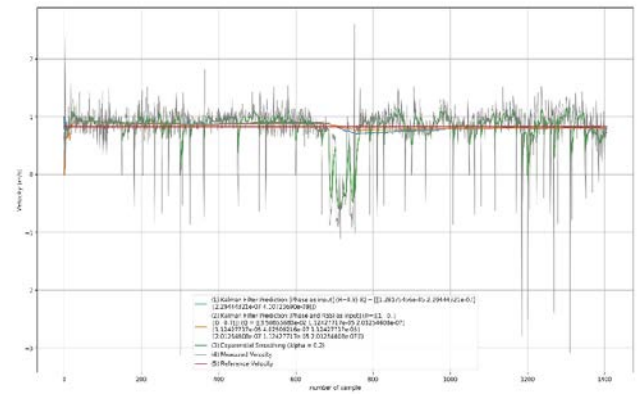


Fig 5: Velocity estimation comparison of the different techniques used for a tag moving at 0.83 m/s

result of the tag moving from the one antenna range to the other. Both the Kalman Filter predictions have an observably good correlation to the reference velocity throughout the movement and especially in the first part. As a result of the lower resolution of change in distance the phase and RSSI informed Kalman Filter converges more slowly to the reference velocity but is less susceptible to sudden detected changes in velocity. This shows in the middle part of the movement where the phase only Kalman Filter moves farther away from the reference velocity while the phase and RSSI informed velocities stays relatively constant. Finally, looking at the number of samples, the advantage of using tags that has a better signal response and thus produces samples from a bigger distance, can be seen. More than 1000 samples were recorded for this iteration of the tag moving at 3km/h. During this experiment it became evident that the tag and antenna combination used for the measurement provided a very consistent number of recorded samples per frequency hop band across the different velocities. The average time between samples changed however. Refer to table 2 for a further explanation at the end of this section.

To illustrate the real advantage of the combined RSS and phase based Kalman Filter fig. 5 and fig. 6 show the distance and velocity estimation for a tag traveling at 4.1 m/s. The time between samples meant that phase unwrapping errors occurred and thus produced inaccurate data, however the

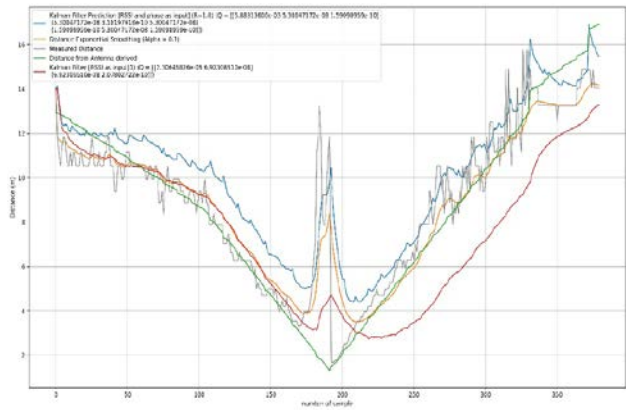


Fig 5: Distance estimation parameters for a tag moving at 4.1 m/s

difference between the Kalman filter implementations are clearer as a result of this.

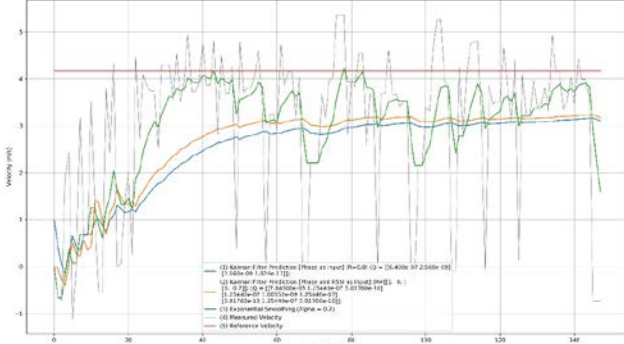


Fig. 6: Velocity estimation comparison of the different techniques used for a tag moving at 4.1 m/s

In Fig. 6 only the first half of the movement's velocity estimation is included to better illustrate the difference between the velocity estimation techniques. This figure shows that it is possible to calculate the velocity, distance and direction of a moving tag and also illustrates the advantage of adding the distance estimation parameter to the Kalman Filter to improve the velocity estimation. The orange line represents the Kalman filter fusion velocity estimation and shows that in this faster moving iteration, with added uncertainty, the velocity estimation is more reliable.

To illustrate the difference between the different estimation techniques at the different velocities, table 1, showing the Mean Absolute Error (MAE) for each estimation technique, is included. Here it can be seen that the Kalman filter that uses both the phase and RSSI as input produced the most accurate measurements, followed by the Kalman filter with only phase as input and finally, the exponential smoothing and raw measurements produced by the bicycle speed sensor.

Table 1: MAE of the different estimation techniques at different speeds

Speed (m/s)	Mean Absolute Error			
	Measurement	Exponential Smoothing	Kalman Filter (Phase)	Kalman Filter (Phase and RSSI)
0,83	0,2839	0,1819	0,0776	0,0681
1,38	0,6376	0,5147	0,3562	0,3500
2,78	2,1896	2,0790	1,4980	1,4852
4,17	2,9286	2,8364	2,1203	2,1019

In the table 1 above it can be seen that the Phase and RSSI based Kalman Filter produces the lowest MAE of all the estimation techniques. Both the Kalman Filters substantially improve on the standard measurement. If only the velocity estimation is included for the part of the movement where the tag is moving away from the antennas, the Kalman Filter using the Phase and RSSI will have an even lower MAE compared to the other techniques.

To illustrate the effects that the different speeds have on the time between samples as well as the average total number of samples recorded the table 2 is included. The longer the time between consecutive samples are, the more difficult unwrapping becomes and less samples means less data to determine the motion estimation for a moving tag.

It can be seen that the higher speed has the fewest samples and the biggest time between samples recorded.

Table 2: Analysis of signal response for each different speed

Speed (m/s)	Average number of samples per frequency hop band	Average time between samples (s)	Average total number of samples recorded for each iteration
0,83	18,56	0,0185	1442,31
1,38	16,98	0,0194	955,48
2,78	14,74	0,0342	540,29
4,17	12,85	0,0387	397,62

The irregular distance estimation produced by the combined Kalman filter can be improved by using a moving average filter to smooth out the RSSI input, resulting in less variability in the input that will produce a more constant velocity estimation output.

B. Influence of stray tags on motion estimation accuracy

Fig. 7 shows the velocity estimation for a tag moving at 1.38 m/s. To show an enhanced image of the irregular velocity estimation only the first half of the movement (i.e. the part of the movement towards the antennas) is included. The away movement did not produce consecutive samples regularly, resulting in instantaneous velocities without any correlation to the previous measurements. The accuracy with regards to the reference velocity of the combined Kalman Filter is lower with this estimation because it normally takes more samples to converge to the same reference value. This is one downside of the technique, but with these parameters chosen it also provides a better smoothing effect. Here only 35 samples are recorded resulting in the lack of conformity to the usual reference value observed.

The irregular sampling rate, due to the samples measured from the stray tags, results in inconsistent velocity estimation. Initially the velocity estimation seems to be accurate but a steady decline in consistent measurement adds to the troublesome detection. The accuracy decreases due to the lack of consecutive samples recorded for the same tag. This means that a big distance is covered by the tag before another consecutive pair of samples are recorded. This results in erroneous unwrapping due to the ambiguity of the scenario and very inconsistent estimations. It is clear that adding more than 15 stray tags in this setup where both antennas read samples, creates a lot of complexity. Using

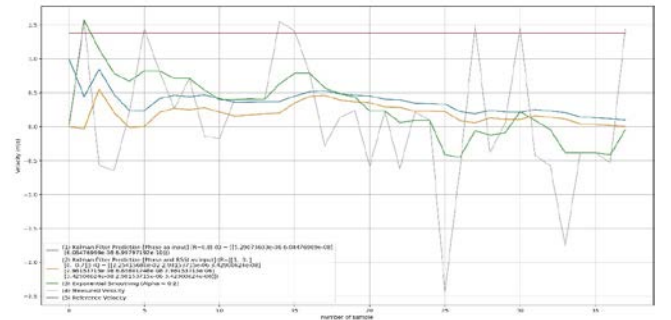


Fig. 7: Velocity estimation of a tag moving at 1.38 m/s, in the presence of several stray tags.

only one antenna per reader or restricting the stray tags to only one side will reduce these effects since it will also reduce the reading of samples on the opposite channel of the one where the moving tag is being monitored. This shows that the stray tags, using a maximum throughput reading mode, has the biggest impact on the current motion estimation technique. Both the Kalman Filters maintain the estimated velocity for longer but the lack of data causes a steady decrease in estimated accuracy. This figure shows that there is sufficient data to determine the direction of the traveling tag, but that there will be a big margin of error in the velocity accuracy. This experiment highlighted one of the biggest problems with motion estimation in real-world scenarios. It showed that an adjustment to the technique is necessary in order to be able to accurately determine the velocity of a moving tag in these conditions. This experiment however showed that even if the conditions are not ideal it is still possible to accurately determine the direction of travel and as long as reflections are minimized a rough distance estimation is still possible.

C. Influence of reflections on motion estimation technique results

It is well known that RFID signals are very susceptible to multipath effects and reflections. In this section the effect of multipath signals on the motion estimation parameters are discussed.

The experimental setup is such that the first part of the movement will be affected by multipath as the tag gets influenced by the reflecting surface. It is important to inspect both the effects on the velocity estimation and the distance estimation, since it is expected that the RSSI signal will be more susceptible to the reflections than the phase values, and that this will show more clearly in the distance estimation. Fig. 8 shows the velocity estimation for a tagged object moving at just over 0.86 m/s.

In fig. 8 it can be seen that the initial velocity estimation is not as accurate as expected, due to the reflections. Up until sample 200, the estimation is lower than expected. Looking at the blue and orange lines, which is respectively the Kalman Filter using only phase as input and the Kalman Filter with both the RSSI and phase as input, it can be seen that there is some difference in the conformation between the two. The orange line increases the velocity prediction at a slower rate than the blue line. Around sample number 150 there is a sudden, excessive drop in the velocity estimation compared to the other velocity estimations. Beyond this point the estimations converge to the same point and the second half of the samples included in this figure, where no significant reflections are present, shows a very good velocity estimation for both techniques.

The behavior of the velocity prediction from the Kalman Filter with both phase and RSSI as input can be explained by looking at the distance estimation for this movement. Fig. 9 shows the distance estimation for this tag's movement.

This figure shows that the distance estimation, as represented by the blue line, starts at the expected distance between 13 and 14 meters from the antenna. After the initial

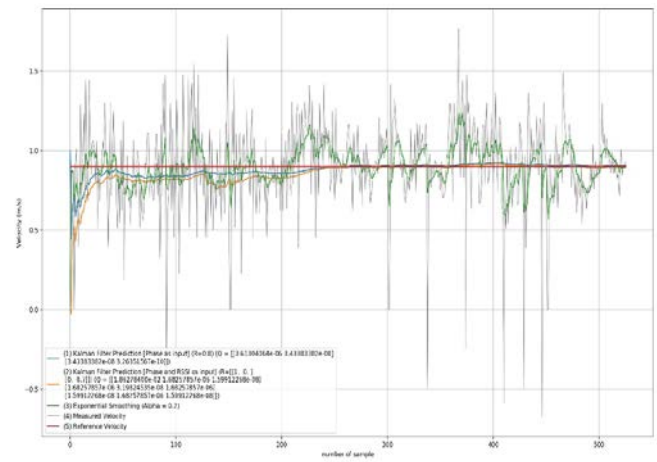


Fig. 8: Velocity estimation of a tag moving at 0.86 m/s, in the presence of a reflecting surface

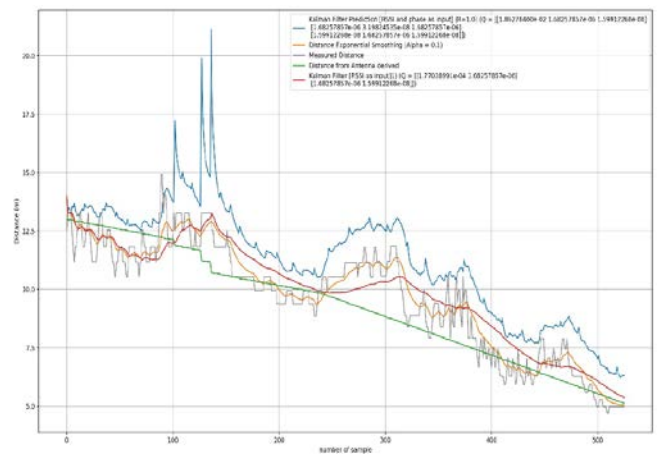


Fig. 9 : Distance estimation of a tag moving at 0.86 m/s, in the presence of a reflecting surface

decrease in distance there is a sudden increase in the distance estimation at sample 100. Two big spikes in distance can be observed between samples 120 and 150 on this blue line. This increase corresponds to the sudden decrease in the velocity estimation observed in the velocity estimation above. There after there is more instability up until sample 300 before a steady decrease in distance is observed. The biggest spikes were observed between samples 120 and 150 and explains the behavior observed in the velocity estimation. This supports the claim that the RSSI signal will be more susceptible to reflections and multipath effects. The distance estimation predictions based on the RSSI parameters were more unstable, while the velocity estimation remained more constant. As a result, the Kalman Filter using only phase produced a more constant velocity prediction compared to the Kalman Filter that uses both RSSI and phase together.

The same pattern was observed at 1.38m/s and higher speeds. Fig. 10 and fig. 11 show the estimation results at 1.38 m/s. To show the impact that the reflections have on the accuracy of the estimation the following table is included.

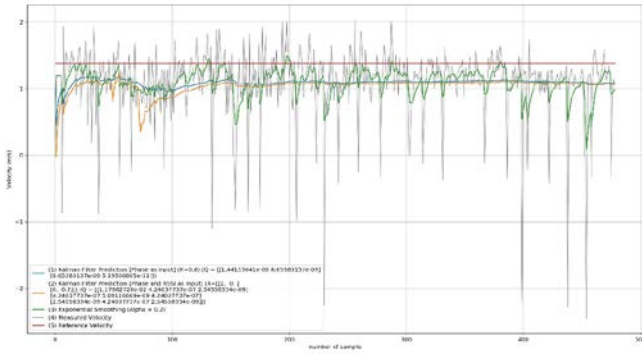


Fig. 10: Velocity estimation of a tag moving at 1.38 m/s, in the presence of a reflecting surface

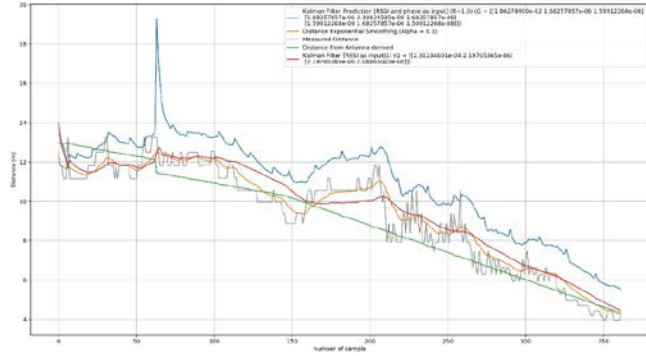


Fig. 11: Distance estimation of a tag moving at 1.38 m/s, in the presence of a reflecting surface

Table 3 clearly shows the reduction in accuracy for the phase and RSSI based Kalman Filter. It is important to note that the standard Kalman Filter still produced the most consistent estimation and that it can still be used to produce a reliable velocity estimation in the presence of reflections.

Table 3: Average error analysis of the different velocity estimation techniques for a tag moving at 1.38 m/s in the presence of reflections

Analysis method	Estimation techniques			
	Measurement	Exponential Smoothing	Kalman Filter (Phase)	Kalman Filter (Phase and RSSI)
MAE	0,3831	0,2934	0,29146	0,3424
MAPE	27,76	21,1907	21,1207	21,12078
RMSE	0,6394	0,35366045	0,2973	0,3665

This section illustrated the effects that multipath and reflections have on the motion estimation parameters. This section also proved that the phase-based velocity estimation technique will work reliably in the presence of limited multipath signals and reflections. This type of non-ideal conditions is something that can be found in most real-world scenarios and is an important consideration when the final velocity estimation and distance estimation techniques are chosen for implementation.

D. Influence of indoor environment with stray tags on estimation accuracy

To show how the velocity estimation technique functions in another non-ideal condition the experiment is performed inside a building with many stray tags in the environment, as well as a short distance over which the reader can track the movement of the tag.

The distance estimation was omitted from this section because of big variations in the RSSI signal. From the literature it is known that the RSSI distance estimation technique is not suited to these conditions. It was thus decided that the testing will only focus on the direction and velocity estimation.

Fig. 12 shows the Kalman Filter of the velocity estimation for each tag that were recorded in the reading range. Only one moving tag is monitored in this iteration. Here it can be seen that one tag clearly stands out as the moving tag in this scenario while all the other tags display a zero average velocity estimation. It can also be seen that only a few samples were recorded for the moving tag. The samples that were recorded for the moving tag (tag number 9) have a lot of variations and a clear velocity estimation is difficult to determine. The average velocity estimation of the moving tag in this scenario was recorded as 0.26 m/s. The next highest velocity estimation recorded is 0.09 m/s, clearly showing the difference between the moving tag and the stationary tags. Accurate velocity estimation however was unsuccessful in this scenario.

Fig. 13 shows similar results where one tag can be identified as the moving tag, but the velocity estimation is unreliable. In this figure, tag number 8 is the moving tag. The average velocity of the moving tag in the figure is 0.19 m/s, while the closest other velocity estimation for the still standing tags is calculated at 0.091 m/s. This again clearly illustrates the problems associated with calculating the motion estimation of a moving tag in very poor conditions.

The same experiment was performed with two tags moving together through this environment. In line with results available from literature the accuracy of the velocity estimation reduced even further. Fig. 14 shows the results from one of these iterations. Erroneous peaks in the velocity estimation of stationary tags can be seen in this figure, but with no consistency in the peaks. The average velocity

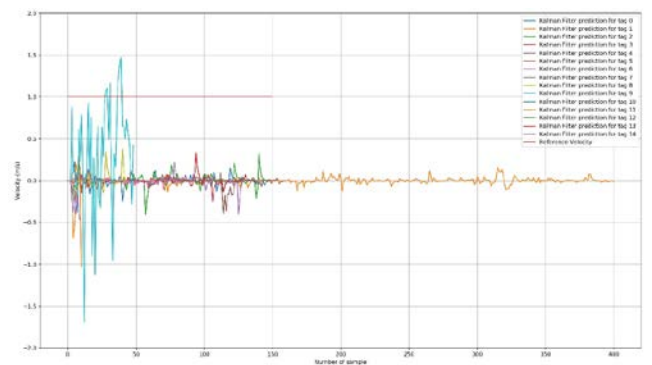


Fig. 12: Velocity estimations of all the tags in the reading range, with one tag moving at 1 m/s and the others acting as still standing stray tags (Iteration 1)

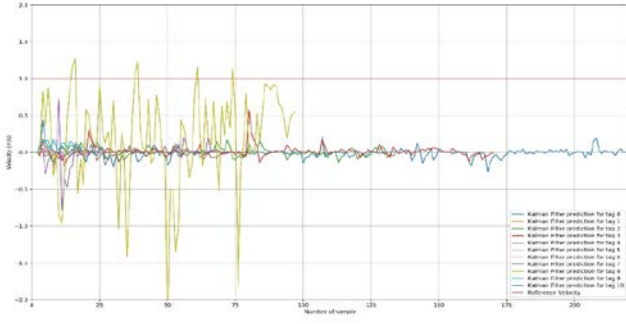


Fig. 13: Velocity estimations of all the tags in the reading range, with one tag moving at 1 m/s and the others acting as still standing stray tags

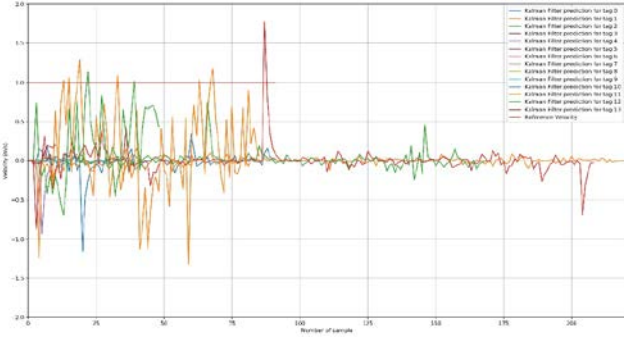


Fig. 14: Velocity estimations of all the tags in the reading range, with two tag moving at 1 m/s and the others acting as still standing stray tags (Iteration 1)

estimation of the moving tags in the first image are 0.1208 m/s and 0.198 m/s, with the closest stationary tag velocity being 0.017 m/s. The two moving tags are represented by the orange and green lines (tag 11 and 12)

In this non-ideal environment the Kalman Filter can not improve the estimation by much, only managing to smooth out some of the variability. This is as a result of the lack of consecutive phase measurements within a certain time period. The next table is included to compare the raw velocity estimation, the exponential smoothing and the Kalman Filter predicted velocity against the estimated reference value for the experiments performed in this section. Here the case where two tags are moved together is compared with the scenario where only one tag is moved through the signal range. It is expected that the MAE for these parameters will be very high since the velocity estimation never established a good estimation. The different techniques can however still be compared in this non-ideal condition. These results are shown in the table 4.

Table 4: Mean Absolute Error of the velocity estimation techniques for a tag moving through the non-ideal environment

Number of moving tags	Estimation techniques		
	MAE Raw Measurement	MAE Exponential Smoothing	MAE Kalman Filter (Phase)
1	0,8321	0,79215	0,7851
2	0,9215	0,8544	0,8427

From this table it is clear that the overall velocity estimation for the moving tag, in this non-ideal environment where there are a lot of reflections as well as several stray tags, is not accurate. It is therefore not recommended to use this technique if an accurate measurement is required. The Kalman Filter managed to remove some of the negative peaks affecting the overall measurement accuracy, but the improvement is negligible. A small difference between the single moving tag and the scenario where two tags are moved simultaneously can be observed. These results do however show that direction estimation is possible and that a clear difference exist between the stationary and the moving tags' velocity estimation.

The results in this section showed that in these types of conditions an accurate velocity estimation using the current estimation technique is still not possible. It did however show that direction determination was still possible and that a clear difference in the velocity estimation between the stationary tags and moving tags is present. This means that the velocity estimation technique can be used to determine which tags are moving in which direction and which tags are stationary. This can then be used as a filter to only focus on the moving tags or to track the movement of the tags in non-ideal conditions.

V. SUMMARY AND CONCLUSIONS

In this article we investigated using a Kalman filter to combine RSS and phase signals to estimate the velocity, distance and direction of a moving tag. The advantage of Kalman Filter techniques to improve the reliability of raw measurements was illustrated, and it was shown how different input parameters influence the accuracy of the predictions. We demonstrated that the combined Kalman filter can improve on the performance of a Kalman filter that only uses phase information. The impact of non-ideal circumstances, including reflections and the presence of stray tags, were characterized and discussed. We illustrated that it is possible to estimate the motion of a moving RFID tag in real-world scenarios, even in the presence of the above non-ideal conditions. In severe conditions, e.g. indoor scenarios with high levels of reflections and many stray tags present, the Kalman filter techniques cannot perform accurate velocity or distance estimation, but can still correctly detect the direction of movement of tags.

Suggested future work includes more precise velocity estimation by first determining the angle of movement with respect to the center line of the antenna using an angle of arrival technique. This will allow the estimation of velocity for tags moving at any angle through a portal of antennas.

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Appendix B: Supporting figures

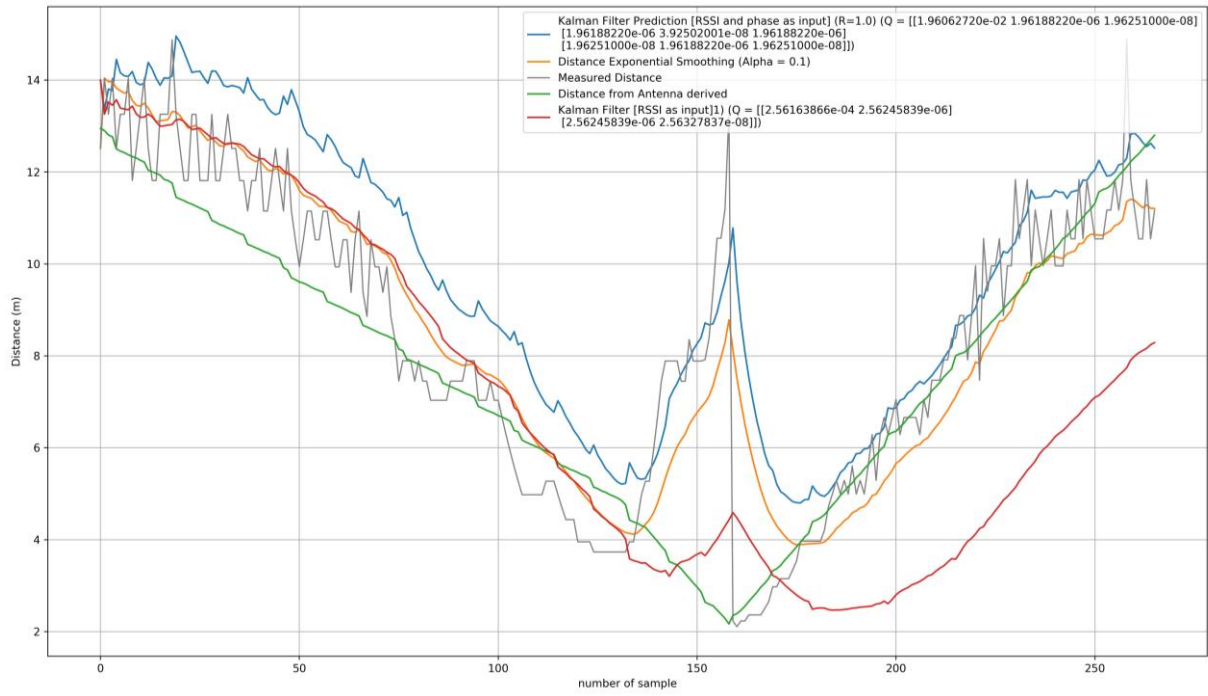


Figure B-1: Distance estimation for a tag traveling at 5 m/s

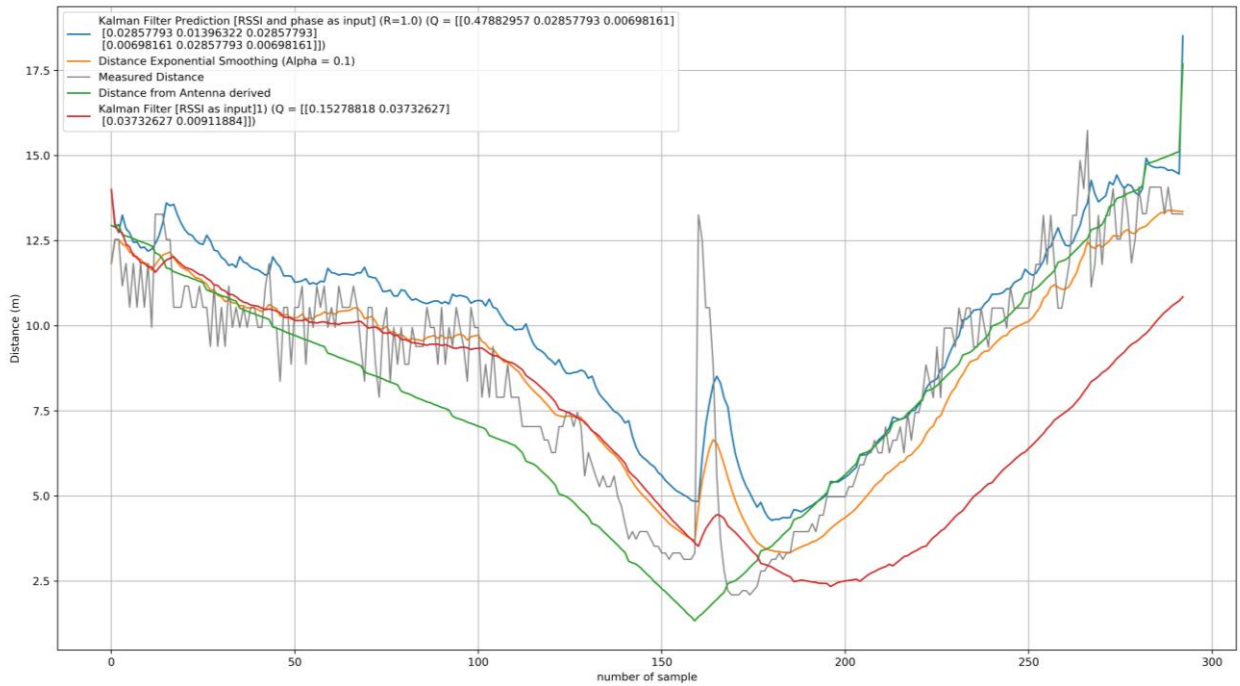


Figure B-2: Distance estimation for a tag traveling at 5.5 m/s

Appendix B: Supporting figures

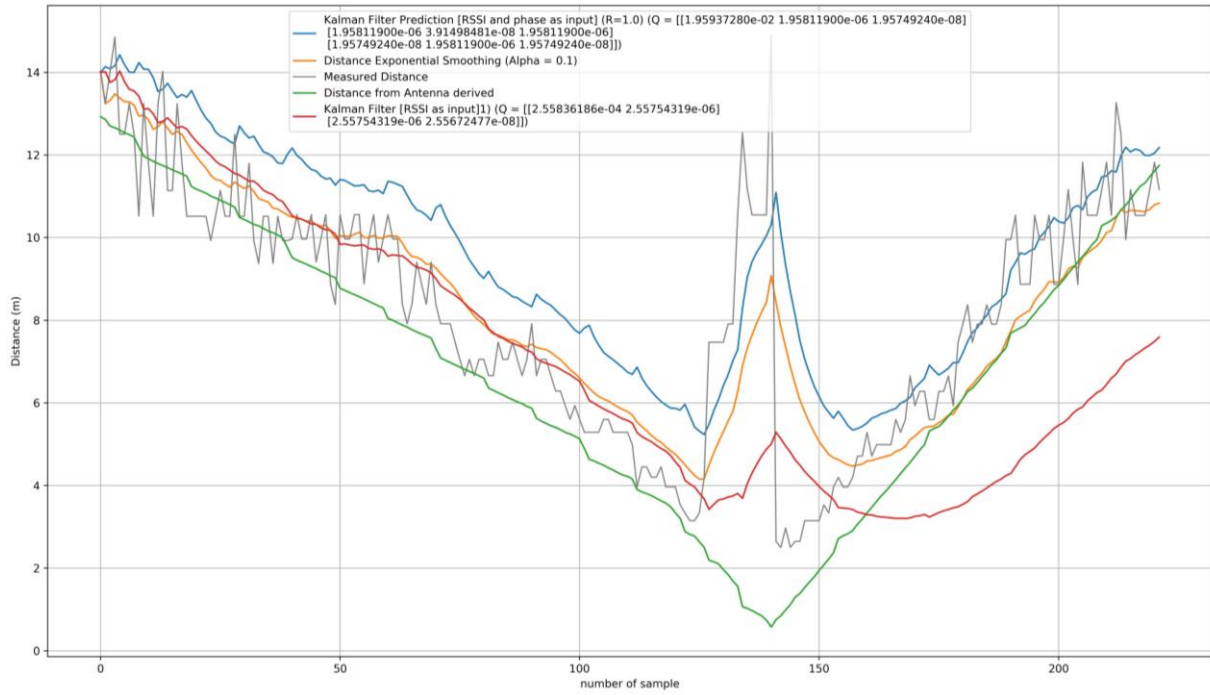


Figure B-3: Distance estimation for a tag traveling at 6.9 m/s