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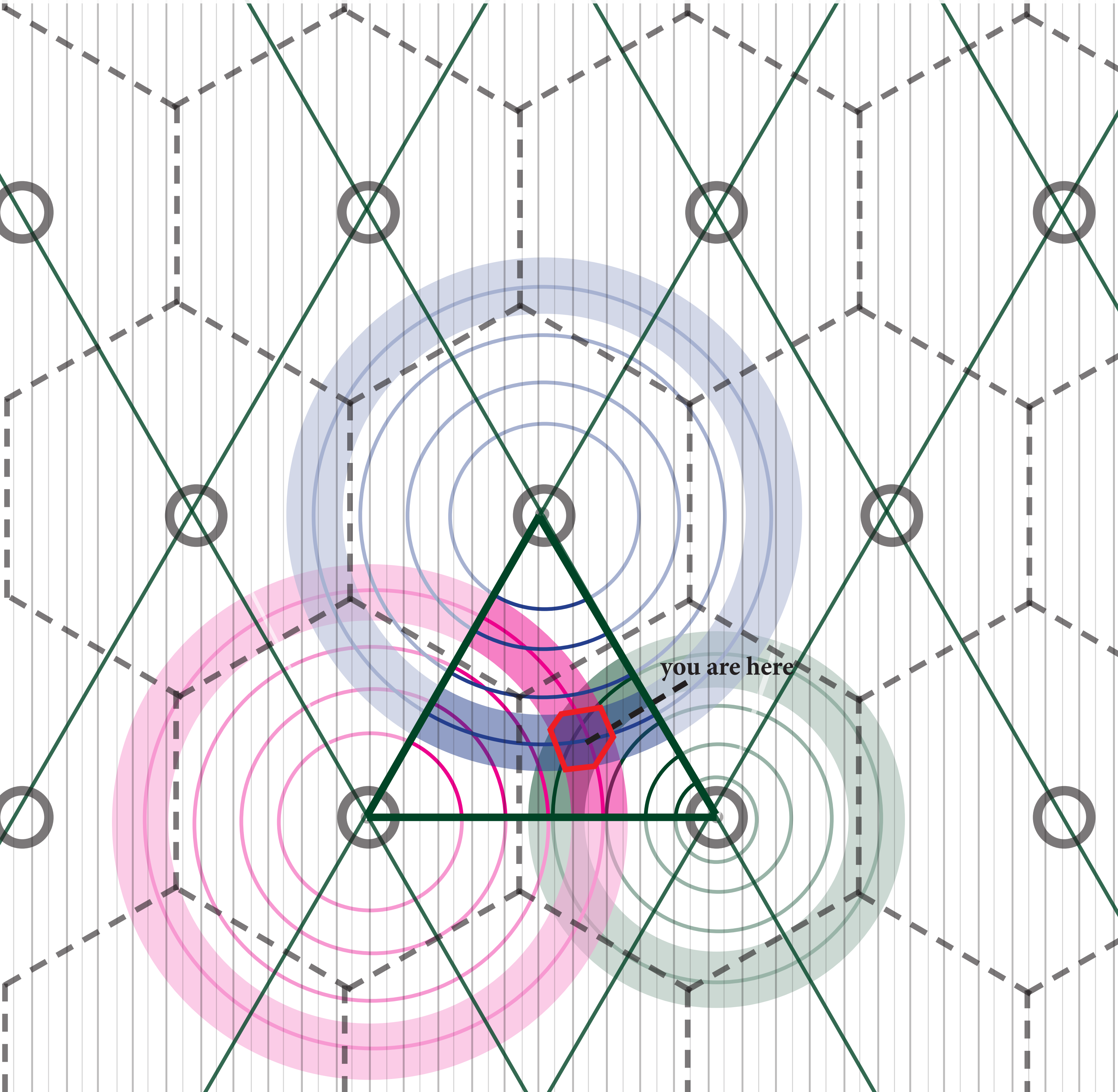
By E.B. van der Laan



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ABSTRACT

Indoor localization is a hot topic since the demand for Location Based Services (LBS) has increased, especially (semi) public places like museums, office buildings and congress halls would benefit from LBS. Outdoor localization and its applications like navigation systems are well implemented in society and used by many on a daily basis. Applications using indoor localization are underrepresented due to the lack of a robust and scalable indoor localization technique. Attempting to solve this problem, first, a suitable indoor localization technique (hardware) is selected and second, an indoor localization method (algorithm) is applied. For the localization technique two radio propagation techniques are tested in this research: first an established technique called Ultra High Frequency Radio Frequency Identification (UHF RFID) and second, a newly arrived technique called Bluetooth Low Energy (BLE). Both techniques use a sensor and tag. In the case of UHF RFID the person to be located carries a tag and is recorded by sensors on the ceiling. In the case of BLE the person to be located holds the sensor in hand and senses the tags on the ceiling. Results show that the UHF RFID is highly sensitive to environmental changes and water bodies (including the user itself). This makes the proximity indication of the technique unpredictable and the technique difficult to use in various locations with a large amount of users, which is often the case in (semi) public places. The BLE shows quite stable results in terms of its sensitivity to interferences and shows a clear correlation between distance and signal strength. The latter two characteristics make it a suitable technique for indoor localization. Two localization algorithms using BLE are proposed; first a dependent algorithm which takes into account the specific characteristics of the sensor, and second, an independent algorithm (referred to as PML) which functions independently from the type of sensor used. The latter is an advantage because the sensor is incorporated in the mobile phone of the user. Especially when there are potentially multiple users holding different types of mobile phones, the sensors can vary widely. The dependent algorithm is based on a probability function using a basic concept of trilateration dependent on the measurements of at least three beacons. PML is based on the ratio between measurements of at least three beacons. Results of both algorithms show in most cases a computed location within a meter of the actual location. Generally, the dependent algorithm shows slightly better results with regards to the PML method. However, the practical usability and scalability of the PML method makes it preferable over the dependent algorithm.

Key words –Bluetooth Low Energy, BLE, Radio Frequency Identification, RFID, LBS, Trilateration, Voronoi-

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CONTENT

LIST OF ABBREVIATIONS

PML	Proportionate Measurement Localization
UHF RFID	Ultra High Frequency Radio Frequent Identification
BLE	Bluetooth Low Energy
RSSI	Received Signal Strength Indication
ToA	Time of Arrival
TDoA	Time Difference of Arrival
DoA	Direction of Arrival
KNN	K-Nearest Neighbour
JSON	JavaScript Object Notation
dBm	decibel-milliwatts
API	Application Programming Interface

1 INTRODUCTION

1.1 LOCATION BASED SERVICES

An increasing need for location aware services has driven researchers to find a way to develop systems that fits this need. The key aspects of an LBS system are:

1 The Mobile device,
2 The communication network,
3 The service content and
4 The positioning system (Steiniger et al., 2006).

1. The mobile device is the tool to transfer the requested information to the user. Mobile devices can be divided into two groups: single-purpose devices and multi-purpose devices. Single-purpose devices are built to achieve one goal. Think of a car navigation system or an emergency device for the elderly (Steiniger et al., 2006). Multi-purpose devices can be used for multiple purposes and are used by a broad number of people and are part of everyday life. Examples are smartphones, laptops and tablets (Steiniger et al., 2006). Because they are widespread in society, this research takes in account multi-purpose devices. In 2013 already over 60 per cent of Dutch people between 15 and 65 had a smartphone (Volkskrant, 20/02/2013). Using smartphones to offer an LBS makes the service easily accessible and scalable.

2. The communication network is the middleman between the service provider and user. It sends request messages from the mobile device to the service provider and sends the requested information back to the mobile device (Steiniger et al., 2006). The communication network could be, for example, the Internet, Intranet or another telecommunications network.

3. The service and content provider includes the arrangement of the content to serve the request for information (Steiniger et al., 2006). An important aspect is the type of information provided to the user and the corresponding information model. Different types of information are often delivered to the user. According to Qiu et al., 2012, four types of Location Based Services systems exist: 1. The 'leisure entertainment', where users are informed about possible activities sometimes including a game mode where social networking is part of the game. Examples of leisure entertainment applications are 'foursquare' and 'MyTown'. 2. The 'life of service' systems. This LBS slowly penetrates into all aspects of our life (Qiu et al., 2012), it makes daily activities easier and life more convenient. Examples of such applications are 'Mokard' and 'Eventbee' which record spending habits based on information on membership cards and provide discount information. 3. A 'social' type of system is distinguished (Qiu et al., 2012). This type of LBS is about social interaction. For example, dating services like 'Grinder' that returns profile information of other users within a certain area. The user can then contact these other users. 4. The 'service' type. The main goal of the service type LBS is to offer users a service which can be promoted by offering discounts in return for an action of the user, for example sign up and leave personal information (Qiu et al., 2012).

Content providing is not only about the type of information provided but it is also about using and providing geographical information. This means that the geospatial organization is important. The indoor area can be geo-fenced and this means that the space is virtually divided into zones. Geo-fencing is a 'virtually fenced geographical Area' (Rahimi et al., 3013). The zones are predetermined and not necessarily based on the physical characteristics of the space.

4. The positioning system is key to an LBS. Outdoor positioning systems and its applications based on GPS, are well known. However, the GPS system used for outdoor positioning is not suited for indoor positioning due to the lack of GPS connectivity inside buildings and other roofed constructions (Nagel, 2010). Also, the accuracy of GPS localisation is relatively low. Indoor positioning demands a high accuracy since the tracking takes place in a relatively limited area. These two disadvantages make it yet impossible to use GPS for positioning and tracking indoors.

1.2 INDOOR LOCALIZATION

Indoor localization systems are underrepresented in practise, in contrast to outdoor positioning systems. Applications using outdoor positioning are well spread throughout day to day life and unthinkable to remove from modern society. Outdoor route planning is the most commonly used application using a GPS system for outdoor positioning. However, as stated above, the GPS system is not suited for indoor positioning (Nagel, 2010).

Localization systems and methods for indoor positioning do exist but indoor localization remains a research challenge. Indoor sensing technologies like Bluetooth, Wi-Fi, RFID (Radio Frequency ID) and infrared, are often not developed for positioning but for other purposes (Nagel, 2010) and can have some drawbacks. Due to environmental dynamics localization methods are often subject to an offline training phase or calibration in order to ensure high accuracy (Lim et al., 2005). The need for constant updating when environmental changes occur makes the scalability of these methods low especially for larger areas like enterprise buildings and other large, complex buildings (Lim et al., 2005).

The question remains how to accomplish indoor localization such that it is low cost, adaptive and robust.

The potentials of LBS using indoor localization are huge. Offering location based services and systems for monitoring and tracking of human assets is not new. Already in 1992, Want and Hopper developed an indoor location system based on infrared technology. Staff from an office were tracked and their location information provides possibilities for applications to take advantage of the data. With the introduction of the Internet, information overload and/or irrelevant information in the form of advertising by third party affiliates, have made finding information both easier and more difficult. The Internet is vast and the links to desired information have addressed finding relevant information only to some degree. Providing users with location-adjusted information increases the efficiency of information exchange. Ideally, this prevents the need to search location specific information. Especially (semi) public places like symposia, shopping malls and museums would benefit from such an application. The demand for location-based services is obvious: for instance information on the subject and location of speakers at a symposium, additional information about food or shops in a shopping mall and information about the objects in the exhibition of the museum you are located at. The latter type of situations are considered as possible application fields for this research. Taking into account the general characteristics of these (semi) public places, which can vary widely and can consists of complex and large buildings, possibly containing hundreds of people. The objective of this research is to provide a method of indoor localization which is:

- low cost, both concerning the hardware and implementation.
- Adaptive, easy to adapt to different circumstances, think of complex shaped rooms.
- Robust, it should be able to function in varying environments.

Such that it is possibly applicable in large, complex buildings holding multiple users. In the next subsections first the objective and research questions are discussed, second the research outline and finally the background and related work are presented.

1.3 OBJECTIVE AND RESEARCH QUESTION

The objective of this research is to propose a suitable technique and method to accomplish indoor localization which can be applied for LBS in (semi) public places. (Semi) public places (like conference halls, museums, office buildings or shopping malls) are assumed to be complex and large buildings potentially holding multiple users. Therefore the localization technique and method should be low cost, adaptive and robust.

The main research question is as follows:
How can indoor localization be accomplished potentially supporting an LBS for (semi) public places?

Sub questions that need to be answered are:

1. What is the most suitable localization technique for an LBS for (semi) public places?

    a) What are the technical requirements an indoor localization technique needs to meet (considering the general requirements of the said LBS)?
    b) What are the practical requirements the indoor localization technique needs to meet in order to localize?

    The Localization technique is the hardware that is used. Localization techniques can vary widely, for example in terms of range, costs, precision etc.. Depending on the requirements of the LBS one or more techniques can be selected. The characteristics of different localization techniques and its capabilities set the preconditions of the localization *method*.

2. What is the most suitable indoor localization method for an LBS applied in (semi) public places?

    a) What are the existing indoor localization methods?

b) Considering the technical capabilities of the technique and requirements of the said LBS, what is a suitable method for indoor localization?
c) Considering both the technique and localization method, what is the most suitable system setup for indoor localization?

The localization method is the software side of the localization. Taking the characteristics of the hardware in to account, a method (algorithm) for localization is designed. This algorithm returns a computed location indication.

3. What are the privacy issues concerning an LBS?

Location information is a key aspect of an LBS and services are made available based on that information. Gathering this location information could be considered personal information. How this personal information is gathered, used and kept are privacy issues to consider so these are taken into account when implementing the LBS.

1.4 RESEARCH OUTLINE

This research contains two main parts, the localization technique (hardware) and the localization method (software). The methodology and results of each part are separated. First the hardware is discussed including its methodology, tests, results and conclusions. Then the Software is presented, which also includes its methodology, tests, results and conclusions. It is necessary to conclude on the research done on the hardware, before the methodology of the software can be presented, because the results of the test done with the hardware have influence on choices made effecting the software.

Chapter 2: Privacy

In chapter 2 the privacy issues concerning an LBS and the gathering of location information is discussed.

Chapter 3: Hardware

A suitable indoor localization technique is chosen in chapter 3. Research question 2 is answered. The methodology is discussed in 3.1. first a general selection of localization techniques is done, second, the method of testing of these techniques is explained. The results of these tests are then presented in 3.2. A discussion and conclusion on the research done to select an appropriate hardware is presented in 3.3.

Chapter 4: Software

A suitable method for indoor localization is chosen in chapter 4. Research question 3 is answered. Section 4.1 describes the methodology. First, existing localization methods are discussed and second, the algorithm design and the mathematical background supporting the algorithms are presented. Two algorithms are proposed: a dependent algorithm and a method referred to as PML. Third, the method of testing the algorithms is discussed. Section 4.2 includes the results of these test and 4.3 contains the conclusions and discussion of this chapter.

Chapter 5: Discussion & future work

Chapter 5 presents the discussion of this research. It also looks at the future work. In section 5.1 the Practice issues of both the hardware and software are discussed. In section 5.2 the next steps concerning this research and topic are presented.

Chapter 6: Conclusions

In chapter 6 the final conclusions of the entire research are presented.

2 PRIVACY

Generally, an LBS gathers personal data. This can be location coordinates but also name, address information or the MAC address of mobile devices. MAC stands for Media Access Control and it is the unique ID of the device containing the manufacture's serial number. Privacy issues can determine the successfulness of the LBS since the gathering of personal data is a key aspect of its functionality. According to Warren and Brandeis (1890), privacy is the right to be left alone. This is a very fundamental description of privacy.

Different types of privacy exist. The application of this research gathers personal information of the user in the form of location information. Therefore, information privacy is looked at. This concerns personal data.

According to Smith et al. (1996) there are four groups of main privacy concerns among users regarding information privacy.
The groups are: Collection, Unauthorized Secondary Use, Errors and Improper Access.

- Collection is about the concerns of users of the personal identifiable data collected and stored in databases.
- Unauthorized Secondary Use is a concern about the collection of personal data for a certain goal but the data is then used to serve another goal.
- Errors and Improper Access are a key issue. The error is about the concern of inadequate protection against errors, whether or not accidental.
- The Improper Access part includes the concern that personal data is accessible to unauthorized persons. These concerns should be taken into account when developing an LBS. Users should be informed about what happens to their personal information and about privacy regulations and rights.

In the Netherlands the privacy regulations are according to the 'Wet Bescherming Persoonsgegevens' (WBP, 2000). This law states that:

- The user has to give his or hers consent before personal information can be gathered and used.
- It should be stated what information is gathered and what it is used for.
- The data cannot be used for other purposes than priory stated and cannot be sold off or shared with third parties without the users consent.
- The data cannot be saved longer than strictly necessary. This means as long as it serves its purpose.
- The data should be protected such that unauthorized access is prevented. These five rules should be applied when putting an LBS into practice.

This research considers a possible application for (semi) public places like shopping malls, office buildings and museums. The latter indicates a commercial use of the LBS. The system makes use of location information in order to safeguard its functioning. The five rules as described above can be applied as follows:

Before visitors make use of the LBS, they should be informed on what personal information is gathered. The user should be informed on what their personal data is used for and what the purpose of this use is. Before their personal information can be used, the person of interest needs to give his or her consent. It would be better to do this before the visitor makes use of the LBS and gives his or her personal information. Personal data is in this case the users' location information and, depending on the specific LBS, other personal information. The purpose is to use the personal data in order to offer the demanded service. The information should only be used for this sole purpose. However, there could be a scenario where there are secondary purposes, think of the analysis of the data in order to gain knowledge on the types of people that visit the (semi) public place in question. If this is the case, the users should be informed on these secondary purposes. As long as these purposes are served, the data is allowed to be held. This personal information should be deleted or returned to a state where it is no longer personally identifiable after the purpose of the data collection is achieved. This means that after the data analysis, personal identifiable information should be removed. The provider should also make sure that unauthorized access is prevented. The data storage must be secured but also the application itself. When the data on locations and potential other personal information are processed in a database, this database should have some kind of authorization like a username and password.

3 HARDWARE

The hardware is the technique used for localization. In this chapter first the methodology is discussed, this includes the selection of hardware based on literature grounds and the method of testing the hardware is explained. Second the results of these tests are presented and finally the discussion and conclusions are aggregately presented.

3.1 METHODOLOGY LOCALIZATION TECHNIQUE: HARDWARE

The final outcome of this research is an indoor localization method. In order to do so, a suitable localization technique (type of hardware) needs to be selected first. In this section sub question 2 is answered:

What is the most suitable localization technique for an LBS for (semi) public places*?*

- *a) What are the technical requirements an indoor localization technique needs to meet (considering the general requirements of the said LBS)?*
- *b) What are the practical requirements the indoor localization technique needs to meet in order to localize?*

In order to answer these questions the following two steps are taken:

1. A general selection is made through a comparison of existing techniques and LBR requirements.
2. These selected techniques are tested to determine their suitability for applying an indoor localization algorithm.

An overview is depicted in the flowchart below (figure 1).

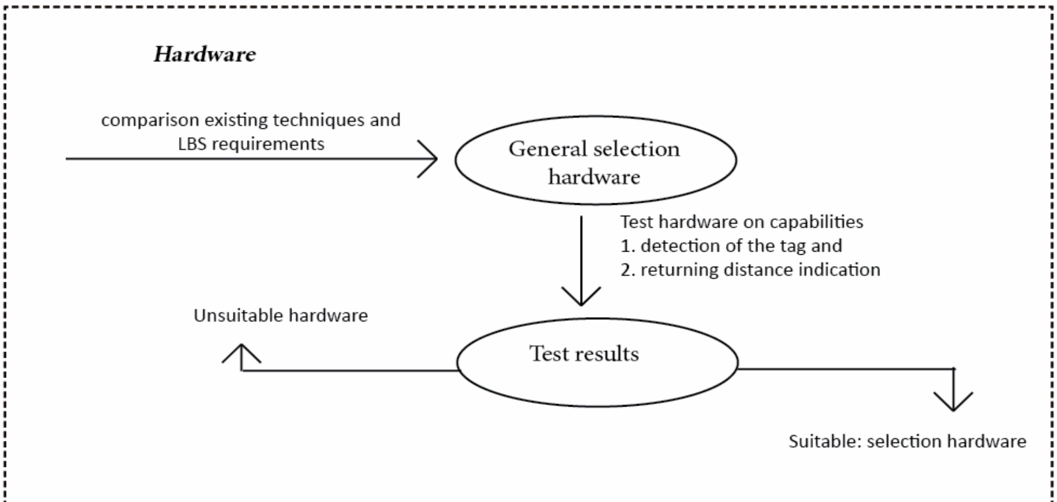


Figure 1. General overview methodology hardware.

GENERAL SELECTION HARDWARE

A general selection of hardware is made in this section by conducting a literature study. The criteria for choosing a localization technique is dependent on the characteristics of each technique and what is necessary for an LBS in (semi) public places. (Semi) Public places are assumed to be complex, large buildings and possibly holding multiple persons. The general characteristics of localization techniques are based on table 1 provided by Martin et al., (2010).

In this section:

- The general characteristics of different localization techniques are looked at and the most appropriate one is chosen.
- Then the choice is further specified and the appropriate techniques are further looked at.

Indoor localization techniques

The following aspects are general characteristics of indoor localization techniques and each characteristic is generally looked at to make a first decision on what technique to use.

Range. The range is the distance between the sensor and the nodes, where the node is detected by the sensor. The range should not exceed the indoor area, nor should the range be so small that the area needs a high density of sensors to achieve complete coverage. Therefore, the range of the localization system should be around five meters.

Precision. The precision of a localization system is the granularity in which a user is located. Some systems might require sub-meter precision, while others localize on room-level granularity. It depends on the service offered what precision is needed. In this research, both room level granularity as well as precision in the order of magnitude of a meter is taken into consideration.

Costs. The costs refer to the costs of the hardware and scaling. Ideally these costs are low. From a scaling perspective, implementation of the system should not be unnecessarily time consuming.

Martin et al. (2010) provide a general overview of the main characteristics of common indoor localization techniques. When looking at the overview, depicted in table 1, and comparing the criteria as described above to the table, RFID is chosen to be the most appropriate technique for this application. However, Bluetooth is in many ways also appropriate. The only drawback according to the chart below is the high scalability costs for Bluetooth. The reason for this, according to Martin et al. (2010), is that Bluetooth is a short range technology which means that multiple beacons are needed to cover the area. Although the hardware might be cheap, this high density of beacons could make the scalability costs high. RFID is said to be cheap, but this is stated only considering the tags and not the reader of the technique. The sensor of RFID can be costly and the scalability costs are therefore not necessarily lower than for Bluetooth.

Both RFID and Bluetooth are further looked at to determine their suitability to function for indoor localization.

Technology	Range	Precision	Cost	Power Consumption	Latency
Wi-Fi	1-200m	Good (meters) with RSSI or ToA/TDoA (with clock enhancement), up to hundreds of meters with Proximity	Moderate	High	Low
Bluetooth	1-20m	Good (meters)	Cheap but high scalability costs	Low	Medium
RFID	0.01-30m	Good (meters)	Very cheap (tags in the order of cents)	Very low (especially passive tags)	Low
Ultra-Wideband	10-200m	Excellent (up to millimetres)	Expensive(systems in the order of $20,000)	High	Very low
Infrared	From centimetres to several meters	Good (meters)	Moderate to expensive (dedicated system)	Low	Low
Cellular Communi-cation	From tens of meters to tens of kilometres	Good (meters) with RSSI fingerprinting for indoors. But very poor (up to kilometres) with Cell ID	Expensive Infrastructure / Moderate receivers	Medium	Medium
Ultrasound	From centimetres to tens of meters	Excellent (centimetres)	Moderate (dedicated system)	Low	Low
Inertial Navigation Systems	Autonomous System	Good (meters)	Decreasing prices of MEMs will make them cheap	Medium	Medium

Table 1. Main Attributes of Common Technologies used for Indoor Localization (Martin et al., 2010).

In the next sections RFID and Bluetooth are further explained.

RFID

Radio Frequency Identification (RFID) has many forms and functions. Basically the system consist of a sensor and a tag (figure 2), interacting through radio communication (Dobkin, 2012). The technique is well developed and widely used for all kinds of applications. A well-known application is the security of items in shops. Items are equipped with an RFID tag and sensors are placed at the exit. When an item passes the exit it is detected and sets off an alarm. But there are many other application fields, think of applications like animal tagging, assistance in supply chain management, electronic payment (Liu & Liu, 2013) baggage handling, fixed asset (Azzouzi et al., 2011). RFID has some important advantages. According to Ni, Liu et al (2004) advantages are 'the no contact and non-line-of-sight nature of this technology' and the fact that tags can be read also in extreme environmental conditions like snow, fog, ice, paint etc. Finally, the tags can be read in less than 100 milliseconds (Ni, Liu et al., 2004).

The sensor and tag of an RFID system communicate through radio frequency energy so that the sensor can identify the tag when in range. Three different tags exist: passive, active and semi-passive tags. In the case of passive tags, the tag has no internal power supply and no radio transmitter. Passive tags generate power by using the received signal to operate their circuitry and send information back to the transmitter (Dobkin, 2012). A UHF (ultra-high frequency) RFID sensor and passive tag are depicted in figure 1a and 1b. Semi-passive tags contain a battery providing power to the circuitry but still use backscatter communication for the tag to sensor communication (Dobkin, 2012). Finally, active tags have a power source and actively transmit (Dobkin, 2012).

Figure 2a. Intellifi UHF RFID Sensor version v0.9R. (Source: www.intellifi.nl.).

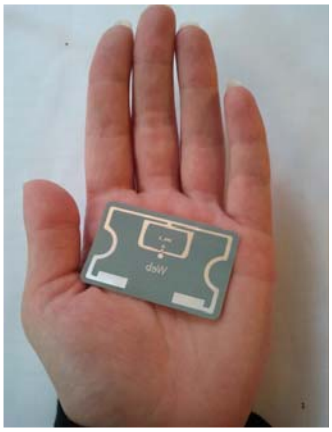


Figure 2b. Passive UHF RFID Tag.

There are different types of RFID systems. Typically, these systems are distinguished by their operating frequency. RFID systems use frequencies ranging from 100 kHz to over 5 GHz (Dobkin, 2012). Low Frequency (LF) operate between 30 and 300 kHz, High Frequency (HF) operate between 3 and 30 MHz and ultra-high frequency (UHF) operate between 300 MHz and 3 GHz. From 2,5 GHz up to 3 GHz is a part of the ultra-high frequency band called microwave band (Dobkin, 2012). Advantages of LF are that its surroundings have little influence, for example the effect of the presence of water and metal has little interference with the signal. Disadvantages are that tags can only be read within half a meter and only small amount of tags, sometimes just one, can be read at the same time (Motorola). Systems that operate within the HF band have a reading distance of approximately 0.45 meter. Advantages are that multiple tags can be read at the same time, and moreover, HF RFID penetrates most materials well and has a reading range up to 1 meter. Disadvantages are that the effectiveness decreases with the presence of metal and the orientation of the tag influences the communication between tag and sensor (Motorola). Systems operating within the UHF band have a reading distance up to approximately 6 meter (Motorola). The advantages are that this system can read many tags at the same time, the data transfer rate is high and UHF RFID has quite a large reading range (up to 6 meters) for the tag size and cost (Motorola).

One of the main disadvantages is that this system is easily influenced by environmental factors like metal and water which interfere with the signals.

Metal and water have an inhibitory effect on radio waves because the metal reflects and the water absorbs and reflects the waves (Clarke et al., 2006). Research shows that water has an effect on the performance of, and especially, UHF RFID (as cited in Clarke et al., 2006). Onderko (2004) elucidated the liquid problem by showing that tag readings on frozen beef were successful while, when the meat was thawed, performance drastically went down. However, Hewlett-Packard (as cited in Clarke et al., 2006) shows that it is possible to overcome these issues by taking the tag orientation into account.

Based on the general characteristics, only one type of system is appropriate for the LBS for this research. Two key aspects of the system are: first, the application needs to function in semi-public places. This implies that the system should be capable to handle multiple tags at the same time. And second, as stated before, the range should be around 6 meters. <u>These two criteria leaves one type of system to choose: Ultra High Frequency RFID.</u>

The read range is the most important factor in this choice. LF and HF would not be appropriate due to their high latency and especially due to the small reading range. Only UHF has a reading range large enough to use it for this application. Moreover, and especially LF, they are not suited for reading many tags in a short time, which is one of the main aspects of the LBS in this research.

The hardware of a typical UHF RFID system consists of a sensor with antenna which communicates through radio waves to a tag (figure 2). The interrogator, also called sensor, is connected to the host computer or network which enables the administrator to control the data. The sensor contains an antenna, which in some cases is integrated with the sensor or else connected through a cable. The tag, also referred to as transponder, contains an integrated circuit which contains the tag id and information for the protocol that guides communication between the tag and sensor (Dobkin, 2012).

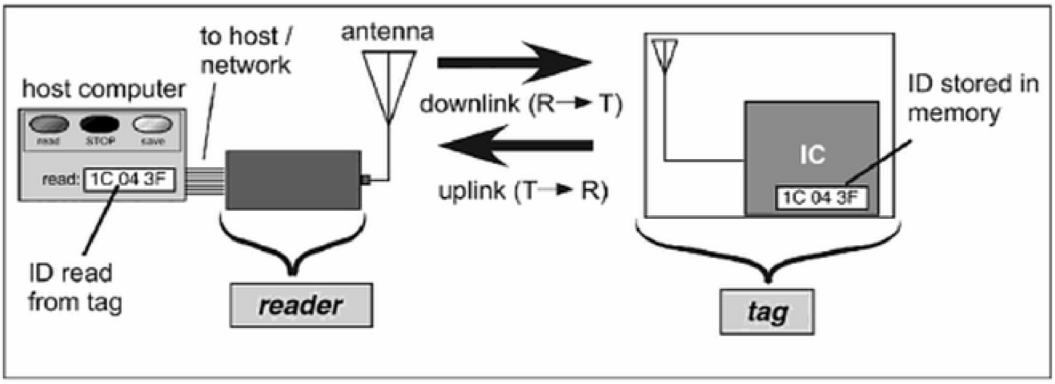


Figure 3. System UHF RFID (Dobkin, 2012, p.22)

The communication from the sensor to the tag is called downlink or forward link (figure 3). Uplink or reverse link is when there is communication going from the tag to the sensor. UHF RFID is radiative which means that the size of the wavelength is comparable to the antenna size of the tag.

For example, at a frequency (f) of 1.5 GHz, which is 1.5*10^9 H. The wavelength (λ) is calculated as follows (formula I):

$$\lambda = \frac{c}{f} \qquad \text{(I)}$$

$$\lambda = \text{wavelength}$$

$$c = \text{speed of light (and electromagnetic waves)}$$

$$f = \text{frequency}$$

$$\frac{300000\ km/s}{1.5 * 10^9\ Hz\ or\ peaks/sec} = 0.0002km, \text{ which is 0.2 m.}$$

The tags of UHF RFID have antennas as small as 5 cm and are comparable in size to the wavelength (Dobkin 2012). For that reason the tags can be incorporated into a variety of items. Passive tags entail no more than a paper sheet with the dimension of a business card (figure 2b).

In this research, for the localization UHF RFID sensors of the brand Intellifi version v0.9R are used. These sensors are attached to the ceiling and detect tags through the use of UHF RFID. The Intellifi UHF RFID sensor is a sensor that communicates with external passive UHF tags and publishes the data on the internet. The sensor is used to locate visitors wearing a UHF passive tag. This sensor has three incorporated antennas which read as one. Intellifi also has a sensor with one incorporated antenna and the possibility of adding another three antennas. The sensors are connected to a router through an Ethernet cable which provides the hardware with both power and internet. The computer is also connected to the internet which allows the administrator to visit an API provided by Intellifi. Through this API the sensors can be controlled by configuring the antennas.
There are two options:

- First: the transmitting power can be changed. Changing the transmitting power is done by altering the antenna power (in dBm) which can be set at a maximum of 30 and minimum of 5. dBm is a power ratio relative to the power in decibels. Decibel describes relative power, for example, a gain of 3 dB indicates that a signal is twice as strong as it was before but it is not defined what the starting point is. By introducing dBm, a scale is added, 0 dBm = 1 mW. The equation to calculate the arbitrary power in mW is as follows (formula II):

  $$x =^{10} \log_{10}(\frac{P}{1mW}) \qquad \text{(II)}$$

  $$x = dBm$$

  $$P = mW$$

  This also means that the dBm can be negative when the mW is between 0 and 1.

- Second: the hold time can be set. The hold time is a feature developed and incorporated by Intellifi. The sensors scan the environment about 150 times per second. Not all this raw data is returned to the administrator. The hold time is the amount of seconds that the sensor is allowed to 'wait' when not detecting a tag before ending the record. If a tag is scanned again within the hold time, the record is not ended. Records contain a start time and end time, the start time is the moment a tag is detected and the end time is the moment that tag is no longer detected. A record means that the end time is determined. The data contains the following information:

Item_code	The unique identifier of a tag
Item_codetype	Refers to the technology that the itemcode is based on (for example EPG-Gen2 for UHF RFID tags)
Time_started	Date and time a tag is detected for the first time
Time_last	Date and time a tag is no longer detected
Proximity	Gives an indication of relative distance of the sensor to the tag. Three options 'Immediate', 'Near' or 'Far'
Hold_delay_s	The holdtime
Is_present	This returns true or false, all records created in the past are false, only the tags that are present in that moment of time have a record 'true'
Spot_id	The unique identifier of a sensor
Key	This is a combination of the spot_id and item_code
_id	unknown

Table 2. The information returned by the Intellifi UHF RFID sensors, and its corresponding meaning.

All the data described above can be viewed live and retrieved online at the Intellifi website by SQL alike commands. Intellifi UHF RFID sensors register the data as a JSON string and is stored in the cloud which allows reading the data when connected to the internet.

Bluetooth

A new type of Bluetooth which is called Bluetooth Low Energy has recently emerged. Bluetooth Low Energy (BLE) is slightly different from common Bluetooth variations. BLE is designed as a low-power solution for control and monitoring purposes (Gomez et al., 2012). Bluetooth Low Energy (BLE) also consist of a sensor and a tag/transmitter and is developed by the Bluetooth Special Interest Group (SIG, 2010) in order to do wireless short-range communication. The main design goal of Bluetooth Low Energy is giving a low-power solution for control and monitoring applications. Other wireless low power techniques, for example ZigBee, 6LoWPAN or Z-Wave, are different from BLE because they need multi-hop networking in contrast to single hop networking. Multi-hop networking leads to an increased power consumption, unlike single hop networking in the case of BLE (Gomez & Paradells, 2010) (Ludovici et al., 2011). The low energy consumption makes BLE also applicable to use in cases in healthcare, consumer electronics, smart energy and security (Gomez et al., 2012). A large advantage of this technique is that the sensor is nowadays embedded into multipurpose devices like smartphones which makes it an easy and accessible way of communication (Huang et al., 2013).

Bluetooth Low Energy consist of a senor, often embedded in the most recent smartphones, and a separate BLE tag (figure 4). This tag is active and it contains its own power supply in the form of a battery. BLE operates in the 2.4 Ghz band. The Bluetooth 4.0 sensors are integrated in the newest smartphones, which gives the general public access to BLE based applications (Huang et al., 2013). BLE communicates through radio link, defining up to 40 channels (Gomez et al., 2012). The channels are used for device discovery, connection establishment and broadcast transmission. A hopping mechanism switches between 37 of those bands which minimizes interferences and wireless propagation issues like fading and multipath (Gomez et al., 2012). Propagation issues can have a large influence on the technique and such a hopping mechanism makes BLE more stable in different environments.

Figure 4. Estimote Bluetooth Low Energy tags. (source: www.flickr.com/photos/ibarthoekstra/11083811654/).

The hardware for localization using Bluetooth Low Energy is done by using tags and sensors. The tags are of the brand 'StickNfind' and 'Estimote'. The tags can be detected by the newest generation of smartphones which are equipped with a Bluetooth 4.0 sensor. The smartphones function as a sensor, detecting the BLE tags in the environment. For this research, Motorola Moto G smartphones are used. The tags of StickNfind are coin shaped and are activated when tabbed. Data acquisition is done by using a simple application on a Motorola Moto G, which collects the signals of the active tags and makes this data available by mailing the records as a string to a predefined email address. The application is owned by Rob van der Veer. The data contains the following information:

Milis	These are the amount of seconds passed since the start date: 1970-01-01
Timestamp	This is the date and time when the tag was detected
Mac	This is an ID which is unique for the BLEtag
RSSI	The RSSI is the Received Signal Strength Indication
Meter	Meters distance for a smartphone (brand unknown)

Table 3. The information given by the BLE records and it's corresponding meaning.

TESTING LOCALIZATION TECHNIQUE

The final outcome of this research is an indoor localization method. The localization algorithm (software) returns a position of a person as an identification of both a coarse localization granularity (a virtual area) and on a sub zone localization granularity. Therefore, the space is both discrete (virtual area) and continuous (sub zone level).
Transmitting beacons are placed in predefined places. When a user is within the range of such a beacon, it is assumed that the visitor is near the predefined location of the beacon. Combining this with differentiation in signal strength decreases the localization area and increases precision of localization.

This can only be accomplished if the localization technique has two basic capabilities:

1. Detect the tag when within the range and
2. Assign a corresponding indication of a distance.

In order to answer the sub question 2b *(What are the practical requirements the indoor localization technique needs to meet in order to localize?),* the two techniques (UFH RFID and BLE), selected in the previous section, are tested. In this section the tests done for both techniques are described.

Ultra High Frequency Radio Frequency Identification (UHF RFID)

Testing UHF RFID sensors and antennas in various situations is necessary in order to gain knowledge on the general characteristics and to explore the localization possibilities of this technique.

These tests are divided into three experimental parts: A, B and C.

- Experiment part A includes the testing of the Intellifi sensor. Its aim is to gain insight on the basic capabilities and functions of UHF RFID technology.
- For Experiment part B the Intellifi hardware is tested in the office of Intellifi which is located in Veenendaal, the Netherlands. The goal of these tests is to see how well the subject can be located inside or outside a zone, using this technique.
- Finally, Experiment part C includes the further testing of the Intellifi equipment in a different environmental setting including more subjects.

For the processing and visualization of the tests described below, three main steps are taken.

1. The retrieval of the string data of the Intellifi hardware is done using PHP within the content management system of the company 'Bureau Browserbeest'. Their content management system uses the client phpMyAdmin to store the data. This client is based on a MySQL database.
2. For further processing the data is exported and loaded into MySQL workbench which is also used for further processing and to extract a clean dataset. This means that it only contains the records during test moments and the information strictly necessary.
3. Finally, this data is visualized and processed using Matlab.

Experiment part A

The tests of the Intellifi equipment take place in Tilburg, The Netherlands, at the office of Itrack. These tests are conducted to determine the preconditions when using the Intellifi UHF RFID sensor, it is not directly linked to localization but to see what the basic capabilities and functions are.

- Test A1 is done to see how the device reacts on the interference of humans by placing the subject repeatedly between the sensor and tag.
- The aim of test A2 and A3 is to explore the reading range and shape of the sensors. This is done by placing a sensor, directing towards the open space of a room and determining where the sensor no longer detects the tag.
- Test A4 was intended to look at how the received signal strength changes in conditions where tags have various orientations.
- In test A5 the capacity of the device to read multiple tags was explored.

Experiment part B

Experiment part B contains the following tests:

- Test B1: Moving between two sensors with an antenna power of 20 and 30 dBm
- Test B2: Moving between four sensors with an antenna power of 20 and 30 dBm

The tests discussed below take place at the office of Intellifi located in Veenedaal with the Intellifi equipment. The tests are conducted in a hall of 8.40 (y direction) by 5.40 (x direction) meters (figure 5). The sensors are attached to the ceiling, which divides the room in four equal, virtual zones. Identifying zones which correspond to the readers is necessary in order to test the possibility of applying zone level localization. A schematic overview of the room and the locations of the sensors are shown in figure 5. The walls and floors are white and one side of the hall consists mainly of a window.

The main objective of this experiment is to firstly determine if this technique meets the requirements in order to use the proximity approach and secondly return a consequent indication of distance or signal strength during real life actions of crossing the room with a slow pace and fast pace.

- In test B1 two sensors are used. The subject walks from one sensor to the other on a line. This can therefore be considered as a 2d situation. The variables are the x position and proximity value of every measurement. The proximity value is an indication of measured proximity, which can be immediate, near or far.
- In test B2 the setting is expanded to working with four sensors creating a 3D situation by adding a y dimension.

One person conducts the experiments for both tests. The subject in question wears three tags, one on the right shoulder, one on the left shoulder and one on the chest. According to the results of test A1 and test A3 this would benefit the detection of the tags.

- First: the most optimal orientation of the tags towards the sensor is achieved and
- Second: it minimizes the interference of the body since there is always one shoulder in direct line with a sensor.

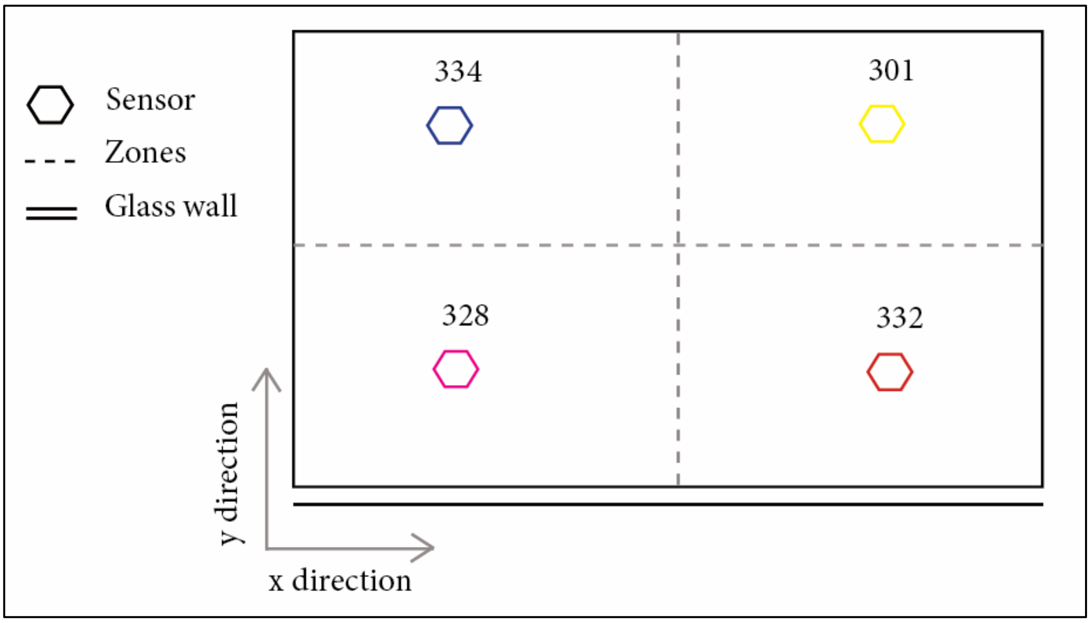


Figure 5. Schematic overview of the room and placements of sensors 334, 301, 328 and 332.

<u>Experiment part C</u>

The tests of Experiment part C take place in Almere. The building is called 'places to work' and located close to the central station of Almere, North-Holland, the Netherlands. In the basement there is a room of 8 by 18 meters with a height of 3.65 meters (figure 6). The stages at the end and at the entrance of the room are 60 cm in height. The ceiling and walls on the top, right and bottom end of the room are covered by wood (figure 7). The left wall of the room partially consists of glass bricks. Two columns prevent the space from being completely open.

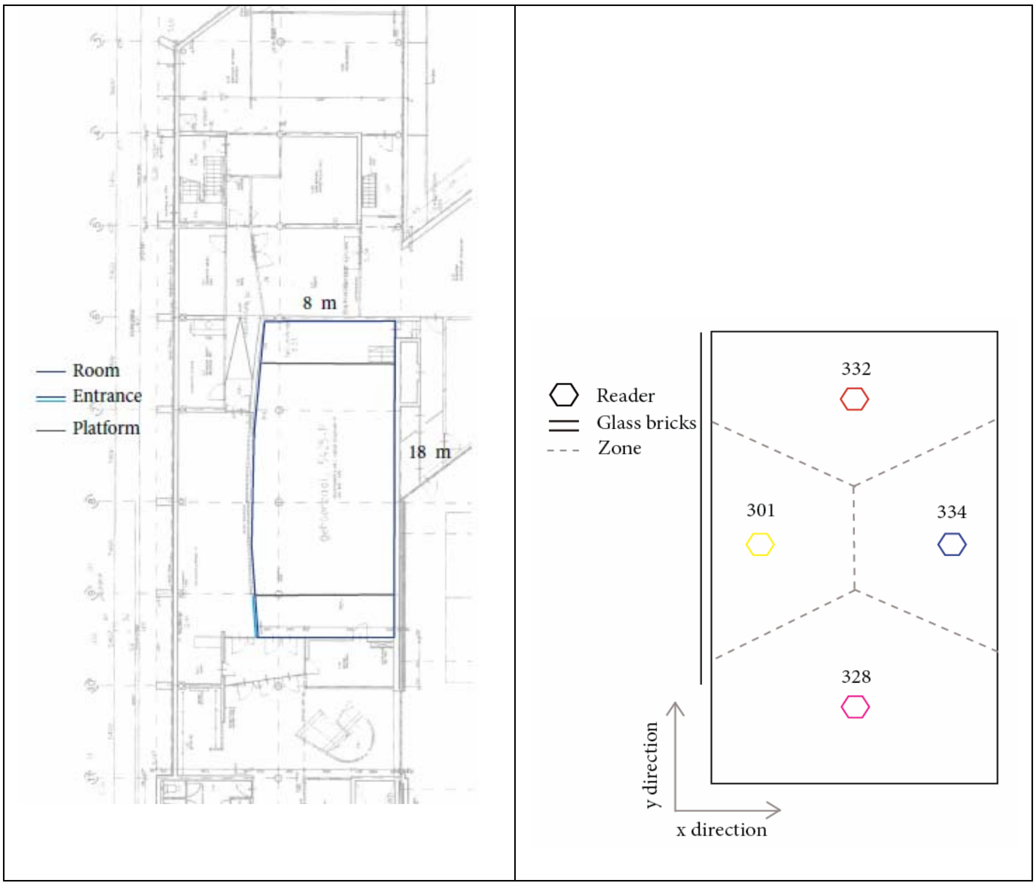


Figure 6. Left: floor plan of basement at 'places 2 work' in Almere. The room used for the tests is highlighted. Right: schematic setup room with sensors and borders zones.

Figure 7. 'Places 2 work' in Almere. The room used for the tests.

The test setup is depicted in figure 6. In order to minimize overlap of the reach of the sensors, the antenna power of sensor 301 (yellow) and 334 (blue) is set on 25 dBm and the antenna power of sensors 332 (red) and 328 (purple) is set on 30 dBm.

The overall goal of this test is to see how the change of environment changes the results found in experiment part B. In experiment part C, a total of 10 subjects participate at the same time. Each subject is provided with 3 tags attached again on the shoulders and chest.

- Over seven small tests have been conducted, three of those where stationary tests. The subject did not walk during those tests (test C1).
- Four tests are not static, in different situations the subject moved from different locations to other zones (test C2).

Bluetooth Low Energy (BLE)

In total three tests are done to determine if the BLE technology is suitable to use for localization. Two different brands of BLE are tested: 'StickNfind' and 'Estimote'.

The tests are divided into three experimental parts: A, B and C.

- Experiment part A includes only the testing of StickNfind hardware and is to explore some of the basic functioning of the technique.
- In Experiment part B, StickNfind tags are used to determine if there is a relation between distance and signal strength.
- Finally, in Experiment part C, the correlation between signal strength and distance is determined for the brand Estimote.

The tags are attached to the ceiling and the subject with sensor in hand is located in the room (figure 8).

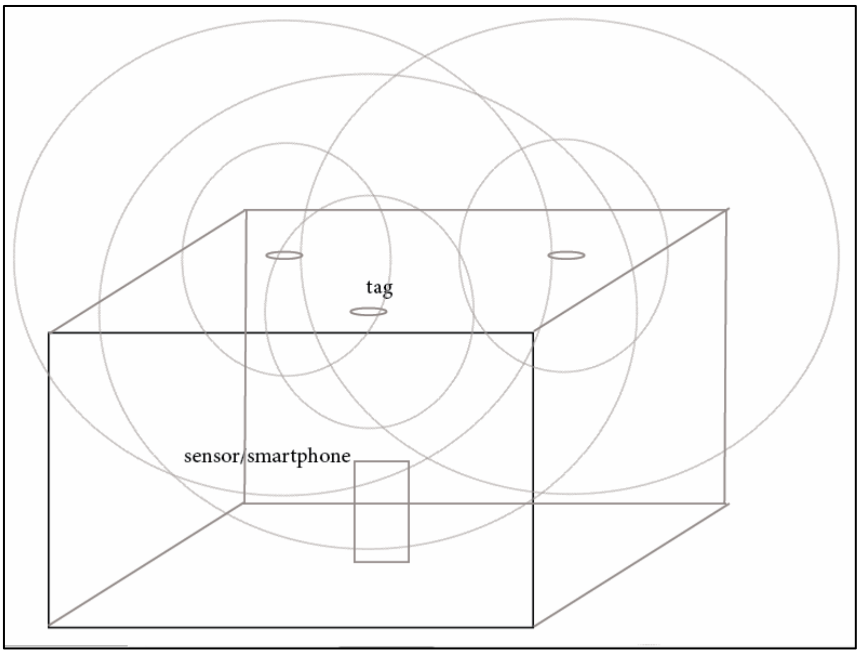


Figure 8. Tags are placed against the ceiling and the sensor (smartphone) is the moving part of the system.

For the processing and visualization of the tests done with Bluetooth Low Energy, two main steps are taken.

1. First, the data is retrieved from an email and loaded into MySQL workbench which is also used for further processing and to create a clean dataset. The dataset only contains the recordings done during the test moments.
2. Second, this data is visualized and processed using Microsoft Excel.

Experiment part A

Experiment part A has taken place in Amsterdam, the Netherlands, at the office of Standard Beacon Network. These tests are done to get an idea of the basic functioning of BLE, it is not directly connected to localization.

- Test A1 is done to determine the influence of the human body on the functioning of the technique and the signal strength. First, the tag is placed in an open and closed hand to determine the differences of the RSSI. Second, the subject is placed repeatedly between the sensor and tag.
- Test A2 is done to see what the reach of the BLE tags are (reading distance). The tag and sensor are placed apart with and increasing distance.

Experiment part B

The test of experiment part B takes place in two different settings. The first setting is Veenendaal, the office of Intellifi using StickNfind tags. The StickNfind tags are hung from the ceiling and the subject with the sensor in hand walkes around the room (figure 9).

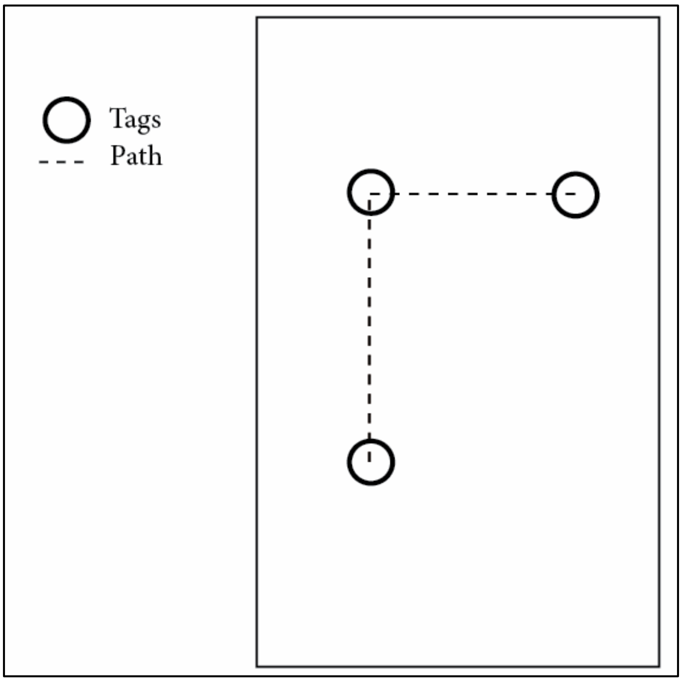


Figure 9. Test setup with the path taken by the subject.

The second setting is the office of Standard Beacon Network located in Amsterdam. The aim of the test is to determine if there is a correlation between distance and signal strength. The subject with the sensor in hand walks up and down between the tags, starting at tags 1 & 2, returning and ending at tags 3 & 4. The scenario is depicted in figure 10.

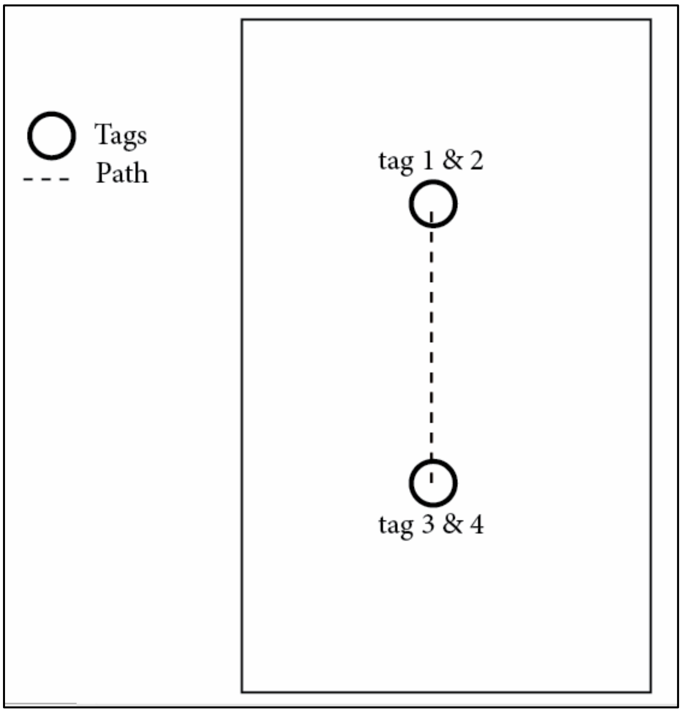


Figure 10. Test setup at office of SBN in Amsterdam.

<u>Experiment part C</u>

In order to use the BLE tags for localization it is necessary to determine the relationship between distance and signal strength for this particular brand of tags and brand of smartphone.

The objective of test C1 is to determine the correlation between distance and signal strength specific for the Estimote tags and the Motorola Moto G smartphone. This is of importance to be able to further specify location on a sub zone level in a later stage. The test is done by placing tags and the sensor apart with increasing distances.

3.2 RESULTS HARDWARE

The results of each experiment part for both UHF RFID and BLE are presented in this section.

UHF RFID

The results of the three experimental parts, A, B and C, done with UHF RFID are presented in the next section:

- Experiment part A includes the testing of the Intellifi sensor in order to gain insight on the basic capabilities of the hardware.
- The goal of Experiment part B is to see how well the subject can be located inside or outside a zone, using UHF RFID.
- Finally, Experiment part C includes the further testing of the Intellifi equipment in a different environmental setting including more subjects.

Experiment part A

In this section the results of experiment part A of UHF RFID tests are discussed. The following tests are done:

- Test A1 is done to see how the device reacts on the interference of humans.
- The aim of test A2 and A3 is to explore the reading distance and shape of the sensors.
- Test A4 was intended to look at how the received signal strength changes in conditions where tags have various orientations.
- In test A5 capacity of the device to read multiple tags was explored.

Test A1: Interferences of humans

The human body exists for around 70 percent of water. Water is the actual source of interference. Since localization should function in (semi) public places potentially holding multiple users, gaining knowledge on how the hardware reacts to human interference is important. This test was done by repeatedly placing a person between a tag and sensor from various distances. It was expected that the signal strength would decrease as soon as a person would be located between the tag and the sensor. However, results show that in every case the signal between the tag and sensor was immediately lost by the sensor when there was interference of a human body, no matter what distance. Even just placing a hand on the tag causes the sensor to no longer detect the tag.

Test A2: The reading distance and shape of the sensors

This test is conducted to explore both the reading distance and shape of the UHF RFID sensors. This is of importance because it determines both the shape and dimension of the zone. The test is done by placing a sensor facing towards the open space of a room (y direction) (figure 11a). Every 50 cm a tag is placed to determine if the sensor detects the tag. Sequentially, by moving perpendicular to the sensor until the sensor loses connection with the tag, the boundary is determined (figure 11b). The result can be viewed in figure 11b.

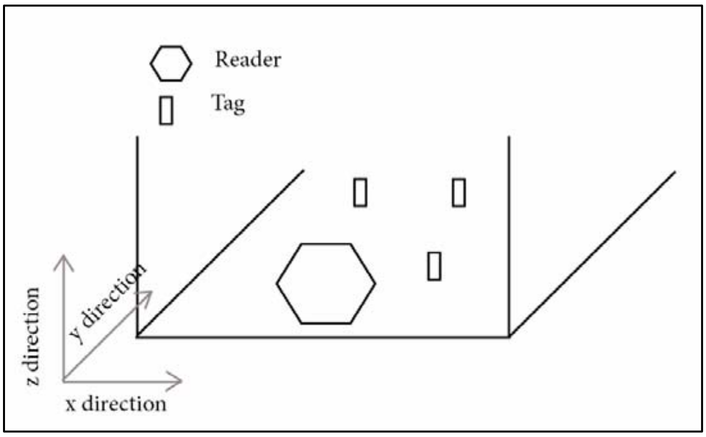


Figure 11a. Test setup of test A2.

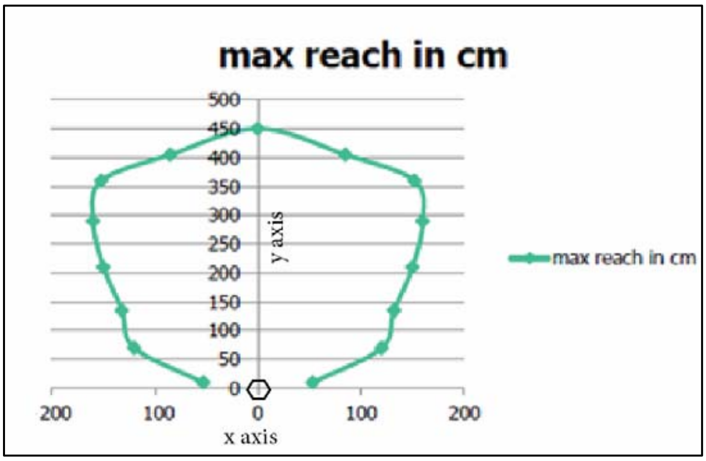


Figure 11b. Results test A2. X(0,0) location sensor facing alongside the y-axis. x and y values are in cm. Green line represents maximum reading range, within this boundary tags are detected by the reader.

The Intellifi sensor detects tags up to a maximum reading range of 4.5 meters. The maximum width is at a distance of 3.5 meters, which implies that at this distance the maximum surface is covered.

Test A3: The orientation of tags

The main goal of this test is to see if the orientation of tags with respect to the sensor would influence the performance of the detection. The test is done by placing a tag close to the sensor and after a minute change the orientation of the tag by turning it 90° on a horizontal line (figure 12). The resulting Proximity indication is noted under the schematic illustration for each orientation. Expected was that the tag would work best when turned with the flat side towards the sensor (figure 12a) and that the signal strength (thus proximity) would reduce as soon as it would be turned with the side of the tag towards the sensor. This is claimed by people working in the field. However, the results show something different. When the short edge is held towards the sensor (figure 12a and 12c) it has a good reading performance (proximity of 'immediate'), no matter if the tag was turned. When the long edge is held towards the sensor (figure 12b and 12d), the reading performance decreases (from a proximity of 'immediate' to a proximity of 'near').

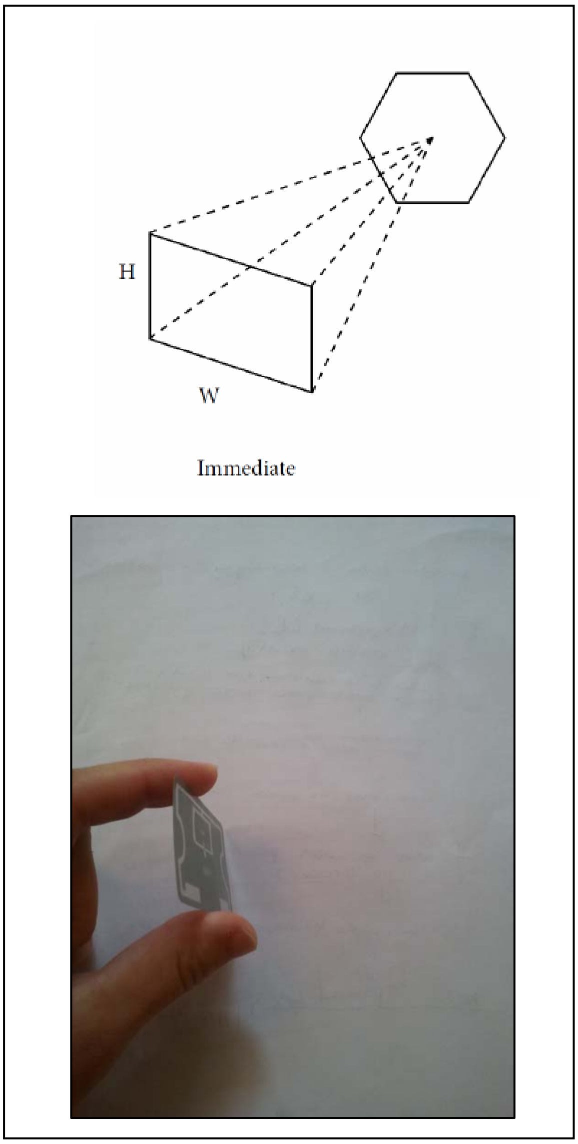


Figure 12a. Orientation tag. Sensor is assumed opposite and directed towards the hand.

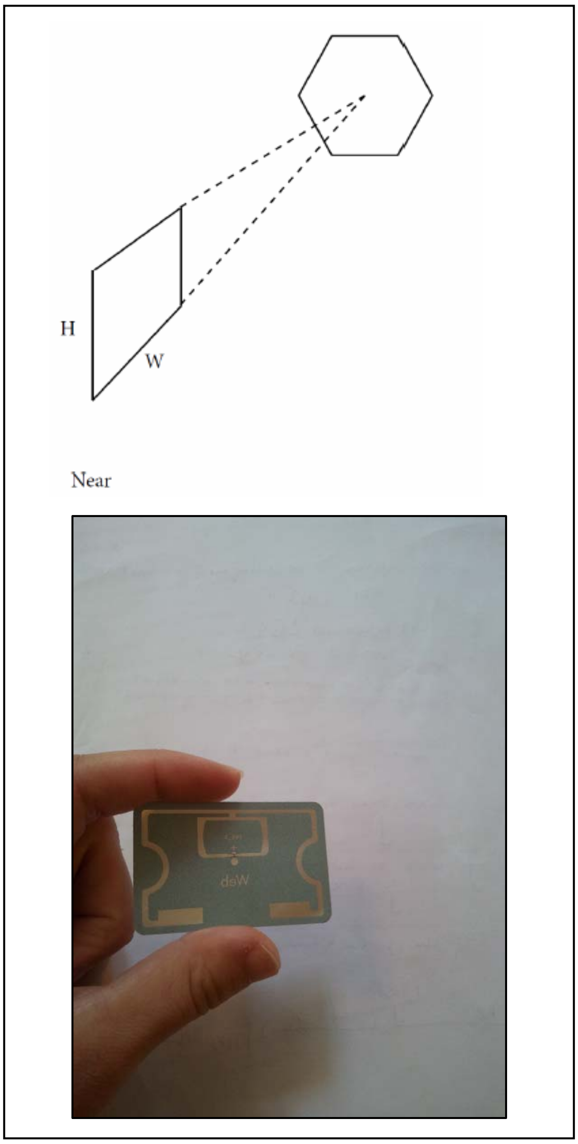


Figure 12b. Orientation tag. Sensor is assumed opposite and directed towards the hand.

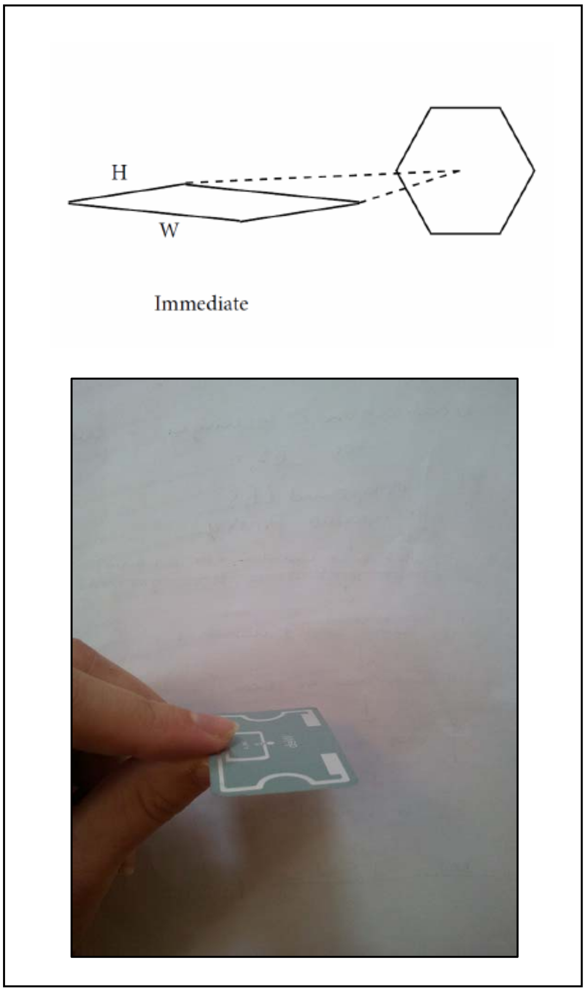


Figure 12c. Orientation tag. Sensor is assumed opposite and directed towards the hand.

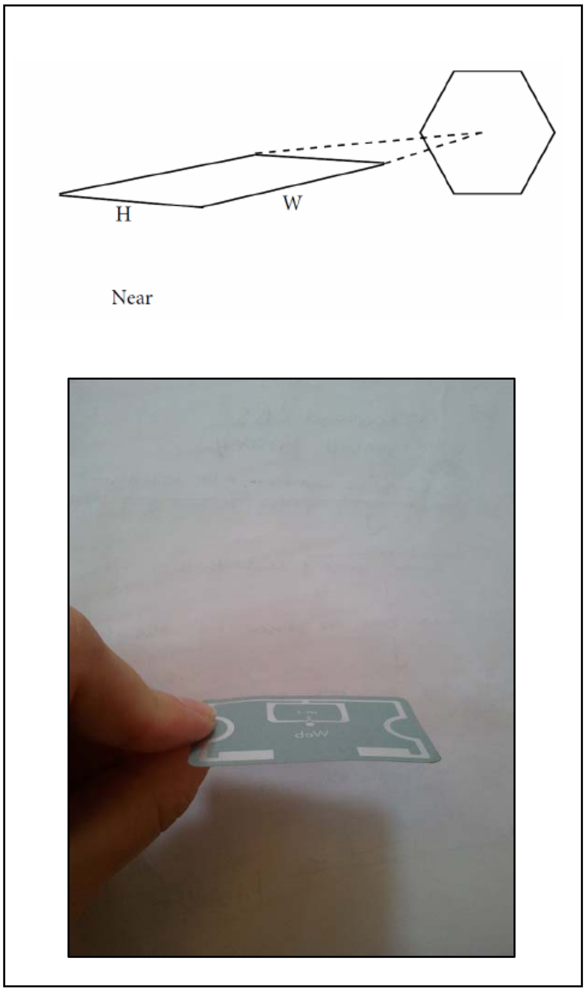


Figure 12d. Orientation tag. Sensor is assumed opposite and directed towards the hand.

Test A4: Reading capacity

The reading capacity gives an indication on the amount of tags that the sensor is capable of detecting. For the localization purposes of the LBS in this research, it gives insight on the amount of people that can be detected per zone. A large amount of tags where repeatedly placed inside the reading range of a sensor and the capacity of detection is reviewed. The Intellifi hardware show a maximum reading capacity between 25 and 30 on the standard provided interface. The sensors scan about 150 times per seconds. Intellifi does however have a public protocol on the hold time in cases where the amount of tags within reach of the sensor increases. This gives direct insight on the expected time needed to scan tags. According to the Intellifi Quick start guide, the hold time goes up when the amount of tags at one sensor increases. With over 32 tags at one sensor, the hold time changes to 8 seconds. With over 64 tags at one sensor, the hold time increases to 16 seconds.

In practise, a reading capacity of 30 tags per zone is enough. Suppose the sensor can read up to 5 meters in diameter, the zone would have approximately a surface of 20 square meters. Assuming the presence of 30 people, that would leave 1.5 person per square meter, which is already crowded.

Experiment part B

The results of experiment part B of UHF RFID tests are presented in this section. The results of the following tests are discussed:

- In test B1 two sensors are used. The subject walks from one sensor to the other on a line. This can therefore be considered as a 2d situation. The variables are the x position and proximity value of every measurement. The proximity value is an indication of measured proximity and this can be immediate, near or far.
- In test B2 the setting is expanded to working with four sensors creating a 3D situation by adding a y dimension.

Test B1: Two sensors with an antenna power of 20 and 30 dBm

Two Intellifi sensors where placed 3,6 meters apart from each other. Two different situations are tested:

- First: moving at a calm pace between the two sensors and
- Second: moving in a fast pace between the two sensors.

These situations are repeated, once when the antenna power of sensors was set to 30 dBm and once with an antenna power of 20 dBm. The antenna power determines the reading range of the sensors (figure 15). With an antenna power of 20 dBm the reading range is 3.8 meters while with an antenna power of 30 dBm the range is 20.5 meters. It is important to look at the difference because the proximity detection is relative to the maximum reading range. So, for example, a proximity of 'far' is measured at a larger distance when the antenna power is set to 30 than to 20. This is further explained in test B2.

All four situations of test 5 show the same basic results. The most striking result is shown in figure 13. These measurements are done while moving slowly between the two sensors both with an antenna power of 30 dBm. The filled blue and yellow dots represent the two sensors. The lines are the measurements, located according to where the subject was moving during the test. Their colour is determined by the sensor that recorded the measurement. The Proximity axis consist of three values which represent the proximity measurement, 1 is 'immediate', 2 is 'near' and 3 is 'far'. This axis should not be confused with the height of the room.

Striking is the occurrence of 'near' measurements done by sensor 301 (yellow) but occurring close to sensor 334 (blue) and vice versa. At a first glance, the measurements seem to be flipped. One may expect that measurements done close to the sensor would have a proximity 'near' or 'immediate' more often while measurements done further away would have expected to show a proximity of 'far' more often. However, the results show that the reverse is the case.

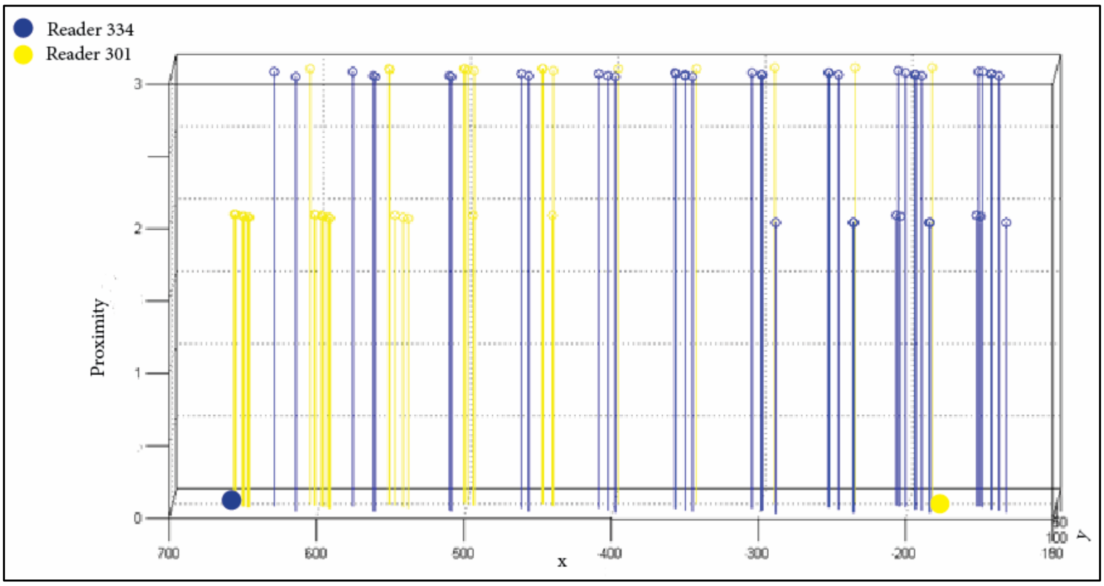


Figure 13. Results moving at a slow pace with an antenna power of 30 dBm. Axis: x and y are dimensions room in cm, Proximity axis represent three levels: 1 = immediate, 2 = near and 3 = far.

Test B2: Four sensors with an antenna power of 20 and 30 dBm

For this test, four Intellifi sensors where placed as shown in figure 14. Again, the same two different situations as in test B1 were tested but in a more complex 3D situation. The first situation entails the subject moving at a calm pace between the four sensors and secondly moving in a fast pace between the four sensors. These situations are also repeated with a varying signal strength, once with an antenna power of 30 dBm and once with an antenna power of 20 dBm.

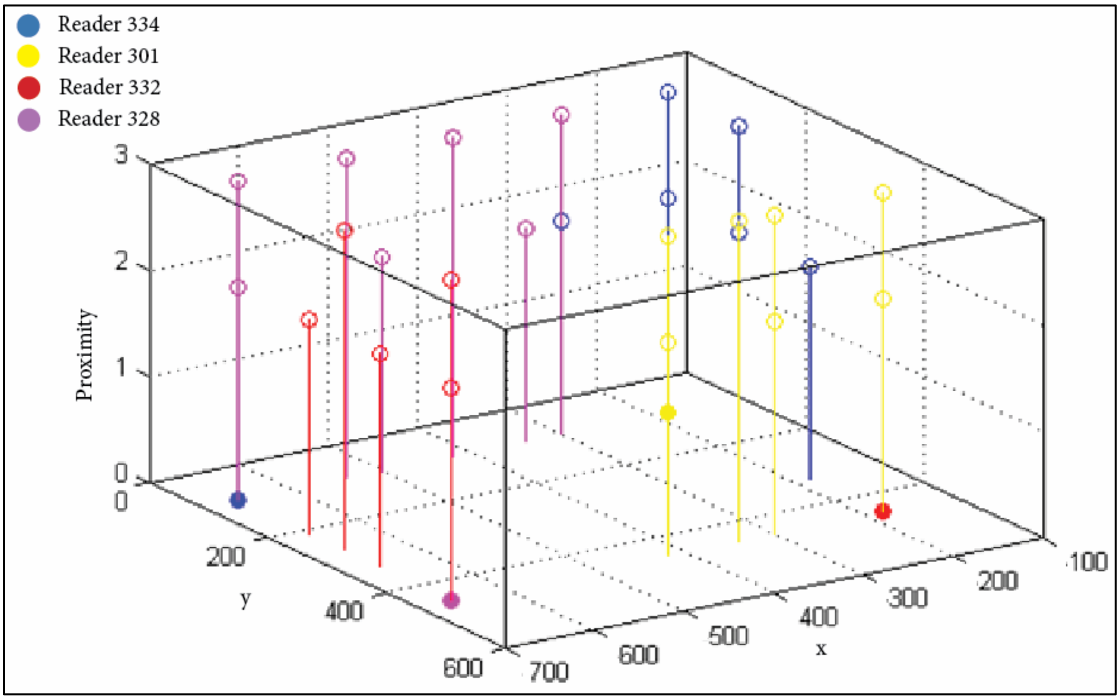


Figure 14. Results moving at a fast pace with an antenna power of 20 dBm. Axis: x and y are dimensions room in cm, Proximity axis represent three levels: 1 = immediate, 2 = near and 3 = far.

The results of test B2 show something interesting, all situations return grouped measurements belonging to the same sensor and a pattern in terms of the location of the measurements. For example, figure 14 shows the results of the subject walking around fast. Visually, it seems that the measurements are turned a quarter clockwise with regards to the location of the corresponding sensor. Although the results of the other tests show a pattern as well, it is not always the same one. This means that the measurements do not always seem to be turned a quarter clockwise but, for example, sometimes it seems like the measurements are turned half way clockwise.

This makes it difficult to predict the location of the measurements. In order to localize, there must be a differentiation between the measurements inside the zone of a sensor and outside its zone.

The results of test B1 and B2 are combined. Table 4 gives an overview of the measurements done with the antenna power of every sensor set on 30 dBm. It shows per sensor the percentage of all measurements done inside and outside its corresponding zone. Then of the three values below that percentage are the percentages that refer to the proximity. This table only shows the percentages.

	percentage of measurements while subject located inside zone (%)			**Percentage of measurements while subject located outside zone (%)**		
Proximity (%)	Immediate	Near	Far	Immediate	Near	Far
Sensor 301 (yellow)	25.35			74.65		
Percentage	0	61.11	38.89	0	66.04	33.96
Sensor 332 (red)	5.56			94.44		
Percentage	0	0	100	0	41.18	58.82
Sensor 334 (blue)	35.62			64.38		
Percentage	0	0	100	0	29.79	70.21
Sensor328 (purple)	26.67			73.33		
Percentage	0	0	100	18.18	27.27	54.55
Average	23.30			76.70		
Average proximity	0	15.28	84.72	4.54	41.07	54.39

Table 4. Percentages regarding zones and proximity with the antenna power set to 30 dBm.

The table shows that, on average, 23 percent of the measurements, done by any sensor with an antenna power of 30 dBm, are done when the subject is inside its corresponding zone (zones are depicted in figure 5), 77 percent are outside the zone. This is not necessarily unexpected as the reach of the sensor might be larger than the borders of its virtual zone and also comprises the remaining three zones where the subject spends 75 percent of the time. It is unexpected however, for the measurements done inside the zone, a proximity of 'immediate' is never returned and only in 15 percent of the cases a proximity of 'near' is returned. Sensors assign to almost 85 percent of the measurements, done inside their own zone, a proximity of 'far'. Of the measurements done while the subject is located outside the zone, only 54 percent is assigned a proximity of 'far'.

The proximity detection doesn't seem to be consistent.

From the Itellifi's guide the next is written on the proximity:
"*Proximity indicates the relative distance to the smart spot in terms of, immediate – very close, near – close, far – not so close. Note: next to the distance, these values may vary depending on sensitivity of tags and the signal quality*" (Quick start guide Intellifi).

reader power (dBm)	5	10	15	20	22	24	26	28	30
max. distance (m)	0,7	1,2	2,2	3,8	4,8	6,1	7,7	9,7	12,2

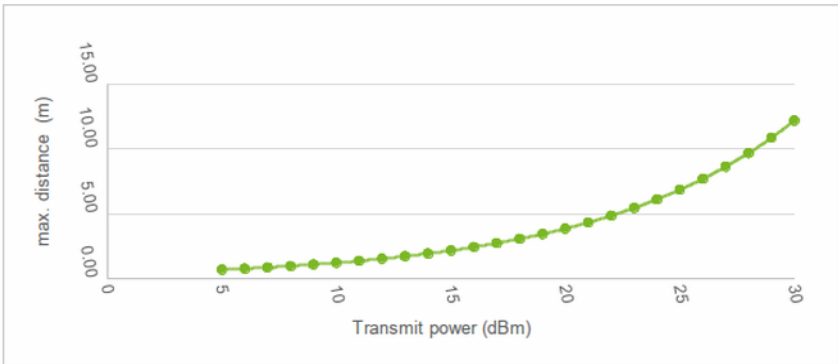


Figure 15. Source: http://brain.intellifi.nl/config/111. Relation maximum reading distance and transmitting power of the antenna. Configuration of any sensor.

The proximity is thus relative and not absolute. Two assumptions are drawn from the information of Intellifi.

- First: tags cannot be seen by the sensor outside the maximum distance determined by the antenna power.
- Second: the proximity is dependent and relative to the maximum distance.

With an antenna power of 30 dBm the maximum distance according to Intellifi is 12,2 meters (figure 15), which comprises all zones in the room and from the visualizations of the tests it is difficult to:

1. Determine where proximity levels go from one to another.
2. Moreover, overlapping reach of multiple sensors can lead to interference which can lead to tags appearing and disappearing, possibly several times (Dobkin, 2012).

<u>For the latter two reasons, the test is redone with an antenna power of 20 dBm.</u> An antenna power of 20 would have a maximum distance from the sensor of 3.8 meters, which would result in a radius of 3.6 meters for each zone assuming the sensors are placed at 2.5 meters and the tags are worn at 1.4 meters of height. This would minimize the areas overlapping and is in the order of magnitude according to the dimensions of the zones and room. It is expected that most measurements done by a sensor are located inside its corresponding zone. The measurements that are located outside its zone are expected to have a proximity of 'far' since the distance from the sensor is then approaching the maximum distance. Table 5 below shows the same information as table 4 but then for the measurements done with an antenna power set to 20 dBm.

	percentage of measurements while subject located inside zone (%)				Percentage of measurements while subject located outside zone (%)		
Proximity (%)	Immediate	Near	Far		Immediate	Near	Far
Sensor301(yellow)	27.27				72.73		
Percentage	0	66.67	33.33		0	67.5	32.5
Sensor332 (red)	1.41				98.59		
Percentage	0	0	100		5.71	45.71	48.58
Sensor334 (blue)	14.39				85.61		
Percentage	0	70	30		0	52.94	47.06
Sensor328 (purple)	74.19				25.81		
Percentage	0	47.83	52.17		0	62.5	37.5
Avarage	29.32				70.68		
Average Proximity	0	46.12	53.88		1.43	57.16	41.41

Table 5. Percentages regarding zones and proximity with the antenna power set to 20 dBm.

Against all expectations, table 5 shows that of all measurements done by a sensor with antenna power of 20 dBm, 29 percent is done when the subject is located inside the corresponding zone. More than 70 percent of the measurements are done when the subject is located outside the sensors zone. Moreover, of the measurements done outside the zone, more than half is assigned a proximity of 'immediate' or 'near' and 41 percent is assigned a proximity of 'far'. An opposite trend emerges for the measurements done inside the zone of a sensor, more than half has a proximity of 'far'. Testing with an antenna power of 20 dBm did not improve the results. The proximity indication does not seem to be consistent also in this case.

Looking at all separate tests, there is one more point standing out. In one third of the cases, the sensor does not measure anything at all in its corresponding zone. In a single experiment, one of the sensors did not 'see' the subject at all.

Experiment part C

The results of experiment part C are discussed in this section. The overall goal of this test is to see how the change of environment changes the results fount in experiment part B. The following results are discussed

- In test C1 multiple subjects are statically grouped.
- In test C2 the subjects move around the room.

In Experiment part C, a total of 10 subjects participate at the same time. Each subject is provided with 3 tags attached again on the shoulders and chest. Over seven small tests have been conducted, three of those where stationary tests. The subject did not walk during those tests. Four tests are not static, in different situations the subject moved from different locations to other zones.

Test C1: Stationary

Multiple small tests are done where the subjects are standing statically in groups underneath the sensors. Visualizing a combination of those tests is depicted in figure 16.

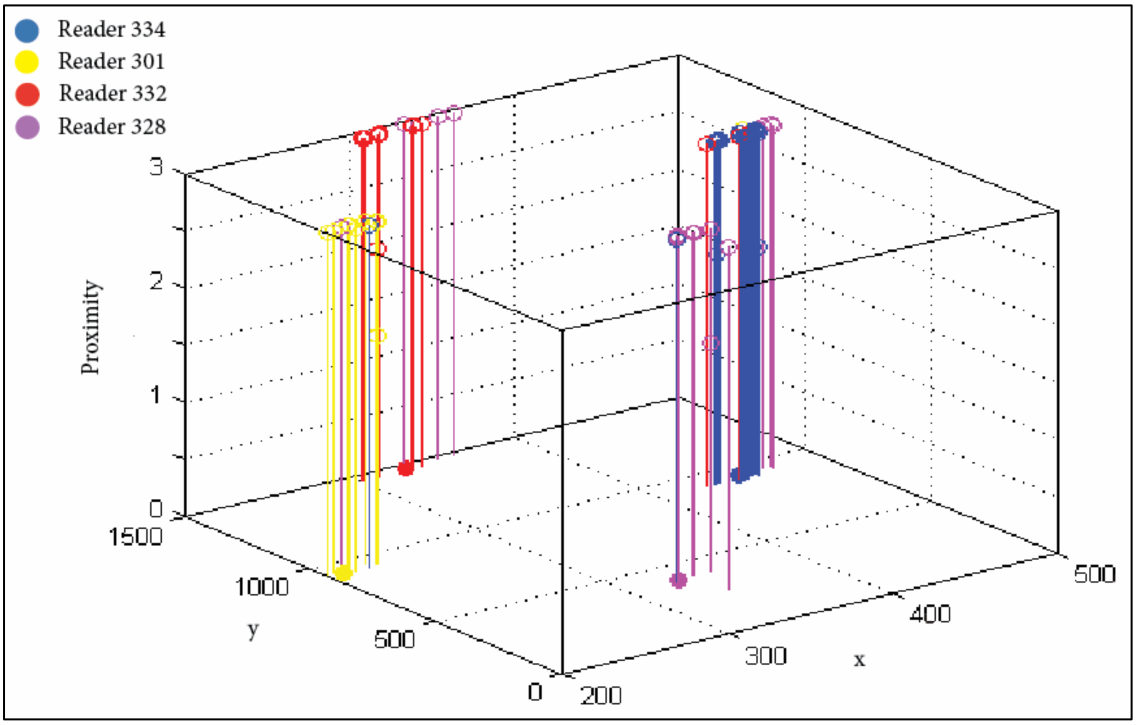


Figure 16. Visualization static tests. Axis: x and y are dimensions room in cm, Proximity axis represent three levels: 1 = immediate, 2 = near and 3 = far.

Clearly visible is that in a static situation the majority of measurements are done by the sensor closest to the subjects. The table below shows a confusion matrix of the measurements done in every zone belonging to the corresponding sensor.

		Actually being measured in zone of			
Detected as being in the zone of sensor	301	328	334	332	Total
301 (yellow)	43	0	2	0	45
328 (purple)	3	28	12	5	48
334 (blue)	1	1	343	0	345
332 (red)	0	0	4	207	211
Total	47	29	361	212	649

Table 6. Confusion matrix static test

The confusion matrix of the stationary tests is shown in table 6. The greater part of the measurements is done in the corresponding zone, over 95 percent of which is correct. The percentages of the measurements inside and outside a zone and their distribution of proximities are shown in table 7. Outside the zone the proximity is always ‘far’. Of the measurements done inside the zone, in almost 5 percent of the cases the proximity is ‘near’. None are ‘immediate’ and over 95 percent has assigned the proximity ‘far’.

Therefore, it is in most cases not possible to make a distinction in actual distances based on the measured proximity.

	percentage of measurements while subject located inside zone (%)				Percentage of measurements while subject located outside zone (%)		
Proximity (%)							
Sensor301 (yellow)	95.56				4.44		
Percentage	0	4.65	95.35		0	0	100
Sensor328 (purple)	58.33				41.67		
Percentage	0	7.14	92.86		0	0	100
Sensor334 (blue)	99.42				0.58		
Percentage	0	5.54	94.46		0	0	100
Sensor332 (red)	98.10				1.90		
Percentage	0	0.488	99.52		0	0	100
Average	87.85				12.15		
Average Proximity	0	4.45	95.55		0	0	100

Table 7. Table with the percentages of the measurements in and outside the zone and proximity for the static tests.

Test C2: Movement

Notable from the visualization in figure 17 is that when the subject walks from one side to the opposite side of the room it seems that the sensor keeps seeing the person as far as the other side of the room, even though, half way, other sensors are clearly closer to the subject. These sensors however, do not seem to see the subject at all.

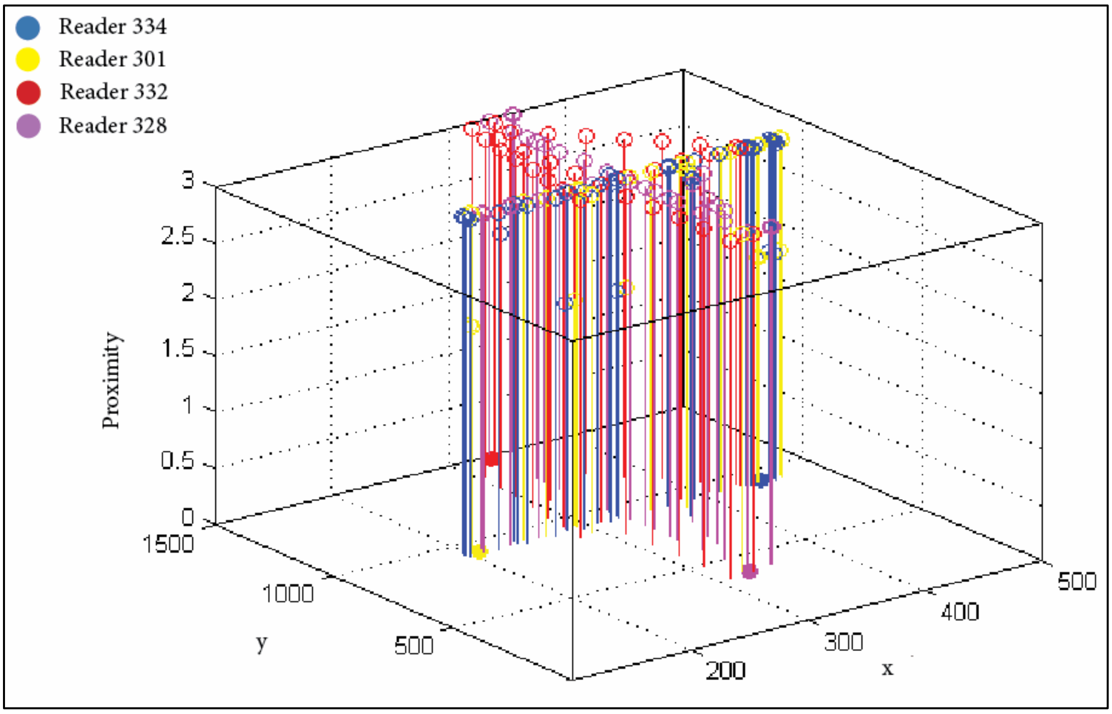


Figure 17. Visualization tests while subjects are moving. Axis: x and y are dimensions room in cm, Proximity axis represent three levels: 1 = immediate, 2 = near and 3 = far.

		Actually being measured in zone of			
Detected as being in the zone of sensor	**301**	**328**	**334**	**332**	**Total**
301 (yellow)	21	1	34	0	56
328 (purple)	13	29	5	21	68
334 (blue)	55	0	91	2	148
332 (red)	0	11	10	23	44
Total	89	41	140	46	316

Table 8. Confusion matrix of the test done while subjects are moving.

The confusion matrix of the tests done while the subjects were moving is shown in table 8. Close to 52 percent of all measurements are correctly done in the corresponding zone. Table 9 provides further insight on the distribution of the proximity. Notable is that the average proximity values both inside and outside the corresponding zone of a sensor are very similar. The proximity 'far' is assigned in almost 92 percent of the cases inside the zone and a 92.5 percent of the cases outside the zone. In both cases the rest of the measurements are assigned a proximity of 'near'. Therefore it is not only impossible to say in what zone a user is but there also seems to be no consistency in the proximity and actual distance of the measurements.

	percentage of measurements while subject located inside zone (%)				Percentage of measurements while subject located outside zone (%)		
Proximity %	**Immediate**	**Near**	**Far**		**Immediate**	**Near**	**Far**
Sensor301 (yellow)	37.5				62.5		
Percentage	0	28.57	71.43		0	22.86	77.14
Sensor328 (purple)	42.65				57.35		
Percentage	0	0	100		0	0	100
Sensor334 (blue)	61.49				38.51		
Percentage	0	4.4	95.60		0	7.02	92.98
Sensor332 (red)	72.73				27.27		
Percentage	0	0	100		0	0	100
Avarage	53.59				46.41		
Average Proximity	0	8.24	91.76		0	7.47	92.53

Table 9. Table with the percentages of the measurements in and outside the zone and proximity for the test done while subjects are moving.

BLE

The results of the tests done with Bluetooth Low Energy are presented in this section. In total three tests are done to determine if the BLE technology is suitable to use for localization (A, B and C):

- Experiment part A includes only the testing of StickNfind hardware and is to explore some of the basic functioning of the technique.

- In Experiment part B, StickNfind tags are used to determine if there is a relation between distance and signal strength.
- Finally, in Experiment part C, the correlation between signal strength and distance is determined for the brand Estimote.

Experiment part A

The results of experiment part A of BLE tests are presented in this section. Experiment part A has taken place in Amsterdam, the Netherlands, at the office of Standard Beacon Network. These tests are done to get an idea of the basic functioning of BLE, it is not directly connected to localization.

- Test A1 is done to determine the influence of the human body on the functioning of the technique and the signal strength.
- Test A2 is done to see what the reading range of the BLE tags are.

Test A1: interference of humans

Water (bodies) prove(s) to be a strong interfering factor for radio waves (Clarke et al., 2006). This test is done by repeatedly placing a tag in an open and closed hand, then placing a person between a tag and sensor. Expected was that the signal strength strongly decreases as soon as a person is located between the tag and the sensor. The result shows that when a tag is placed in an open hand and then closed, on average, the RSSI decreases with 86 percent of the original (open hand) signal strength. However, since in practise, the tags are attached to the ceiling, a more realistic situation is a person standing between the tag and sensor. The influence of a human body directly between the tag and sensor leads to a decrease in RSSI of 6 percent with regards to the original signal strength when standing with the sensor towards a tag.

Test A2: reading distance

Test 2 is done to gain insight on the reading distance of the BLE technology. The tags are active and therefore expected to have a reading distance much larger than the few meters seen with passive tags. When tested the tags prove to be sensed at a distance of over 30 meters. In experiment part C this is further elaborated on when a correlation between distance and signal strength is determined.

Experiment part B

The results of the test of experiment part B are discussed below. The aim of the test is to determine if there is a correlation between distance and signal strength. The correlation itself is determined in experiment part C.

Tests B: Distance & signal strength

The test took place in Veenendaal, in the same room the UHF RFID is tested.

Against all expectations, the results show gaps in its measurements and there is no clear coherency between the distance travelled from the various tags and signal strength. A common problem with this brand of BLE is the fact that the active tags go in to sleep mode and need to be 'awakened' before broadcasting signals again. This is done to preserve battery power. Therefore the results of this test are probably inconsistent and therefore not trustworthy. A test examining the distance and signal strength is redone and the results are presented below.

Distance & signal strength retake

The test is redone at the office of Standard Beacon Network located in Amsterdam, The Netherlands. For this test two people are each given two active tags of the brand 'StickNfind' and where instructed to stay at a fixed location, five meters apart, and keep the tags 'awake' by tabbing them continuously. The subject with the sensor in hand walked up and down between the tags.

The results show a weak trend between distance and signal strength. The RSSI (in dBm) goes up toward 0 when the subject is close to one pair of tags and the RSSI of the other pair of tags simultaneously goes into the opposite direction (towards -100 dBm).

Experiment part C

In order to use the BLE tags for localization it is necessary to determine the relationship between distance and signal strength for this particular brand of tags and brand of smartphone. The results of test C are discussed below.

Test C: Correlation Distance signal strength Estimote

The objective of test C1 is to determine the correlation between distance and signal strength specific for the Estimote tags and the Motorola Moto G smartphone. The test is done by placing tags and the sensor apart with increasing distances. The statistical results of the test is presented in the table 10.

Distance (m)	1	2	3	4	5	6	8	10
Population size	49	67	83	46	44	40	5	67
Minimum (in dBm)	-82	-91	-96	-93	-105	-104	-98	-104
Maximum (in dBm)	-68	-67	-73	-81	-88	-93	-94	-91
Mean (μ)	-73.78	-79.76	-82.77	-86.67	-94.20	-97.87	-96.40	-97.43
Median (in dBm)	-73	-79	-82	-87	-93	-98	-96	-97
Mode (in dBm)	-72	-78	-82	-86	-92	-98	-98;-96	-96
Standard deviation (σ)	2.54	4.73	3.82	2.94	3.37	2.40	1.50	2.56
Inter Quartile Range	4	5	4	4.25	5	3	3	3

Table 10. Statistical values of measurements per distance from 1 to 10 meters.

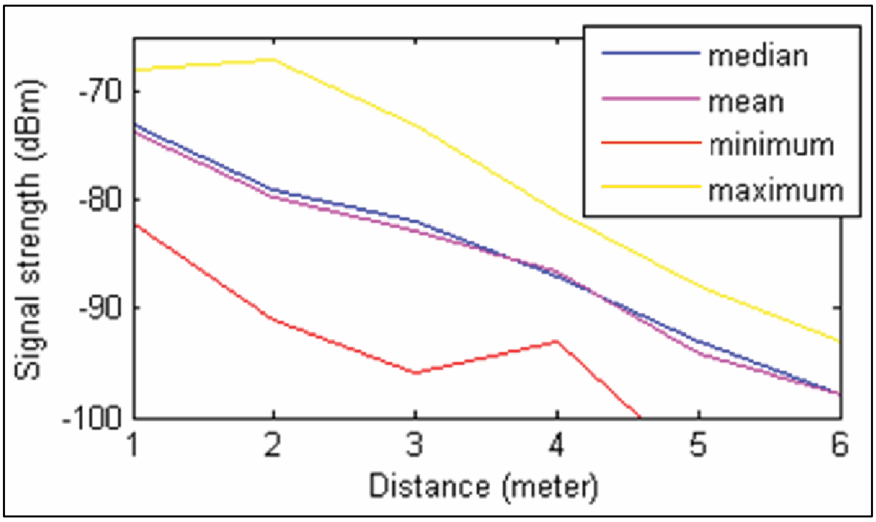


Figure 18. The median, mean, minimum value and maximum value with regards to distance of test 5.

Between 1 and 6 meters the median and distance seem to approach a linear relationship between distance and RSSI between 1 and 6 meters according to the tests (figure 18). The function can be approximated by the formula (III) below, representing the relation between distance *d* between tag *i* and the sensor and the RSSI *s* of tag *i*.

$$d_i = -5 * s_i - 68 \quad \text{(III)}$$

This is the case as long as the distances are between 1 and 6 meters. The dispersion seems quite large (figure 18) which gives the impression that multiple measurements are necessary to get the correct mean value. For each distance mean value is plotted against the sequence of measurements (figure 19). The plots show that in most cases the final mean value is already approached before or around 10 to 15 measurements.

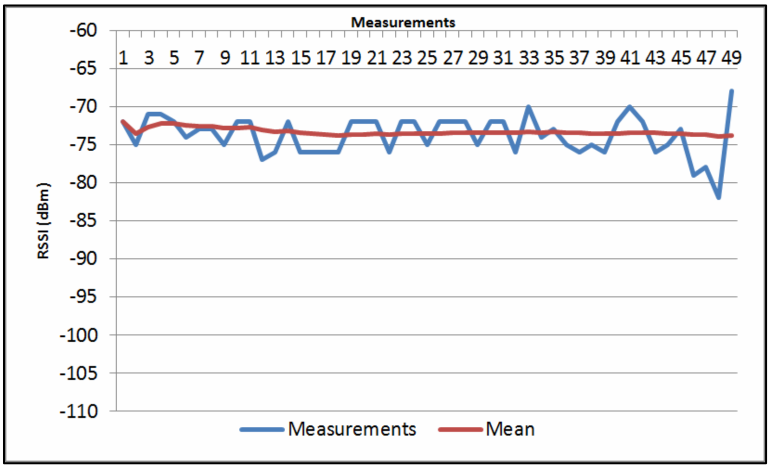


Figure 19 a. 1 meter distance

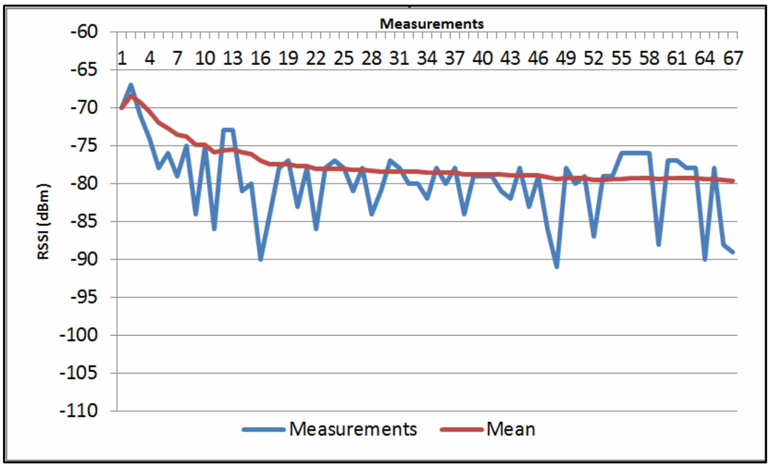


Figure 19 b. 2 meter distance

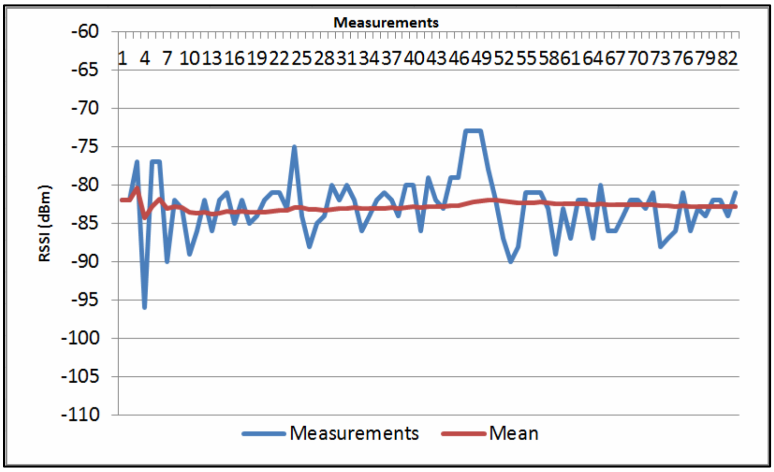


Figure 19 c. 3 meter distance

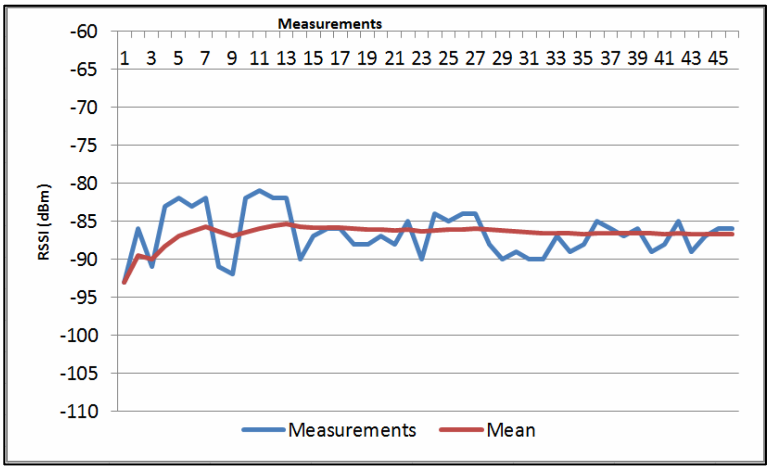


Figure 19 d. 4 meter distance

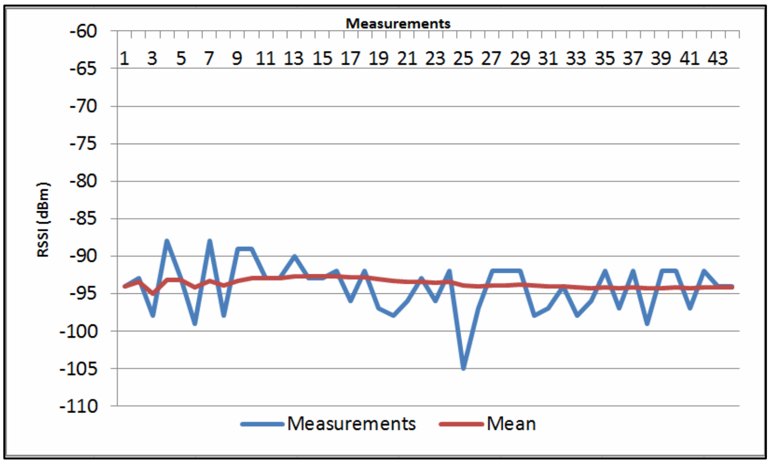


Figure 19 e. 5 meter distance

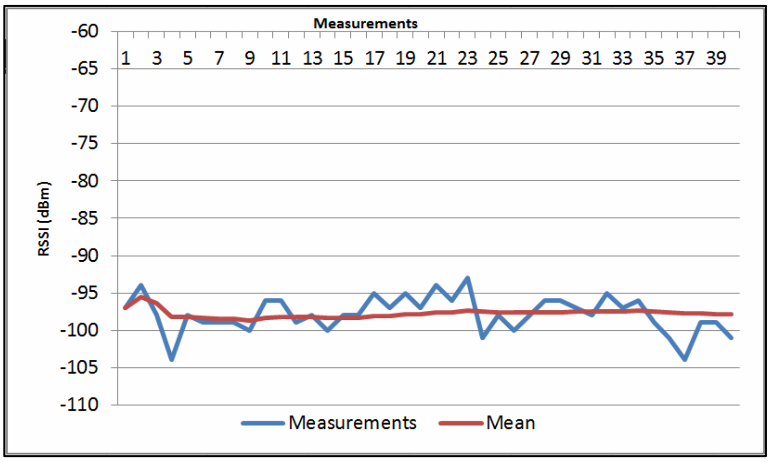


Figure 19 f. 6 meter distance

3.3 DISCUSSION AND CONCLUSION HARDWARE

The discussion and conclusions of each experiment part for both UHF RFID and BLE are presented in this section.

UHF RFID

Experimental part A

The most important result of experiment A is the fact that this technique is strongly influenced by water. In order to compensate for this, the tags should be carefully placed so that it is optimally orientated towards the sensor. Assuming the sensors are hung from the ceiling, this means that the tags can be placed on the shoulders and/or chest, preferably with the long edge of the tag towards the reader. This might be a solution for the testing of the hardware but one may discuss the practice usability of this. Asking visitors of (semi) public placed to wear a visitors badge is already common (think of visitors in a congress centre) and it would be easy to incorporate a UHF RFID tag inside the badge. However, it is unpractical to ask visitors of a (semi) public place to stick three tags on both of their shoulders and chest. Moreover, the maximum reading with could form a constraint. The maximum coverage of the sensor is at a distance of 3.5 meters. Assuming that the chest/shoulders of an average person is at a height of 1.5 meter, in order to accomplish a maximum coverage, the sensors should be mounted at a height of 1.5 + 3.5 = 5 meters.

Experimental part B

Overall, both test B1 and B2 show unexpected results. In many cases the tags are seen but it is difficult to say in what part of the room and with what proximity. There is an inconsistency in both the location of the measurements and the proximity assigned to them. This makes it, despite of the clear groups of measurements, difficult to predict where a subject is located according to merely the measurement returned by the sensor. Restriction of the antenna power did not solve this problem but instead showed similar results. The question remains: what causes these inconsistencies?

A possible explanation can be the following: all radio propagation techniques are subject to interferences when used indoors, for example multipath, rare line-of sight path, absorption, diffraction, and reflection (Rappaport, 2001). Although sensor's antenna power decreases quadratic with the distance travelled, in practice, a room with partially reflecting floor and walls lead to a complex propagation environment. Close to the sensor the antenna power falls monotonically. However at distances more than 1 meter the propagation environment becomes very complex, which is clearly depicted in figure 20 (Dobkin, 2012). The decreasing received power near the peak is fluent but after that varies widely.

According to Dobkin (2012) during propagation in the real world, the emitted waves interact with the environment, like obstacles. This can lead to fading. Fading is the phenomenon where a wide variety of signal strengths is received with a small change in frequency or position.

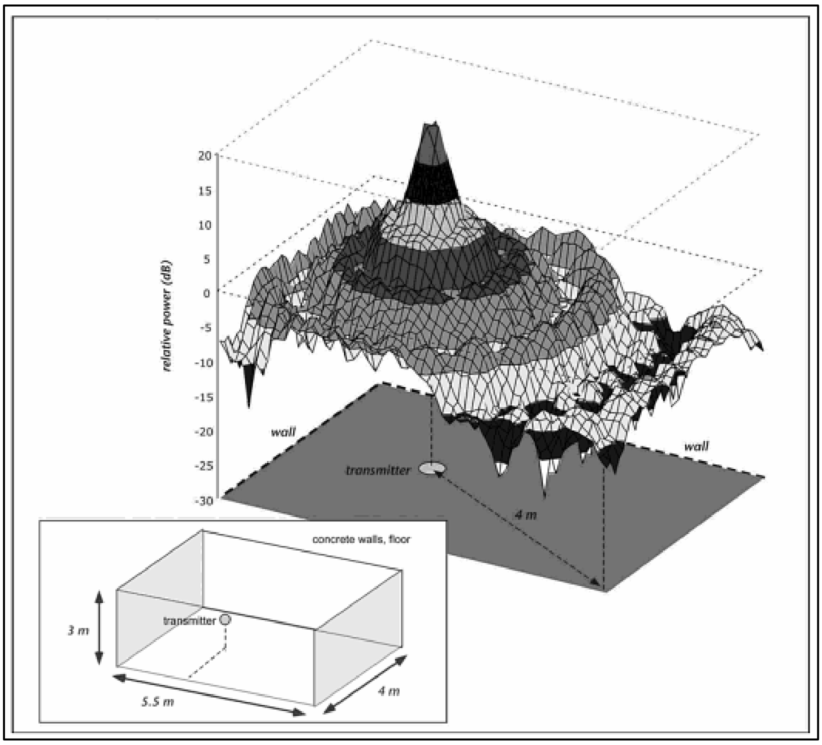


Figure 20. Dobkin, 2012 p. 27. Simple model of the received power density in a room with partially reflecting walls and floor.

This is caused by the interaction between direct waves and scattered of reflected waves which is depicted in figure 21.

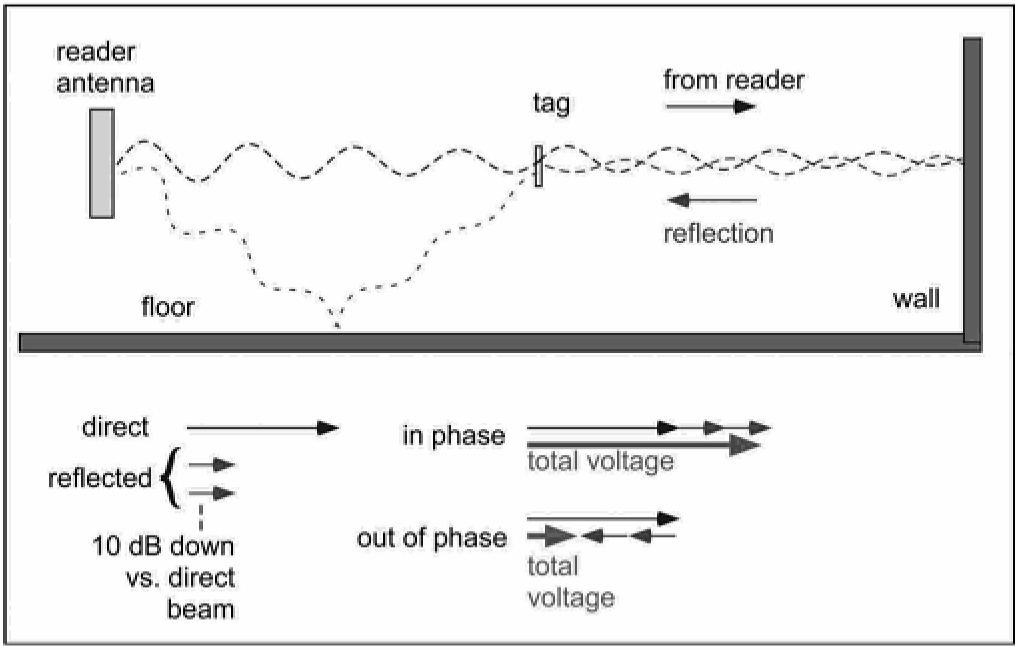


Figure 21. Dobkin, 2012. P.94. Interference of direct and reflected beams.

The phases of the waves are important factors: if a reflected beam travels a quarter of a wavelength more than the direct beam it leads to a 90 degree phase shift. If the reflected and the direct beam are in phase with each other, it increases the returned power of the tag antenna. However, when the beams are exactly out of phase, the power is strongly diminished, even if the reflecting beam has only a fraction of the power of the direct beam (figure 21)(Dobkin, 2012). For this reason it is sometimes necessary to move tags and rotate objects in order for the tags to be read.

The complex propagation environment in Veenendaal could be the reason for the inconsistencies found in the tests above. The variety of signal strengths can be caused by the reflecting walls and floors in combination with the obstacles in the room and the overlapping reach of the multiple sensors leading to interaction between the waves. This variety of signal strengths can be the reason for the inconsistent proximity and readings found in the tests. In general it leads to an unpredictable and variable propagation environment. Experiment part C is therefore done to see if a different environment with less reflecting objects improves the results.

Experimental part C

From the results in experimental part C it becomes clear that for stationary situations the UHF RFID works well. However, once the subjects move it is hard to discover distinguishing patterns in the measurements that would aid localization. Although the environment did change the general characteristics of the measurements, for example, half of all measurements of any sensor are done inside its corresponding zone in Almere (experiment part B) against only around 30 percent in Veenendaal (Experiment part C), it is not (yet) predictable and stable enough to use for indoor localization. In order to have a functional application the technique should also be scalable. This means it ideally should be stable functioning in various environments. This is not the case. The influences of environmental factors and objects on the signal strength makes it even more complex to extract a trustworthy proximity from the measurements and is therefore not possible to use this to improve localization.

Altogether, UHF RFID does not meet the requirements and is not considered fit for this research. Although the technique often measures the presence of the tags, the indication of distance assigned to the records is not consequent. The UHF RFID sensors can possibly be used for many applications, including indoor enhancements. It is very well capable of noting the presence of tags in general. Although the potential of this technique is huge, it is not considered suited for this application. <u>This technique has proven not to be consistent enough in order to locate humans in an open space in different environments.</u>

BLE

Potentially, BLE could solve some of the problems described before when using UHF RFID. One of the difficulties with UHF RIFID is that every subject needs to wear three tags due to the strong influence the body has on the signal power. Since the sensor for BLE is embedded into a smartphone, it is decided that the tags can be placed in a predefined place in the room and the subject walks around with the sensor in hand instead of the other way around (figure 8). The smartphone in hand gives it a more free position from the body rather than a tag against the body. The reversed setup also takes away the ambiguity of UHF RFID: it is not necessary for a visitor to walk with a smartphone in hand to access an application and with tags on the body. The data is directly gathered by the smartphone and can be used in the application. Moreover, it is not necessary for the organization of a networking event to purchase expensive hardware (sensors) and distribute tags to their visitors. Another advantage of BLE in comparison to UHF RFID is that the measurements return signal strength in absolute values which gives it a degree of consistency to work with in an algorithm. Last but not least, BLE has a built in multi-hop mechanism which decreases the problem of fading. Hopping between frequencies so that the wavelengths vary is an effective way to diminish the interference due to fading. Problems with fading occur when there is a phase difference between multiple beams. By hopping between frequencies, the maximum phase difference is minimized because the difference between beams with varying wavelengths cannot reach the exact opposite of 180 degree (Dobkin, 2012).

Experimental part A
Interferences of the human body is in this case leads to a decrease of RSSI of 6%. Although it is not much, practically, it could have an influence on the localization precision since a lower RSSI is associated with more distance between the sensor and tag.

Experimental part B
A positive result is the fact that BLE seems to be able to give an indication of distance through its RSSI. However, due to the 'sleeping mode' of the StickNfind hardware it is impossible to use these tags in practise. This brand does not meet the basic requirement that it can be measured at all times. This initiated the option of purchasing BLE tags from a different brand to use for localization which does not go into sleep mode. The brand 'Estimote' was purchased and tested. There is a relationship between the measured RSSI and distance which gives impetus to determine this relationship done in experimental part C.

Experimental part C
Between 1 and 6 meters there is a linear correlation between signal strength and distance. From 6 meters up there is no clear distinction in signal strength and distance. The minimum and maximum values measured can be quite far apart from the mean. Due to this dispersion, 10 to 15 measurements are necessary to get a trustworthy mean and distance estimation. The latter should be taken into account when designing a localization algorithm. Multiple measurements per tag are necessary to get a trustworthy distant estimation, moreover, this influences the time it takes the system to obtain enough information to produce a location. The two basic capabilities in order to design an localization algorithm where the following:

1. Detect the tag when within the range and
2. Assign a corresponding indication of a distance.

<u>In general, BLE meets the basic requirements to be used for localization; it reads the tags within range and gives an indication of distance through its RSSI measurements. Therefore BLE is considered a suitable technique for this research.</u>

4 SOFTWARE

The localization method is the software side of the localization. Taking the characteristics of the BLE hardware in to account, various methods (algorithms) for indoor localization are proposed. In this chapter first the methodology is discussed, this includes 1. looking at existing indoor localization methods using radio propagation techniques, 2. the theoretical background and method of computation of the localization algorithms. The method of testing these algorithms is also explained. Second the results of these tests are discussed and finally the discussion and conclusions are aggregately presented.

4.1 METHODOLOGY LOCALIZATION METHOD: SOFTWARE

The localization method is the software side of the localization. Taking the characteristics of the hardware in to account, a method (algorithm) for localization is explained and proposed in this chapter. The localization algorithm returns a position of a person as an identification of both a coarse localization granularity (a virtual area) and on a sub zone localization granularity (figure 22). Therefore, the space is both discrete (virtual area) and continuous (sub zone level).

Sub question 3 is answered in this section.

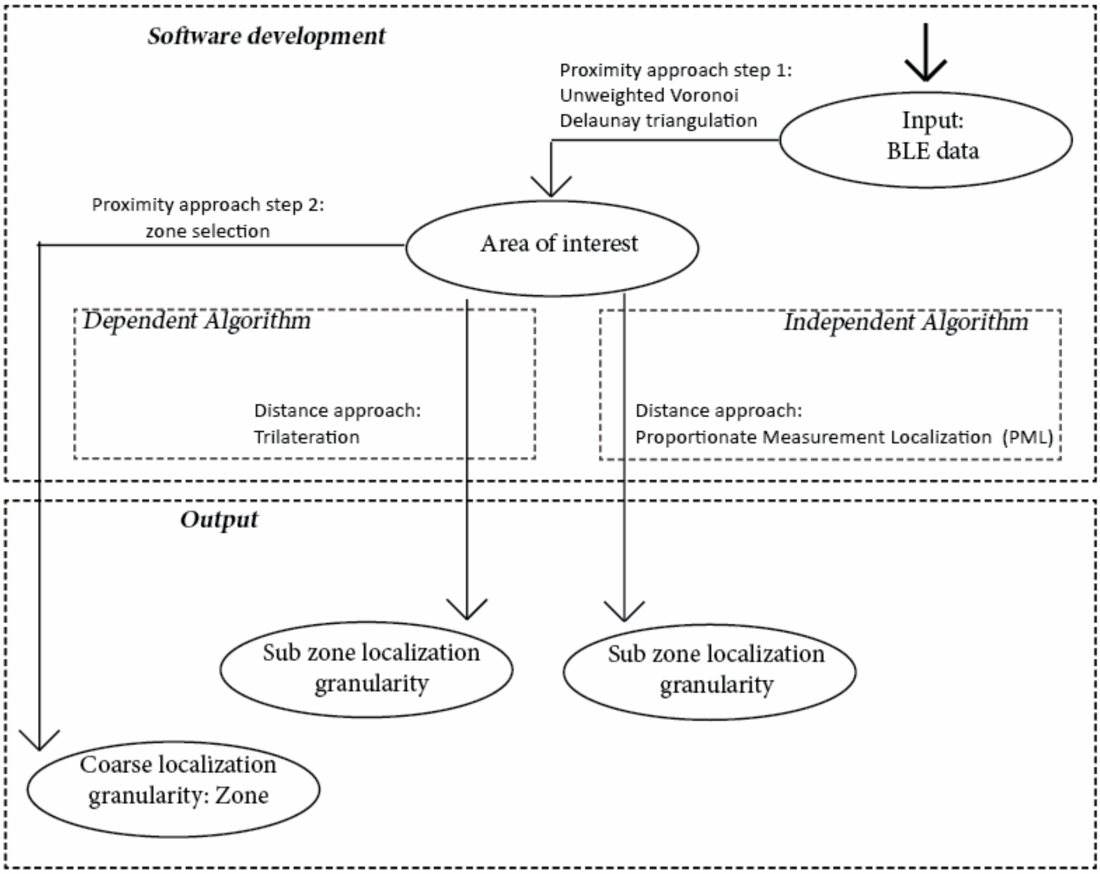


Figure 22. General overview methodology software.

What is the most suitable indoor localization method for an LBS applied in (semi) public places?

a) What are the existing indoor localization methods?
b) Considering the technical capabilities of the technique (and requirements of the said LBS), what is a suitable method for indoor localization?
c) Considering both the technique and localization method, what is the most suitable system setup for indoor localization?

In this section:

- First the previously developed indoor localization methods are discussed.
- Secondly the theory behind the localization algorithms are explained and
- Finally these algorithms are tested.

DEVELOPED INDOOR LOCALIZATION METHODS

The technology of Bluetooth low energy is developed in 2010 and researched for all kinds of applications. Think of applications in healthcare, wellness and sports; where classic Bluetooth has already been used (Chang et al., 2012)(Nakamura et al., 2011) and BLE can introduce improvements (Patel and Wang, 2010). For example; by using BLE as "activity monitors and heart rate sensors to be used to monitor a user's health and fitness levels" (Helge Omre, 2010). BLE could also be used as a remote control for devices in home like for smart energy or home security (Gomez et al., 2012). BLE could also play a key role in mobile payment, ticketing or other contactless applications (Gomez et al., 2012). BLE is also appropriate to use in industrial environments where interference due to multipath fading and radio interference from machinery is common (Tinka et al., 2010). As mentioned before, BLE has a multi-hop mechanism which provides a solution for the latter problems (Gomez et al., 2012).

<u>Despite the research and applications of BLE, there is little prior research on indoor localization with the help of this technique.</u>

There are applications using BLE for the detection of objects, for example the StickNfind application. However, such applications do not localize the object but returns a signal strength to determine how close an object is to the user of the application. In 2013 Portnoi and Chung Shen described a system where people in an office where able to make use of a simple login depending on their location. Bluetooth LE beacons where placed to exchange encrypted messages when the person of interest was in range. This combines providing a service with location awareness. However, the research mainly focuses on the exchange of the encrypted messages rather than localization and thus provides little information on the functioning of the BLE when used for localization.

Localization methods for indoor radio propagation usually make use of distant estimation, scene analysis or proximity (Bouet, 2008). Unlike for Bluetooth low energy, there are numerous researches on these localization methods using RFID, which will be discussed in this section in order to get an idea of existing indoor localization methods using this radio propagation technique.

1. Distant estimation is done by applying range measurement techniques such as trilateration or triangulation so the object can be localized.
2. Scene analysis is usually composed from two separate steps. In the first step, environmental information is collected, which is called fingerprinting. In the second step, online measurements are compared with the previously acquired information.
3. The last method is proximity. This is when antennas are densely placed and it is assumed that when an object enters the range of an antenna the object is near the receiver (Bouet, 2008).

In some cases described below, tags are used for two different purposes. Sometimes tags are placed in predefined, known places. These are called reference tags. Other tags are used as tracking tags. The whereabouts of these tags are unknown and the objective is to determine their location.

1. Distant estimation includes applying range measurement techniques. By determining the distance, the subject can be localized. The following are localization methods using RFID based on distant estimation as their main method for localization.

SpotON. This method is developed by Hightower et al., (2000). It is based on using long range active RFID tags to collect the signal strength. With the help of an empirically defined function, the distance is determined. Then trilateration is used to localize tags.

SAW ID . Bechteler and Yenigun presented the method for the first time in 2003. The ASW id-tags method makes use of passive tags. The Time Of Arrival of the signals between the tag and the antenna is measured. The distance between the receiver and tag can be determined and, with three distances, trilateration is applied.

LPM. LPM stands for Local Position Measurements and is developed by Stelzer et al., (2004). This method uses active tags and is based on the time differences of arrival. The system is setup using reference tags. Reference tags are tags placed at known, predefined and set locations. The tracking tags are the tags whose location is unknown and need to be determined. The LPM method localizes the tracking tags by first determining the time differences of the signals between the tracking tag and antenna. Then a weighted mean squares methodology is used for the estimation of the location of the tracking tags.

In 2007 Zhang et al., proposed a method which uses passive RFID tags. This method is based on the use of the Direction Of Arrival (DOA). Sensors are placed in set locations and the phase differences between the two are calculated as the tag is moving which indicates the direction. With several records available, the localization is done by applying a least-squares fitting technique.

2. Scene Analysis is a different approach towards indoor localization. Scene analysis is composed from two steps, fist the offline phase where environmental information is collected (fingerprinting). Second, the comparison between the online measurements and the previously acquired information. Examples of these types of methods are:

Landmarc. Ni et al., developed the system called Landmarc in 2003. It is based on the K-Nearest Neighbour algorithm technique. The method makes use of active reference tags, which are placed in fixed locations, and active tracking tags. Sensors employ eight different power levels. The relation between the reference and tracking tag is determined after which locations of the k nearest reference tags are used to localize the tracking tag.

VIRE (Zhao et al., 2007). This method is based on the Landmarc system. The difference is that the VIRE method includes proximity maps. Each reference tag corresponds to its own region. Every reader has its own proximity map. If the differences between the RSSI measurement of the tracking tag and the RSSI measurements of the region are not far apart (so that is does not exceed a certain threshold) they are assigned '1'. This leads to a proximity map of each sensor containing a grid with '1' and '0'. Combining the proximity of the maps of each sensor provides an overall proximity map which indicates the location of the tracking tag.

Simplex. In 2007 Wang et al., published a paper on indoor localization with RFID called Simplex. It uses reference tags and sensors with multiple transmission power levels. The sensors gradually emit each power level after each other until the tracking tag responds. In the meantime, the sensor also receives responses of the reference tags. The distance between the sensor and tracking tag is estimated by averaging the distance of the reference tags and sensor in the same power level as the tracking tag responded. Finally the error function is minimized to get an optimal result.

Kalman filtering. The Kalman filtering approach is described by Bekkali et al., in 2007. In this method the distance between a reference tag and tracing tag is calculated with the help of signal strength measurements of two separate sensors. The location of the reference tag is then calculated by solving non-linear equations using the minimum mean squared error. Then a probabilistic map of the error measurements is created. This is done for each reference tag. Then the Kalman filter is used to reduce the error of the measurement and improve accuracy of the localization. The Kalman filter is a particle filter often applied on tracking algorithms and not necessarily for direct localization. This is because it bases its location estimation on difference between previous measurements and current measurements. One may assume that when standing still these differences are minimal while when moving the differences can be used for applying a particle filter.

Scout. The Scout method (Huang et al., 2006) is a probabilistic localization technique. The method makes use of active tags. These tags are localized by three steps. First: propagation parameters are determined using reference tags. Second: the distance between the tracking tag and sensor is determined using a probabilistic RSS model. And third: the location of the tracking tag is calculated by applying Bayesian inference.

3. Proximity approach can also be used to accomplish Indoor localization. The main assumption is that when an object enters the range of an antenna the object is near the receiver. Examples of such an approach are:

3D constraints. This method is developed by Bouet and Pujolle in 2008. It is based only on connectivity data. Basis is the assumption that if the sensor detects a tag, that implies that the distance between the sensor and tag is within the reading range of the sensor. There are exclusive constraints for multiple points in the space. The point that corresponds to the maximum of constraints is the estimated location of the tag.

Gossipy. Gossipy was described by Eslim et al., in 2013. It takes into account proximity information on the tags in each interrogation area. Localization is based on sharing the proximity information under a time constraints of the multiple sensors, either by pushing methods (giving the information) or pulling methods (requesting the information).

In 2014, Montaser and Moselhi described a proximity approached way of localization of both materials and workers for a case study. Localization is done by placing a set of passive reference tags in pre known locations and calculating the average RSSI for each reference tag and then converts the average RSSI into a weight. The materials are also equipped with RFID tags to which is referred as tracking tags. The employers carry mobile RFID sensors which sense the reference tags and tracking tags. The signal strengths of the reference tags and the tracking tags (on the materials) are determined. Based on a comparison of both signal strengths, the algorithm returns a location.

Reviewing the localization methods discussed in the section above, both the distant estimation and scene analysis methods assume a continuous space. The proximity approach is an easy and scalable method based on a discrete space. Combining the proximity approach with a distant estimation could provide the possibility of accomplish firstly zone level localization and finally bringing the localization to a sub zone level.

LOCALIZATION ALGORITHM DESIGN

The designs of two localization algorithms, using Bluetooth low energy are described in this section. First: a dependent algorithm and second: an independent algorithm called PML.

- The dependent algorithm makes use of the earlier defined correlation between the distance and signal strength. This correlation is defined for the Estimote tag and Motorola smartphone (sensor).
- PML is a method of localization done without any pre-knowledge of the sensor. For that reason, PML can be applied with any BLE sensor in hand.

The final result of both localization algorithms is to return a region where the subject is localized. To accomplish this, the proximity approach is combined with the distance approach. The proximity approach includes that beacons are densely placed, in this case attached to the ceiling. The main assumption of the proximity approach is that when the subject enters the range of the beacon, the subject is near the receiver (Bouet, 2008). Then a distance approach is applied. The approach is different for the each algorithm.

Both algorithms follow the same Proximity approach but differ in their distance approach and are presented as follows:

1. Proximity approach:
    a) Area of interest
    b) Zone determination

2. Distance approach:
    a) Dependent algorithm: trilateration
    b) Independent algorithm: Proportionate Measurement Localization (PML)

The following general assumptions are done:

Assumption 1. People hold their mobile phone on a height of 115.

Assumption 2: Above 6 meters distance no longer reliable. Therefore, when standing exactly in de middle between two tags, the distance of the sensor to the tag should have a maximum of 6 meters. The distance between tags is therefore dependent on the height of the ceiling, since the tags are mounted to the ceiling and the sensor moves below the tags.

Assumption 3: The Inter Quartile Range varies between 3 and 5 according to the results of experiment part C of the BLE hardware under section 3.2. The Inter Quartile Range is a measurement of dispersion, it is the difference between the first and third quartile. 50% of the measurements are between these quartiles with the median as the center of the sorted measurements. It is assumed that every measurement done could have ranged with 4 dBm.

Assumption 4: The closer a subject is to a tag, the higher the (mean) RSSI measurements of that tag.

Proximity approach

The proximity approach is an approach where the main assumption is that when a tag is in range of a sensor it means the tag is close to the sensor. In this research, this approach is used in two phases:

- First, the area of interest is determined. Considering a large indoor space, the space is divided into areas. The area of interest is one of these areas where the subject is located according to the proximity approach.
- Second, zone selection takes place. Each tag has a corresponding zone. Zone selection is done by defining the overlap by combining the area and the zone.

Area of interest

The goal of this step is to 'zoom' to the area where the person is most likely to be located. This is especially efficient and reduces redundancy in cases where the localization area is large, which is assumed the case in (semi) public places, with many tags in place in order to cover the entire area. In such cases it is helpful to first identify the area where the subject is located and only apply the distance approach to this area.

Let us consider a space X, with a set of tags (points) P. For example as depicted in figure 23.

A subject with a sensor is located at any given point x in space X collecting measurements of the RSSI s of a set P of tags p_i.

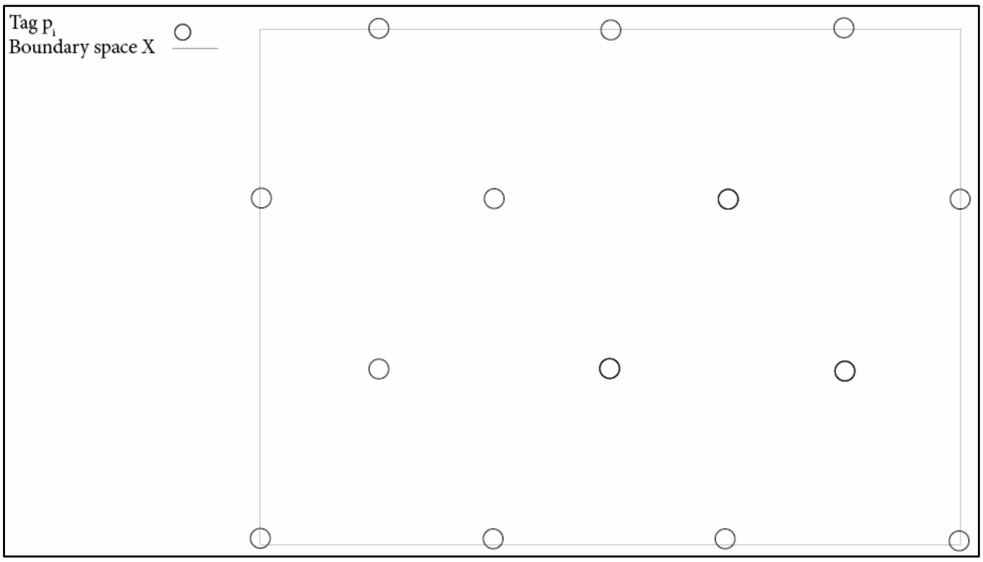


Figure 23. Exemplary case: a room with 14 tags.

The mean RSSI S for each point p_i is defined by dividing the sum of all incoming RSSI measurements s by the total amount of incoming measurements n (formula IV).

$$S_i = \frac{1}{n}\sum_{t=1}^{n} s_t \qquad \text{(IV)}$$

The space can be divided into areas using a Delaunay triangulation as depicted in figure 24. Each triangle is considered an area.

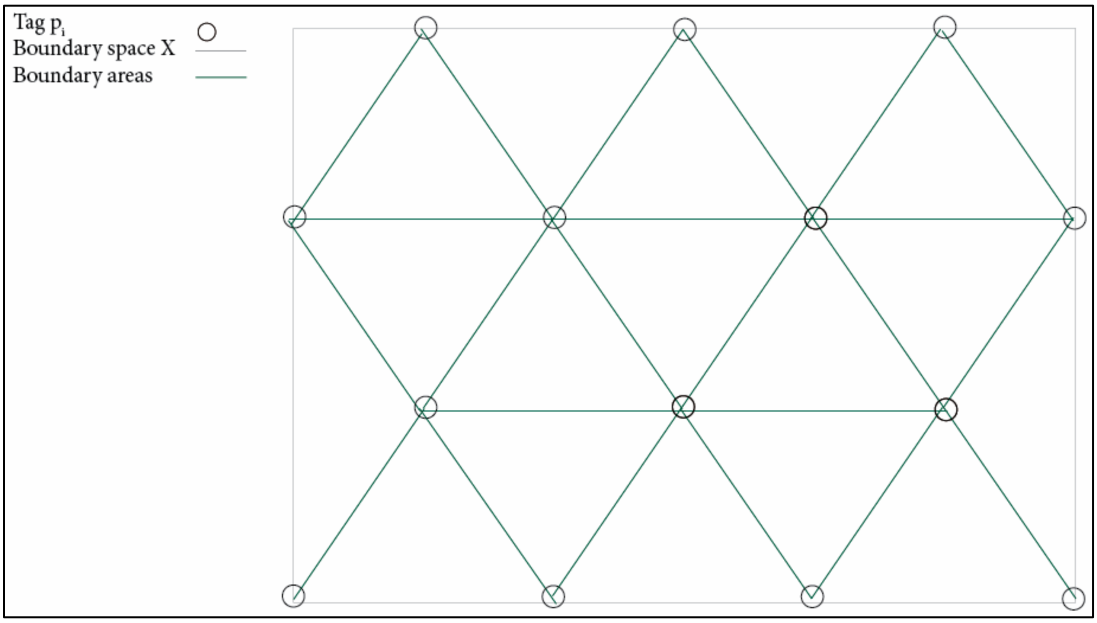


Figure 24. Delaunay triangulation determining the area of interest.

Typically, each area is defined by three tags. It is assumed that the closer a subject is to a tag, the higher the RSSI measurements of that tag. In order to select the area the subject is located at, the three tags with the highest mean RSSI S are determined.

$$\{p_m, p_n, p_o\} \subseteq P \text{ for which}$$
$$\forall\{S(p_m), S(p_n), S(p_o) \geq S(p_i) | i \neq m, n, o\}$$

It is assumed that the subject is located between those three tags forming a triangle. This area is referred to as delta Δ. An example of a selected area is depicted in figure 25 assuming the in yellow highlighted tags to have the highest mean RSSI.

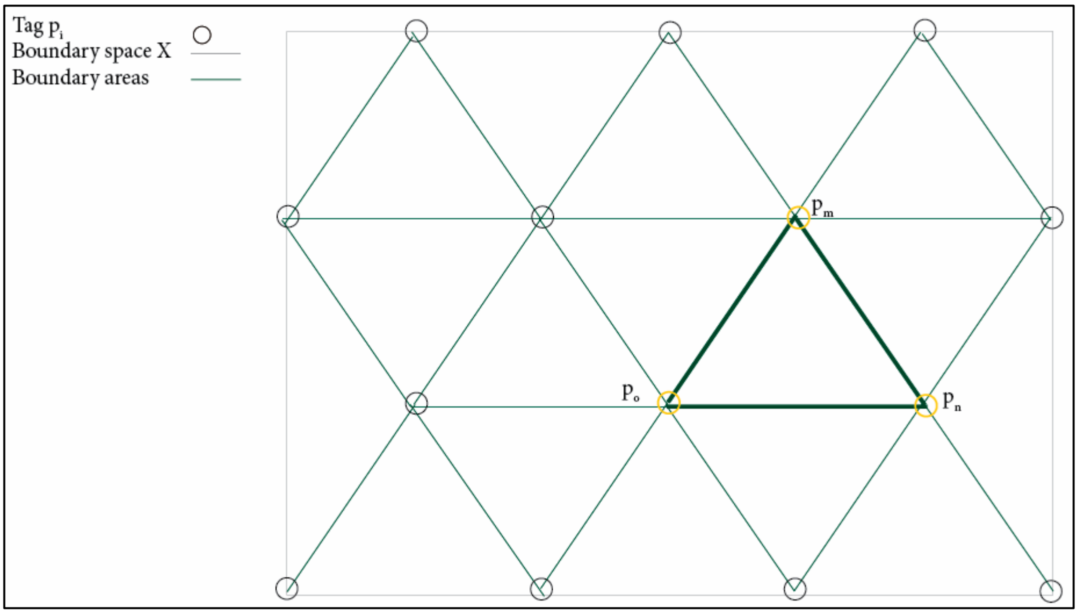


Figure 25. Area defined by p_o, p_m and p_n.

The area of interest Δ is used in the next steps for two separate goals:

1. It determines the area where distant approach is applied.
2. It plays a role in zone selection. Zone selection is explained in the next section.

<u>Zone selection</u>

This step produces an output: it selects a zone where the subject is likely to be located. This is a coarse localization granularity which can be useful and functional for many applications. In cases commercial parties (of (semi) public places) are not interested in a fine localization granularity but knowing what the approximate location of a subject is can be enough. Think, for example, of a hospital. Maybe it is useful to know what room a patient or a doctor is located at, but knowing if the patient or doctor is in the left of right corner of the room is unnecessary.

Each tag p, has a corresponding cell C. These cells are created according to a Voronoi diagram. The Voronoi diagram consists of cells on a plane according to a set of points. Each cell corresponds to one point. The cell contains the space closer to its point than to any other point in the set. Where there is more than one single closest point, a boundary is determined (Dobrin, 2005).

The Delaunay triangulation, as discussed above, is the dual of the Voronoi diagram, both are depicted below in figure 26.

The BLE tags are hung from the ceiling so that the subject is never further away than 6 meters from the closest three tags. This can create a regular spatial pattern of points and thus a regular Voronoi diagram in the shape of a honeycomb as in the figures. But it is also possible to hang them anywhere between 1 to 6 meters distance from the subject which gives the opportunity to implement this in rooms and buildings with irregular or complex shapes. The Voronoi diagram delimits the cells, corresponding to every tag.

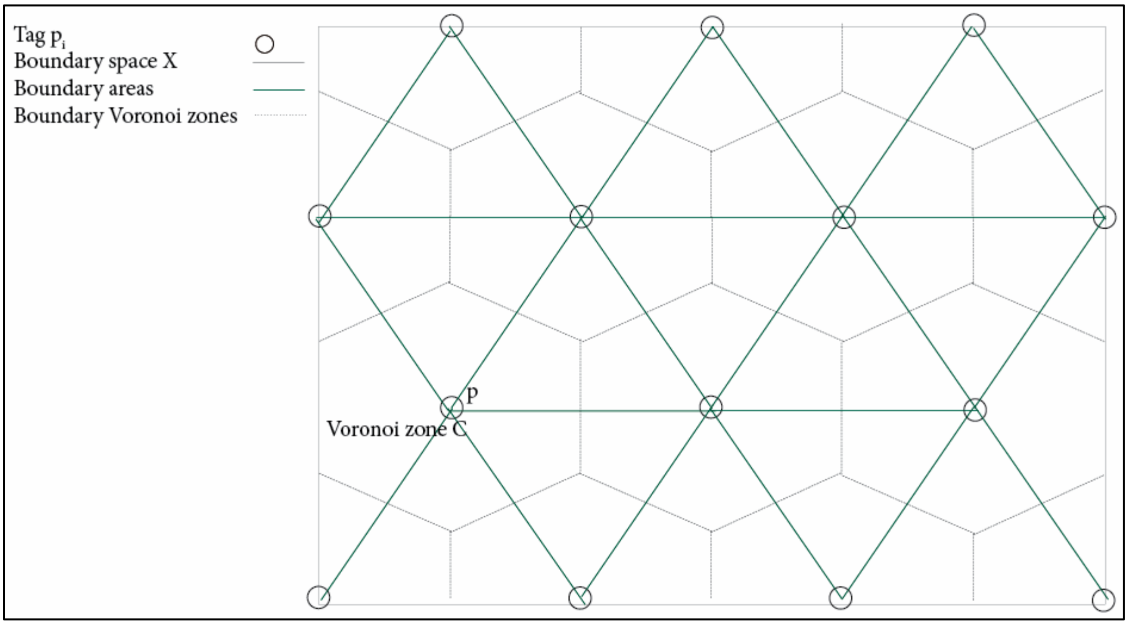


Fig 26. Voronoi diagram and its dual Delaunay triangulation.

Considering Space X, with a set P of tags (points) p_i. The Voronoi cell C of each p_i is determined by the distance d between any given location *x* to the location of p_i being smaller than the distance *d* to any other tag p_j.

$$C_i = \{x \in X | d(x, p_i) \leq d(x, p_j)) \text{ for all } j \neq i\}$$

In the former step the area of interest Δ is selected by determining the three tags with the highest mean RSSI *S*. The cell *C* is selected by determining the one tag with the highest mean RSSI *S*. This is one of the tags p_m p_n p_o that are part of the area of interest.

This leaves both knowing the area of interest Δ_i and the cell C_i. Where both the interior of the area Δ_i and the interior of the Voronoi cell C_i meet, two overlapping polygonal geometries, is the zone that is selected.

The zone selection is where

$$C_i \bigcap \Delta_i$$

For example, the subject with sensor is closest to tag p_o, the zone is depicted in figure 27.

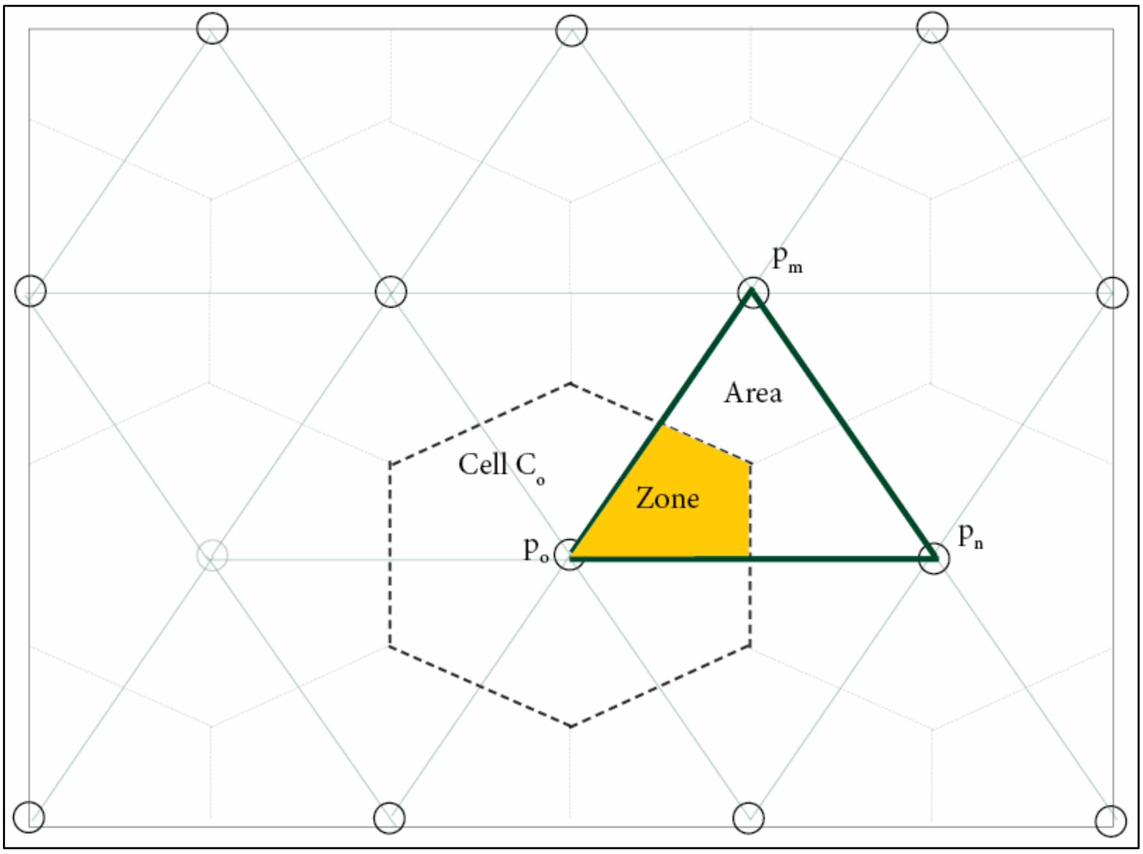


Figure 27. Zone determination for area p_m, p_n and p_o when p_o has the maximum mean RSSI S.

The zone is predefined, dependent on the overlap between the Voronoi cell of a tag and the area of interest. However, possibly, a commercial party could combine zones to create virtual places that are connected to a real places. Think of localizing in terms of places in your shopping mall, is someone in the coffee corner or in the restaurant? Zones can be merged in order to create such places by combining this localization with geo-fencing.

Distance approach

The distance approach uses range measurements to estimate distance in order to localize. In this research two different algorithms are proposed that differ in the distance approach used to localize a subject. The following sections are discussed.

- Dependent algorithm. The dependent algorithm uses the empirically defined function between distance and RSSI and uses the basics of trilateration in order to localize.
- Independent algorithm (PML). PML assumes only the linear approached correlation between the distance and signal strength to be consistent. This enables the use of this algorithm with different sensors (smartphones). The independent algorithm is referred

to as PML (Proportionate Measurement Localization) because this method makes use of the RSSI measurements of beacons in relation to each other.

In both subsections:

- First, the theory and mathematical support behind the dependent algorithm is presented
- Second, the general approach concerning the computation is discussed. There are many ways to compute the theory behind the algorithms. However, in order to understand the results of the tests the chosen approach is briefly explained. The source code can be found in the appendix, section 8.2.

Dependent algorithm

The dependent algorithm makes use of the empirically defined function between the RSSI s measured by the sensor and the distance d between a tag i on location p and sensor. The basic concept of trilateration is applied.

Theory and mathematical support

Trilateration is a localization method where the location estimation is based on the overlapping or intersecting parts of spheres or circles (figure 28). Assumed is that every circle and corresponding rang are known so that he intersections between the circles can be calculated (Awad et al., 2007). So the localization of a subject is done by determining the distance between the subject and three tags which are placed in predefined an known locations. These distances form spheres around the nodes and where the spheres intersect the subject is assumed to be located.

Let us consider the three tags p_n, p_m and p_o and an example where the subject is located on the yellow point (figure 28).

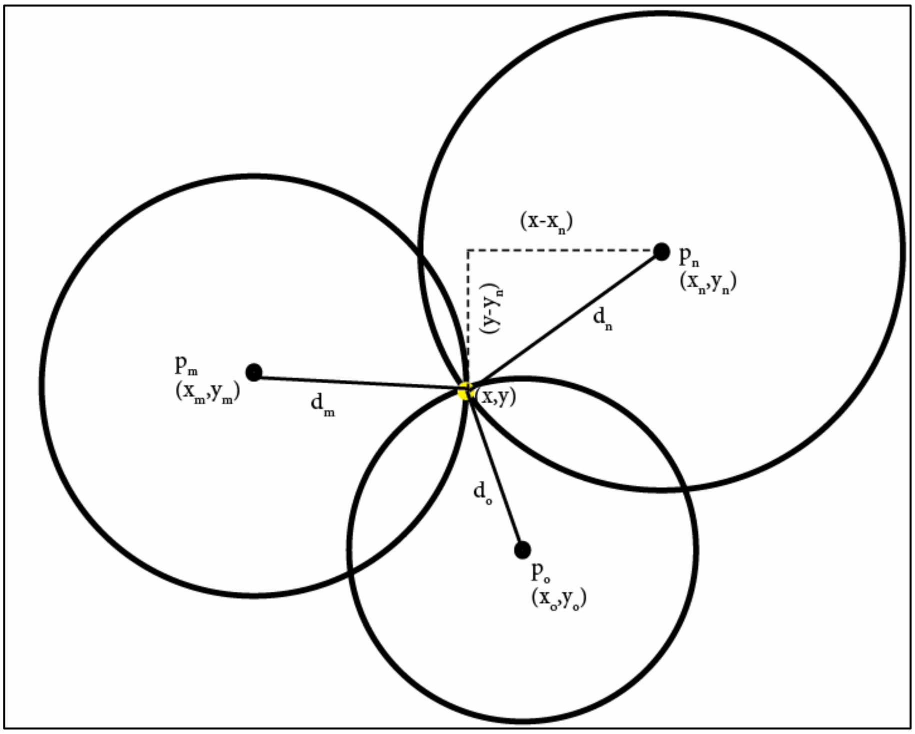


Figure 28. Concept of trilateration.

The location (x,y) of p_n, p_m and p_o are known. The distance d for each p can be determined by the previously determined correlation between RSSI and distance:

$$d_i = -5 * s_i - 68$$

The goal is to find (x,y) of the subject (yellow point). The following equations (V – VII) are determined by the theorem of Pythagoras. The unknown are x and y of the yellow point.

$$d_m^2 = (x - x_m)^2 + (y - y_m)^2 \qquad \text{(V)}$$

$$d_n^2 = (x - x_n)^2 + (y - y_n)^2 \qquad \text{(VI)}$$

$$d_o^2 = (x - x_o)^2 + (y - y_o)^2 \qquad \text{(VII)}$$

Rewriting these equations results in:

$$d_m^2 = x^2 - 2x * x_m + x_m^2 + y^2 - 2y * y_m + y_m^2 \qquad \text{(VIII)}$$

$$d_n^2 = x^2 - 2x * x_n + x_n^2 + y^2 - 2y * y_n + y_n^2 \qquad \text{(IX)}$$

$$d_o^2 = x^2 - 2x * x_o + x_o^2 + y^2 - 2y * y_o + y_o^2 \qquad \text{(X)}$$

In order to get the intersection point of these three spheres the method of Dixon (2009) is followed. Both equations VIII and X are subtracted from equation IX and then rearranged.

Subtraction:

(XI)

$$d_n^2 - d_m^2 =$$

$$d_n^2 - d_m^2 = 2x(x_m - x_n) + x_n^2 - x_m^2 + 2y(y_m - y_n) + y_n^2 - y_m^2$$

(XII)

$$d_n^2 - d_o^2 =$$

$$d_n^2 - d_o^2 = 2x(x_o - x_n) + x_n^2 - x_o^2 + 2y(y_o - y_n) + y_n^2 - y_o^2$$

Rearrangement:

$$v_a = x(x_m - x_n) + y(y_m - y_n) \tag{XIII}$$

$$= (d_n^2 - d_m^2) - (x_n^2 - x_m^2) - (y_n^2 - y_m^2)$$

$$v_b = x(x_o - x_n) + y(y_o - y_n) \tag{XIV}$$

$$= (d_n^2 - d_o^2) - (x_n^2 - x_o^2) - (y_n^2 - y_o^2)$$

Rearranging these equations leaves the formulas (XV and XVI) to calculate the x and y position of the intersection point. First the y position is calculated, then using this value, the x position can be acquired.

$$y = \frac{v_b(xc - xb) - v_a(xa - xb)}{(ya - yb)(xc - xb) - (yc - yb)} \tag{XV}$$

$$x = \frac{v_a - y(yc - yb)}{(xc - xb)} \tag{XVI}$$

Approach of computation

The above theory is a perfect example where there is a single point where the spheres cross. In the practice of this research that is often not the case. In this research the distance d is determined by the empirically found function between distance and RSSI. The Inter Quartile Range (measurement of dispersion) is quite large. This means that the distances can vary with about half a meter which can lead to multiple intersection points, or no intersection points at all. For example, measurements done at the location L can range such that the distance belonging to the measured RSSI could be throughout the blue circle which represent the Inter Quartile Range (IQR) of the distance of the mean RSSI *S* belonging to measurements from location L. For example, three measurements could come in (represented in pink in figure 29) which have no intersections at all. Another possibility is that tree measurements come in (represented in green in figure 29) which have multiple intersections.

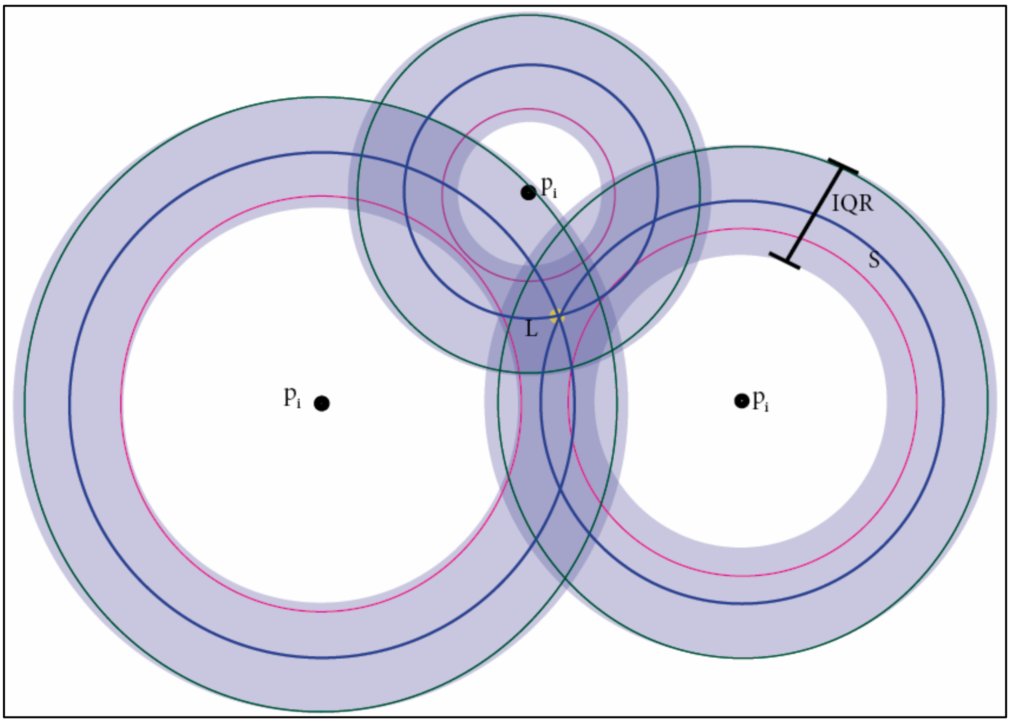


Figure 29. Example how measurements done at location L can vary within the Inter Quartile Range.

Moreover, the measurements of each of the three tags are not measured at the same time. Also, results from the testing of the BLE hardware (section 3.2) shows that 10 to 15 measurements are necessary in order to get a trustworthy mean. Therefore, when computing the dependent algorithm, a probability grid has been used. This entails that the area is represented in a grid and each grid cell is assigned values representing the probability that a subject is located at that location. All grid cells at the distance (and grid cells within deviation of the Inter Quartile Range) belonging to the RSSI of the measurement is assigned a higher probability creating a circle of high probably grid cells around every tag. Using this approach makes it unnecessary to calculate the intersection. This is repeated for each incoming measurement which normalizes and updates the probability of the area every time a measurement comes in. For example, if six measurements would come in (two measurement per tag) and the grid cells within the IQR of each measurement are assigned higher probabilities then the grid cells delimited by the red in figure 30 would have the highest probability. <u>In practice, many more measurements would be taken into account and thus gives a more differentiated result.</u>

The grid cells with the top 0,25 σ probability values are selected as a potential location of the sensor. This results in an subzone localization.

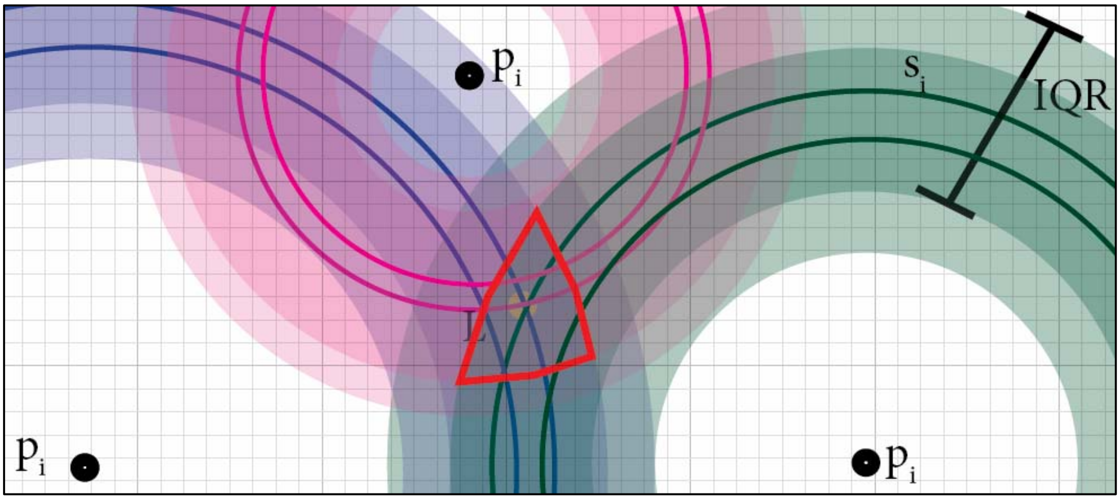


Figure 30. Example of six measurements and it's IQR with the red delimiting the area (grid cells) with the highest probability.

Independent algorithm: Proportionate Measurement Localization (PML)

The approach used for the dependent algorithm described above is not necessarily well adjusted to the practical goal it should serve because pre-knowledge of the sensor (smartphone) which is used to collect measurements is critical to its functioning. Assuming that (semi) public places can have visitors holding many different sensors, this pre-knowledge is in practice not available and time consuming to acquire and to keep updated. In order to design an algorithm which is independent of the type of sensor (smartphone) and thus get around the hardware specific knowledge, an independent algorithm (PML) is now proposed. Not being dependent on specific hardware requirements would add huge value and would make this localization practice usable for many different kind of smartphones and thus scalable.

The following additional assumption is done:

Assumption: although the sensor might be different, and therefore the absolute measurements, the linear correlation between the distance and signal strength is consistent. This means that in the function $d_i = -5*s_i - 68$ *the value -68 is no longer known. However, the slope of -5 is known and constant.*

Theory and mathematical support

As stated before the slope of -5 is assumed to be constant between 1 and 6 meters. This means that every meter the tag and sensor are removed from each other, the RSSI decreases with 5.

Let's consider an area delimited by p_m, p_n and p_o forming a equilateral triangle (all sides l are equal in length). The sensor is located at point L. The centroid is also depicted and the lines d to the centroid are all of equal length.

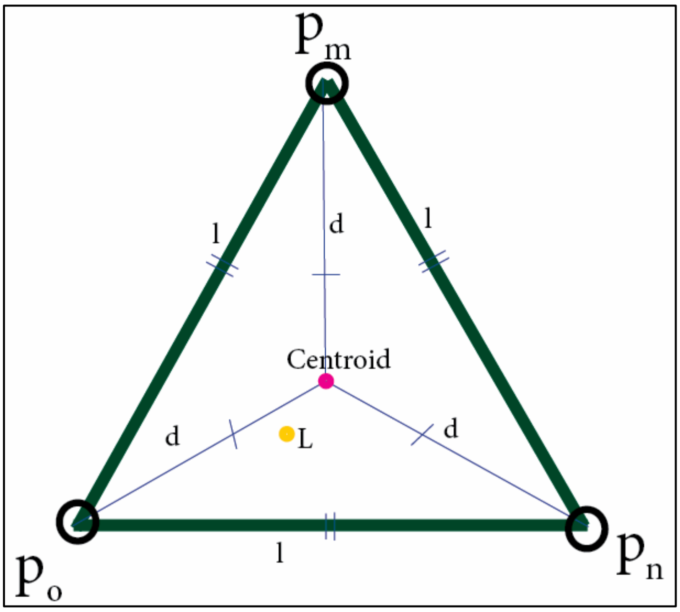


Figure 31. Exemplary case: area delimited by p_m, p_n and p_o and sensor located at point L.

The subject at location L collects measurements for each tag p. During the proximity approach the mean RSSI S is determined. The mean RSSI S for each point p_i is defined by dividing the sum of all incoming RSSI measurements s by the total amount of incoming measurements as stated in formula IV.

For example, the mean RSSI *S* of p_m, p_n and p_o is $S_m = -86$ $S_n = -84$ $S_o = -81$. In order to calculate the x,y position of location L the absolute distance between L and each tag needed. In this case these are the distances d_n, d_m and d_o between location L and each of the tags.

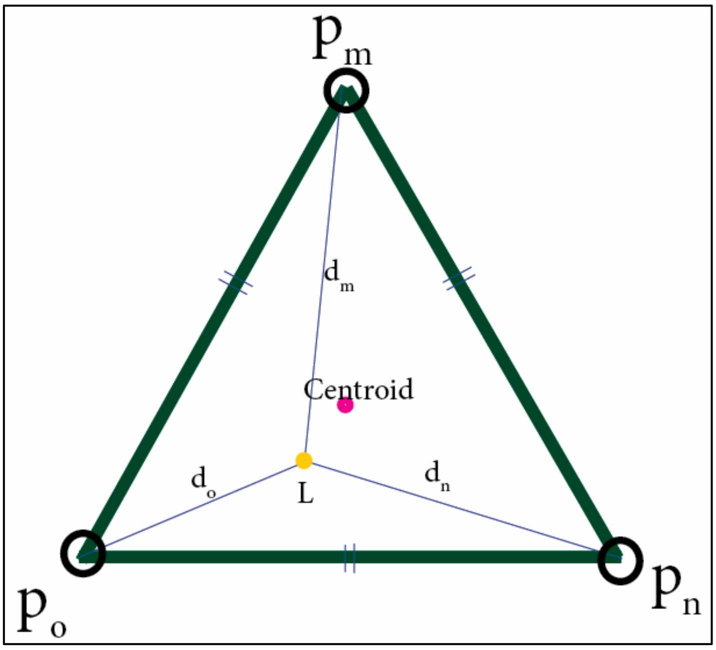


Figure 32. Exemplary case: area delimited by p_m, p_n and p_o and sensor located at point L. Distances d_o, d_n, d_m from sensor to each tag.

A step of 5 in mean RSSI S is assumed to be one meter (since the slope of the empirically found function between distance and RSSI is 5) and the differences between the mean RSSI can be converted to distance. For example, the differences/offset o for p_n and p_o is calculated as follows ;

$$o = \frac{|S_n - S_o| * 100}{5} \qquad \text{(XVII)}$$

Offset $o_{n,o}$ is 60 cm. This means that the subject in location L is located 60 cm closer to p_o than to p_n. So d_n is $o_{n,o}$ longer than d_o (figure 33). Distances d_n and d_m can be rewritten in terms of d_o.

$$d_n = d_o + o_{o,n} \qquad \text{(XVIII)}$$

$$d_m = d_o + o_{o,m} \qquad \text{(XIX)}$$

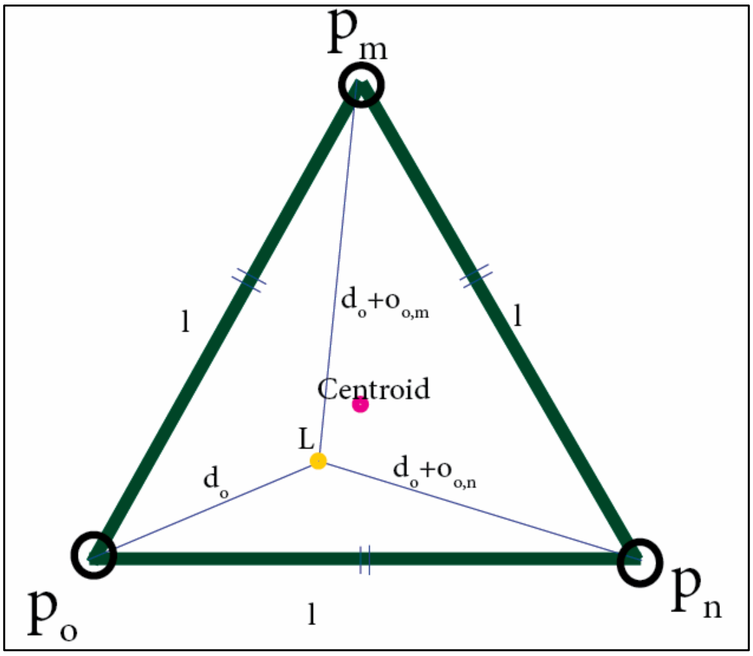


Figure 33. Distances d_o, d_n, d_m rewritten in terms of d_o.

Let us consider the triangle L, p_n, p_o. One way of calculation the location of L, x_L,y_L, is by first using the law of cosines to determine angle α (figure 34). Then determining w and h.

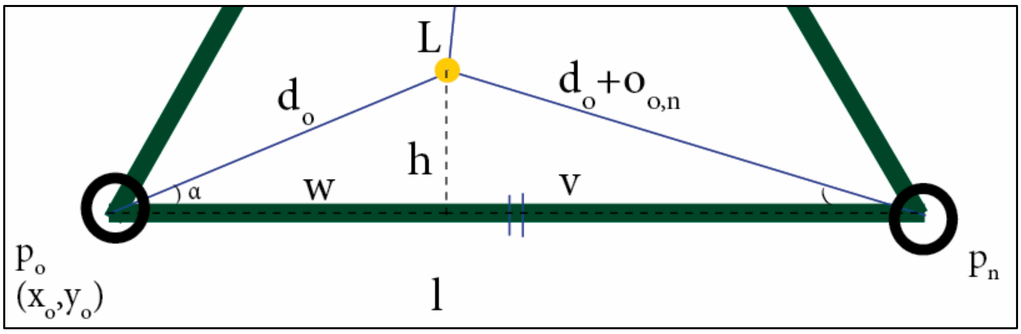


Figure 34. Triangle L, p_n, p_o and variables h, w, v, l, α, d_o and $o_{o,n}$.

The law of cosines states the correlation between an angle and the dimensions of the sides.

$$(d_o + o_{o,n})^2 = d_o^2 + l^2 - 2 * d_o * l * cos(\alpha) \qquad \text{(XX)}$$

This can be rewritten as formula XXI in order to obtain angle α.

$$\alpha = \cos^{-1}\left(\frac{l^2 - 2d_o o_{o,n}}{2ld_o}\right) \qquad \text{(XXI)}$$

Variables w and h can be determined as follows:

$$w = \cos(\alpha) * d_o \qquad \text{(XXII)}$$

$$h = \sin(\alpha) * d_o \qquad \text{(XXIII)}$$

Which can then be used to calculate the x (formula XXIV) and y (formula XXV) of location L.

$$x_L = x_o + w \qquad \text{(XXIV)}$$

$$y_L = y_o + h \qquad \text{(XXV)}$$

Side v could be calculated in a similar way. Both l and O are known, d_o , d_n ,d_m , w, h are unknown. Without any additional information (for example an angle), there are more unknowns than known variables. therefore the angle α and thus location of L cannot be calculated algebraically. In order to retrieve a location of point L, the issue is solved computationally by applying an iteration implicitly finding the d_o for which $w + v = l$

How this is done is explained in the next section.

Method of computation

Let us follow the exemplary situation illustrated above. The situation above can be translated to the following; the location L is determined by the distance d to each tag p and can be described by three circles. These circles have a radius of d and intersect at location L.

However, variable d is unknown. Location L is determined by first creating circles around each tag with a radius equal to 100 cm + the offset o. The additional 100 cm is needed so that the smallest d (offset = 0) has a 'baseline' radius of 100+0 = 100. In a practice setting, the sensor is held at 115 cm above the ground. A ceiling is at least 250 meter in height so even is the subject would be located directly underneath the tag, the distance between the tag and sensor would be 250-115 = 135 cm. Therefore the additional 100 cm has no influence on the localization. The circles are equally enlarged until all three circles overlap. The width of the circles is the Inter Quartile Range.

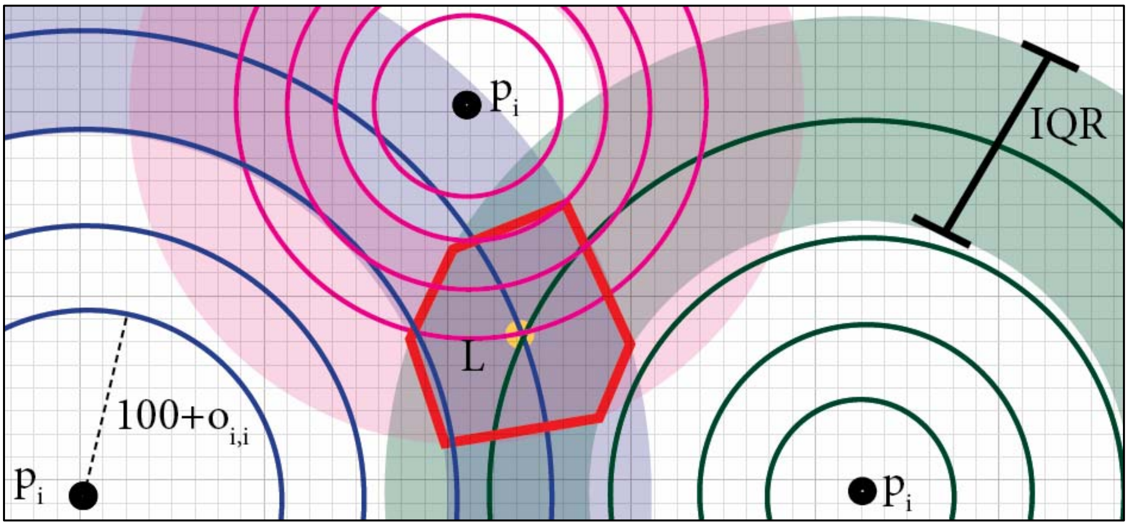


Figure 35. Example of enlarging the circles around three tags p until they overlap. The red delimited area is the computed location area returned by the algorithm.

Again, the area is represented in a grid. The circles are simultaneously enlarged until they overlap. The grid cells within the IQR of the measurement are assigned a probability, when the three circles overlap, the probability of these grid cells increase. All grid cells in the area where the circles overlap are highlighted. These grid cells are considered possible locations of the sensor.

A big difference with the dependent algorithm is that this one doesn't update per measurement but needs knowledge of all measurements at once to give an indication of location.

TESTING LOCALIZATION METHOD

Multiple tests are done in order to gain insight on the performance of the algorithms described above. Both localization algorithms are based on the assumption that there is a correlation between the RSSI and distance between 1 and 6 meters from a tag. This is based on the results of experiment part C of BLE under section 3.2. Moreover, the results show that the dispersion of measurements is quite large. In order to compensate for this dispersion, various methods have been incorporated into the localization algorithm; for example, the need to collect at least 15 measurements to get a trustworthy result and also taking into account an Inter Quartile Range. The dispersion can be caused by all kinds of influences of the real world, for example, fading but also humidity differences and temperature variations. If these environmental influences would not exist and the direct correlation between RSSI and distance would be flawless and without dispersion, the algorithms would certainly work perfectly since it is a mathematical fact. Obviously, the complexity of different environments in the real world is one of the challenges for indoor localization and makes the following question relevant:

How well do the algorithms estimate the location of the sensor in real world experiments?

Testing the dependent algorithm and PML is both done with the same data and at the same location.

All tests have taken place in Amsterdam, the Netherlands. The room is 5.50 wide, 4.20 meters deep and 2.50 meters in height. The following assumption is done: *the subject holds the mobile phone (sensor) in hand at a height of 115 cm which is a minimum of, (with the total height of the room being 250 cm) 250-115=135 cm from the tag.*

Three tags (one area) are fastened to the ceiling and Voronoi cells are created, since only three tags are present, these Voronoi cells are also the zones corresponding to each tag (figure 36).

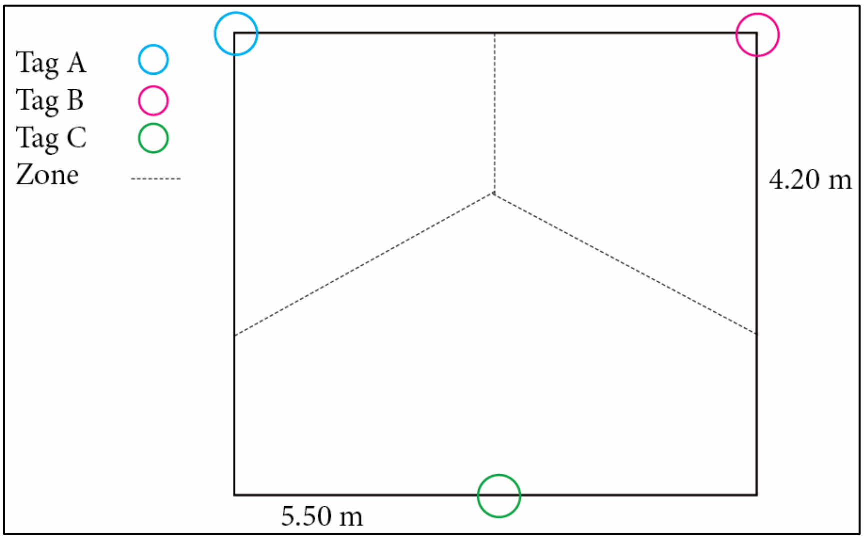


Figure 36. Test setup including placements tags and virtual boundaries according to a Voronoi diagram.

Both the dependent and independent algorithms (PML) are tested for the same cases and with the same data. The following cases are tested:

- **Test case 1**: In this test case, the subject holding the sensor is located at clearly distinctive distances of each tag.
- **Test case 2**: In test case number 2 the subject is located at the border of the zone belonging to tag C and tag A. There is no clear distinction between the distances from the sensor to tag A and from the sensor to tag C.
- **Test case 3 and 4**: Test cases 3 and 4 are looked at together because both cases represent two very comparable situations. It is interesting to see if the algorithms make a distinction between these cases.

In each case, the subject holds the sensor (Motorola Moto G) at different locations. For each stationary test, data is collected for around one minute. The locations of where the subject is located when collecting the data is depicted in figure 37.

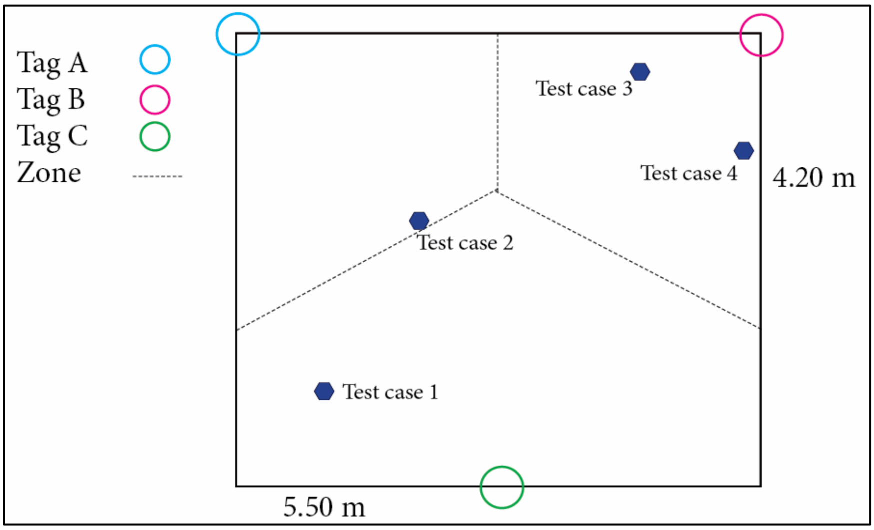


Figure 37. The locations of where the subject is located when collecting the data for each test case.

4.2 RESULTS SOFTWARE

The results of each test case is discussed in this section.

TEST CASE 1: CLEAR DIFFERENCE IN DISTANCE FROM EACH TAG

Test case 1 is done in a location where all three tags have a clear different distance to the subject holding the sensor (figure 38). Assuming this differentiation in distances is measured by returning corresponding RSSI by each tag, it means that all three tags are equally influencing the localization. It is expected that the algorithms work well and the localization is 'easy'. A more complex situation, for example, would be in a case where the sensor is located on the border of two zones: the tag belonging to the third zone determines where on the border the subject is located. The impact of the measurement of this third tag is large and the localization therefore considered more complex, in case 2 such a situation is tested. In this case however, both the algorithms use three unique variables to determine a location.

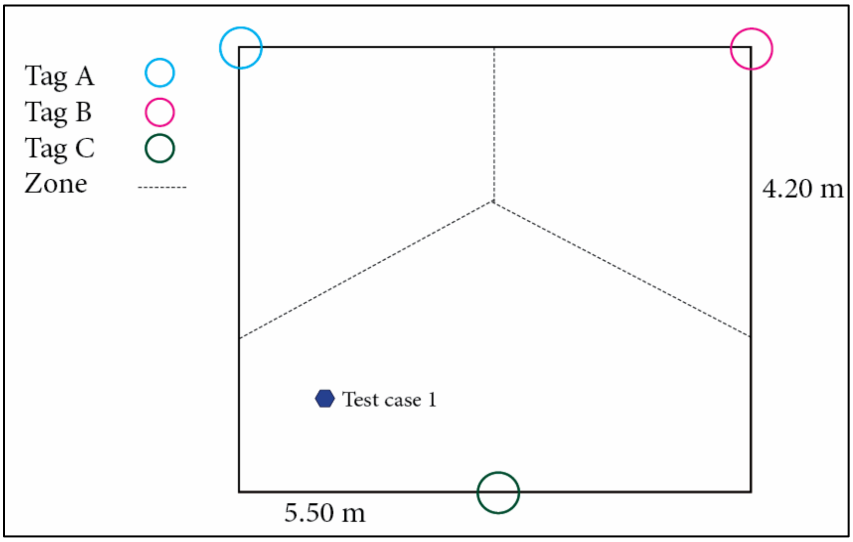


Figure 38. Test case 1, dark blue symbol is location of the subject with sensor in hand.

The first step for both algorithms is the coarse location granularity, based on zone selection. For both the independent and PML algorithms, the zone corresponding to tag C was correctly selected.

The results of test case 1 are presented in the following order:

1. First the results of the dependent algorithm are discussed.
2. Then this is repeated for the Independent algorithm (PML).

The results of the **dependent algorithm** localization on sub zone level are depicted in figure 39 a-d. Red indicates a high probability. The probability map both in 2D and 3D (figure 39a and 39b) show a clear areas of low (dark blue), medium (orange) and high (red) probability. The location area computed by the dependent algorithm is highlighted in bright blue in figure 39c and 39d. The red point is the centroid of the location area. The yellow point is the actual location of the subject during test case 1.

When comparing the location area to the actual location of the subject (figure 39d), the actual location falls just outside the location area generated by the algorithm. The distance between the centroid (red) and the actual location sensor (yellow) is 38 cm (figure 39d).

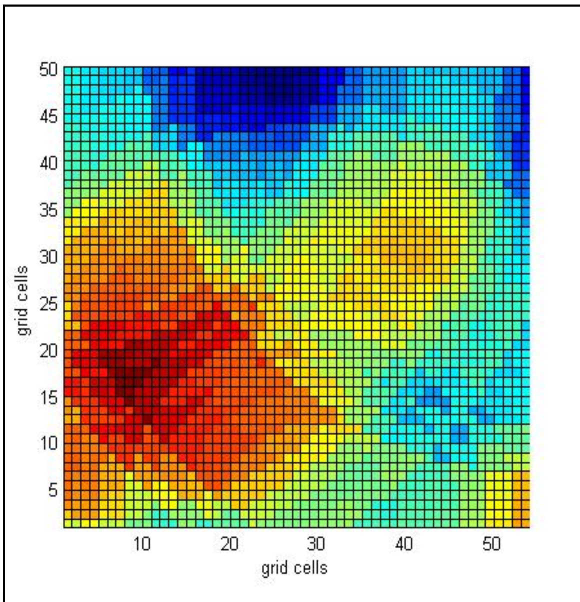


Figure 39a . Results test case 1, 2D probability map. Dependent algorithm.

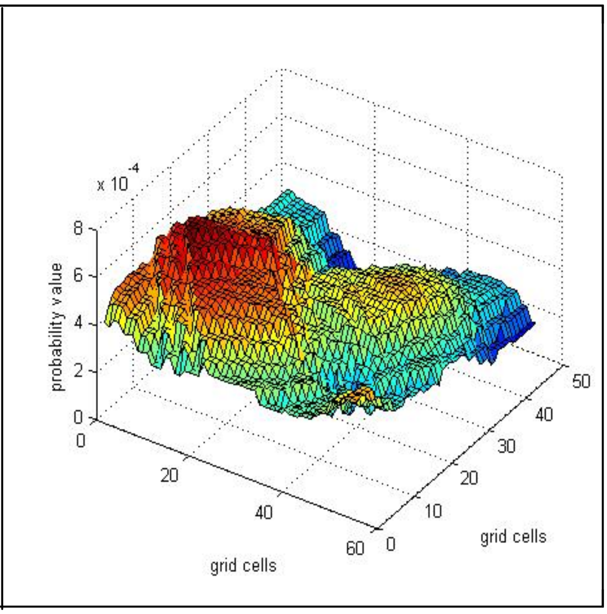


Figure 39b . Results test case 1, 3D probability map. Dependent algorithm.

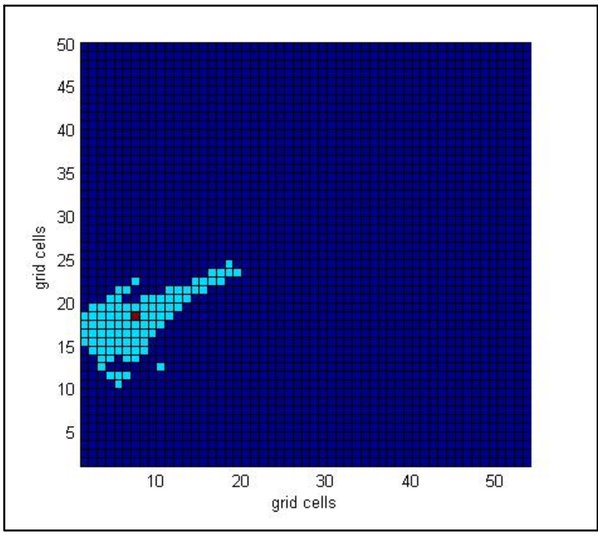


Figure 39c. Results test case 1. Location area (bright blue) and centroid of the area (red). Dependent algorithm.

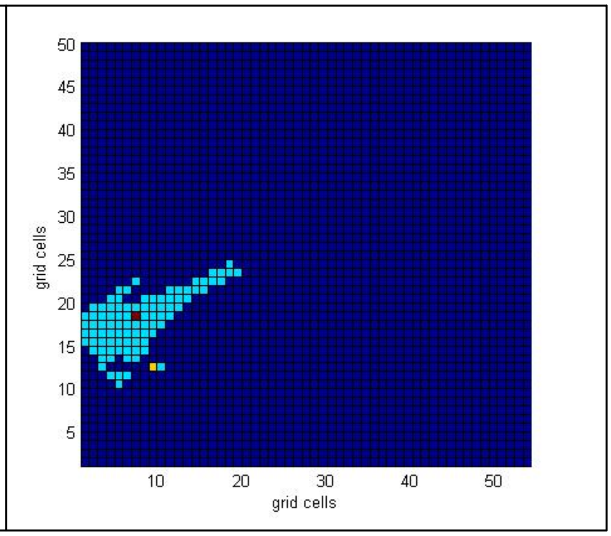


Figure 39d. Results test case 1. Location area (bright blue), centroid of the area (red) and actual location sensor (yellow). Dependent algorithm.

The results for **PML** regarding test case 1 are given in figure 40a-e. The map both in 2D and 3D (figure 40a and 40b) clearly indicate the circles belonging to each tag as explained in the methodology of the PML under 4.1. Where two circles overlap, the weight increases and is depicted orange. Where all three circles overlap, the location area is created (figure 40d). The actual location of the sensor and the generated location area by the PML method do not overlap (figure 40e). The distance between the centroid (red) and the actual location sensor (yellow) is 173 cm (figure 40d).

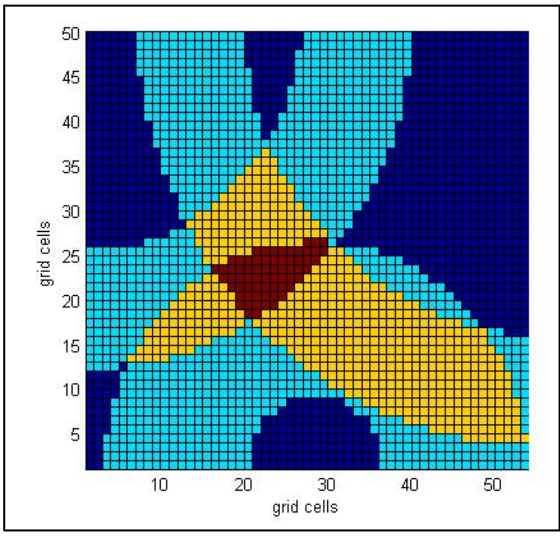


Figure 40a. Results test case 1, 2D probability map. PML.

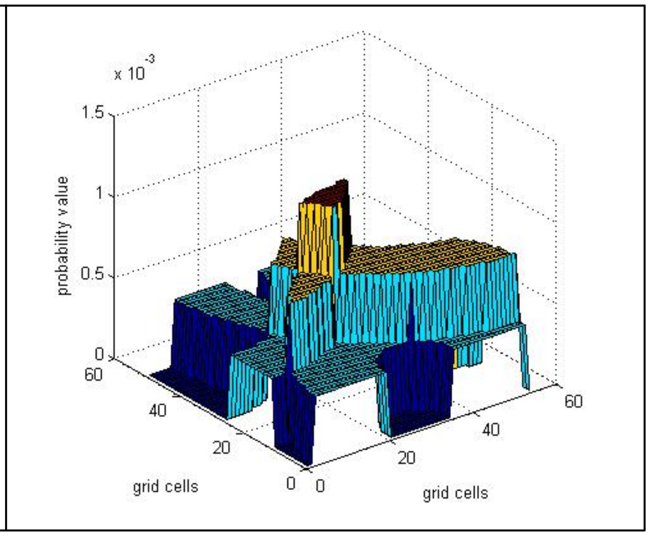


Figure 40b. Results test case 1, 3D probability map. PML.

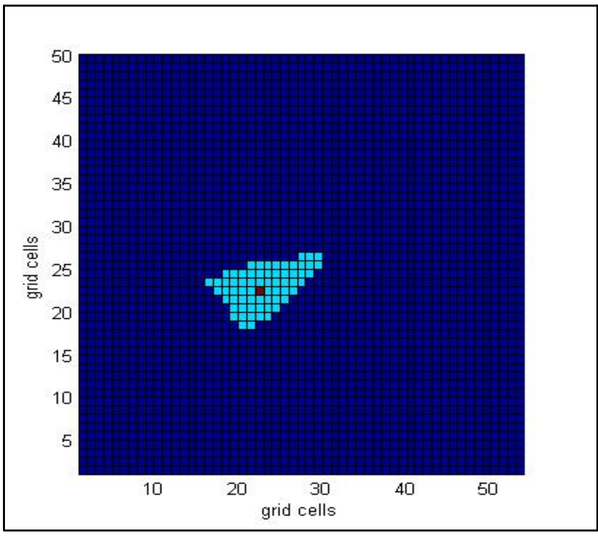


Figure 40c. Results test case 1. Location area (bright blue) and centroid of the area (red). PML.

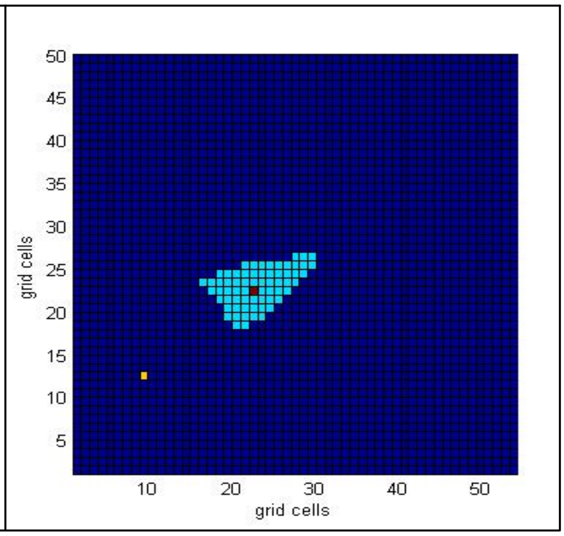


Figure 40d. Results test case 1. Location area (bright blue), centroid of the area (red) and actual location sensor (yellow). PML.

TEST CASE 2: ON THE BOUNDARY OF TWO ZONES

Case 2 is done to see how well the localization works for a more complicated situation where the subject is located close to the border of two zones (figure 41). As stated before, in case the sensor is located close to the border of two zones, the tag belonging to the third zone determines where on the border the subject is located. The measurements belonging to the third tag are key to the localization. The influence of each tag, in this situation, is not equal.

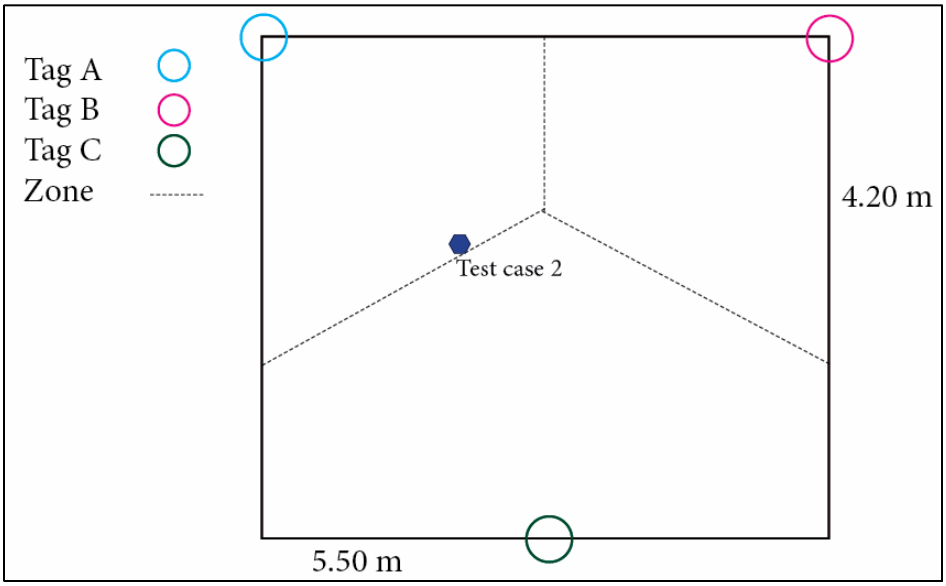


Figure 41. Test case 2, dark blue symbol is location of the subject with sensor in hand.

For both algorithms is the coarse location granularity based on zone selection. For both the independent and PML algorithms, the zone corresponding to tag A was correctly selected.

This section describes the results of test case 2 in the following order:

1. First the results of the dependent algorithm are discussed.
2. Then this is repeated for the independent algorithm (PML).

The results of the **dependent algorithm** regarding a localization granularity on sub zone level can be viewed in figure 42 a-d. Clearly visible is the high probability alongside the border between tag A and tag C (figure 42a). Also visible in figure 42c is that the location area is directed alongside the border of the zones. This can be explained by the fact that the measurements of the remaining tag B determines where on the border the subject is localized. However, the dispersion of the measurements of tag B are not limited by the measurements of the other two tags and therefore the result shows an area stretched along the border of the zone belonging to tag A and C. Comparing the actual location of the sensor and the generated location by the dependent algorithm (figure 42d), the location area overlaps the actual location. The distance between the centroid (red) of the location area and the actual location sensor (yellow) is 11 cm (figure 42d).

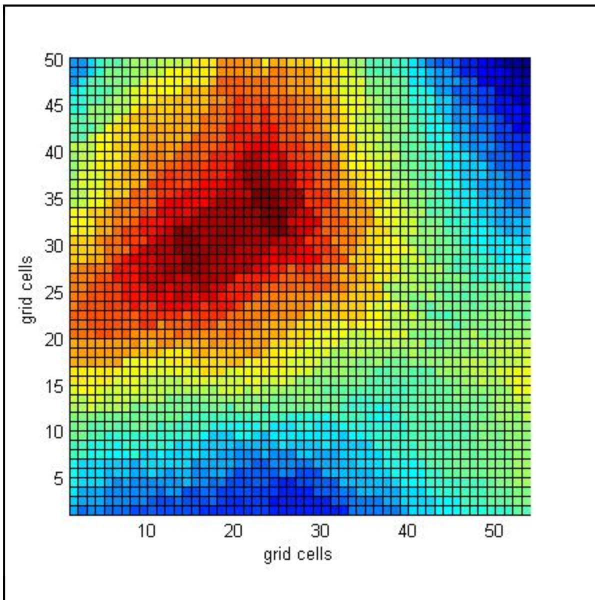


Figure 42a. Results test case 2, 2D probability map. Dependent algorithm.

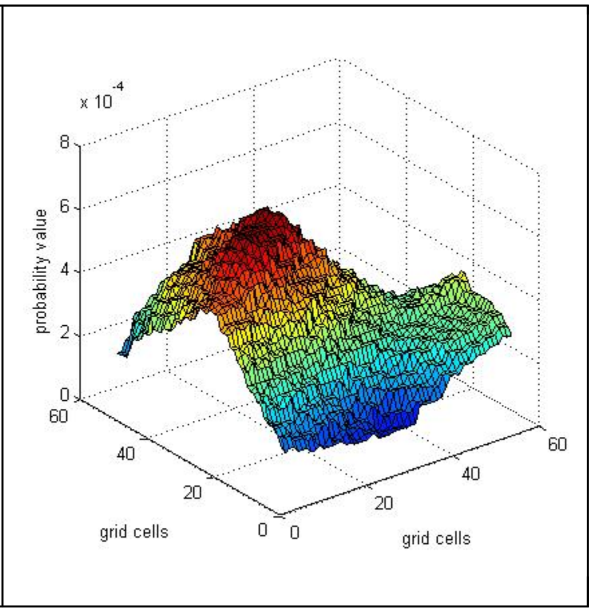


Figure 42b. Results test case 2, 3D probability map. Dependent algorithm.

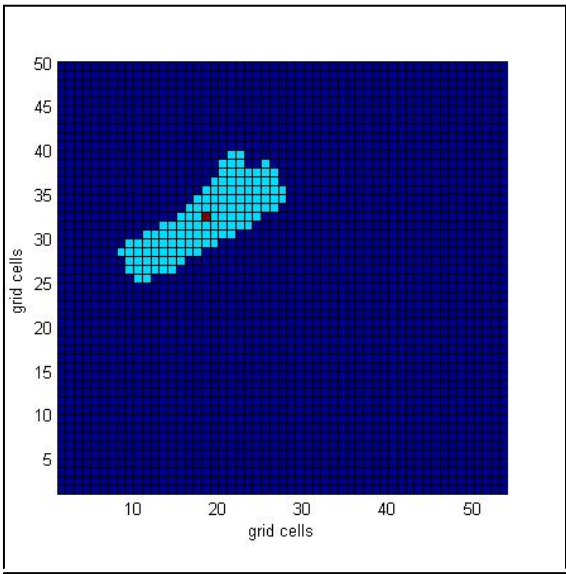


Figure 42c. Results test case 2. Location area (bright blue) and centroid of the area (red). Dependent algorithm.

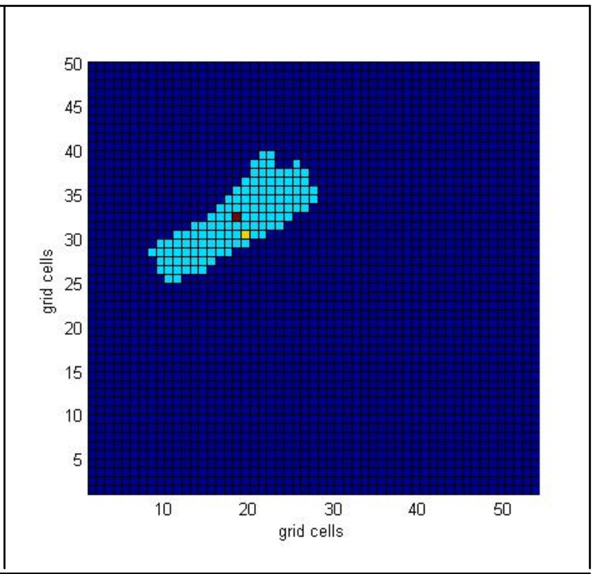


Figure 42d. Results test case 2. Location area (bright blue), centroid of the area (red) and actual location sensor (yellow). Dependent algorithm.

The results of the **PML** independent algorithm of test case 2 are given in figure 43a-d. The map in figure 43a shows the area where the three circles overlap highlighted in red. The comparison between the actual location of the sensor and the computed location (figure 43d) shows that the computed area overlaps the actual location. The location indication is correct, the centroid of the computed area and the actual location are 19 cm apart (fig 43d).

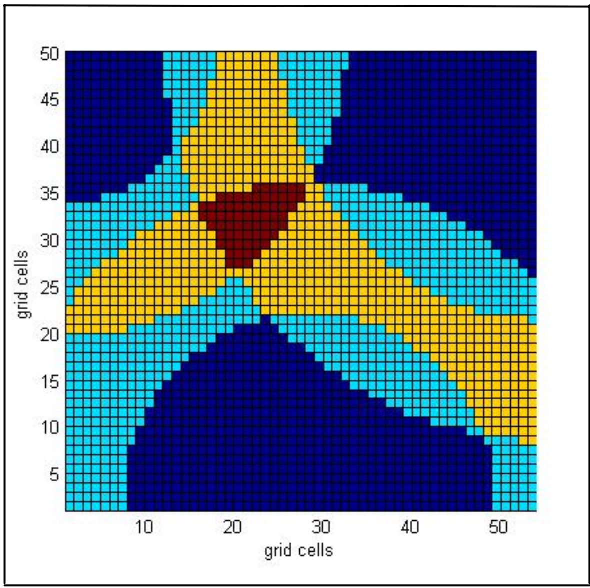


Figure 43a. Results test case 2, 2D probability map. PML.

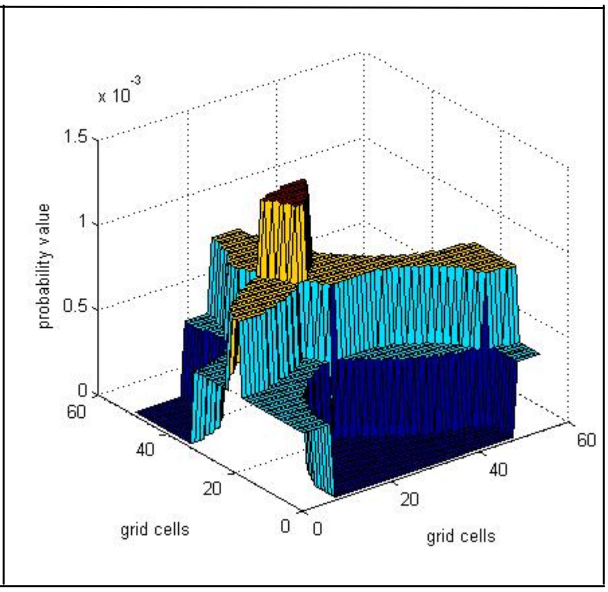


Figure 43b. Results test case 2, 3D probability map. PML.

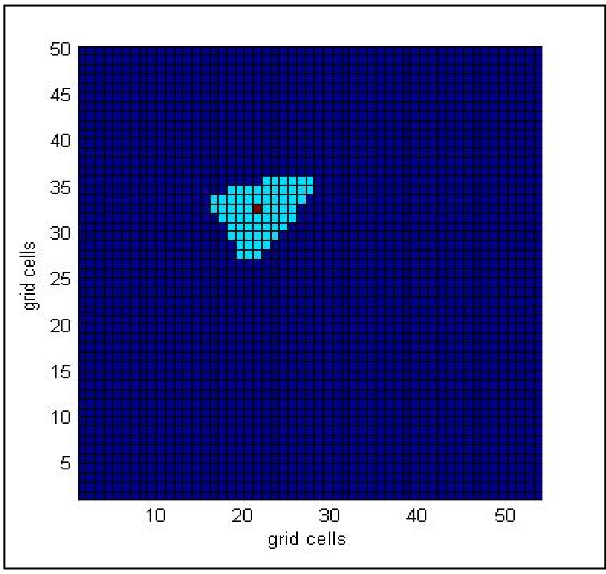


Figure 43c. Results test case 2. Location area (bright blue) and centroid of the area (red). PML.

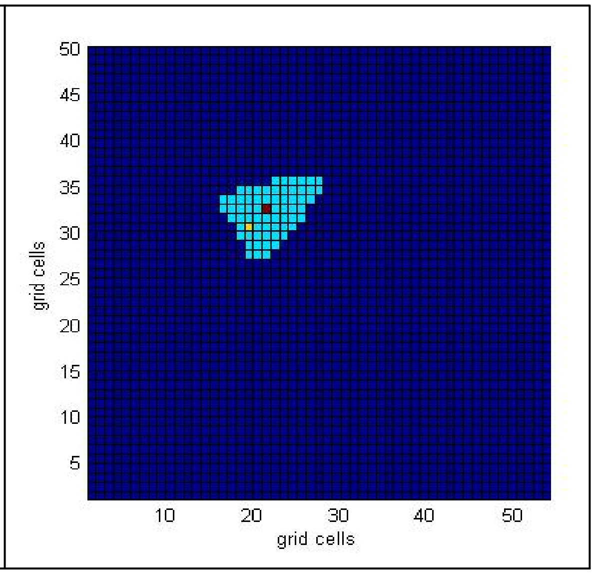


Figure 43d. Results test case 2. Location area (bright blue), centroid of the area (red) and actual location sensor (yellow). PML.

TEST CASE 3 AND 4: DISTINCTION COMPARABLE LOCATIONS

Test cases 3 and 4 are looked at together because both cases represent two very comparable situations. It is interesting to see if the algorithms are capable in generating locations which make a distinction between these cases. In case 3 and in case 4 the sensor is located at the edge of the room close to tag A (figure 44). In both cases the distances between the sensor and each tag is comparable.

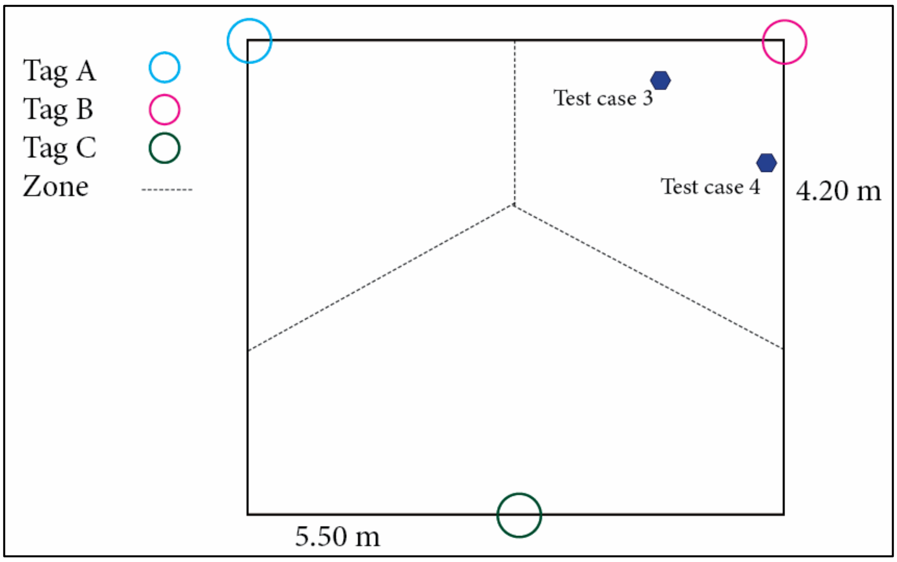


Figure 44. Test case 3 dark blue symbols are locations of the subject with sensor in hand.

This section describes both cases for each algorithm in the following order:

1. First the dependent algorithm is discussed for both test case 3 and 4.
2. Then this is repeated for the independent algorithm (PML).

For both algorithms and both cases the zone selection (coarse location granularity) returned the zone corresponding to tag B.
The results test case 3 for the dependent algorithm is depicted in figure 45a-d. Clearly visible is the circle of grid cells with high probabilities (figure 45a) around tag B. Although the computed localization area and the actual location of the sensor overlap, the island indicates an area right in front of Tag B rather than on the side. The results of test case 4 are depicted in figure 46a-d. Comparing the results of test case 3 to the results of test case 4, the probability map (figure 46a) shows a high probability clearly towards the correct side of tag B. Also visible in the results is that in test case 4 the subject was located further to the edge of the room than in test case 3. The centroid of the computed area and the actual

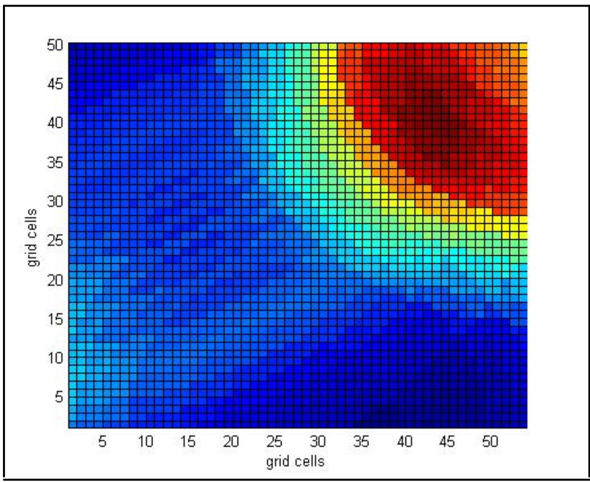


Figure 45a. Results test case 3, 2D probability map. Dependent algorithm.

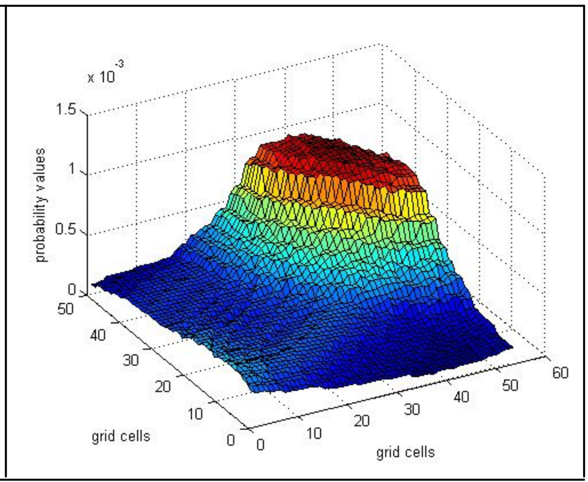


Figure 45b. Results test case 3, 3D probability map. Dependent algorithm.

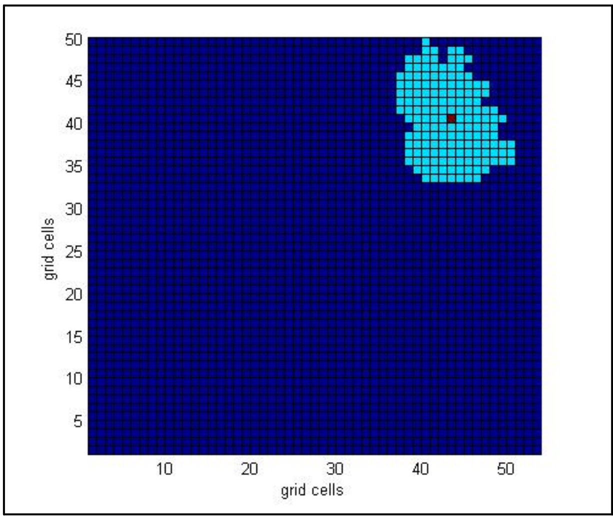
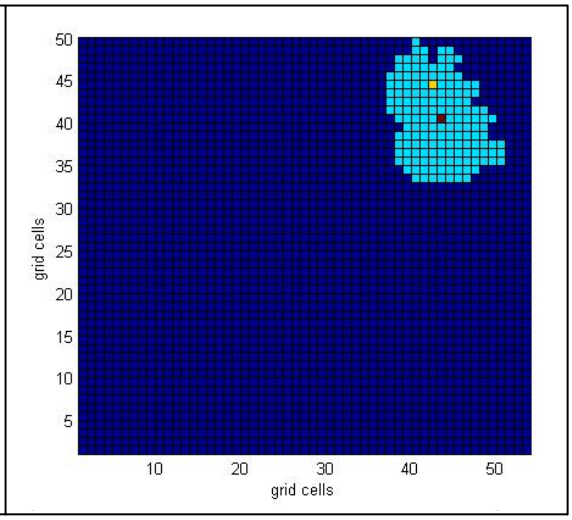


Figure 45c. Results test case 3. Location area (bright blue) and centroid of the area (red). Dependent algorithm.



blue), centroid of the area (red) and actual location sensor (yellow). Dependent algorithm.

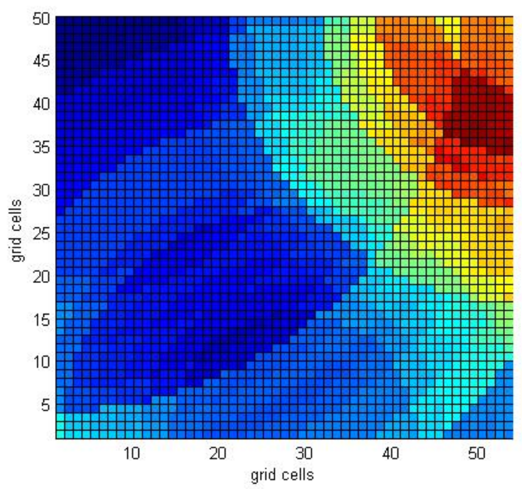


Figure 46a. Results test case 4, 2D probability map. Dependent algorithm.

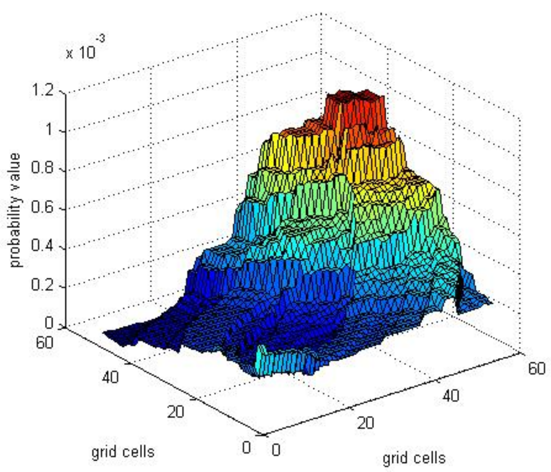


Figure 46b. Results test case 4, 3D probability map. Dependent algorithm.

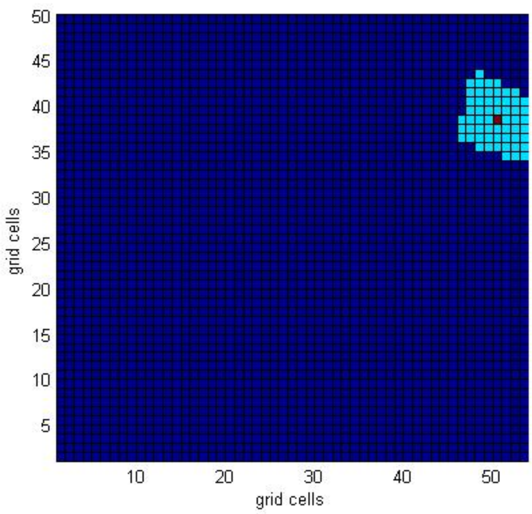


Figure 46c. Results test case 4. Location area (bright blue) and centroid of the area (red). Dependent algorithm.

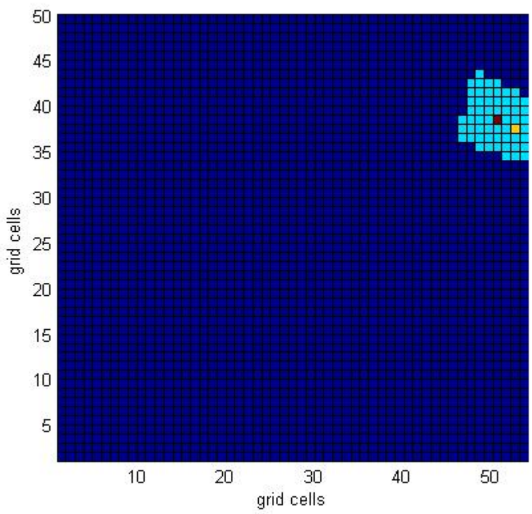


Figure 46d. Results test case 4. Location area (bright blue), centroid of the area (red) and actual location sensor (yellow). Dependent algorithm.

The test results of test case 3 for the **PML** is depicted in figure 47a-d. The test results for test case 4 are depicted in figure 48a-d. Results of case 3, depicted in figure 47a, show an area highlighted in red, right in front of tag B. The actual location of the subject and the computed location area (figure 47d) show no overlap. The subject is located at a distance of 53 cm of the centroid of the location area. Looking at the results of case 4 (figure 48d), the produced location area is very close to the actual location of the subject (distance between centroid and actual location is 24 cm).

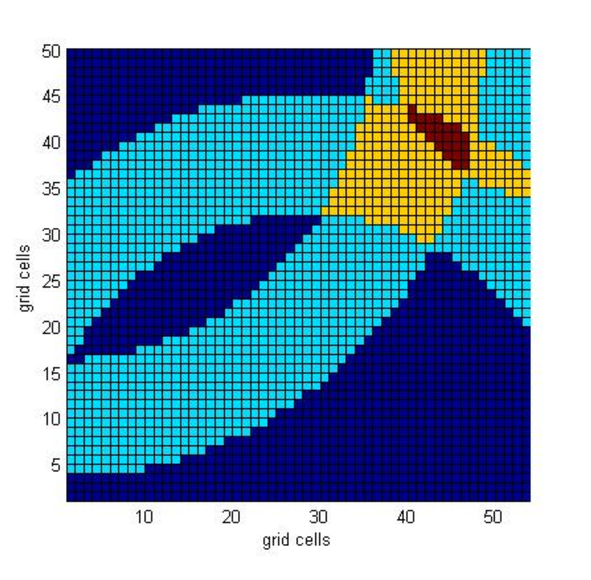


Figure 47a. Results test case 3, 2D probability map. PML.

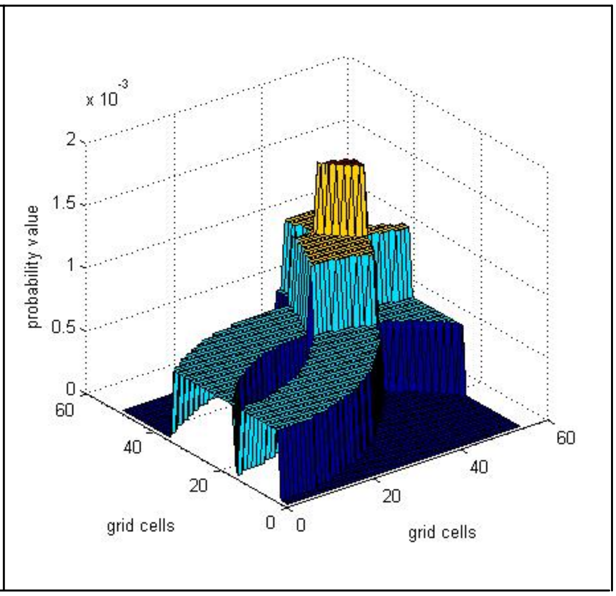


Figure 47b. Results test case 3, 3D probability map. PML.

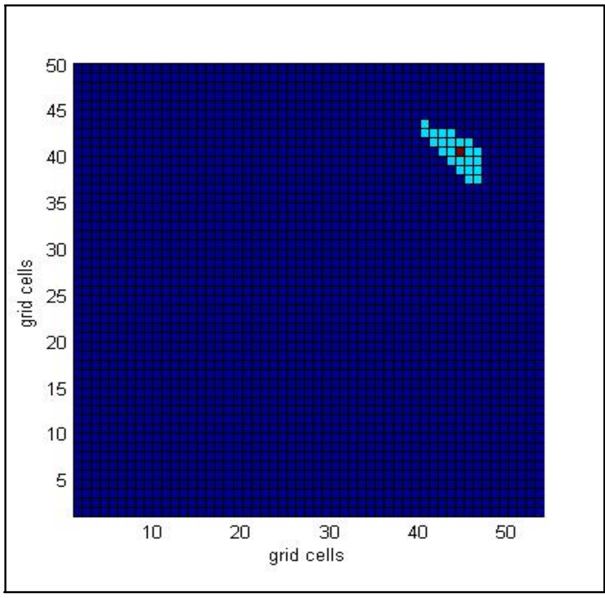


Figure 47c. Results test case 3. Location area (bright blue) and centroid of the area (red). PML.

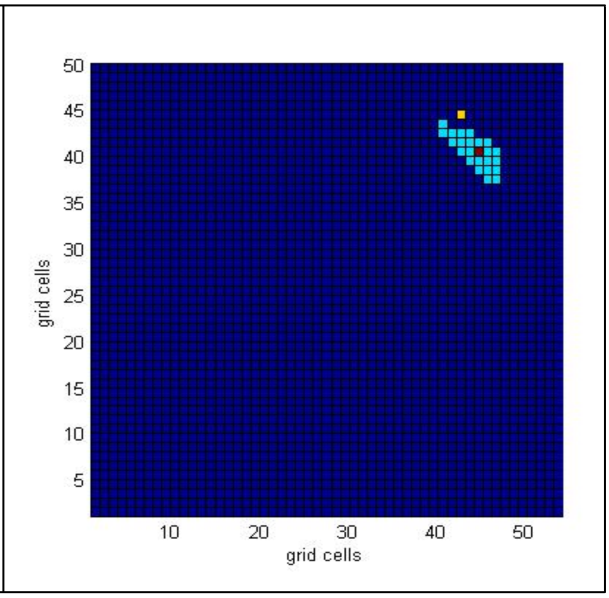


Figure 47d. Results test case 3. Location area (bright blue), centroid of the area (red) and actual location sensor (yellow). PML.

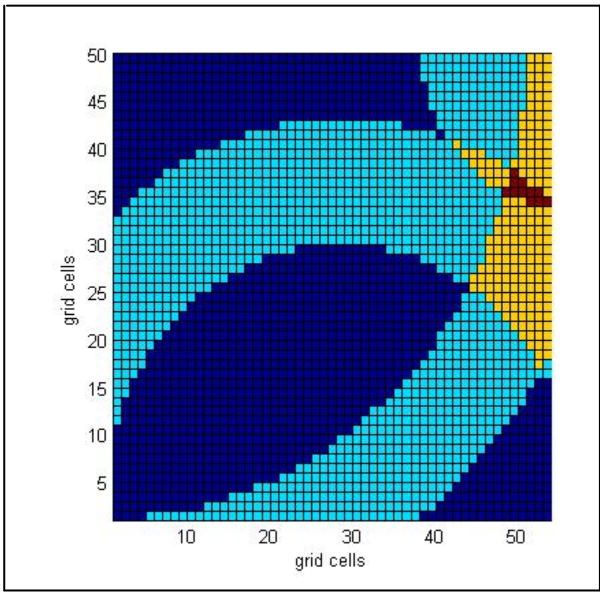


Figure 48a. Results test case 4, 2D probability map. PML.

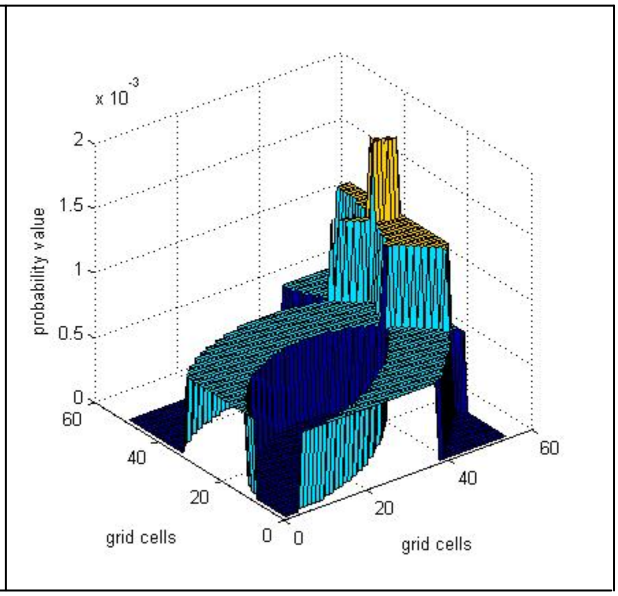


Figure 48b. Results test case 4, 3D probability map. PML.

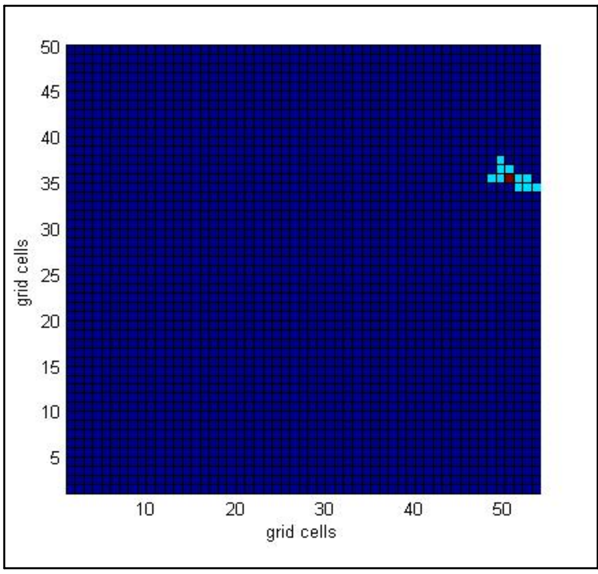


Figure 48c. Results test case 4. Location area (bright blue) and centroid of the area (red). PML.

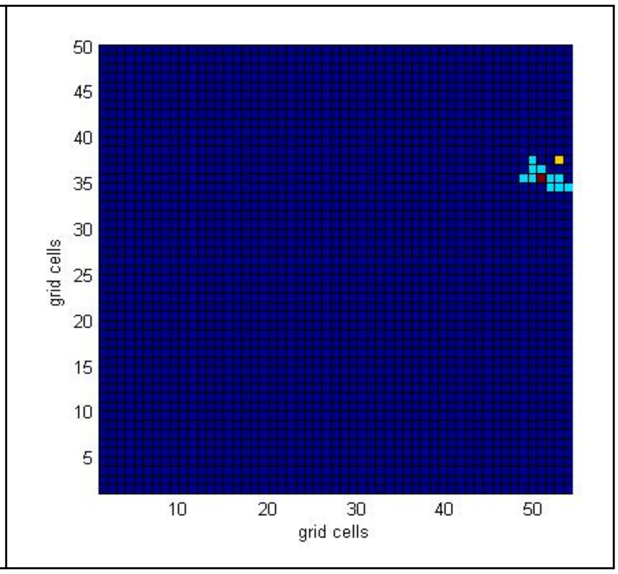


Figure 48d. Results test case 4. Location area (bright blue), centroid of the area (red) and actual location sensor (yellow). PML.

4.3 DISCUSSION & CONCLUSIONS SOFTWARE

The discussion and conclusions of the algorithm design and tests are aggregately presented in this section.

LOCALIZATION METHODS

The area of interest is selected by applying the assumption that the highest mean RSSI is measured for the closest three tags. Theoretically, the subject is then always located between three tags in a Delaunay triangulation. However, in practise, radio propagation techniques are influences by environmental factors. For that reason, it could be that the three tags having the highest mean RSSI are not the tags forming the Delaunay triangulation. An example is given in figure 49.

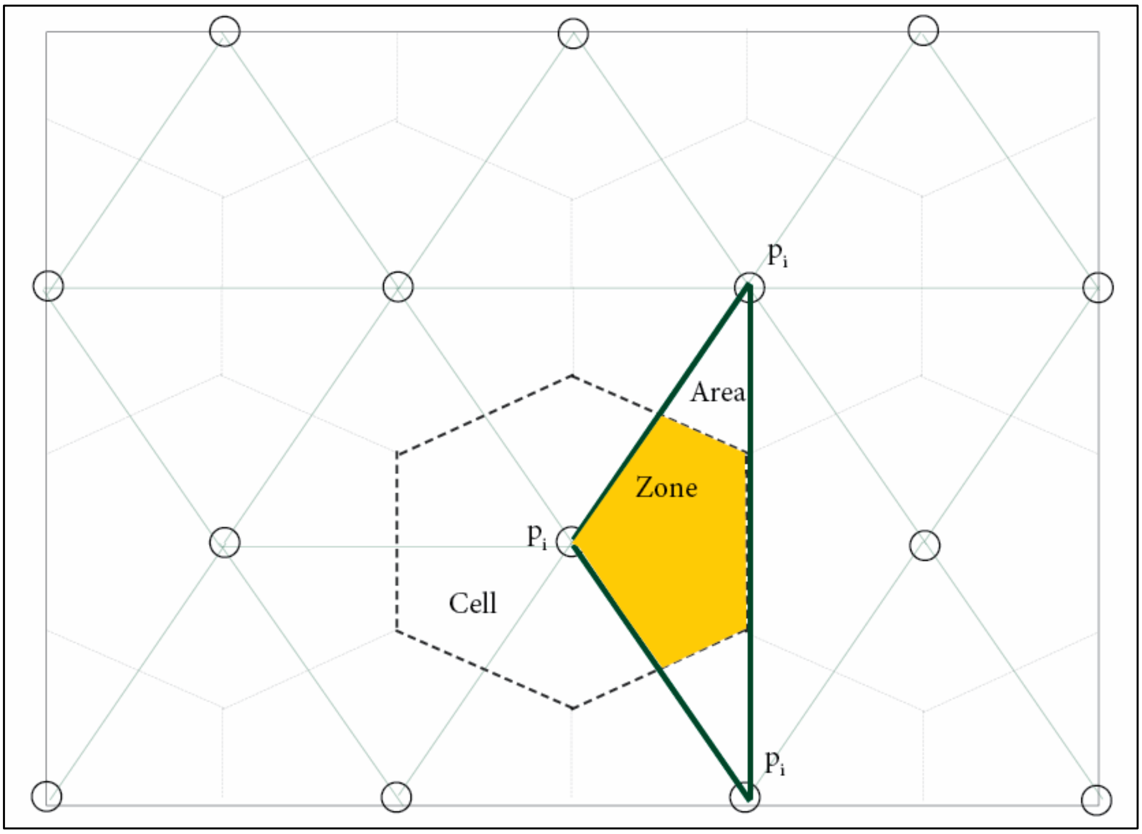


Figure 49. Illustrative case where the area is a triangle is not according to the Delaunay triangulation.

Combining the area of interest, even if it is not according to the Delaunay triangulation, with the Voronoi cell of a tag returns a zone. The dimensions of the zone are then dependent on the type of triangle. If a commercial party decides to use this approach in combination with geo-fencing these type of practical issues should be taken into account since the zone can then be partially outside the geo-fenced area if merely the possibility of a Delaunay triangulation is assumed.

TESTS
For each test, both the dependent algorithm and the PML zone selection (the correct cell was identified) is correct in all test cases. This is a promising result. The zone selection returns a coarse localization granularity which can be used in applications that do not require a fine localization granularity. The distinction between a fine and coarse localization granularity is important; the application determines the indoor localization approach.

In test case 1, The generated location of the subject is better done with the dependent algorithm than the PML. The PML produced a location area with a centroid over 1.5 meters from the actual location of the sensor. The question remains why the result of the PML in test case 1 has an error larger than the other results and dependent algorithm. A possible explanation could be that in the PML algorithm the outliers and measurements with a large deviation from the mean RSSI have a direct influence on the calculation of this mean RSSI which can 'shift' the mean RSSI towards the values of the outliers. While the final location area in the dependent algorithm is little influenced by these outliers since the probability is calculated separately for each measurement and the outliers do not form the greatest group of measurements. Therefore the impact of these type of measurements could be smaller than for the PML algorithm.

The results of the Dependent and PML algorithm in test case 2 both show a correct computed location area compared to the actual location of the sensor. The dependent algorithm indicates a quite large, stretched location area alongside the border of zone A and C. The location area of the PML method return a more compact area. Both algorithms are capable of identifying a location area corresponding to the actual area when the subject is located on the border of two zones. This indicates a certain capability of handling complex cases like the situation in test case 2.

For test case 3 and 4, when comparing the results of the Dependent and Independent localization algorithm, it is notable that both algorithms make a distinction between the two locations. This shows that both algorithms are capable in handling small differences in (mean) RSSI measurements.

Generally, the dependent algorithm returns a more differentiated result than the PML. This is because the dependent algorithm updates the probability of every given location each time a measurement comes in while PML uses a mean of all the measurements at once. PML seems to generally indicate more compact computed localization areas than the dependent Algorithm. This gives an impression of better localization, however, this is not necessarily the case. The circles around each tag are enlarged with predefined steps having a set value. This means that the degree of overlap is greatly dependent the latter in combination with the amount of grid cells and the radius of the circles before they are enlarged.

In order to give an indication of the localization, the centroid of each island is computed and the distance between the centroids and actual location of the sensor calculated for each case.

Distance (cm) between centroid computed area and actual location sensor	Test case 1	Test case 2	Test case 3	Test case 4
Dependent algorithm	38	12	51	19
PML	173	19	53	24

Table 11. Overview of the distances between the centroid of the computed area and the actual location sensor for each case.

Although it is difficult to draw hard conclusions on the capabilities of the algorithms from merely four tests, the results are promising. From the current results it could be concluded that the dependent algorithm is capable of localizing a subject within about half a meter distance from the actual location. The PML is in most cases able to produce a location area with a centroid less than and around half a meter away from the actual location. It also shows a case where the centroid of the location area and the actual location of the sensor are 1.73 meters apart. This is clearly distinctive from the other results. This could be explained through the difference in localization methodology between the dependent algorithm and the PML method. Although the results of the test cases give an idea of the capabilities of the algorithms, many more tests are necessary in order to verify these conclusions.

Although the dependent algorithm returns a better result than the PML algorithm, the latter would be easier to implement. PML functions without pre-knowledge of the type of sensors, it only considers knowledge of the tag. This dependent algorithm needs sensor specific knowledge in order to function. In practise, (semi) public places are visited by many people carrying different smart phones holding a variety of sensors. Using an algorithm that functions autonomous from that, makes the PML method scalable. The simplicity of the localization algorithm is what makes it high value, applicable and especially scalable. A point to keep in mind though, is that the PML could be computationally more costly than the dependent algorithm due to repeatedly enlarging the circles around the tags and each time checking if they overlap or not. Improving this by using zone determination and a well-designed program (by for example using binary search to improve efficiency), could provide an outcome.

5 DISCUSSION & FUTURE WORK

Part of the objective of this research was to propose an indoor localization technique and method for LBS applied in (semi) public places. Therefore the localization technique and method should be low cost, adaptive and robust. Both chapter 3 about the hardware and chapter 4 about the software contain their specific discussion (and conclusions). This is not repeated in this chapter. The main focus of this section is the application side since that is the main goal of the research. The following is discussed:

1. The practical issues and applicability of the hardware and software for (semi) public places.
2. The next steps an future work.

5.1 PRACTICE ISSUES AND SCALABILITY

There are various practice issues concerning both the hardware and localization algorithm. The distinction between a coarse and fine localization granularity is important. The distinction between coarse and fine localization granularity is depend on the demand of the LBS. For example, a shopping mall might want to close the gap between virtual and 'real life' shopping by offer their customers an LBS to find an item inside the physical world which was found online. In that case the LBS might require localization on sub zone level (for example in figure 50a). However, for example a hospital might want an LBS which locates doctors or patients. In such a case there is no need for a sub zone localization but a coarse localization granularity would do (figure 50b).

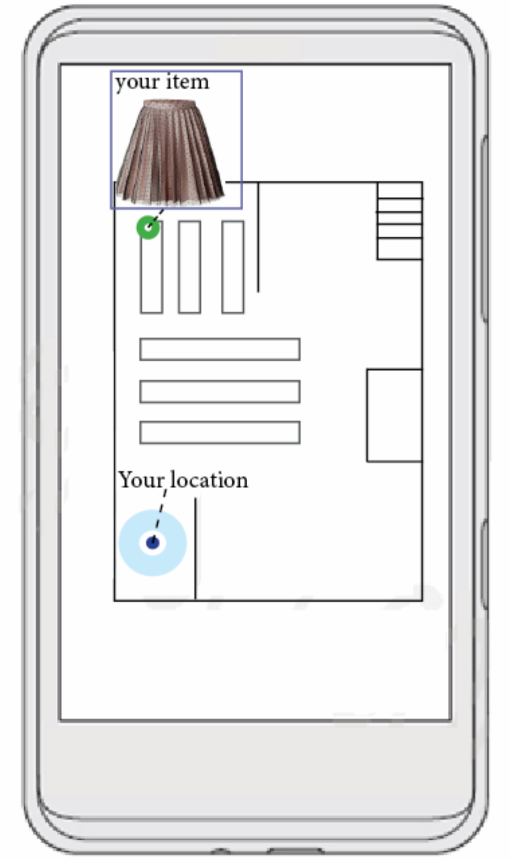


Figure 50a. Example LBS using fine localization granularity.

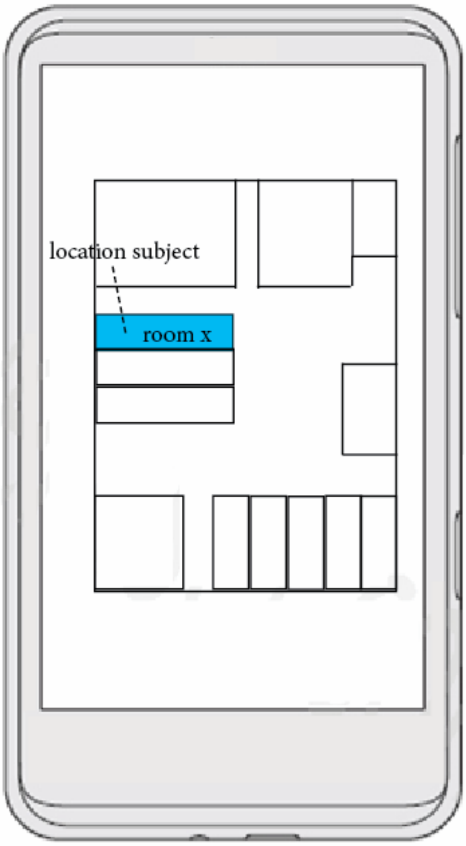


Figure 50b. Example LBS using coarse localization granularity.

PML method for fine localization granularity was found most appropriate indoor localization method for practice reasons. PML functions independently from the type of sensor used and is based on the difference of the mean RSSI of at least three tags. In practise, (semi) public places are visited by many people carrying different smart phones holding a variety of sensors. PM functions autonomous from that, which makes it a practical and scalable method. While BLE was found the most suitable hardware for the indoor localization method applied in this research. However, keeping the final goal of this research in mind, is BLE also practically easy to implement? BLE would be easier to implement in (semi) public places than UHF RFID. In the case of BLE, the sensors are brought by the users themselves (smartphone) while in the case of UHF RFID the subjects need to wear tags on their bodies. This would practically mean that the organisation of (semi) public places would have to provide all users with these tags and register which tag belongs to which user.

Moreover, BLE tags are not expensive and they are small and use little energy. Despite this, at some point, the batteries of the hardware would have to be replaced, probably every couple of years. Imagine a large shopping mall with tags every couple of meters. The cost in both time and effort to replace them would be high. Considering also the fact that not all tags are out of battery at the same time, thus, this would need to be checked and kept up to date constantly. In order to bypass such a situation, a possible simple change to the hardware could provide the solution. One solution would be to connect the BLE tags directly to the power system of the building, assuming there is a connection regularly available. However, another solution would be to provide the tags with a small solar cell charging the battery when light is present. This would give the freedom to place the tags anywhere necessary as long as there is light now and then. Another practical restriction of the present situation is that when the distance between the sensor and tag is larger than 6 meters, the correlation between the measured RSSI and distance is no longer in place. This means that the ceiling cannot be too high or else the tags need to be hung lower than the ceiling. Although the height of the ceiling is a restriction, BLE technology characteristics also poses opportunities regarding it being adaptive. The distance between the sensor and closest three tags can be anywhere between 1 and 6 meters and thus, depending on the dimensions and shape of the room, the distances between the tags can vary from tag to tag. This is possible because the localization method (for both coarse and fine localization) does not necessarily need a regular shaped Voronoi diagram for the cells in order to function. This means that localization can take place also in complex buildings and irregular shaped rooms. Applying indoor localization as proposed in large and complex areas would require a constrained Delaunay triangulation to make a distinction between spaces that are separated from each other. The constrains can be determined by the walls and obstacles but also by virtual areas (for example the coffee corner in a company).

5.2 TO DO AND NEXT STEPS

In order to define and delimit this research, many assumptions are done. The testing of the hardware is limited. Many environmental influences are not taken into account, for example, think of the influence of temperature and humidity differences. These influences can have an impact on the correlation found between RSSI and distance. Extensive testing of the hardware would give a more complete overview of the capabilities of the said technique and possible opportunities and improvements for the localization algorithm.

The localization algorithms both show promising results, however, the tests should be repeated and tested in different environments and circumstances in order to determine more precisely the capabilities of the algorithms. In this research, both are tested in a small environment with only three tags. It would be interesting to see how this algorithm performs in more complex environments with more than 3 tags and multiple users.

In this research the localization is based on two basic factors: mean of the measurements and distance. This works quite well (the simpler the better). However, localization might benefit from finding other factors that can improve the probability factor further. Possibly, the localization algorithms could be improved by including the measurements of a 4th tag. A next step could be, apart from localizing, to track subject, in such a situation the algorithm is not sufficient. Possibly, by applying a Kalman filter or particle filter, the algorithm could become suitable for tracking as well. An opportunity of using the system setup as proposed in this research is that it can be extended. With the current system setup, only sensors are located in a predefined area but, by placing BLE tracking tags on objects, the same system setup could be used to both locate the sensor and tracking tag. In that case, not only humans but also objects are located. However, the algorithm needs to be extended in that case. In order to make the step from this research to an actual product, the practical and scalability issues discussed above should be solved and implemented.

6 CONCLUSIONS

The objective of this research was to propose a suitable technique and method to accomplish indoor localization which can be applied for LBS in (semi) public places. These (semi) public places are assumed to be complex and large buildings potentially holding multiple users and for that reason the localization technique en method is supposed to be low cost, adaptive and robust. In this section the conclusions are presented with regards to the following sub questions:

1. What is the most suitable localization technique for an LBS for (semi) public places?
2. What is the most suitable indoor localization method for an LBS applied in (semi) public places?

6.1 LOCALIZATION TECHNIQUE: HARDWARE

Through a literature study multiple indoor localization techniques were considered. Based on the need for an LBS in (semi) public places, two techniques were selected: RFID and Bluetooth. UHF RFID was selected due to its reading capacity in the order of magnitude of 6 meters. For Bluetooth, a recent upcoming technique was chosen: Bluetooth Low Energy (BLE). Both techniques were tested in order to determine their suitability for indoor localization. The simple requirements are that the sensor of the technique should detect the tag when in range and return a consequent indication of distance or signal strength.

UHF RFID is found to be highly sensitive to interferences of the body of the subject which led to the sensor losing the ability to read the tag when a user is standing in between the tag and sensor. However, this can partially be compensated by placing multiple tags on the chest and shoulders. In the case where the subject is moving between sensors, both the zone determination and proximity are inconclusive. From the measurements it is not clear in what zone the subject was located nor at what distance. However, subjects in the stationary tests are found to be measured by the sensor in the zone where they are actually located in 95% of the measurements. From these measurements it is possible to say, in most cases, in what zone a subject is located. However, also in this case, the distance indication was not found consequent. The main difficulty of a system setup with UHF RFID, like tested in this research, is that the proximity is not consistent. This makes it particularly difficult to use for localization. Although RFID is a technique with great potential in indoor enhancements, due to the latter problem, this system is considered unsuitable to use for this application. RFID is rejected for further use for indoor localization in this research.

BLE technology seemed to be less influenced by the environmental interferences and humans. Although the measured RSSI decreased when a subject was located between the sensor and tag, the tag was still sensed. Moreover, from the results of testing BLE technology, a linear correlation was found between the distance and measured RSSI. At first sight the technique seems robust. However, extensive testing of this technique in different circumstances is necessary in order to confirm these findings. From the tests, it is concluded that this technique meets the requirements to be used for localization.

6.2 LOCALIZATION METHOD: SOFTWARE

The localization method is the software side of the localization. Taking the characteristics of the BLE hardware into account, a method (algorithm) for localization is designed. This algorithm returns a computed location indication. Two location granularities are returned, first a coarse location granularity and second a fine location granularity. A coarse location granularity is acquired through zone selection. In order to achieve a fine localization granularity two indoor localization algorithms where proposed: a Dependent indoor localization algorithm and an algorithm called PML.

In order to select a zone, first the area of interest is determined. This was done by selecting the tree tags with the highest mean RSSI measured. The zone is where the Voronoi cell of the tag with the highest mean RSSI overlaps the area of interest. Although this is not tested with multiple areas of interest due to the limited amount of available BLE tags, the results of the tests show a correct identification of zones for each test case. The use of a Voronoi diagram and its dual as Delaunay triangulation.

The dependent algorithm takes into account the specific characteristics of the sensor and is based on a probability function using a basic concept of trilateration dependent on the measurements of at least three tags. The results of testing of the dependent algorithm show that, in most cases, the computed area is varyingly consistent with the location of the subject. The centroid of the computed location area and the actual location of the subject are in all test results less than or close to half a meter apart.

PML functions independently from the type of sensor used and is based on the difference of the mean RSSI of at least three tags. The PML is in most cases able to produce a location area with a centroid less than and around half a meter away from the actual location. In one case the distance between the centroid and actual location is larger than 1.5 meters. This is probably due to the influence of outliers for this method of localization.

Although the dependent algorithm generally returns a better result than the PML algorithm, the latter would be easier to implement since PML functions without pre-knowledge of the type of sensors. Existing indoor localization methods often include knowledge on the sensor. PML however is distinctive in its kind because it uses distance approach without directly deriving the distance but approaching it while calculation the location of the sensor. In practise, (semi) public places are visited by many people carrying different types of sensors (smartphones). PML functions autonomous from that which makes this method more suitable for an LBS for (semi) public places. This research is explorative and there are numerous additional testing and development necessary in order to gain more knowledge and improve the practical usability of the proposed indoor localization technique and method. However, the findings in this research clearly show a huge potential of this technique and method for a variety of applications; the hardware is scalable in price and can become scalable in maintenance-costs if the hardware is provided with a small solar cell. The characteristics of BLE make it adaptive to different shapes and forms of buildings. The influence of environmental factor on BLE seems to be limited and it can be considered a robust technique. Combining this with the proposed localization method (PML), which can be applied in a variety of rooms and irregular spaces with any type of sensor, makes the combination extremely flexible, scalable and widely applicable.

7 LITERATURE

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8 APPENDIX

8.1 REFLECTION AND PROCESS EVALUATION

An indoor localization method resulting in both coarse and fine location granularity using Bluetooth Low Energy tags for (semi) public places is proposed in this thesis.

This research took place over the course of a year. The initial planning was that the research would take 8 months. Due to unforeseen circumstances I was unfortunately forced to deflect from the initial planning. However, this also positively influenced this research; it gave the time and possibility to think the research process over and to proceed in a sub zone localization granularity.

Initially, the goal of this research was to localize on zone level for a more specific case study: a congress setting. However, the possibilities of BLE gave the incentive to take the localization to the next level (a finer localization granularity) which made the method applicable for a larger group of applications. This is a research challenge in the domain of Geomatics. Specific features related to the initial case study, for example profile matching, where lost and replaced with a further technical development of the localization system.

Indoor localization systems are underrepresented in practise, in contrast to outdoor positioning systems. Applications using outdoor positioning are well spread throughout day to day life. Localization systems and methods for indoor positioning do exist but indoor localization remains a research challenge. From a broader social perspective, this research adds to the development of an indoor localization method, which could become applicable in society, eventually equal to how outdoor localization nowadays plays a role in the daily life of many people. Services using indoor localization, positioning, tracking and tracing can all take their advantage of the methods proposed in this research. This research is innovative; the combination of BLE hardware and a range free localization technique are new. Moreover, a robust, adaptive and scalable indoor localization system (hardware and software) is proposed which both answers to a demand from society and is an remaining research challenge.

This research and the field of Geomatics are strongly related. The field of Geomatics is engaged with the analysis, acquisition, management, and visualisation of geographic data. This research includes these topics and applied the knowledge gained during the Geomatics courses. Appling spatial analysis and determining spatial relationships by using Voronoi and Delaunay diagrams, localization while processing of the data, modelling and visualizing spatial data are done in this research. These processes are made possible by the gained knowledge from the core Geomatics courses on SQL, programming, GIS and positioning and location awareness. This research combines knowledge from different fields and specializations like; Telecommunication, Mathematics and (Geo-) Computer Science, which relates seamlessly to the interdisciplinary nature of Geomatics.

According to the TU Delft website about the MSc Geomatics:

"Geomatics data management and analysis techniques allow us to turn these measurements into useful information and knowledge with which we can identify patterns, track feature behaviour over time and predict the future state."

This is extremely illustrative for this research, it includes both the management and analysis concerning spatial information but also puts emphasis on the importance of adding value and using this information for a practical purpose: proposing the basis for LBS in (semi) public places.

8.2 SOURCE CODES LOCALIZATION ALGORITHMS.

DEPENDENT ALGORITHM

```
%%  localization algorithm
data = testdata22;
with = 450;
length = 420;
y = 50;
x = 54;

n = with/x;
m = length/y;

DistanceMapB = ones(y,x); %map containing distances from spot B
DistanceMapC = ones(y,x); %map containing distances from spot C

proxMapA =   ones(y,x);           %proximity map tag A
proxMapB =   ones(y,x);           %proximity map tag B
proxMapC =   ones(y,x);           %proximity map tag C

proxMapZoneA =    zeros(y,x);      %proximity map zone A
proxMapZoneB =   zeros(y,x);       %proximity map zone B
proxMapZoneC =    zeros(y,x);      %proximity map zone C

%% initialization

for t = 1:y
    for r = 1:x
        %create distance map for B
        A = t*m;
        B = r*n;
        Dis = sqrt((A^2)+(B^2));
        DistanceMapB(t,r) = DistanceMapB(t,r)*Dis;

        %create distance map for C
        Bpos = (r-1)*n;
        Aa = length-A;
        if B <=225
            Bb = 225-Bpos;
            DisC = sqrt((Aa^2)+(Bb^2));
            DistanceMapC(t,r) = DistanceMapC(t,r)*DisC;
        elseif B == 225
            DistanceMapC(t,r) = DistanceMapC(t,r)* Aa
        else
            Bb = Bpos-225;
            DisC = sqrt((Aa^2)+(Bb^2));
```

```
            DistanceMapC(t,r) = DistanceMapC(t,r)*DisC;
        end

    end
end

% create distance map for A
DistanceMapA = fliplr(DistanceMapB);

%% Distance approach

%turn distance maps in RSSI maps for a person holding a sensor 135
cm from
%the ceiling.

RSSIMapA = ones(y,x);
RSSIMapB = ones(y,x);
RSSIMapC = ones(y,x);
DistanceMapAa = ones(y,x);
DistanceMapBb = ones(y,x);
DistanceMapCc = ones(y,x);
height = 135;

for p = 1:y
    for o = 1:x
        DistanceMapAa(p,o) = sqrt((135^2)+(DistanceMapA(p,o)^2));
        DistanceMapBb(p,o) = sqrt((135^2)+(DistanceMapB(p,o)^2));
        DistanceMapCc(p,o) = sqrt((135^2)+(DistanceMapC(p,o)^2));
        RSSIMapA(p,o) = (-0.05)*DistanceMapAa(p,o) -68;
        RSSIMapB(p,o) = (-0.05)*DistanceMapBb(p,o) -68;
        RSSIMapC(p,o) = (-0.05)*DistanceMapCc(p,o) -68;
    end
end
% create Voronoi cell maps for A, B and C
for w = 1:y
    for q = 1:x
        if DistanceMapA(w,q)<= DistanceMapC(w,q) &&
DistanceMapA(w,q)<= DistanceMapB(w,q)
            proxMapZoneA(w,q) = proxMapZoneA(w,q)+100;

        elseif DistanceMapB(w,q)<= DistanceMapC(w,q) &&
DistanceMapB(w,q)<= DistanceMapA(w,q)
            proxMapZoneB(w,q) = proxMapZoneB(w,q)+100;

        elseif DistanceMapC(w,q)<= DistanceMapA(w,q) &&
DistanceMapC(w,q)<= DistanceMapB(w,q)
            proxMapZoneC(w,q) = proxMapZoneC(w,q)+100;
        end
    end
end

%% proximity approach
%add weight dependent on distance to create a proximity map of
each zone

[h g] = size(data);
Aa = 0;
Bb = 0;
```

```
Cc = 0;
totalA = 0;
totalB = 0;
totalC = 0;
l = 4; %all RSSI within range of 4 dBm

for f = 1:h
        RSSI = cell2mat(data(f,1));
        comp1 = strcmpi(data(f,2),'A');
        comp2 = strcmpi(data(f,2),'B');
        comp3 = strcmpi(data(f,2),'C');
        if comp1 == 1
            Aa = Aa+1;
            totalA = totalA+RSSI;
            MatrixA = ones(y,x)*RSSI;
            Diff = abs(RSSIMapA-MatrixA); %differences between
mesurement and map
           for n = 1:y
            for g = 1:x
                 if Diff(n,g) <=l %all RSSI within range of 4 dBm
                     proxMapA(n,g) = proxMapA(n,g)+10;
                 end
            end
           end
        elseif comp2 == 1
            Bb = Bb+1;
            totalB = totalB+RSSI;
            MatrixB = ones(y,x)*RSSI;
            Diff = abs(RSSIMapB-MatrixB); %differences between
mesurement and map
           for n = 1:y
            for g = 1:x
                 if Diff(n,g) <=l %all RSSI within range of 2.5
dBm
                     proxMapB(n,g) = proxMapB(n,g)+10;
                 end
            end
           end
        elseif comp3 == 1
            Cc = Cc+1;
            totalC = totalC+RSSI;
            MatrixC = ones(y,x)*RSSI;
            Diff = abs(RSSIMapC-MatrixC); %differences between
mesurement and map
           for n = 1:y
            for g = 1:x
                 if Diff(n,g) <=l %all RSSI within range of 2.5
dBm
                     proxMapC(n,g) = proxMapC(n,g)+10;
                 end
            end
           end
        end
end

Mean = ones(3,1);
Mean(1,1) = abs(totalA/Aa);
Mean(2,1) = abs(totalB/Bb);
Mean(3,1) = abs(totalC/Cc);
[value, index] = min(Mean(:));
```

```
%% output

somA = sum(proxMapA(:));
totalproxA = proxMapA./somA;

somB = sum(proxMapB(:));
totalproxB = proxMapB./somB;

somC = sum(proxMapC(:));
totalproxC = proxMapC./somC;

combiprox = (totalproxA + totalproxB + totalproxC);
combisom = sum(combiprox(:)); %is drie
totalprox = combiprox./combisom;


%% result
sigma = std2(totalprox);
[val, ind] = max(totalprox(:));
islands = zeros(y,x);
islandsfin = zeros(y,x);
Centroid = zeros(y,x);
RealLoc = zeros(y,x);
% all islands with values 1 sigma away from the max

for b = 1:y
    for v = 1:x
        di = val-totalprox(b,v);
        if di <=(sigma/4)
            islands(b,v) = islands(b,v)+totalprox(b,v);
        end

    end
end

for b = 1:y
    for v = 1:x
        if islands(b,v) == 0
            islandsfin(b,v)=0;
        else
            islandsfin(b,v) = 1;
        end
    end
end

% real location and centroid of computed location area
L = logical(islandsfin);
Stats = regionprops(L,'Centroid');
betw = struct2cell(Stats);
StatMat = round(cell2mat(betw));
CentroidX = StatMat(1);
CentroidY = StatMat(2);
Centroid = Centroid+islandsfin;
Centroid(CentroidY,CentroidX) = Centroid(CentroidY,CentroidX)+2;
pcolor(flipud(Centroid))
```

```
RealLoc = RealLoc+Centroid;


%RealLoc(y-11,9) = RealLoc(y-11,9)+2; %for testdata, actual
location testc1
%RealLoc(y-29,19) = RealLoc(y-11,9)+2; %for testdata3, actual
location - testcase 2
%RealLoc(y-36,52) = RealLoc(y-11,9)+2; %for testdata4, actual
location - testcase 4
%RealLoc(y-43,42) = RealLoc(y-11,9)+2; %for testdata22, actual
location - testcase 3

subplot(1,2,2), surf(flipud(totalprox))
subplot(1,2,1), pcolor(flipud(totalprox))
%subplot(1,2,1), pcolor(flipud(Centroid))
%subplot(1,2,2), pcolor(flipud(RealLoc))
```

PML

```
%%  localization alghoritm
data = testdata3;
with = 450;
length = 420;
y = 50;
x = 54;

n = with/x;
m = length/y;

DistanceMapB = ones(y,x); %map containing distances from spot B
DistanceMapC = ones(y,x); %map containing distances from spot C

proxMapA =   zeros(y,x);          %proximity map tag A
proxMapB =   ones(y,x);          %proximity map tag B
proxMapC =   ones(y,x);          %proximity map tag C

proxMapZoneA =    zeros(y,x);      %proximity map zone A
proxMapZoneB =   zeros(y,x);       %proximity map zone B
proxMapZoneC =    zeros(y,x);      %proximity map zone C

%% initialization

for t = 1:y
    for r = 1:x
        %creat distance map for B
        A = t*m;
        B = r*n;
        Dis = sqrt((A^2)+(B^2));
        DistanceMapB(t,r) = DistanceMapB(t,r)*Dis;

        %create distance map for C
        Bpos = (r-1)*n;
        Aa = length-A;
        if B <=225
            Bb = 225-Bpos;
            DisC = sqrt((Aa^2)+(Bb^2));
            DistanceMapC(t,r) = DistanceMapC(t,r)*DisC;
        elseif B == 225
            DistanceMapC(t,r) = DistanceMapC(t,r)* Aa
```

```
        else
            Bb = Bpos-225;
            DisC = sqrt((Aa^2)+(Bb^2));
            DistanceMapC(t,r) = DistanceMapC(t,r)*DisC;
        end

    end
end

% create distance map for A
DistanceMapA = fliplr(DistanceMapB);

%% Distance approach


% create zone maps for A, B and C
for w = 1:y
    for q = 1:x
        if DistanceMapA(w,q)<= DistanceMapC(w,q) &&
DistanceMapA(w,q)<= DistanceMapB(w,q)
            proxMapZoneA(w,q) = proxMapZoneA(w,q)+100;

        elseif DistanceMapB(w,q)<= DistanceMapC(w,q) &&
DistanceMapB(w,q)<= DistanceMapA(w,q)
            proxMapZoneB(w,q) = proxMapZoneB(w,q)+100;

        elseif DistanceMapC(w,q)<= DistanceMapA(w,q) &&
DistanceMapC(w,q)<= DistanceMapB(w,q)
            proxMapZoneC(w,q) = proxMapZoneC(w,q)+100;
        end
    end
end

%% proximity approach
%add weight dependent on distance to create a proximity map of
each zone

[h g] = size(data);
Aa = 0;
Bb = 0;
Cc = 0;
totalA = 0;
totalB = 0;
totalC = 0;
l = 4; %all RSSI within range of 4 dBm

%turn distance maps in distance maps for a person holding a sensor
135 cm from
%the ceiling.

DistanceMapAa = ones(y,x);
DistanceMapBb = ones(y,x);
DistanceMapCc = ones(y,x);
height = 135;

for p = 1:y
    for o = 1:x
        DistanceMapAa(p,o) = sqrt((135^2)+(DistanceMapA(p,o)^2));
```

```
        DistanceMapBb(p,o) = sqrt((135^2)+(DistanceMapB(p,o)^2));
        DistanceMapCc(p,o) = sqrt((135^2)+(DistanceMapC(p,o)^2));
    end
end


for f = 1:h
        RSSI = cell2mat(data(f,1));
        comp1 = strcmpi(data(f,2),'A');
        comp2 = strcmpi(data(f,2),'B');
        comp3 = strcmpi(data(f,2),'C');
        if comp1 == 1
            Aa = Aa+1;
            totalA = totalA+RSSI;
        elseif comp2 == 1
            Bb = Bb+1;
            totalB = totalB+RSSI;

        elseif comp3 == 1
            Cc = Cc+1;
            totalC = totalC+RSSI;
        end
end

Mean = ones(3,1);
Mean(1,1) = abs(totalA/Aa);
Mean(2,1) = abs(totalB/Bb);
Mean(3,1) = abs(totalC/Cc);
[value, index] = min(Mean(:));
plus = 0;
first = 100;

if index ==1

    DifAB = abs(Mean(1,1)-Mean(2,1));
    DifAC = abs(Mean(1,1)-Mean(3,1));
    increseSec = (DifAB/5)*100;
    increaseThir = (DifAC/5)*100;
    DistanceMapFirst = DistanceMapAa;
    DistanceMapSecond = DistanceMapBb;
    DistanceMapThird = DistanceMapCc;
    proxMapZone = proxMapZoneA;
elseif index == 2

    DifBA = abs(Mean(2,1)-Mean(1,1));
    DifBC = abs(Mean(2,1)-Mean(3,1));
    increseSec = (DifBA/5)*100;
    increaseThir = (DifBC/5)*100;
    DistanceMapFirst = DistanceMapBb;
    DistanceMapSecond = DistanceMapAa;
    DistanceMapThird = DistanceMapCc;
    proxMapZone = proxMapZoneB;
elseif index == 3

    DifCA = abs(Mean(3,1)-Mean(1,1));
    DifCB = abs(Mean(3,1)-Mean(2,1));
    increseSec = (DifCA/5)*100;
    increaseThir = (DifCB/5)*100;
    DistanceMapFirst = DistanceMapCc;
```

```
    DistanceMapSecond = DistanceMapAa;
    DistanceMapThird = DistanceMapBb;
    proxMapZone = proxMapZoneC;
end

proxmapFirst = zeros(y,x);
proxmapSecond = zeros(y,x);
proxmapThird = zeros(y,x);
Combined = ones(x,y);
qww=0;
qee = 0;

while max(Combined(:))<30
    qww=qww+1
    proxmapFirst = zeros(y,x);
    proxmapSecond = zeros(y,x);
    proxmapThird = zeros(y,x);
    first = first+plus; %increase every time with 50 cm
    for a = 1:y
        for s = 1:x
            if DistanceMapFirst(a,s) <= (first+50) &&
DistanceMapFirst(a,s) >= (first-50)
            proxmapFirst(a,s) = proxmapFirst(a,s)+10;
            qee =qee+1;
            end
            if DistanceMapSecond(a,s) <= (first+50+increseSec) &&
DistanceMapSecond(a,s) >= (first-50+increseSec)
               proxmapSecond(a,s) = proxmapSecond(a,s)+10;
            end
            if DistanceMapThird(a,s) <= (first+50+increaseThir) &&
DistanceMapThird(a,s) >= (first-50+increaseThir)
                proxmapThird(a,s) = proxmapThird(a,s)+10;
            end
        end
    end
    Combined = proxmapFirst+proxmapSecond+proxmapThird;
    first = first+50;
end

%% result

Som = sum(Combined(:));
normalized = Combined./Som;

% islands

islands = ones(y,x);
for v = 1:y
    for c = 1:x
        if Combined(v,c)==30
            islands(v,c) = islands(v,c)*10;
        else
            islands(v,c) = islands(v,c)*0;
        end
    end
end

Centroid = zeros(y,x);
RealLoc = zeros(y,x);
```

```
islandsfin = zeros(y,x);
for b = 1:y
    for v = 1:x
        if islands(b,v) == 0
            islandsfin(b,v)=0;
        else
            islandsfin(b,v) = 1;
        end
    end
end


L = logical(islandsfin);
Stats = regionprops(L,'Centroid');
betw = struct2cell(Stats);
StatMat = round(cell2mat(betw));
CentroidX = StatMat(1);
CentroidY = StatMat(2);
Centroid = Centroid+islandsfin;
Centroid(CentroidY,CentroidX) = Centroid(CentroidY,CentroidX)+2;
pcolor(flipud(Centroid))
RealLoc = RealLoc+Centroid;


%RealLoc(y-11,9) = RealLoc(y-11,9)+2; %for testdata, actual
location testc1
%RealLoc(y-29,19) = RealLoc(y-11,9)+2; %for testdata3, actual
location - testcase 2
%RealLoc(y-36,52) = RealLoc(y-11,9)+2; %for testdata4, actual
location - testcase 4
%RealLoc(y-43,42) = RealLoc(y-11,9)+2; %for testdata22, actual
location - testcase 3

%subplot(1,2,1), pcolor(flipud(Centroid))
%subplot(1,2,2), pcolor(flipud(RealLoc))

subplot(1,2,2), surf(flipud(normalized))
subplot(1,2,1), pcolor(flipud(normalized))

%subplot(1,2,1), pcolor(flipud(Combined.*proxMapZone))
%subplot(1,2,2), pcolor(flipud(islands))
```