FAKULTÄT FÜR INFORMATIK
DER TECHNISCHEN UNIVERSITÄT MÜNCHEN

Development of an Indoor Location Tracking System for the Operating Room

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Abstract

Location- and navigation systems are finding increasing use in areas such as logistics, medicine and security. These systems help exploit bottlenecks/weak points and analyze procedures and work flows. There are several technologies which, depending on the use case, can be applied to a location tracking system. For example, GPS is a technology which is used outdoors for navigation in cars. We look for a similar technology to GPS which should work indoors.
Since this thesis was conducted in the medical technology company Trumpf Medical, the use case as well as environment was defined as the operating room and the adjacent corridors. This thesis evaluates optical, radio-based and acoustic technologies to develop a system for the use in the operating room. The purpose was to detect and tell if a mobile device was located inside or outside of a specific room. The user can then control medical devices located in the room such as OR tables or OR lights depending on their position.
However, various requirements regarding healthcare facilities and the operating room make it difficult to select an appropriate technology. For instance, because of medical equipment, it is possible that no line of sight is given or that the environment (devices or people) changes which has a negative effect on the accuracy of the location tracking system. Interferences through already existing technologies are also a problem. After an evaluation and classification of several technologies, we focused on the radio-based ones. Furthermore, we also tested systems which were already available on the market and described first hand experiences and best practices. The goal was to develop a location tracking system, which tracks devices indoors with room level accuracy. Regarding radio-based technologies, we tested passive/active RFID, ZigBee, WiFi and Bluetooth. We looked at the advantages and disadvantages as well as the environmental requirements of each technology to see if they could be used in the OR. Based on the results, we developed a proximity-based location tracking system with Bluetooth Low Energy. With this system, we can achieve an accuracy of 1 to 3 meters. Depending on the environment and its conditions, the reliability can improve or drop. There were several problems such as signal strength fluctuations or the correct antenna orientation of the modules to solve and deal with during the development phase. Some issues were optimized but there is still room for improvement. Besides guide lines on how to install and configure the system, we also developed an automatic test procedure with a robot to save both time and money. We describe three practical use cases with the location tracking system as well as the option to combine the existing system with another, additional technology. In the end, we show various applications which can build on the developed system. They would first, improve the user experience and second, include new features to further enhance the system.

Zusammenfassung

Lokalisierungs- und Navigationssysteme werden immer häufiger in Bereichen wie der Logistik, der Medizin oder der Sicherheitstechnik eingesetzt. Sie zeigen Schwachpunkte auf und helfen Prozesse sowie Arbeitsabläufe zu analysieren. Es gibt verschiedene Technologien, die je nach Art der Anwendung, als Lokalisierungssystem eingesetzt werden können. Für Anwendungen im Freien gibt es zum Beispiel das GPS, welches für die Navigation in Autos verantwortlich ist. Ähnlich zu dieser wird eine Technologie zur Anwendung innerhalb von Gebäuden gesucht.
Da diese Arbeit in der Medizintechnik-Firma Trumpf Medical entstand, war der Einsatzort und Anwendungsfall auf den Operationsraum und umliegende Korridore festgelegt. Darauf basierend werden verschiedene optische, funkbasierte und akustische Technologien evaluiert, um ein adäquates Verfahren für den Einsatz im Operationsraum zu entwickeln. Dabei soll erkannt werden, ob sich ein mobiles Gerät innerhalb oder außerhalb eines vordefinierten Raumes befindet. In Folge dessen kann der Benutzer je nach Position bestimmte medizinische Geräte, wie OP-Tisch oder OP-Leuchte, steuern.
Verschiedene Anforderungen, die speziell für den Anwendungsfall Krankenhaus und Operationsraum zutreffen, erschweren die Auswahl der geeigneten Technologie. Beispielsweise können sich medizinische Geräte im OP negativ auf die Sichtverbindung auswirken. Darüber hinaus kann es zu wiederholten Veränderungen der Umgebung durch Menschen oder Maschinen kommen, was ebenfalls die Genauigkeit der Lokalisierung beeinträchtigt. Interferenzen durch andere bestehende Technologien stellen ebenfalls ein Problem dar. Durch eine Evaluation und Sichtung von verschiedenen Technologien wurde der Fokus auf funkbasierte Technologien gelegt. Zudem wurden auch bereits kommerziell vertriebene Systeme getestet und Anwendungsfälle sowie Erfahrungen aus erster Hand beschrieben. Das Ziel war es, ein System zu entwickeln, welches Geräte raumgenau innerhalb eines Gebäudes orten kann. Von den funkbasierten Technologien werden passives/aktives RFID, ZigBee, WiFi und Bluetooth für den Zweck der Lokalisierung getestet. Basierend auf räumlichen Anforderungen, der Infrastruktur und den Ergebnissen der Evaluation wurden anschließend Vor- sowie Nachteile der einzelnen Technologien erarbeitet, die daraufhin entsprechend den Einsatz und die Eignung im OP näher bestimmen. Im Anschluss an diese Auswertung wurde ein Lokalisierungssystem mittels Bluetooth Low Energy und der Abstandsmessung entwickelt. Mit diesem Lokalisierungssystem kann eine Genauigkeit von 1 bis 3 Metern erreicht werden. Dabei wirken sich die jeweiligen Umgebungsbedingungen positiv beziehungsweise negativ auf die Zuverlässigkeit aus. Während der Entwicklung galt es verschiedene Probleme zu lösen, zum Beispiel, Signalstärkeschwankungen oder die richtige Antennenorientierung der Module, die näher untersucht wurden. Zwar konnten im Rahmen der Entwicklung, Verbesserungen vorgenommen werden, Raum zur Optimierung bleibt jedoch weiterhin bestehen. Neben Anweisungen, wie das System am besten installiert und konfiguriert wird, wurde ein automatisiertes Testsystem mit einem Roboter entwickelt, welches dem Benutzer Arbeit und Zeit abnehmen soll. Es werden drei konkrete Anwendungsfälle des Lokalisierungssystems in der Praxis und die Erfahrungswerte daraus beschrieben. Auch die Möglichkeit, das bestehende System mit einer anderen, zusätzlichen Technologie zu kombinieren, wird betrachtet. Am Schluss zeigen wir verschiedene Anwendungen, die basierend auf dem System weiterentwickelt werden können. Diese dienen vor allem zur Verbesserung der User Experience und beinhalten zusätzlich fortführende, neue Funktionen für das System.

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I assure the single handed composition of this thesis only supported by declared resources.

Ich versichere, dass ich diese Arbeit selbständig verfasst und nur die angegebenen Quellen und Hilfsmittel verwendet habe.

München, den 14. Dezember 2015 Gel Han

Contents

Abbreviations

AFH	Adaptive Frequency Hopping
AoA	Angle of Arrival
BLE	Bluetooth Low Energy
EKF	Extended Kalman Filter
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
HF	High Frequency
HIS	Hospital Information System
IMU	Inertial Measurement Unit
IR	Infrared
KF	Kalman Filter
LF	Low Frequency
LOS	Line Of Sight
LWBS	Left Without Being Seen
ML	Maximum Likelihood
MMSE	Minimum Mean-Square Error
NLOS	No Line Of Sight
NN	Nearest Neighbor
NSR	Non-Significant Risk
OR	Operating Room
PLE	Path Loss Exponent
PoE	Power over Ethernet
RFID	Radio Frequency Identification
ROI	Return Of Investment
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RTLS	Real Time Locating System
SNR	Signal to Noise Ratio
TDoA	Time Difference of Arrival
ToA	Time of Arrival
ToF	Time of Flight
UHF	Ultra High Frequency
UWB	Ultra-Wide Band
WSN	Wireless Sensor Network

1 Introduction

In recent years, the use of location tracking systems in various areas such as transportation, logistics and medicine increased. These systems are used to primarily help locate people or devices and subsequently improve an existing process. Depending on the application, location tracking systems with different methods and technologies can be used. Global Positioning System, short GPS, is one of the most well-known and common technologies. It provides locations for devices such as cars. However, it only works efficiently when used outdoors. Companies such as *Ekahau* (Helsinki, Finland) or *STANLEY Healthcare* (Waltham, United States) offer RTLS (real time locating systems) for hospitals and healthcare facilities with a wide variety of technologies deployed. In most cases, these systems are used indoors, in patient rooms and corridors, to locate staff and required medical equipment. There are various technologies and methods for location tracking systems depending on factors such as scalability, accuracy, update-rate, price and range. Almost all systems provided by RTLS suppliers have their own infrastructure which leads to large installment and maintenance costs.

In this thesis, the main focus is on operating rooms (OR) and adjacent corridors as the area where objects and people should be tracked. The application, for which RTLS is required, can be described as mobile remote control for multiple different medical devices in the OR. The goal is, to find out if the remote control is located inside or outside a room to either enable or disable functions to control highly sensitive medical devices for a user. Several conditions have to be considered because of the OR environment and the application itself. Based on these, a location tracking system is developed and evaluated for the use in the operating room. The system uses Bluetooth Low Energy (BLE) as its main technology and relies on signal strength readings to determine, in which proximity a mobile device is located in regard to a stationary reader module (also called "anchor"). The developed system fulfills most of the requirements for the use in operating rooms but comes with a few disadvantages due to its technical specifications and nature. We try to bypass these disadvantages by applying algorithms and using additional sensors from the mobile device to obtain more data. These can be used to make the system more stable and reliable.

There are different applications, which can be tested and realized when the approximate locations of mobile devices and the medical staff are known. We evaluated some of these ideas and integrated the results into the final product: the location tracking system. As with all products in development, all the work done for this thesis was first tested in laboratory settings. Only once the results were satisfying, the work was applied to real surgeries. This was mainly made possible by tryouts of the final product in selected hospitals.

In the following, an outline is given with what to expect in each of the chapters of this thesis:

Chapter 2: Background and motivation
In this chapter, a background is provided on why RTLS are important and what their advantages as well

as disadvantages are. Since many systems are already commercially available and are deployed at hospitals, we look at existing work and studies about some of the requirements an RTLS has to fulfill for the use in a healthcare facility. Furthermore, we look into the issue of investment for an RTLS and what the drawbacks could be.

Chapter 3: Material and methods
This chapter provides information about components, technologies and methods which are or can be used for location tracking systems. We also try to categorize available technologies on their compatibility as a tracking system in the OR and rate them according to the factors mentioned in the beginning.

Chapter 4: Related work
We go through already existing work and studies on RTLS use cases in hospitals and technologies/methods being applied. This chapter provides a state-of-the-art overview with references and rough explanations on the findings of other studies in this area.

Chapter 5: RTLS systems in hospitals and ORs
In this chapter, we deal with the technologies and methods most used by already existing and deployed RTLS. We look at some of the companies and go through some first-hand experiences/case studies of their systems. This leads directly to the question, what the current, still open and unsolved problems concerning RTLS are.

Chapter 6: Evaluation
It was important to evaluate and analyze the technologies used in RTLS to get a better understanding on what the problems are or might be. We also wanted to test if we encountered the same advantages/disadvantages of the technologies as our research would suggest.

Chapter 7: Developing a location tracking system
This chapter describes the process of developing a location tracking system based on Bluetooth Low Energy from scratch but with all the previous research and requirements in mind for the use in the OR. Aside from hard- and software, we also take a closer look on how we could improve certain aspects to make it more stable, reliable and most importantly, provide results from various experiments.

Chapter 8: Applications
We present several applications with the developed location tracking system to support the users in the hospital/OR. We introduce three of these ideas and give a rough outline of the intentions as well as some first test results of mockups and prototypes.

Chapter 9: Discussion and further work
In this chapter, we discuss all the issues and problems we encountered during the development of the location tracking system and give an outline on things to work on in the future.

Chapter 10: Conclusion
This chapter provides the final conclusion of this thesis.

2 Background and motivation

In this chapter, we go into detail as to why RTLS are needed by pointing out some of the problems and issues hospitals are facing. The requirements which have to be met when using an RTLS in such facilities are explained and the benefits of a successfully deployed location tracking system are presented.

All the research and work for this thesis was done at the company *Trumpf Medical* (Puchheim, Germany). Trumpf Medical is a company providing medical technology solutions and equipment for the OR and has branches in several countries worldwide. In 2013, the company presented an OR integration system called "TruConnect", which connected various medical devices such as the OR table or OR lights to a remote control (see figure 2.1). The connection was established with optical as well as radio-based methods. Through the remote control, a mobile device such as a tablet, an authenticated and authorized user could control and change settings of the connected medical devices. One of the open requirements for a user of TruConnect was to move around and change rooms where the system had been installed and control respective devices in that particular room. What would happen if the user were to control one of the sensitive devices such as the OR table while walking out of the OR where the remote control was located? Not having a clear line-of-sight (LOS) to the patient on the OR table could lead to dangerous and life-threatening situations for the patient. So, once the user leaves an OR with his remote control, controlling the previously connected medical devices should be deactivated. Otherwise, a user could unintentionally control devices from adjacent operating rooms or corridors.

The goal was to develop a location tracking system for mobile devices which could be used to control highly sensitive medical devices in the OR.

2.1 Why RTLS are needed

Location tracking systems are being used in different areas such as logistics, marketing and medicine. Companies for consumer products such as *Apple* (Cupertino, United States) have been setting the trend to release and support tracking components which are affordable and accessible for the mass market. Taking the current trend as an indicator, the market for tracking systems will grow rapidly in the foreseeable future. In 2011, 256 million dollars were invested in RTLS worldwide and it is predicted [Res12] that that sum will increase with more systems being deployed in American and Asian markets.

Searching for specific medical devices and equipment in the OR and nearby corridors appears to be a problem and a big issue in larger hospitals since the time looking for and getting the equipment translates to wasted time of the staff members. [MTG+06] state that medical assistants usually spend 37 minutes, nurses 18 minutes and medical doctors 6 minutes per day to find certain people or the right equipment. Tracking these would therefore support the staff and make the management of inventory more effective.

Figure 2.1: Staff members can control medical devices through a remote control. The mobile device can be sterilized and offers an intuitive graphical user interface (GUI) with 2D/3D representations of the table, lights and other equipment in the OR. Image courtesy of Trumpf Medical.

Consequently, this leads to an improved organization and a more effective use of devices [KBB12]. As a result, storage and maintenance costs, which would be spent in investing in new devices and accessories [KLM10], are decreased. Since the medical staff is a part of the location tracking system, them having to waste less time for the search of devices can improve their performance and satisfaction, which in return can lead to improved patient care. According to [CW07], hospitals such as the *Harmon Medical & Rehab Hospital* (Las Vegas, United States), *Cardinal Health Inc.* (Dublin, United States) or the *Chang Gung Memorial Hospital* (Taoyuan City, Taiwan) already work with RTLS and are using it to track surgical patients, medical assets and hospital staff.

There is already quite a bit of research on location tracking in the fields of radio engineering, electrical engineering and computer science. The first step was to gather information about the environment and working conditions under which the location tracking system had to be used by the users to sort out technologies/methods which did not fit. A few of these conditions are listed below:

- (Moving) objects consisting of metal or similar material present in the OR
- At least four staff members present in the OR, either standing/sitting still or moving
- Many sensitive devices in the OR, some of them working on radio basis
- Changing light conditions depending on the surgery, inconsistent sound level/noise
- Constantly changing environment
- At least two doors (one for entering and one for exiting the patients on the OR tables) for each operating room
- Some operating rooms are adjacent (and might be connected through a smaller storage room) to each other

- A corridor leads to all the operating rooms
- In some operating rooms, there are walls consisting of reinforced concrete
- Shielded rooms
- It is difficult to lay long cables through several rooms and get power/electricity from the ceiling or walls

It will get clear in the later chapters why many of these requirements already eliminate a lot of technologies/methods in the first place. Considering these conditions, various companies offering RTLS for healthcare facilities were evaluated and analyzed. Most of them use a combination of two technologies to guarantee a certain accuracy, update-rate and scalability. We also tested some of the widely-used technologies in RTLS and rated them by the following criteria: **Scalability**, **Price**, **Accuracy**, **Update-rate**, **Range** and **Battery life**. These criteria will be explained in detail in chapter 3.1.

With a hospital's building structure and infrastructure in mind, we also look at the requirements a location tracking system should fulfill when used in such an environment [FM12]:

- Small form factor and easily attachable
- Low need for maintenance, long lasting batteries
- Connection to the internal hospital network
- Storage for calculated data
- Accuracy at least at room level
- Sterilizable tags
- One anchor can detect up to 20 tags
- Indication of the device status such as "in use" or "not in use"
- High reliability, little to no fluctuations in the calculated positions
- Flexible and highly reactive with changed positions (within 10 seconds)
- Robust with little to no probability of failure

Depending on the use case of how the location tracking system is deployed, different factors are important. For instance, when it comes to asset management, "Connection to the internal hospital network" is a substantial requirement to have. With a connection to the network, an application could read and list all available and tracked medical devices and display them to the user. If the use case for the system is to find certain accessories for an OR table, the determination of whether room level accuracy is sufficient for that task, needs to be assessed.

2.2 Investing into RTLS and its outcomes

We have made the experience that commercially available multi-room location tracking solutions come with a very high price tag. In almost all cases, tags are the cheapest while the anchors and the location engine are the most expensive components of an RTLS. For an RTLS using ultra-wide band (UWB) technology and requiring four anchors per room, installing it in one OR could cost up to 10.000 Euro. Scaling this sum to more than one room, it is clear that the hospital has to initially invest a large sum to deploy such a system. [Jou11] explain, how this sum can be calculated for a specific setup and how long it takes to see a return of investment (ROI). There are a lot of advantages when using an RTLS and also many possibilities to combine RTLS with other context-sensitive/aware applications:

- Get the position of staff members and devices when looking for someone/something specific (and notify them if needed).
- Automatically trigger events by marking certain areas (zones) such as alarms or displaying patient data on screens when he or she is being transferred into the OR.
- Automatically update the OR schedule by intelligently observing the OR times and call for the next patient to be prepared for the upcoming procedure. Also, notify specific staff members that the next patient is coming.
- Calculate exact OR times for automatic controlling.
- Identifying automatically, which accessories are attached to medical devices, for example, an OR table.

These advantages are compared against the time it takes for the RTLS to have an ROI. Only if the requirements and use cases for the RTLS and the return in terms of money and time are clear, it is recommended to deploy an RTLS in a hospital [FM12] [KBB12]. Companies such as *CenTrak Inc.* (Newtown, United States) or *Ekahau* (Helsinki, Finland) have successfully deployed systems in many hospitals with an ROI of five to six digit figures and more. Figures like these prove the immediate as well as fast savings in money and time because of efficient tracking and finding of equipment and/or people. On the downside, the ROI decreases over the years due to maintenance and support expenses for an already deployed system.

While tracking personnel or equipment can be invoked actively by a user, the location tracking system always works passively in the background. By knowing that a certain person with, for example, a badge has entered a specific room or area, the tracking system can set off certain events or processes such as handling and performing checks the person would have to make manually or by sending information to people. The location tracking system, once deployed and running, acts as a ubiquitous system which collects, computes and provides data to an application for the end user.

3 Material and methods

As mentioned in chapter 2, the task was to develop a location tracking system which fulfilled most of the requirements to be used for TruConnect. In this chapter, all the material as well as methods used during the development are presented. We give an overview of various tracking technologies and methods to calculate positions for tags, only going into depth when necessary. Parts of this chapter were published at the "Deutsche Gesellschaft für Computer- und Roboterassistierte Chirurgie e.V. (CURAC)" in Bremen in 2015 [HMVK15].

3.1 General

There are different parts of a location tracking system, which play an important role when obtaining a position. The most important ones are the anchor and the tag. These components will be explained more thoroughly in the following.

3.1.1 Components of an RTLS

According to [Mal09], an RTLS mainly consists of three components:

- **Anchors**
  These are in most cases the modules mounted on ceilings or walls. They scan the environment/area for other modules (tags), which send out information to detect them.
- **Tags**
  The sender modules, also called "Tags", are attached to trackable devices or people and send out ("advertise") information in a specific time interval for the anchors to find them. Usually, the tags run on batteries and have a small size factor.
- **Location engine**
  The location engine is a software installed on a computer in the back end where all the collected data of the anchors comes together to compute a position of a tag. There are several different possibilities on how to calculate a position, which will be described in the following subsections. In most cases, there is an interface for the location engine providing a graphical interpretation or visualization of the system for the users.

The information, where a certain tag is located, is provided by the location engine. Figure 3.1 shows, how all the components work together. All the anchors are connected to either a gateway or the computer directly, where the calculations of the tag's positions happen. This procedure/setup is used similarly in all the tracking technologies including optical, radio-based and acoustic ones. Criteria such as price and scalability are dependent on the number of rooms (basically the building infrastructure) and also the number of components being required. The amount of anchors also directly influences the possible range of the system. In the following section, the criteria used for the evaluation of the technologies are briefly explained.

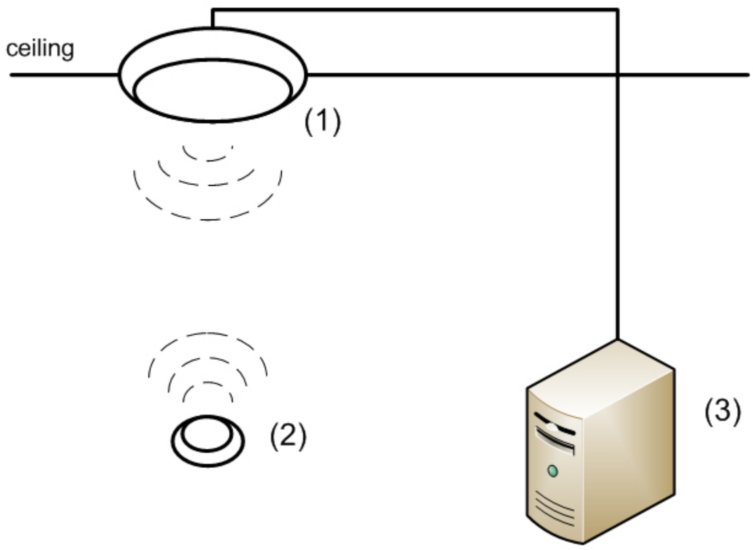


Figure 3.1: The components of an RTLS. (1) is the anchor, which is usually mounted on a ceiling and therefore stationary. (2) is the tag attached onto a device or a person and (3) represents a computer with the installed location engine.

For all the technologies, there are three types of tags to be differentiated:

- **Passive tags**
  Passive tags work without batteries and once detected in the anchor's RF field, send out data such as an ID. They receive a very small amount of energy in the RF field to transmit data back to the anchor (also called "backscatter"). The range, in which the tags can be detected, is very dependent on the antenna of the anchor and there are limitations regarding the data throughput of the tags. Compared to other tags, passive ones are very simple and therefore, inexpensive. In real life application, they are used for anti-theft protection in stores or in tracking of animals.

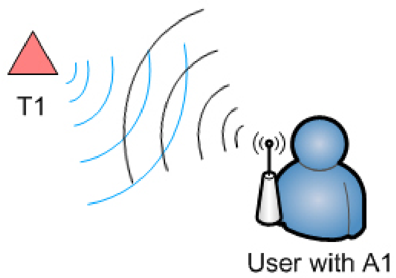
- **Semi-passive tags**
  These tags work in the same way passive tags do, but they additionally include a battery. The battery is used to power additional sensors on the tags or to transmit data more reliably by expanding the range [Mal09]. Detection of the semi-passive tags is still accomplished with backscatter.

- **Active tags**
  Active tags are powered by a battery and include a radio module which can be used to send out data autonomously or to communicate with an anchor. These tags also come with a chip for processing data (a processor) and a higher range than the other tags but are in most cases, far more expensive. Due to the tags being active (processing and sending out/communicating), the energy consumption increases which affects the battery negatively. On the one hand, the size is bigger because of the built-in hardware but on the other hand, data can be computed and operations can be made on

the tags because of the processor. Another advantage is that the user can configure, what is transmitted and in which time intervals. Small applications for the tags such as sending out information frequently when in motion and pausing when idle can be implemented due to the availability and the options of including additional sensors.

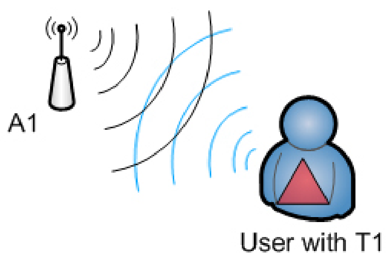
There are a few variations on how a tracking system can work: inside-out, outside-in or inside-in. In most cases, the technologies are based on the outside-in principle.

- **Inside-out**



In this case, the tags (T1) are mounted stationary in the environment and the anchors (A1) are placed on the mobile object(s).

- **Outside-in**



The anchors are mounted stationary in the environment and the tags are placed on the mobile object.

- **Inside-in**
  The anchors and the tags are both mounted on the mobile object [Kei11].

When talking about RTLS, the question remains what the definition of "real time" is. Every system comes with latencies due to hardware or software issues and all providers or developers of RTLS specify a certain time span between action A and action B where an event C should happen. Real time is more commonly used as a term to describe that in a live system, data is being measured, processed or computed continuously. The update-rate, which is closely related to “real time”, is discussed in more detail in the following section and in chapter 4.1.

3.1.2 Criteria for technologies

Most of the following definitions and explanations of the criteria important to us align with those of [LDBL07] and [GLN09].

- **Scalability**
  This criteria describes how well the technology is scalable for two variables: infrastructure and tags. In case the area for tracking expands, the effort to install new tracking modules, to connect new infrastructure to existing one and to configure the system for the new rooms should be reasonable. The same goes for additional tags/badges for an increased number of users/equipment. Other factors such as accuracy or update-rate should not decrease when more tags are being used.

- **Price**
  The price range of technologies varies vastly depending on the use case. Few technologies are affordable. However, affordability comes with a price: These technologies do not offer high accuracy. There are also technologies, which are quite new and caught interest in the recent years (such as UWB). Usually, these are pricier than the other technologies, which already existed longer. Nowadays, in most RTLS, the location engine is the most expensive part. Tags such as passive RFID stickers are generally the most affordable components. Another important factor is maintenance and support required for the used solution in the RTLS. Depending on if a calibration process has to be done just once at the beginning or every month to guarantee a certain accuracy, the costs could accumulate to a larger sum. Long-lasting batteries for tags can also reduce the maintenance time and the costs to replace them.

- **Accuracy**
  The accuracy can be defined as follows:

  - Zone level
    A defined area (zones can represent patient beds or cover an entire floor of a building), where tags can be found.
  - Room level
    Tags can be assigned to specific rooms.
  - Sub-room level
    It is possible to divide a room virtually in several small areas, where the tag is located.
  - Association level
    A tag can be located in the immediate vicinity of another tag.
  - Exit/entry level
    A tag is located when it passes a choke point (for example doors).
  - Distance
    The estimation error of a tag between the real and the calculated position can be given at any time with an accuracy of 95%.

Usually, accuracy is one of the most important criteria and is often taken to compare two RTLS. It stands for the average Euclidean distance between the computed position by the RTLS and the actual one (also called position/location error). The smaller the distance, the more accurate the system. However, in many cases, increased accuracy also comes with higher expenses for better components. Another criteria which is closely related to accuracy is “Precision”. It specifies in percentages, how often a certain position error occurs. For example: It is very common for RTLS providers to declare in their specifications that their system is reliable and can reach 2 meters 99% of the time (with 2 meters being the accuracy and 99% the precision).

- **Update-rate**
  The update-rate describes at which rate new information from either the tags or the anchors can be processed by the RTLS to obtain a new calculated position. This criteria is important when looking at the latencies the RTLS might bring, for instance in case the results/positions need to be visually shown to the user. Most technologies come with an update-rate in seconds. These are also the affordable ones (BLE) while others have faster update-rates but are more expensive (WiFi, UWB). The used update-rate depends on the application and needs to be chosen wisely, regarding sufficiency and satisfaction.

- **Range**
  Although most of the mentioned technologies are only used indoors, the range plays an important role when deploying an RTLS in a new environment such as a hospital. The range is normally defined by the maximum distance between an anchor and a tag without them being disconnected. The higher the range, the fewer anchors are needed depending on the method of calculating the tag’s position. The range is highly dependent on the technology used. For optical tracking systems, among other factors, it is given by the focal length of the camera while for radio-based systems, it is specified by factors such as the wavelength, transmitting power, antenna types, radio propagation or the path loss.

- **Battery life**
  A long battery life is important for tags to ensure smooth operations for a longer period of time. The longer the battery life, the less support and maintenance is needed. Typically, the battery life is specified in years (for example, Bluetooth tags usually last 2-5 years on a coin cell battery).

Aside from these, other criteria include “Integrity”, “Interface”, “Privacy”, “Security”, “Infrastructure” which will not be discussed any further here.

3.2 Methods

In the following, various methods on how to measure and collect data with the tracking technologies are described. We only go into detail about the most interesting ones and the ones we used and tested in experiments ourselves. For more information about these as well as other methods such as Round Trip Time (RTT) or Phase of Arrival (PoA), see [Mau12] and [Mal09].

3.2.1 Time of Arrival (ToA), Time Difference of Arrival (TDoA)

Time of Arrival (ToA)

In Time of Arrival (used synonymously for "Time of Flight" (ToF)), the absolute travel time of the signal (also called "propagation delay") between the anchor and the tag or vice versa is taken and converted to a distance value. The time is usually multiplied with the speed of the propagating signal (speed of light) which results in the distance between the two components. To determine the propagation delay, anchor and tags need to run synchronized clocks with nanosecond-resolution. Offsets or drifts in the clocks can result in large location errors.

Time Difference of Arrival (TDoA)

Time Difference of Arrival is different from ToA as it takes the times, when a signal was sent from a tag and when the same signal arrived at an anchor, to calculate the difference resulting in the distance between anchor and tag. Similar to ToA, the use and the correctness of the synchronized clocks play a very important role when determining an accurate position in the end. The signal traveling from anchor to tag can be reflected, scattered, diffracted or refracted. These effects would result in a longer traveling time, hence line of sight (LOS) would increase the location accuracy significantly.

3.2.2 Angle of Arrival (AoA), Angulation

The Angle of Arrival (AoA) is used to compute the position of a tag by measuring the directions (or the angles) from an antenna array and then calculating the intersection point of the signal propagation paths. Generally, two or more anchors with directional antennas are used to measure the angles of propagating signals from a tag. Depending on the resolution and the error of the angle measurements, the location error of a tag can increase/decrease significantly. AoA is recommended for use in environments, where direct LOS measurements are given.

3.2.3 Received Signal Strength Indicator (RSSI)

A tag emits a signal with a certain power level which decreases over distance through various influences such as multipath effects, shadowing, obstacles or even temperature and humidity (see [Gol05]). The anchor can then measure the strength of the received signal and use it as an indicator for the remaining power of the propagated signal from the tag. The received signal strength (RSS) is usually specified in dBm (ratio of measured power in relation to 1 milliwatt) and a non-linear translation of the RSS values results in RSSI values, typically ranging from 0 to 100.

The signal attenuation can be defined by a path loss model which is described in the following. When specific variables such as a reference RSSI value at position d_0 and the attenuation factor γ (also called Path Loss Exponent) are known, the Log-Distance propagation model can be used to estimate signal strength values at a distance d.

Once a radio signal is emitted from a tag, it attenuates and decreases in power/strength until it is received by an anchor. The decrease in the power level can be measured by path loss models which consider absorption characteristics of objects obscuring the LOS between anchor and tag. There are various path loss models such as the "Okumura" model, "Hata" model or the "Piecewise Linear Multislope" model

[Gol05] which are all applicable and designed for different distances and frequency ranges. For tests with radio-based technologies such as WiFi or Bluetooth, we look at the Free-Space path loss model which is used to describe the signal attenuation in an environment where LOS between the anchor and the tag is guaranteed. The "Free-Space" path loss P_L is defined as:

$$P_L \text{ [dB]} = 10 \, log_{10} \frac{P_t}{P_r} = -10 \, log_{10} \left[\frac{\sqrt{G_l}\lambda}{4\pi d} \right]^2 \tag{3.1}$$

P_t is the transmitted signal strength and $\sqrt{G_l}$ can be derived from the "Friis" transmission equation (see [Mol05]) which is the product of the transmitting and receiving antenna gains G_t and G_r. λ is the signal wavelength and assuming we have isotropic antennas, the signal propagation is uniform and can be taken as a sphere (surface $A = 4\pi r^2$) with an antenna aperture of $\frac{\lambda^2}{4\pi}$ ($\frac{P_r}{P_t} = \frac{G_t}{4\pi d^2} \frac{\lambda^2}{4\pi} G_r$). To calculate the received signal strength for a certain distance d, we would need to convert equation 3.1 for P_r. Instead of using the equation from the Free-Space path loss model, we take the equation from the "Simplified Path Loss" model (also known as the "Log-Distance" propagation model) which is simple and more commonly used when working with signal propagation as well as attenuation. This gives us the following equation:

$$P_r \text{ [dBm]} = P_t \text{ [dBm]} + K \text{ [dB]} - 10 \, \gamma \, log_{10}(\frac{d}{d_0}) \tag{3.2}$$

With a signal strength value P_t measured at distance d_0, we can calculate the RSS value in dBm at distance d. γ represents the attenuation factor (also called Path loss exponent) which describes the path loss effect of the signal for various environments. Factors such as different material composition for walls and floors, size of the room, objects consisting of different materials occluding the LOS, windows, people present and the number of floors in a building are considered. Table 3.1 shows the Path loss exponents from [Gol05]. [Gol05] also state that the higher the frequency used by the technology to emit a signal, the larger the path loss (per floor).

Table 3.1: Path loss exponents for different environments

Environment	**Path loss exponent (range)**
Factory	1.6 - 3.3
Office building (same floor)	1.6 - 3.5
Store	1.8 - 2.2
Free space	2
Office building (multiple floors)	2 - 6
Urban microcells	2.7 - 3.5
Home	3
Urban macrocells	3.7 - 6.5

Equation 3.2 can be modified to include the shadowing effect χ which results in the "Log Normal Shadowing" model. χ is a zero-mean normally distributed value:

$$\chi_\sigma \sim N(0, \sigma^2)$$

If the frequency is higher, the possible range of the radio-based module decreases. The design of the antennas in the tags and anchors also plays a major role when it comes to reliable signal strength measurements. [BKRG$^+$14] and [RH91] conducted tests with various types of antennas (linear and circular) and the test results showed that for RTLS purposes, the circular polarized antennas were advantageous because of reduced multipath effects. Most of the modules with embedded chips come with linear polarized internal antennas but the providers offer variants with connectors for external ones with different propagation patterns.

When taking the signal strength values to compute a position, ideally we can rely on its stability for a stationary module. However, this is not the case. The electromagnetic waves used by the radio-based technologies can be either reflected, scattered, diffracted or refracted which causes the measured signal strength value to fluctuate. This effect is called "multipath fading" and is caused by objects which are obstructing the LOS. Signals thus have a shorter/longer path to their destination than intended.

3.3 How to compute the position

In the following, various approaches on how to compute the final position of a tag when all the data is gathered are explained. The approaches can not be applied to any method/technology but rather rely on the existing/available one. Techniques such as "Cell of Origin" (CoO) or "Connectivity Based Positioning" are omitted from this section because of their inapplicable functionality and inaccurate/unsatisfactory outcomes for our purposes.

3.3.1 Proximity Detection

This method is used specifically for radio-based technologies. There are two options to implement it: either the anchors solely check if tags are in range or the signal strength of the tags is measured and, depending on the highest signal strength value, it is assigned to a certain anchor. The first variant applies to technologies which already have limited range and do not have ToA, TDoA or ToF capabilities. The second option can be implemented by most radio-based technologies as measuring the signal strength is a very standard procedure [PH03] [BLCG09]. However, various undesired problems regarding signal strength measurement such as multipath effects, reflections or shadowing can occur which make this method inaccurate when calculating a location. With filtering algorithms, these problems can be handled to a certain degree but they cannot be removed/solved completely due to the physical aspects of the transmitting radio-based signal and its behavior (see [Gol05]).

3.3.2 Trilateration

Trilateration uses the ranges measured (or estimated) from at least three anchors to compute the position of a tag. These ranges/distances are usually derived from the time a signal takes to travel from the tag to the anchor (ToA) but can also be taken from propagation models in combination with RSSI measurements. In figure 3.2, the approach on how the position is calculated can be seen. As with any method using the time of traveling radio-based signals, the computation can be difficult because of inaccurate clocks on tags/anchors or environmental influences such as multipath effects. Trilateration is one of the most used methods in location tracking because of its simple implementation for a relatively precise position definition (see [HHB$^+$03]).

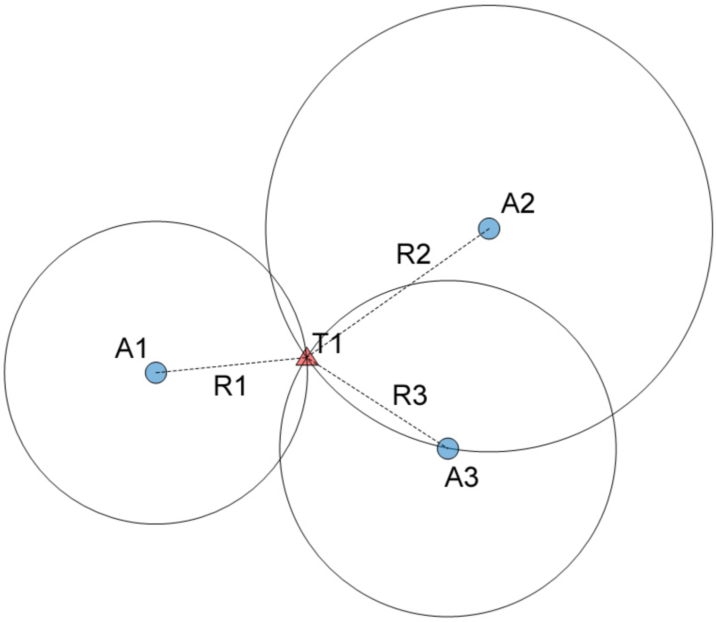


Figure 3.2: Through ToA or TDoA, the three radii R1-R3 of the anchors A1-A3 are determined and the intersection of these radii represents the position of the tag T1.

3.3.3 Triangulation

To compute the position of a user in 2D with Triangulation, the angles measured by two anchors with respect to a sensed tag are required. The path between anchor A and anchor B is used as base line. A line from anchor A in direction of a tag T can be drawn with an angle α and a second line can be drawn from anchor B but with angle β, basically forming a triangle with varying sides. The intersecting point C should represent the position of the tag T. For a calculation in 3D, at least three anchors are needed. Depending on the implementation and definition of the angle for anchors and tags, three conical shapes can be drawn around each anchor with their respective angles. All three shapes and their angular lines should intersect at one point which represents the position of the user. No positional information can be given if there is no unique intersection point.

3.3.4 Dead Reckoning

In Dead Reckoning, the information of various inertial sensors such as velocity (speed and direction) or acceleration from tags with attached inertial measurement units (IMU) are used to estimate and calculate the position. Using a certain initialization position and including the tag's parameters, its movement is analyzed [FNI13] [Mol05]. The tags can be attached to objects such as patient beds or worn by the medical staff members. The main problem with this method is the possibility to "drift". Small errors and deviations in the sensor measurements (and therefore also in the position estimates) will accumulate for all subsequent positions. [Mal09] specify, how additional information from other sensors can be used to reset the position and decrease the likelihood of errors. If inertial sensors are available to the user, Dead Reckoning is an essential method when combining it with other solutions/technologies to improve the accuracy of an RTLS. It works complementary to direct sensing and is important to have in cases when other technologies with direct sensing are temporarily not available. It is also used quite frequently when the options of installing location infrastructure such as anchors in rooms are limited. Another advantage is the high accuracy (in centimeters) in case the position is not drifting. On the other hand, high power consumption of the sensors and the high maintenance effort/costs as well as the requirement for repeated accurate initialization positions make the method difficult to use in uncontrolled environments. For more details about inertial sensors, see section 3.4.

3.3.5 Fingerprinting

This method consists of a map and two stages [Mau12]: in the first stage, a lot of data is recorded from the anchors and saved into a database (also called the offline phase). The data consists of signal strength measurements between the distributed anchors A_1, A_2, A_3 (at least three anchors to make it uniquely identifiable) and a tag and a position p on a map. In the second stage (online phase), the live data/the signal strength measurement of the anchors is compared to the already recorded data and depending on the comparison method, a location of the tag is determined. Usually, in the first stage, the user is moving around in the area covered by the location tracking system and pinpoints his position on a map. At the same time, a measurement is recorded to give the current position a unique identifier (mostly consisting of a triple combination of signal strengths or other parameters). These identifiers are stored in a database with the corresponding positions on the map.

Once the user gets the live data in stage two, they are compared to the existing identifiers in the database. It is recommended that fingerprints are recorded every time, changes occur in the environment since these changes can lead to different signal strength values for the area. The user will be getting satisfying location tracking results when the map was recently created and all the fingerprints were recorded in the same environment where the user will be testing the system. But once something changes, the map for the environment has to be remade which increases the calibration effort. Also, other radio-based technologies could interfere when measuring the signal strength values to be stored in the database. Figure 3.3 shows a map with fingerprints recorded in a test area with three anchors.

When measuring the tag's signal strength values from anchors, the location engine usually measures several values from which the average is stored in the database. For our tests with Fingerprinting, we chose to compute the positions with the help of "Pattern Recognition" and "Maximum Likelihood". These two methods will be described briefly in the following paragraphs. In general, if more fingerprints are taken and the fingerprint map is more dense, the better the accuracy when calculating a position. One disadvantage of using just the minimum amount of anchors for fingerprinting occurs when multiple identical RSSI combinations are measured at different positions (also called "aliasing"). This is caused by fluctuating RSSI values and leads to inaccurate results in the end.

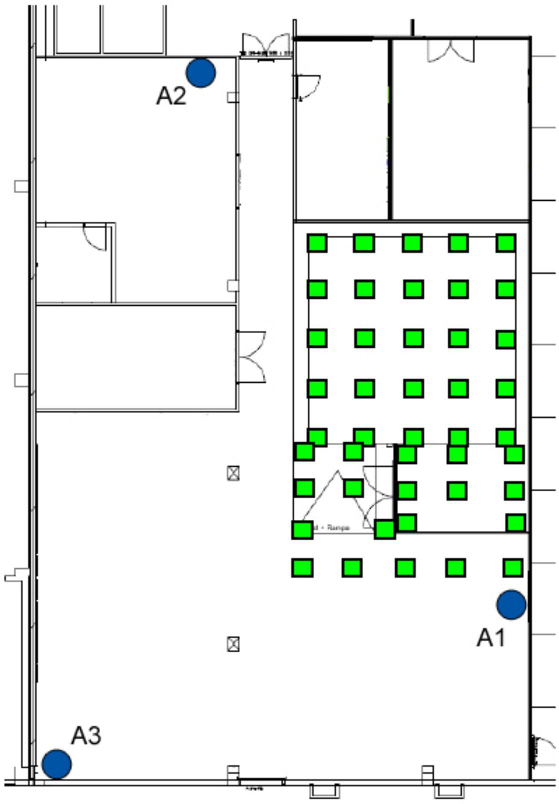


Figure 3.3: An example on how the fingerprint map can look like. A1-A3 represent WiFi anchors distributed in the area and the green squares represent the fingerprints taken at the respective positions on the map. Figure from [Mei14].

Pattern Recognition

A widely-used prediction method to assign a position from live RSSI measurements is the "Nearest Neighbor" method. The Euclidean distance is calculated between the live RSSI measurement of three different anchors of the tag and the stored fingerprints in the database. The fingerprint and consequently the position with the minimal Euclidean distance serves as the result for the Nearest Neighbor. Another variation, the "k-Nearest Neighbor" (kNN) considers k fingerprints which are closest to the measured RSSI combination according to the Euclidean distance. Then, the centroid of these k fingerprints is computed which also serves as the estimated position of the tag. An extension of the kNN is the inclusion of weights for the k fingerprints. If the distance between fingerprint k_i and the current signal strength measurement is small, k_i is given more weight and vice versa.

Maximum Likelihood (ML)

At each position p_i of the map where a fingerprint is recorded, a histogram is saved in the database with the percentages of how often an RSSI value was recorded during measurements in the offline phase for each anchor. The histogram for each position and anchor would range from the minimum to the maximum RSSI value measured at that point. In the online phase, the signal strength value measured from each of the anchors is then cross-referenced in the histograms. The percentages computed for a specific RSSI value for each anchor at various positions are then multiplied for all the anchors. The tag is then assumed to be located at the position with the highest percentage value. For more details about the Maximum Likelihood, see [Gol05]. Similar to the kNN, the centroid of the k positions for ML with the highest calculated percentages can be taken as the estimated position of the tag. Additionally, as mentioned in the last section about Pattern Recognition, weights could be used to make the method more accurate.

3.3.6 Filtering

One of the most commonly used methods with radio-based technologies is RSSI measurement. The signal strength of a tag is measured to find out if it is in proximity of an anchor or not. Before computing the position of a tag with the measured signal strength values, a filter can be used to smoothen the recorded values. In the following, some of these filters we used for experiments are presented.

Raw values
Here, we just take the raw values as they come in to calculate the position.

Average
We calculate the average value of the newest signal strength value and the previous one, which was stored by the location engine. Then we declare it as the new value with which the position should be calculated.

Moving average
Instead of calculating the average value with just the previous signal strength value, we take more stored values into consideration. We declare x the amount of the last measured signal strength values we want to use for the average. The sum of all x signal strength values is calculated and then divided by x. The new value is then taken to calculate the final position. This filter helps to smooth out the signal when there are a lot of fluctuations. The larger x, the smoother the signal but the responsivity/reactivity decreases and as a consequence, quick changes in the position are detected with more latency.

Weighted moving average
This filter is similar to the moving average described previously but before calculating the sum of all signal strength values, they are multiplied by weights. The weights add up to 1 and represent the percentage of how much a particular value is factored into the new signal strength value. Usually, old signal values are only accounted for with small weights while newer signal strength values are multiplied with bigger weights.

Kalman filter
The Kalman filter is one of the most used filters for real time applications because of its ability to process inaccuracies and interferences for unknown variables. It takes measurements of variables over a certain time-span and estimates the next values for these variables through observations. For linear conditions, the Kalman filter represents an optimal minimum mean-square error (MMSE) estimator [Gol05]. The filter works recursively and only needs the current measurement of the variables and estimate of the previous step to calculate the next state.

The algorithm works in two steps/states:

1. **Prediction**
   In this step, the previous estimate at time step $k-1$ is used to compute a new estimate at time step k. This new estimate is called the "a posteriori" state estimate and is given as [KPV12]:

$$\hat{x}(k|k-1) = F\ \hat{x}(k-1|k-1) \tag{3.3}$$

   F is a matrix which describes the transition from one state to another. The covariance matrix, which represents the accuracy of the "a posteriori" state estimate, is given as:

$$P(k|k-1) = F\ P(k-1|k-1)\ F^T + Q \tag{3.4}$$

   Here, Q is the noise covariance matrix and is further described in [KPV12].

2. **Update**
   In the update step, the "Kalman gain" given as K is computed with:

$$K = P(k|k-1)\ H\ [H\ P(k|k-1)\ H^T + P_r]^{-1} \tag{3.5}$$

   Then, the "a posteriori" state estimate and covariance matrix are updated:

$$\hat{x}(k|k) = \hat{x}(k|k-1) + K(r(k) - H\ \hat{x}(k|k-1)) \tag{3.6}$$

$$P(k|k) = (1 - K\ H)\ P(k|k-1)\ (1 - K\ H)^T + K\ P_r\ K^T \tag{3.7}$$

   r represents the observations made at time step k and is given as:

$$r(k) = H\ x(k) + v(k) \tag{3.8}$$

   v is a variable depicting noise and uncertainties in the model. Generally, a zero-mean, Gaussian white noise sequence is used. As initial state, a Gaussian random variable is used for both the state estimate and the covariance matrix.

For non-linear observation models, the “Extended Kalman Filter” (EKF) can be used. [KPV12] and [S. 08] present several variations of the Kalman filter and give more insight into their derivations to the original Kalman filter and for which applications they can be used.

Gaussian filter
The Gaussian filter is primarily used in image processing and is a low pass filter for smoothing and removing noise from images (also called “Gaussian Blur”). The one dimensional variant of the Gaussian filter can also be used for smoothing RSSI values with the following Gaussian function:

$$G(x) = \frac{1}{\sqrt{2\pi} \cdot \sigma} \cdot e^{-\frac{x^2}{2\sigma^2}} \tag{3.9}$$

x in this case is the input and measured signal strength value and σ^2 the variance, which is set at the beginning when initializing the filter. The function is used to calculate the Gaussian kernel for a particular kernel size n which consists of values following a Gaussian distribution. Both, the kernel size and the variance, play an important role when it comes to the strength and magnitude of blurring.

3.4 Technologies

We look at commonly used optical, radio-based, acoustic and inertial technologies for location tracking in an indoor environment and rate them according to the criteria from section 3.1 with the following legend:

+	positive, better, affordable, more accurate, smaller in size
o	sufficient, even
-	negative, worse, expensive, less accurate, bigger in size
/	unknown, not applicable

3.4.1 Optical

In an optical tracking system, a camera acts as anchor with the video-feed of the area as the source for tracking. The images taken from the camera are scanned for tags. The better the camera, the better the achievable range with the tracking system. In an outside-in system, simple tags are sufficient to detect objects in several degrees of freedom. One of the disadvantages is the high cost of the anchors and the large amount of image data, which is constantly recorded and analyzed. Since computers improved in their performance over the years, the problems of processing the images and hence, the latency when computing coordinates for tags decreased. However, there is still the issue of necessary LOS in an optical tracking system.
To get the position of a tag in 2D coordinates, one image source (for example a camera) is sufficient. To have coordinates in 3D with several degrees of freedom (translation and rotation), at least two cameras are required.

Marker

There are several different approaches for markers. The most common ones are retro-reflecting balls and bit-patterns, which are mounted on objects. Then, the video images are scanned for these markers. When they are found, the position of the object can be calculated through the positioning of the markers in the environment. For the retro-reflecting markers, infrared cameras are used. The cameras send out infrared signals, which are reflected to the emitting cameras by the balls. In both cases, the balls and the bit-patterns, unique constructs (specific arrangement of balls on sticks, see figure 7.15) are used to clearly identify the objects in the images.

Object-based / 3D-model

The images from the anchors are scanned for objects with known outlines or proportions (for example based on a 3D-model). One of the advantages is that this method does not require any hardware or reference tag besides the anchors.

Projection

One or more reference points are projected on the mobile object of choice. Then, these reference points are detected in the images retrieved by the anchors. One disadvantage is that both, projector and anchor/camera, require LOS to the mobile object.

Image-based

This method consists of two phases: the offline- and the online-phase. A camera mounted on the mobile object records images at specific positions (these positions are also saved on a map) with a site survey in the offline-phase. In the online-phase, the actual live-images are then taken and compared to the ones saved from the offline-phase. The position, where the offline-image has been recorded, can be further taken as the estimation/assumption of the user's current position. One of the difficulties with this method is the high processing power required for comparing large amounts of image data. This can also influence the latency negatively but as already mentioned, this problem improved significantly throughout the last years because of better processing units in computers.

Infrared

Infrared is used mostly because of the property that signals can not penetrate objects and that it is reflected by surfaces to stay inside a room and therefore achieve room level accuracy. Infrared cameras are used as anchors and modules which send out infrared signals as tags. There are two variations of infrared tracking: "Direct IR", which uses a 1-1 connection/relation between anchors and tags (LOS is therefore necessary) and "Diffused IR", which floods a room with infrared signals from tags where one or more anchors can pick them or their reflections up.

Comparison between optical technologies

Table 3.2 shows all the mentioned advantages and disadvantages of the optical technologies summarized for the criteria from section 3.1.

Table 3.2: Comparison between optical technologies.

Technology	Scalability	Price	Accuracy	Update-rate	Range	Durability
Marker-Tracking	+	-	++	++	o	/
Infrared	-	o	+	+	-	+
Object-based	+	-	o	++	o	/
Projection	o	-	+	++	-	/
Image-based	+	-	+	++	o	/

3.4.2 Radio-based

All the discussed technologies are available as off-the-shelf products from various companies. Some of these products are evaluated and tested in later chapters. The used frequencies from these technologies range from 30 kHz (LF RFID) to 10.6 GHz (UWB) (see figure 3.4).

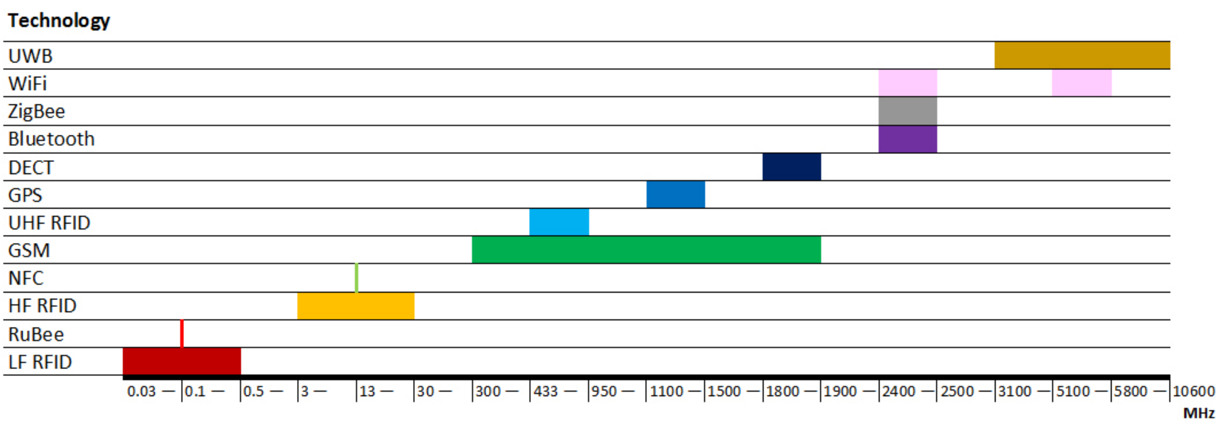


Figure 3.4: This graph shows most of the radio-based technologies including their frequencies and range (in MHz).

Most of the technologies discussed in the following rely on an IEEE standard such as ZigBee (802.15.4) or WiFi (802.11) and provide detailed specifications as well as various modifications of the standard itself. All the methods work with electromagnetic waves (in the range of 10^7 kHz) which implies that they also come with all their physical advantages and disadvantages. Figure 3.5 shows the radio-based technologies with respect to their resolution/viable accuracy and scale/use case.

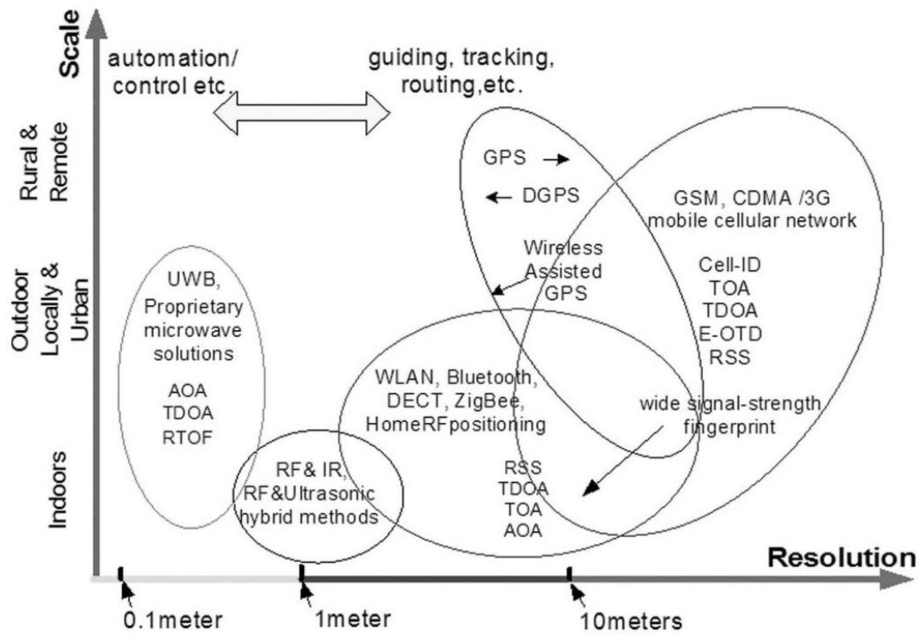


Figure 3.5: The most common radio-based technologies categorized by resolution and scale. We focus on the technologies with resolutions below 10 meters (which means that GPS, GSM are not discussed). Figure taken from [LDBL07].

RFID

- Advantage: cheap depending on the used method, good accuracy.
- Disadvantage: no uniform standard, problems with environmental influences with specific methods.

There are three types of RFID:

- Low Frequency RFID (LF RFID) with frequencies from 30 to 500 kHz
- High Frequency RFID (HF RFID) with frequencies from 3 to 30 MHz
- Ultrahigh Frequency (UHF RFID) with frequencies from 433/850 to 950 MHz

The higher the frequency, the better the range and data transfer rate. On the downside, the modules become more prone to interferences caused by metallic objects or liquid in the area [Cla07]. There are two ways to operate RFID tags: active or passive. Active tags are powered by batteries and send out information to the anchors whereas in passive systems, the anchors send out a RF signal to the tags which they reflect back. The range in active systems is specified as around 100 meters and in passive systems as under 10 meters.

Bluetooth

- Advantages: based on standard, low energy consumption, cheap.
- Disadvantage: small range, slow update-rates.

Bluetooth is part of the 802.15.1 standard and its recent iteration consists of two types of operation modes:

- Classic
  Bluetooth works in the 2.4 GHz frequency-band just as ZigBee or WiFi but uses channels which do not overlap with the existing ones from the two other technologies. An integrated frequency-hopping tries to send messages automatically on free Bluetooth-channels.

- Low Energy
  In recent years, the 4.0 standard for Bluetooth was introduced. The new specification included "Low Energy" which, compared to the classic version, offered a compelling price/performance ratio for modules with predefined services, excellent battery performance but a slow update-rate.

According to [WYZ+13], Bluetooth modules consume 80% less power and are in general, less expensive compared to similar modules using WiFi. But the data throughput as well as the possible range with these modules is less than that of other comparable technologies [NS]. Bluetooth Classic uses 79 channels with a bandwidth of 1 MHz for communication while Bluetooth Low Energy uses just 37 with a bandwidth of 2 MHz and 3 additional channels for advertising (see figure 3.6). Both operation modes come with "Adaptive Frequency Hopping" (AFH) which allows the modules to jump on frequencies with less interference. In general, Bluetooth Classic requires more channels for inquiry or connection purposes which is why co-existing radio-based technologies in the same 2.4 GHz frequency band (such as WiFi) can interfere. Bluetooth Low Energy, on the other hand, uses frequencies to avoid any interference problems (particularly with WiFi).

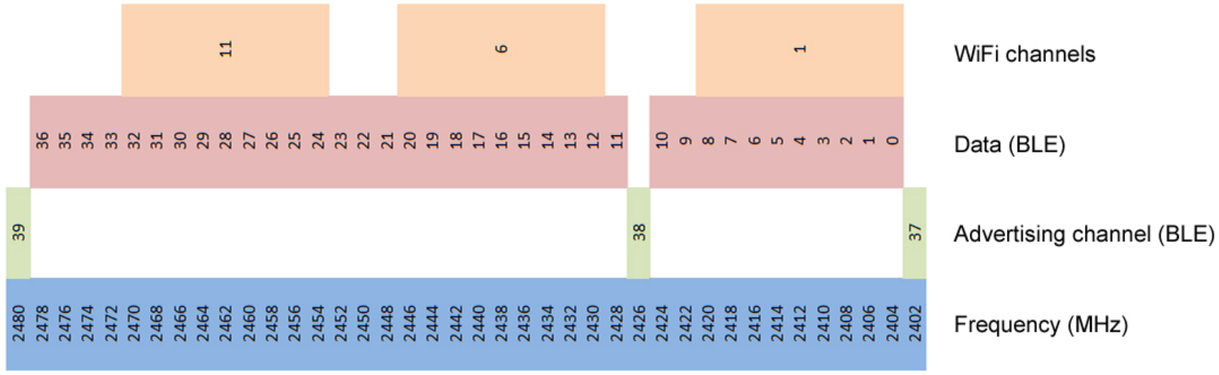


Figure 3.6: The figure shows the occupied frequencies by WiFi (at the top) with the frequencies used by BLE for communication. The three advertising channels 37, 38 and 39 do not overlap with any of the frequencies used by WiFi.

WiFi

- Advantage: based on standards, networks can be used for other things beside location tracking, high range, already deployed infrastructure can be used.
- Disadvantage: problems with influences/interferences coming from other networks or technologies in the same frequency band.

Access points or routers are used as anchors and small battery-powered WiFi modules are used as tags. These can either work in the 2.4 or 5 GHz frequency band. Information is sent between the anchors and tags to calculate/estimate a position for the user. A big disadvantage is the possibility of interference problems when using WiFi on the same channels/frequencies as other devices which create huge amounts of data traffic. Also, metallic objects or liquid can cause signal fluctuations and subsequently result in inaccurately calculated positions. But on the other hand, existing WiFi infrastructure can be used for location tracking purposes and the possible detection range as well as data throughput rates are high [Coo04].

ZigBee

- Advantages: based on standards, good performance even in difficult environments, long battery life, cheap, tags communicating with each other which can lead to building a bigger network consisting of tags.
- Disadvantage: Problem with interferences still exists.

ZigBee is based on the IEEE 802.15.4 standard and extends it with a specification regarding radio-based networks with a maximum range of 100 meters. One of the features of ZigBee is the ability to link modules to a network of tags (also called "Wireless Sensor Networks" (WSN)), which also leads to better accuracies of 1 meter and a good battery life. ZigBee works in the 2.4 GHz frequency band and is often used in the home automation as well as the location tracking sector. Problems with ZigBee arise through interferences when it is used in coexistence with other technologies in the same frequency band [Far08].

Ultra-wide band

- Advantage: high accuracy, no problems with interferences or difficult environments, high range.
- Disadvantage: high costs.

Ultra-wide band uses the frequency spectrum of 3.1 to 10.6 GHz and features a high frequency bandwidth of more than 500 MHz and very short pulse signals (<1 nanosecond) which lead to very high data rates [LDBL07]. These help to reduce reflections, multipath fading and overlapping signals [PR07]. UWB is being used more frequently in the last years for accurate location tracking in research but has the big disadvantage of being too expensive. Due to its limited signal power, the maximum range of UWB is usually specified as 50 meters [SBNW07].

RuBee

RuBee is a radio-based technology designed for military and medical asset tracking. It was developed by the company *Visible Assets* (Stratham, United States) and is represented by the IEEE standard 1902.1. The technology serves as an alternative to RFID and tries to overcome the problems and issues of the later one.

According to [Vis10b], the detection range can be up to 100 feet and the batteries of RuBee tags can last between 5 and 15 years. Low frequencies (131 kHz) lead to less power consumption and with a long wavelength of 2.289 meters, it is less prone to interferences than other comparable technologies such as RFID, even penetrating steel and water [Vis10a].

Another advantage of RuBee is the high scalability with an anchor being capable of managing up to 1000 tags. The tags come in a really slim form factor (usually credit card size). On the downside, the data throughput is worse than with WiFi or ZigBee.

Although the technology comes with many advantages such as being classified as a “Non-Significant Risk” (NSR) class 1 device in medical visibility applications by the FDA or having no EMI or EMC in the operating room, we omitted it from the comparison table 3.3. The reason is that there was hardly no literature or empirical data available on RuBee. Also, we could not get any development kits by providers to test and analyze the technology ourselves.

Comparison between radio-based technologies

Table 3.3: Comparison between radio-based technologies.

Technology	Scalability	Price	Accuracy	Update-rate	Range	Durability
RFID	/	o	+	o	o	+
WiFi	+	o	o	+	++	o
Bluetooth	o	+	o	o	o	++
ZigBee	+	o	o	o	+	+
UWB	/	-	++	++	+	+

3.4.3 Acoustic

Ultrasound

The ultrasound tags send out pulses which are recorded by the anchors/microphones. Ultrasound pulses have a very small wavelength and can be sent in various frequencies. Similar to infrared, the signals are distributed and mostly stay in a room, which is why the technology is commonly used to achieve room level or sub-room level accuracy. Its propagation speed lies at around 340 meters per second, which is quite low, and it also returns results with a low time resolution. This means that with less expensive hardware, it is possible to measure and use methods such as the ToA or TDoA [TSFC10] [YCL10].

Table 3.4: Comparison between acoustic technologies.

Technology	Scalability	Price	Accuracy	Update-rate	Range	Durability
Ultrasound	+	o	+	+	-	+

3.4.4 Inertial

In general, an inertial navigation system is used with the method “Dead Reckoning” and requires two components: inertial sensors and a starting position. Inertial sensors can include accelerometers, gyroscopes or magnetometers. They measure the non-gravitational acceleration, the orientation or the strength/direction of a magnetic field. With measurements like these, distances, angles or the cardinal points can be calculated and used for further computation. Since the sensors can only detect changes from one state to another (the difference between state s_1 and s_2), a starting position has to be set and known to the inertial navigation system. From the state s_0 at the starting position, all changes/measurements are added up to determine the current state. Usually, these sensors are complementary to other tracking technologies such as WiFi or ZigBee. The advantages as well as disadvantages are described in section 3.3 and are all related to the "Dead Reckoning" method.

4 Related work

This chapter presents all the related work regarding this thesis. The first section deals with RTLS in general and goes into detail about possible applications using location tracking systems in hospitals as well as its effects and impacts. The second section focuses more on the technologies and methods which can be used for these tracking systems. This chapter is divided into several subsections to further differentiate between the approaches and work which has already been conducted and published.

During the last four years, four students, Sonja Vogl [Vog14], Susanne Meindl [Mei14], Tilman Nölle [Noe14] and Umair Saleem [Sal15], were under my supervision and worked on their respective Bachelor's/Master's thesis. They were of significant help in evaluating, testing, analyzing and providing important results for conference papers as well as this thesis.

4.1 RTLS in hospitals and its applications

[KBB12] provided a primer on how RTLS could be used in hospitals. They highlighted the advantages of using an RTLS such as improvements in the workflow. Moreover, they stated that using the correct location tracking system for the given or required use case was crucial. Otherwise the hospital's management would feel unsatisfied and the performance-to-price ratio would be negatively skewed. An interesting aspect to point out is that they counted roughly 68 (medical) devices across all different hospital departments which were used on a daily basis and could be tracked. The most common use cases of RTLS in hospitals were tracking patients (most commonly Alzheimer's and dementia patients), alarming the medical staff if their patients left or entered certain areas and also for improving patient throughput. RTLS helped in finding and analyzing bottlenecks to optimize the workflow process. If, for example, all patients wore tags, data about them such as health records could be easily accessed across different departments of the hospital. By supporting the medical staff with automated tasks or processes and providing them with information such as a certain device's location, their time could be spent more productively. Regarding the financial benefits of an RTLS, they found out that with a deployed system, there would be savings with an estimated ROI of 134.5%. These savings were immediate once the investment for buying and deploying the RTLS had been done. The ROI was even greater for more expensive medical devices and in the end, the costs for new investments in equipment decreased.

[Kon08] identified four steps that have to be considered when buying and deploying an RTLS for the use in the hospital. These four steps included assessing the value of using an RTLS and understanding its initial costs, selecting the right vendors to partner with, defining a cost profile for rolling out and deploying the RTLS in the right areas for the right use cases.

Once an RTLS was deployed, the average time needed (22 minutes) to search for equipment could be decreased by 91% [Sys13]. Also, [Gro13] stated that connectivity as well as mobility was becoming more and more important in the operating room. While there are various technologies and ways available to control or monitor devices in the OR, most of the actions are all done with one central device (such as a wall control panel). This reinforces Trumpf Medical's approach to have a remote control to operate other (medical) devices but making it decentralized and user-oriented (see chapter 2).

[D'S11] also gave an overview of the advantages and challenges of using an RTLS in healthcare facilities. The paper was more directed towards the use case of emergency responses and how medical staff could benefit from an RTLS by using, for example, patient tracking. Some challenges the paper pointed out included the ROI considerations or possibilities of interference with other medical devices and technologies.

According to [Kro08], RTLS applications could be categorized into asset tracking, workflow improvement and patient as well as staff tracking. Furthermore, Krohn et al. said that many requirements regarding the use of a location tracking system need to be fulfilled and that preparations for the right application were extensive. Only by considering these aspects, expectations of an RTLS could be met and would consequently lead to a satisfying performance of the system. Hybrid technologies consisting of, for example, Infrared and WiFi were also pointed out to be more reliable.

According to [OLC+03], it is also interesting to have the RTLS connected to the hospital network, which would then directly obtain or forward data such as the location or status of equipment to the "Hospital Information System" (HIS). A use case would be having a middleware collect the time of use for a device and its status, if it is currently occupied or not. In case that it is not, it would be displayed as "free" with its location to the user [KBB12].

[LJ12] mentioned that, to avoid waiting time and to decrease the percentage of patients left without being seen (LWBS), an RTLS by the company *Awarepoint* (San Diego, United States) was deployed in the *Wilmington Hospital* (Wilmington, United States) to support the staff members in workflow, asset management and patient tracking. An interesting aspect here is that the installed RTLS was only tracking patients and the medical staff members in selected areas. For example, restrooms or break areas were left out and did not have any devices installed for tracking. With more than 400 sensors for location tracking deployed, the throughput of low-, medium- as well as high-acuity patients decreased significantly over the years.

[CJ10] stated that for using mobile devices in the OR to control other devices, the location tracking system should at least reach "room level" accuracy. "Room level" is described by the distance error between the computed and the actual position being smaller than 1 meter and that it needs to be located in the correct room at all times. That also includes reliability when tracking equipment. Having results with repeated fluctuations and hops between rooms would not help in decreasing the time to search for devices.

"Real-time" is a very important factor for location tracking systems but the term is often misused and confused with "latency" or "update-rate". The definition of "real-time" is described in chapter 3.1. The optimal update-rate for an RTLS used in a clinical environment lies around 5 seconds according to [SSHR08].

While there are certain risks and problems with an RTLS, overall the advantages outweigh the disadvantages [Fro], especially with the market size and growth potential being high for the healthcare sector.

4.2 Methods and technologies used in tracking systems

In this section, the most common methods and techniques to measure data and compute the position are described and referenced. Calculating a position for a tag is done by the location engine while measurements are performed by the anchors of a location tracking system. We point out interesting aspects of papers dealing with the same or similar approaches we used for our experiments and mention noteworthy work which we could take into account for further research/future development.

4.2.1 Methods

[BONL07] [SSO08] [ZXY+10] and [DCD15] provided an overview of location tracking systems and the most common methods to calculate a position for the user. They explained methods such as "Time of Arrival", "Angle of Arrival" or "Trilateration" for computing the position. Concerning distance or angle estimation between an anchor and a tag, they further provided the following average accuracies:

- RSSI $\rightarrow$ 1-4 meters
- Time of Arrival $\rightarrow$ 2-3 centimeters
- Time Difference of Arrival $\rightarrow$ 2-3 centimeters
- Angle of Arrival $\rightarrow$ 5°

[Mau12] went into more detail in describing techniques for measuring data and methods to compute the position. The following techniques were listed: Time of Arrival (ToA), Time of Flight (ToF), Time Difference of Arrival (TDoA), Round Trip Time (RTT), Roundtrip Time of Flight (RToF), Two Way Ranging (TWR), Phase of Arrival (PoA), Phase Difference (PD), Near-Field Electromagnetic Ranging (NFER), Angle of Arrival (AoA), Doppler Ranging, Received Signal Strength Indicator (RSSI).

For computing the final position from the measured data, the following methods can be used: Cell of Origin (CoO), Proximity Detection, Connectivity Based Positioning, Centroid Determination, Lateration, Trilateration, Multilateration, Angulation, Triangulation, Polar Point Method, Range-Bearing Positioning, Fingerprinting, Scene Analysis, Pattern Matching, Dead Reckoning, Map Matching.

[Hoe08] showed that methods such as RTT and ToA could be combined in case the expensive hardware was lacking accurate time measurements. The combination still achieved an average accuracy of 4 meters. From all these methods, we tested "Trilateration", "Proximity Detection" and "Fingerprinting" with RSSI measurements.

Although others talk extensively about "Received Signal Strength Indicator" (RSSI) measurements, the definition is often misused. RSSI represents an indicator, which states if the received signal power of a sender module is sufficient for communicating with the reader module in relation to the "Golden Receive Power Range". The Golden Receive Power Range is a range covering 20 dB $\pm$ 6 dB and depending on if the received signal strength is below, in or above that range, a different RSSI is returned. Depending on the RSSI, the reader module can increase or decrease the output power of the sender module through a Bluetooth feature called "power control". RSSI is often declared as a parameter without a unit while the actual “Received Signal Strength” (RSS) is measured in decibel milliwatt (dBm). In this thesis, RSSI and RSS are used as synonyms. In many cases, the Bluetooth hardware provides RSS values as RSSI minus the Golden Receive Power Range.

Work from [Chu07] [RASR10] or [WJC07] made it clear that RSSI could only be used when (filtering) algorithms were applied. Otherwise, due to its physical limitations, the position errors would always lead to poor results.

4.2.2 Computing the position

Microsoft (Redmond, United States) introduced a system called “RADAR” which reached accuracies of 2 to 3 meters [BP]. RADAR uses maps with fingerprints which were collected in an offline phase and pre-calculated through known propagation models to complete the maps. Companies such as Ekahau, which also use Fingerprinting, reach accuracies in meters. The “HORUS” system developed by [YA05], which uses RSSI histograms calculated at the fingerprint positions, promises radial errors below 1 meter.

[ZHKC06] presented a very interesting method using only a single access point for WiFi location tracking consisting of five steps:

1. Define the area for tracking and create a map placing elements such as exterior/interior walls, windows and the access point.
2. Record fingerprints at defined spots in the area. The minimum number of fingerprints which has to be taken depends on the number of obstacles in the environment. Also: the more fingerprints are taken, the better the accuracy.
3. Calculate a polynomial by ray-tracing from the measured fingerprints and the access point. The polynomial represents the signal strength at each of the measured fingerprint positions.
4. The reflection and transmission parameters can be calculated for all the obstacles through simulated annealing (SA) with the fingerprints recorded in step 2.
5. Create the radio map for the entire area through ray-tracing using the previously calculated reflection and transmission parameters.

This radio map in combination with a particle filter that was applied to the live RSSI values, resulted in an average positional error of 1 meter. However, the downside of this work was that all the experiments with the mentioned steps were simulated and not conducted in reality.

[DH10] published a study testing and comparing the three methods “Fingerprinting”, “Range-based” and “Proximity” regarding the effort for calibration and accuracy. “Range-based” in combination with the Log Normal Shadowing model (see chapter 3.2) was deemed as the overall best method while the amount of effort for Fingerprinting was considered to be too high and the poor accuracy was disadvantageous for Proximity. [Hen12] determined that Fingerprinting was the most accurate method but demanded a lot of effort in calibration. [DH10] showed that, on the other hand, range- and proximity-based location tracking systems performed better with less calibration effort. In general, Henniges et al. noted that choosing the right technique for measuring data was very dependent on the environment and situation. [NPYY11] introduced a method to reduce the calibration effort for fingerprinting systems by recording the minimal amount of required RSSI fingerprints and then predicting the remaining ones through a modified one-slope model (OSM). [SC10] utilized "Simultaneous Localization and Mapping" (SLAM) to create fingerprinting maps through RSSI measurements. According to [WMXD11], neural networks could be used to create dynamic fingerprinting maps where a relation between calibration and reference spots was established in the offline-phase. In the online-phase, the signal strength values at the reference points were predicted when measuring the current RSSI values at the calibration points. [YLTY10] interpolated between a few sample points taken in the test environment during the offline-phase to create the complete fingerprinting map.

[Hon09] compared various fingerprinting algorithms and pointed out that the inclusion of the tag's orientation during the offline-/calibration-phase led to significant improvements in the results.

[Cin13] presented a paper, mentioning the importance of the anchors' orientation when positioning them. They pointed out that Gaussian and Kalman filters yielded the best results when applied to the raw signal strength values. They also used an adaptive system where a base station (one of the anchors) constantly updated the used path loss model with new calibration parameters to calculate a new position for the user. Cinefra et al. determined the following parameters to have a negative effect on location tracking accuracy: various sender devices having varying levels of transmitting power, the height of the sender devices and people's presence when tracking the sender modules. However, they were not able to analyze and prove any effects in detail.

[PH03] used a proximity-based location tracking system. They analyzed it with the Cramér-Rao bound to determine, how an unbiased RTLS without channel fading and multipath effects would look like. They mentioned that a more precise location tracking system implied higher costs, overall bigger devices and increased power consumption. Those were the reasons why they continued with a simple proximity-based system and RSSI measurements.

[KMCH05] and [MSKA03] also used a proximity-based location tracking system but with an anchor grid to estimate the target's position. They tried to use anchors as reference modules and more sensors to increase stability and accuracy.

[EGT$^+$06] and [SM11] worked on the Log Normal Shadowing model which calculated the path loss of a signal over a certain distance. We used this model because of its accurate estimations which furthermore took effects such as multipath and shadowing into account. The Log Normal Shadowing model could also be used to calculate the Path Loss Exponents of various test setups when the signal strength values were known. The PLE values gave us more information about the test environment.

Through the implementation of the "Kalman Filter" (KF) (described in chapter 3.3) or the "Extended Kalman Filter" (EKF), [YJJP08] or [CBM10] also reached sufficient results with position errors being around 2 meters. Similar to the Kalman filter, Particle filters can be used for computing the position of the user or parameters of the propagation models such as the "Path Loss Exponent" (PLE) (see chapter 3.2). [KCO12] [WH08] and [TFBD01] presented papers where the addition of a particle filter led to significant improvements in the results.

Probabilistic approaches described in [RMT02] and [SQN09] also yielded promising results with modest calibration effort. However, they often require more processing power for the calculations.

4.2.3 Technologies

[GLN09] [KK09] [SS14] and [Mau12] provide very good overviews of the available technologies for location tracking purposes. While they focused on practical indoor positioning systems, there are also a few technologies such as Global Positioning System (GPS), TV Signal Positioning, Surface Acoustic Wave (SAW), which are not going to be described in detail here but can be looked up in [Vog14].

Optical

Chapter 3.4 describes a few possibilities to track people and objects with optical tracking system. Problems such as NLOS or privacy concerns and the difficulty of meeting the requirements from chapter 2.1 led us to stop looking further into optical but more into other technologies. While [Cha00] [YP05] or [Gre06] try to improve the issues with NLOS or costs, it is challenging to find a system which fulfills all requirements set in the previous chapters.

[Sie07] showed that for Medical Augmented Reality applications, for which tracking is essential, one of the most accepted technologies for intra-operative procedures was infrared. The achievable accuracy outweighed the limitations, such as NLOS.

In 1992, [WHFaG92] introduced the “Active Badge” system which worked solely on infrared. Badges sent out infrared pulses representing an ID every 15 seconds and anchors mounted on walls or ceiling were able to detect these and relate a badge to a specific area/cell. Disadvantages for this system were issues with LOS and interferences due to other light sources in the same frequency band. The focus of Want et al. was not if a location tracking system with infrared could be created but rather if such a system would be accepted among people with privacy concerns.

Radio-based

Most of the research and work available revolves around WiFi as the technology used for location tracking. The reason is simple: it is affordable and very accessible in terms of availability of consumer products. Plus, there is already a lot of existing work and different approaches in this field.

[Gol05] published a book about various radio-based technologies (including Bluetooth), describing the RSSI-distance relation as well as several propagation effects on the signal power.

[BdS08] gave an overview of methods and techniques for active as well as passive RFID. Some of the evaluated systems were well known, such as “Landmarc” [NLLP03] and compared to each other based on what reference tags were needed or what positioning algorithm (kNN, RSS lateration etc.) was used. Bouet et al. concluded that the choice, which methods and techniques to use, was very much dependent on the use case since accuracy and costs among other factors varied greatly.

In 2000, [BP] introduced "RADAR", a location tracking system based on 2.4 GHz RF. In this particular case, a combination of Fingerprinting and Triangulation was used with signal strength and signal-to-noise ratio (SNR) measurements. The authors used a signal propagation model (see chapter 3.2) to estimate the distance from a signal strength measurement. In the end, they computed the user's position through a Nearest Neighbor (see chapter 3.3) with an accuracy of 2-3 meters.

[Vog14] conducted a survey and tested most of the available radio-based technologies which could be used for location tracking purposes in the OR. All the viable technologies, which could be used specifically in a medical context, were pointed out: WiFi, Bluetooth, RFID, UWB and RuBee. All these technologies are described in chapter 3.4. ZigBee was omitted due to coexistence issues with other wireless technologies such as WiFi in the same 2.4 GHz frequency band while infrared was removed because of potential LOS problems and the small reading range. For ultrasound: it would be prone to other sound sources, produce high failure rates and therefore be less reliable than other technologies. In most cases, ultrasound is used complementary to other RF technologies [PCB00] [SBGP04].

While GPS is the most common technology for location tracking outdoors, [Eis05] investigated how well GPS could be used for indoor tracking. Due to the material composition of buildings and their absorption, acquiring a useful signal and computing the position took minutes and resulted in average position errors of 15 meters upwards. Eissfeller et al. stated that for improvements in terms of update-rate and accuracy, differential GPS and optimizations with GSM were a necessity.

[KKL11] published a paper for an ultra high frequency (UHF) RFID reader which used a phased array of three antennas for AoA calculations. First tests seemed promising as the average error was 3.6°and the maximum error was less than 10°.

[Man10] presented an UHF RFID location tracking system based on passive tags which were used as reference nodes. These nodes were mounted on the ceiling as a grid (with different grid sizes for the tests) and two RFID anchors were installed in the corners of the room to measure the distances of RFID tags as well as the nodes. With the distance measurements, a relation could be created to where a tag would be positioned in relation to its nearest nodes. Through AoA applied on the nearest nodes, the final position of a tag was calculated. The average error achieved was around 1.05 meters but with a very dense grid size of 1 meter. The error increased with the grid size: the bigger the grid size, the bigger the error.

[Cat10] described a WiFi location tracking system based on the method of RSSI fingerprinting. For each of the test rooms, up to 100 fingerprints were recorded. Other than most evaluations, here, fingerprints were measured at two different floors and in rooms below/above each other. A wearable tag generated the following results: accuracy of up to 87% for two rooms on the same floor and 86% where one room was located above the other. A longer test with a stationary tag revealed that a positional error of 2 meters could be reached for 50% of all calculations and 4 meters for 88%.

[CEY+09] evaluated the limits of using signal strength values for location tracking. Some lateration- as well as classification-based algorithms were compared and when it came to poor data quality (how well a distance estimation with a propagation model and RSSI measurements could be compared to the actual distance), lateration-based algorithms performed worse than classification-based ones. The best performing algorithm overall was the “M1”, which is based on Bayesian Networks and also relies on a propagation model in its back end. An average accuracy of 0.24 meters could be reached while the maximum position error was 1.60 meters.

[Dal06] also recognized that for their WiFi location tracking system based on fingerprinting, the orientation and different RSSI for each tag had a significant impact on the results. In fact, for every tag even if they were based on the same hardware, separate radio maps were needed. The average accuracy was determined to be between 2.5 and 3 meters but a maximum position error of over 8 meters made the system not feasible for the use in real environments. In general, the average accuracy reachable with WiFi was conducted to be around 10 feet which translates to approximately 3 meters [EM04]. [JKZ11] made use of both WiFi frequency bands, 2.4 and 5 GHz, to investigate if using either one or both combined would bring any significant improvements. [Qua10] also tested WiFi fingerprinting and conducted a test (online phase) on the same day as they recorded the fingerprints (offline phase). The results were promising but after a week and using the same map, the accuracy decreased significantly.

[BIG08] presented a location tracking system based on Bluetooth, which used inquiry response rates and fingerprinting to compute the tag’s position. The offline phases for recording fingerprints lasted between 5 to 30 minutes and during the test/online phase, the tag was placed at several positions in two rooms for 1 hour. Accuracies of up to 98% were achieved. The received signal strength was considered too weak as an indicator to use for position estimation.

Further work revolving around Bluetooth location tracking came from [CnSE+04], where they used several Bluetooth sensors as anchors and triangulation with the parameters “transmitted power” and “RSSI” to compute a position. Again, a signal propagation model was applied and the calculated position deviated by 3 meters from its actual one.

[PCL+10] worked on an inquiry-based Bluetooth location tracking system where 3 anchors were used to create fingerprinting maps. These maps only included a handful of fingerprints while the rest was estimated/completed with a Weibull distribution function. They reached a mean error of 5.1 meters.

[vdTRvLER+08] conducted tests with RFID systems and medical equipment to analyze the safety and security of the later items. 41 medical devices such as defibrillators, anesthesia devices or pacemakers and respirators of various providers were tested repeatedly in the distance range of 1 centimeter to 6 meters. Out of 123 “Electro Magnetic Interference” (EMI) tests, 34 cases were reported with 22 being severe and endangering to the patient. In these 22 cases, the medical devices were directly influenced by the RFID systems and did not behave as expected. Passive UHF RFID working with a frequency of 868 MHz caused the most problems compared to others such as active LF RFID with a frequency of 125 kHz.

[Jia10] used a combination of ultra-wide band (UWB) and GPS for indoor and outdoor location tracking. The system worked seamlessly with GPS when a user left a building and switched to UWB in case he entered the building again. Accuracies of 15 centimeters for UWB and 10 meters for GPS were achieved.

[MBL+09] tried to calculate the position of a mobile station based on three WiFi access points and trilateration. They came up with a similar idea to what we proposed in chapter 7.11: analyze the environment and modify the propagation models accordingly to calculate a position through an algorithm. With the measured RSSI value between the mobile station and one of the access points, the path loss exponent was calculated and then put into the model to return the distance. This method incorporated more environmental changes and observations than others which were just translating the distance from the RSSI value. Their system achieved a mean error of 4 meters.

Another very important aspect about using RSSI for WiFi location tracking is the fact, that the signal strength distribution is typically not Gaussian [Kae06].

While there are physical limitations to some technologies, algorithms such as [FLM12] [LC07] [Yan08] or [FA11] try to make radio-based systems more reliable and accurate. But in many cases, experiments and tests were conducted in controlled environments with little to no interferences which led to good but still insufficient solutions and results.

Acoustic

The "Active Bat" system by [WJH] was the successor to "Active Badge" based on ultrasound to compute a position through trilateration. Several anchors with ultrasound receivers were mounted on ceilings as well as arranged in a very specific way and connected to a server in the back end with the location engine. The server was also equipped with ultrasound transmitters as well as 433 MHz RF which allowed for direct communication with the badges (which came with the same technology). Through the RF link, the server could trigger the badges to send out short ultrasound pulses with an ID which were then detected by the anchors on the ceiling. Since the time, at which the pulses were triggered, was known, the TDoA and consequently, the distances between a badge and at least three anchors could be calculated and then used for Trilateration. The achievable accuracy was specified in centimeters and compared to other approaches, it was possible to get the position in 3D and the orientation of a badge could be obtained as well. But the amount of anchors required to cover a larger area as well as the infrastructure behind it and installation/deployment made the system difficult to handle.

[PCB00] presented a paper in 2000 about a hybrid location tracking system called "Cricket". One or more beacons were placed in the environment and sent out data concurrently via 418 MHz RF and ultrasound with a frequency of 40 kHz. Since the speed of RF is faster than sound, a listener/anchor detected the RF message first and could measure the time-of-flight for the ultrasound signal. Through TDoA, a distance value could be determined and with at least three beacons and trilateration applied, an average positional error of a few inches could be achieved. But it was also shown that the setup of beacons and their orientation had to follow strict guidelines to achieve such results as for example a listener could detect RF/ultrasound messages from an adjacent room if doors would stay open.

Inertial

[WH08] used a combination of an inertial sensor and WiFi fingerprinting to locate a person in a multi-floor building. The WiFi location tracking system was only used as a constraint to pinpoint the user in a certain area on a floor. The foot-mounted inertial sensor returned angular velocity as well as acceleration and combined with a particle filter, a computer-readable map of the building and the results of WiFi fingerprinting, an average accuracy of less than 1 meter was reached.

Other

[ZH11] proposed a location tracking system to track a robot using a combination of sensors (infrared, odometry and gyroscope) and sensor fusion through a Kalman filter. An inside-out system called "Northstar" was presented. It projected spots onto the ceiling of a room with an infrared beacon. A detector on the robot caught these spots and computed the position through triangulation.

[Zho06] presented a hybrid solution consisting of the technologies WiFi and Bluetooth. Together, they reached an average accuracy of 3 meters for mobile and 1.5 meters for stationary measurements. For WiFi, a history-based approach which considered previously recorded signal strength measurements of access points was used. Bluetooth supported WiFi with proximity-based tracking using nodes. These nodes were distributed in the area and had the tag actively scanning for them. A node in one of the areas was determined as result and its location was included in the final position computations. Unfortunately, the algorithm behind Bluetooth was not specified in depth but it was once again emphasized, that the orientation of the tag was an important factor that could (highly) influence the results.

4.2.4 Misc.

[JHP11] presented a very interesting paper regarding the simulation of a TDoA location tracking system using LED lamps hanging from the ceiling. Assuming there would be at least three lamps sending out different frequency IDs, a tag could receive and forward the light wave signals to compute the TDoA and consequently, the position through trilateration. While this was only simulated and not proven with a real test setup, the theoretical accuracy would have been less than 1 centimeter in a 5 x 5 x 3 meter test bed. While it makes perfectly sense to use existing light infrastructure for tracking purposes, issues such as NLOS would still exist.

[ECF11] published a paper about a hybrid tracking system consisting of infrared and inertial measurement unit (IMU) sensors. Infrared served as the primary technology. Several IR cameras were placed in the corners of rooms and IR reflectors were used as tags. The IMU returned accelerometer-, gyroscope- and magnetometer-data and with sensor fusion using a Kalman filter, a position of the tag was calculated. In a test setup with controlled light conditions, the system reached accuracies of 1-2 centimeters and even in the worst case scenario, when there was 50% NLOS between the infrared cameras and the reflector, the maximum position error achieved was 10 centimeters.

Pan et al. [PKYP07] [PSYK08] [PZYH08] published several papers which described how an RSSI calibrated fingerprinting map could be transferred across space and time to represent a changed environment. This process allowed a constant update of the fingerprinting map. The same approach was pursued by [ZY10] to reduce calibration effort in a multi-floor building with the assumption that all the floors had been built similarly. They collected sample fingerprints on one floor of a building and "unlabeled" fingerprints on the others to create the fingerprint maps. While the sample fingerprints were measured at specific spots on one floor, the "unlabeled" ones were recorded arbitrarily by the user.

Online calibration was also presented by [CCC+05] where the task was to act upon environmental changes and its effects on the RSSI. They used an existing WiFi location tracking system with fingerprinting and complemented it with RFID technology to re-calibrate the fingerprinting maps in the online phase. The only downside was that the online calibration was only tested in corridors but not in rooms. Still, an improvement of 2.6 meters in the position error was achieved when the RSSI measurements of the RFID hardware were incorporated.

[TSS11] used a self-calibrating location tracking system based on WiFi. They collected fingerprints from access points of known positions and used them for calibrating the new environment for the system. They concluded that when using 802.11 access points, it was unrealistic to set up a location tracking system with an accuracy better than five meters due to environmental as well as algorithmic issues.

The so-called "time-out", a procedure done in the operating room to reduce safety and security risks (such as operating the wrong patient or performing the wrong procedure on the patient), has been implemented in many hospitals worldwide [PJR+13]. During the time-out, all medical staff members communicate actively to discuss the details before the operation starts. Normally, the time-out takes place before invasive procedures and is started and documented by one of the participating staff members by going through a checklist. Three of the most important issues to check during the time-out according to [The], are:

- **Checking the patient ID:** Do we have the right patient here?
- **Checking the procedure:** Is that the right procedure we are going to perform on this patient?
- **Checking the site:** Is this the right site/OR for this operation?

These are the basic and most common questions asked and documented in a time-out for each procedure. Since the amount to document is vastly increasing, it is more efficient to do these things digitally, especially with support of an RTLS [O'L12].

5 RTLS systems in hospitals and ORs

In this chapter, we deal with already existing and commercially available RTLS on the market. We take a look at their specifications, mentioned advantages as well as disadvantages and go into detail with first-hand experiences. We will then cover the problems of the RTLS and the requirements that they are either fulfilling or failing to meet.

5.1 Examples (Hybrid RTLS)

Through a comparison of various technologies according to the specified criteria, some can be identified as more suitable for the use in the operating room. The technologies to fulfill most of the requirements related to the six criteria are marker-tracking, WiFi, Bluetooth, ZigBee as well as ultrasound. Many RTLS providers have shown that with a hybrid solution of two technologies, stability as well as accuracy can be increased to have a more reliable and well-rounded system. Using a combination makes sense since none of the evaluated technologies are free of disadvantages. In the following, some combinations of technologies are presented. Most of these solutions can already be purchased commercially. It is interesting to note that many companies rely on RFID even if the technology is rated worse compared to WiFi or UWB in terms of update-rate or range. Reasons in favor of RFID are its affordable price and the technology's stability. Even in difficult environments and with a small range, RFID can reach sub-room level accuracy. Almost none of the providers mention any details on the criteria "scalability" or "price". They, for instance, do not go into detail as to how much one would have to pay for a one-room solution including all expenses regarding infrastructure.

5.1.1 WiFi & Ultrasound & LF RFID

Sonitor Technologies, Inc. (Stamford. United States) offers a hybrid RTLS solution consisting of WiFi, ultrasound and LF RFID. To decrease the energy consumption of the tags, motion sensors are integrated to only send out data when activity is detected. Ultrasound is used because of its property to achieve room level accuracy. The main use case of the system is tracking patients and devices to optimize workflow and for automatically notifying staff in certain situations or events. The tags are small, lightweight and promise battery life of up to 5 years [GLN09].

5.1.2 WiFi & Infrared

Ekahau (Helsinki, Finland) uses WiFi combined with infrared in their RTLS. The environment is calibrated through measurements of WiFi RSSI fingerprints. With online measurements, comparisons to saved positions and with infrared anchors installed in certain spots, sub-room level accuracy is achieved. WiFi is used primarily because of its wide range while infrared offers small range for defined zones. Since the environment is constantly changing in the operating room, the question remains if the once calibrated and saved fingerprints can be transferred and used in the new, changed environment or if the fingerprint maps have to be created again. According to [Ban11], the tags last around 3-4 years and the accuracy without infrared lies around 8-10 feet. Without infrared, the room level accuracy adds up to 80% of the time while with infrared, the percentage increases to 90%.

Case study: Carolinas Healthcare System (CHS) [Eka15]

Carolinas Healthcare System is a network of hospitals and healthcare facilities based in North and South Carolina (United States) with 25 locations and 5000 patient beds. The task of Ekahau's RTLS was to track assets such as IV pumps or other mobile equipment even when in transit from one facility to another (equipment could stay with the patient). Staff members would spend too much time looking for the correct or free/available equipment. RTLS would help solve this issue. CHS state that the reasons for choosing Ekahau over other RTLS providers were the promised accuracy of under 10 feet and ease of deployment. Since the facilities had already an enterprise-grade WiFi network, it was relatively easy to deploy the RTLS for Ekahau. CHS's main purpose of using an RTLS was not to save money and have an ROI but to organize and locate all the existing and necessary equipment from all the locations at all times. By using the RTLS, each of the facilities had a balanced amount of equipment and did not require to rent additional equipment due to it being lost, which was often the case in the past. Since deployment, an ROI of 200.000 dollars, usually for equipment rental fees, was registered.

2000 tags were attached to medical devices, mainly intravenous (IV) pumps. Whenever a patient with his pump was transferred from hospital A to hospital B, it was always clear and easy to track, to which hospital a certain pump had to return. This was important to assure that each facility was equipped with the right amount of pumps or equipment in general. Also, when an item was due for maintenance, it was easier for the staff to pinpoint its location using the RTLS. Other use cases such as tracking non-invasive vital sign carts or balloon pumps led to an increase of 3400 tags across the hospitals. Ekahau's RTLS was well accepted by CHS and according to the case study, they also wanted to track Voice-over-IP (VoIP) handsets used by the staff members as well.

5.1.3 WiFi & Infrared & LF RFID

CenTrak Inc. (Newtown, United States) uses a combination of WiFi, infrared and LF RFID. The company guarantees "certainty accuracy" with its hybrid solution. According to CenTrak, their RTLS can also be used in operating rooms and corridors. Effective and optimized scheduling of operating rooms can be achieved with the RTLS: the patient throughput of one hospital with 16 operating rooms was 23% higher than without an RTLS because of better workflow and improved scheduling of the ORs. CenTrak guarantees a 99% room level accuracy and batteries which last 2 to 5 years [Ban11].

5.1.4 WiFi & Active RFID

The "AeroScout" system by the company *STANLEY Healthcare* (Waltham, United States) uses tags which combine WiFi and Active RFID capabilities to track objects. The anchors seem to offer a wide-stretched WiFi network where the tags can communicate, mainly with the location engine in the back end. Another way to expand the range of the network is to use and integrate traditional access points. Depending on the used hardware, the position of the tags is computed with TDoA. An accuracy of 3 to 4.5 meters and a battery life of up to 4 years are specified [STA]. The RTLS is already used extensively with around 300 hospitals having the system deployed. Features such as key-buttons on their tags and a small size factor make the system attractive for the use in healthcare facilities.

5.1.5 Bluetooth Low Energy & WiFi

Awarepoint (San Diego, United States) formerly used ZigBee as their main technology for location tracking solutions but changed to a combination of Bluetooth Low Energy and WiFi instead. [Ban11] state that the batteries for the ZigBee tags last between 2 to 7 years (depending on their usage) and that 99% room level accuracy is guaranteed. With BLE and WiFi, the accuracy is specified to reach 1 to 3 meters [Awa]. They state that with the deployed system, a return on investment is guaranteed with 3 to 7 dollars in hard ROI for every dollar spent. If the system is purchased, 500.000 dollars are immediately saved (ROI) for a facility with an average bed count of 500. Annual savings add up to 100.000 dollars regarding lost or stolen equipment [Blo].

5.1.6 Infrared & RFID

Versus Technology, Inc. (Traverse City, United States) uses a combination of Infrared and 433 MHz Active RFID to provide a location tracking system for room, bed and chair level accuracy. Infrared is used in defined locations to reach sub-room level accuracy. The tags emit low-powered Infrared (IR) and RFID signals. The battery of the tags should last 1.5 to 2 years [Ban11]. The overall time of surgeries decreased, for example the duration of a hand surgery was reduced by approximately 13 minutes. 250.000 dollars are saved when it comes to finding existing, unused equipment and the time to find certain items is reduced from 45-60 minutes to just a few minutes [Teca]. According to [Tecb], the system is deployed in more than 700 healthcare facilities in the US.

Case study: Nor-Lea Medical Clinic in Lovington, United States

The company has released a case study [Ver15] of the *Nor-Lea Medical Clinic* in Lovington, United States, where the RTLS was deployed to improve the patient throughput and the workflow. The system was installed in 31 rooms with 2 treatment beds each and 110 badges were used by both, staff and patients. With the RTLS in use, staff members could see which rooms would be free or where patients were and how long they have been waiting. History/protocol data such as if a patient had already seen a caregiver would be also provided. Another information, which all physicians thought was useful was the current location of other staff members if a certain person was needed.

It is interesting to see that the Versus RTLS collects all the history data (wait times, locations of patients and staff, door-to-doctor times) to analyze workflow improvements. This led to assigning two medical assistants to each physician instead of one which would increase the efficiency. Also, instead of offering 1 hour appointments, the patients were booked for 15 or 30 minute slots. From June to December 2014, patient throughput improved by 49 percent for urgent care and 45 percent for primary care.

5.1.7 Infrared & Ultra-wide band

The RTLS by *decaWave* (Dublin, Ireland) is based on infrared and ultra-wide band. It provides the position of tags with an accuracy of 10 centimeters. A range of 300 meters as well as several years of battery life for the tags are specified. The company also highlights the fact that they are the only ones currently offering an RTLS on the IEEE 802.15.4-2011 standard. Usually, power consumption is high for ultra-wide band modules but decaWave has reduced the consumption to a fraction, allowing the tags to last longer without changing the batteries. For difficult environments with lots of metal and liquids, infrared is used to compensate fluctuations and make the system more stable [dec].

5.1.8 Ultra-wide band

Zebra Technology (Lincolnshire, United States) uses ultra-wide band for its RTLS to deliver accuracies of 30 centimeters and a battery life of up to 7 years with an update-rate of 1 Hz. The range of the system is specified to 200 meters and according to information online, the system is easy to install and to configure (single day installation) [Tecc].

Another company named *PLUS Location Systems* (Huntsville, United States) is also using UWB with middle frequencies of 6.6 or 7.3 GHz for tracking equipment or people in the hospital. The accuracy is specified to be ±10 centimeters and the battery should last several weeks to years depending on the update-rate. The update-rate can vary between 1 and 50 Hz [PLU].

According to [GLN09], the UWB RTLS by *Ubisense* (Cambridge, United Kingdom) reaches an average accuracy of 15 centimeters with a battery lifetime of 1 year.

5.1.9 Comparison

We compare some of the mentioned hybrid solutions against each other and use the same criteria as in chapter 3.1 to point out positive/negative aspects. Most of the specifications used to rate the following combinations were obtained from [Mau12] [New09] and [GLN09]. Due to sparse and incomplete information provided by the companies, little to no information can be provided for the criteria “scalability” and “price”.

Table 5.1: Comparison between hybrid solutions.

Technology	Accuracy	Update-rate	Range	Durability
WiFi & Ultrasound & LF RFID	+	++	+	o
WiFi & Infrared	o	+	+	+
WiFi & Infrared & LF RFID	+	+	+	+

Compared to the ratings of the technologies from chapter 3.4, it is apparent that the combination of two or more solutions brings an overall improvement to the location tracking system. The combinations WiFi & Ultrasound & LF RFID and WiFi & Infrared & LF RFID fared better than WiFi & Infrared. Most of the mentioned systems might be very accurate and provide good range/coverage, but considering the conditions in the ORs (see chapter 2.1), none can fulfill all the requirements to a satisfying degree. Plus, for the usage in TruConnect, the systems are too expensive and too difficult to handle in terms of scalability and maintenance.

5.2 Experience and best practices

In one of the biggest hospitals in Stuttgart (Germany), a hybrid-solution (WiFi & Infrared) was deployed for patient tracking. Based on statements by the medical staff, the system never reached the promised accuracy and was unreliable over time. These were the reasons for its termination. This case is also a good example of unmet expectations towards an RTLS. An RTLS needs certain conditions to work properly but can perform poorly when the requirements are not given (entirely) or when it is applied to the wrong use case.

Another case where an RTLS has been used with a more promising outlook is tracking patient beds by the company *Hill-Rom* (Batesville, United States). The RTLS is mainly used in hospitals for maintenance and safety issues. A combination of WiFi & Infrared & LF RFID is deployed to compute and gather the locations of patient beds equipped with tags. The medical as well as the service staff are notified when problems occur with one of the beds. They can request the exact location of the specific bed through the RTLS. This helps reduce the search times considering that a hospital can hold up to 500 beds.

5.3 Challenges and requirements

Most of the problems of RTLS arise from interferences due to other technologies/hardware or the (changing) environment when using wireless/radio-based technologies for location tracking. Depending on the issues, computed distances could deviate vastly from the actual ones and as a result, an RTLS could perform poorly or be unreliable (or both). These problems can be partly dealt with in two ways: by using the right (but most of the times expensive) hardware or by applying software algorithms for filtering. When it comes to hardware, external antennas with well-defined propagation characteristics could be used or clocks could be provided on the hardware modules for accurate time measurements. But software algorithms can only decrease the error to a certain degree and never remove it completely.

When it comes to scalable and still low-cost solutions, customers opt to go for radio-based (hybrid) systems. More accurate technologies such as optical tracking systems come with LOS problems and are very difficult to deploy for buildings with higher room counts. They also need to consider synchronization and data processing problems.

6 Evaluation

After doing research on the different technologies, we decided to order various development kits for each of the radio-based technologies. The main purpose was to get a better understanding of each technology and its behavior in different environments, with blocking/obscuring (metallic) objects or liquids. We also wanted to analyze criteria such as range, battery life or accuracy. Except for UWB, most of the radio-based technologies described in chapter 3.4 were evaluated. In the end, for developing a location tracking system which fulfills the requirements to track mobile devices in the operating rooms and corridors (see chapter 2.1), Bluetooth (Low Energy) was used.

6.1 Tests with RFID

We started our first experiments with a simple RFID development kit. At the beginning, we focused on the viability of radio-based technologies and wanted to check if influences such as metallic objects or moving people would actually have a significant impact on the accuracy of such solutions.

6.1.1 Passive RFID

First tests were conducted with the technology passive LF RFID to check if it could be used for location tracking applications. The fact that only a minimal amount of data could be read from passive tags and that they did not include substantial information such as the RSSI did rule them out as technology for RTLS purposes with methods such as proximity detection or fingerprinting. The only data we could obtain from the ID-12LA passive RFID development kit by *SparkFun Electronics* (Boulder, United States) was the 32 bit unique ID. Detecting the tag was comparable to switching a Boolean flag as the tag was only detected once it came into range and removed when outside. The ID-12LA module (2) (see figure 6.1) was mounted on a USB serial board (3) and then attached to a PC with a USB cable. Both components combined acted as an anchor while cards (1) with passive RFID strips were used as tags for tests. The frequency of reading the RFID strips was 125 kHz.

One of the tests included the occlusion of the line of sight between the reader and a tag/card to see, how detection would behave. The detection range is limited because of how Passive RFID works (see chapter 3.4). Results showed that when occluding the LOS with a human hand, the range decreased by a few millimeters while metal would completely block the signals. A paper stack of 1 centimeter thickness between tag and reader did not make any difference when detecting the tag. The modules by SparkFun provided a minimum range of 5 and a maximum of 15 centimeters. Only in that specified vicinity, the tags were registered. Also, the update-rate was determined to be at around 1100 milliseconds.

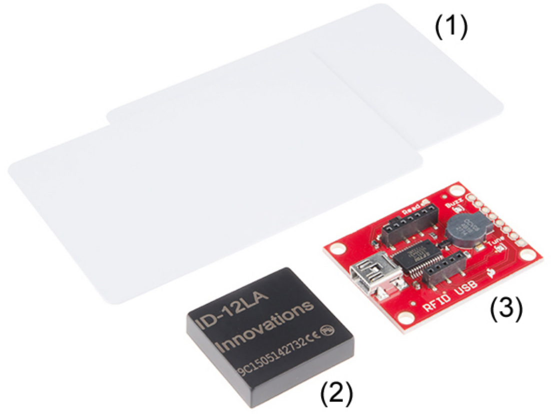


Figure 6.1: The SparkFun ID-12LA development kit for testing Passive RFID. (1) are cards with integrated passive RFID strips, (2) the ID-12LA RFID module for detecting the cards and (3) the USB serial board for communication with a PC.

Several orientations and positions of the tag in respect to the reader were tested. The results showed that only when the tag was positioned parallel to the reader, readings were possible. Otherwise, because of the built-in antenna and its directivity, the reader did not detect the card when it was perpendicularly placed to the reader. Additionally, the tag could only be detected facing the reader from one side but not from others.

All these restrictions, the small range and no options to send/read certain data from an anchor or a tag prevented us from testing Passive RFID more thoroughly.

6.1.2 Active RFID

Tests with Active RFID were conducted by using a development kit of the company *Value-ID* (Salzburg, Austria). The kit consisted of four anchors, a gateway-reader and several tags, all working with UHF RFID in the frequency band of 2.4 - 2.483 GHz. Figure 6.2 visualizes the communication between the anchors, the gateway reader and the computer in the back end. The firmware on the gateway reader scans for available tags in the vicinity through the anchors in 2 second intervals and computes a distance value based on RSSI measurements.

First, the viability of using RFID for tracking was investigated. The anchor was mounted on a tripod in 2.5 meters height while the tag was placed on the floor in various distances to the anchor. Measurements were made for 3 minutes. Figure 6.3 shows the actual distance as the red lines in the graphs and the measured distances over time as blue dots. When the tag was placed directly underneath the anchor (with a distance of 2.5 meters), the position error was around 28 centimeters but the other graphs display that if the distance increases, the deviation of the measured distance to the actual one increases as well. Also, objects or people moving in the LOS led to significant fluctuations as seen in the last graph of figure 6.3. Graph 2 in figure 6.3 shows signal fluctuations when a hand was held between the tag and the anchor for about 1 minute.

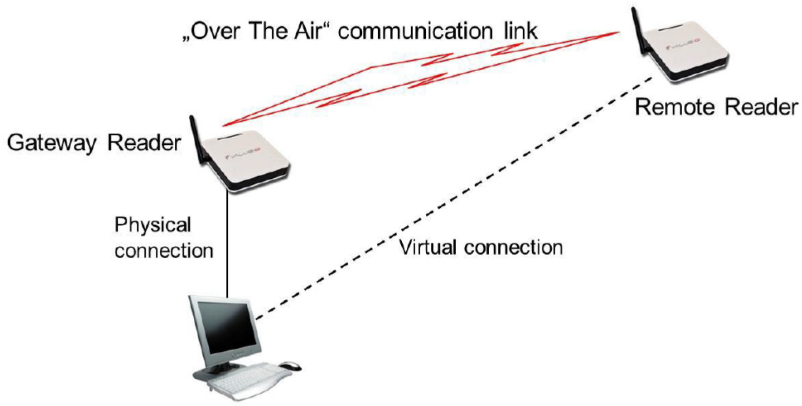


Figure 6.2: How the communication works between the different anchors of the Value-ID system. The remote readers are placed at specific positions and orientations to cover the area to detect tags. The gateway reader can be placed outside of the tracking region and its purpose is to communicate with all the remote readers, gather the data and provide it to the connected PC in the back end. The PC comes with a test application which has the algorithms implemented and computes the location. Figure taken from the Value-ID manual.

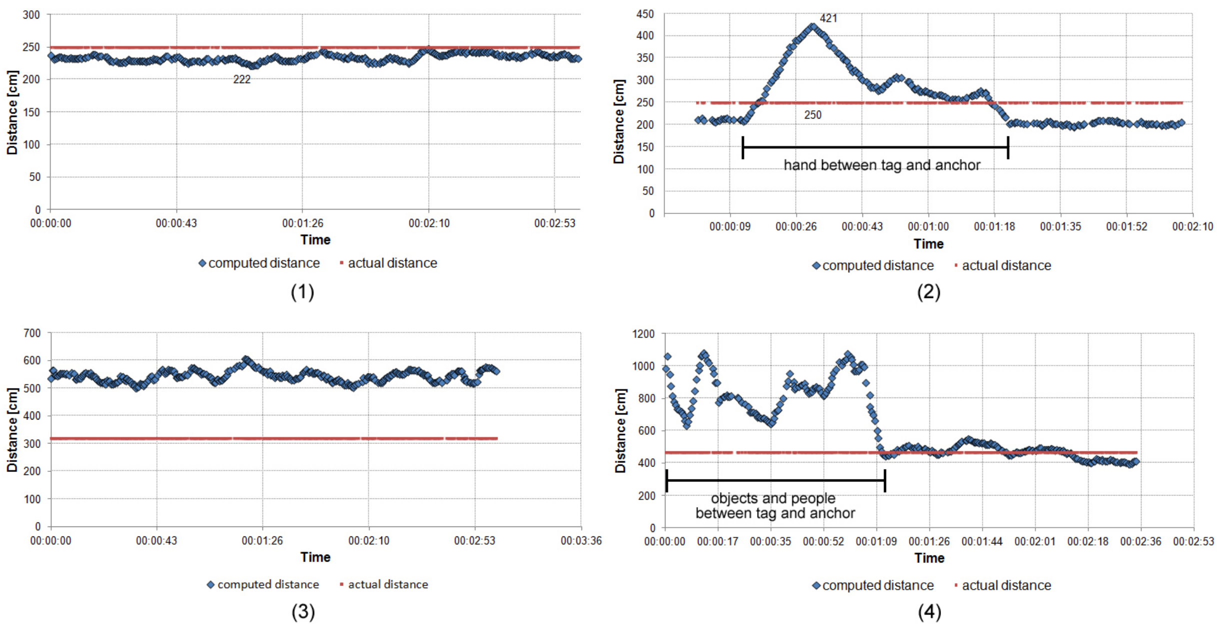


Figure 6.3: Simple tests with the Active RFID system by Value-ID. The tag was placed at different distances (2.22 meters at (1), 3.20 meters at (3) and 4.70 meters at (4)) to the anchor and measurements were made to see, if the calculated distance would coincide with the actual one. In graph (2), a human hand was held between the tag and anchor for approximately 1 minute. As a result, the system measured fluctuating signals. The last graph (4) also shows fluctuations when objects and people were moving in the LOS of the tag and the anchor (also for around 1 minute). Figure from [Mei14].

Influences and impact on results

Different objects were put between tag and reader to check their impact on the distance computations of Value-ID's RFID system. A sheet of metal caused the most significant fluctuations while influences by other objects such as paper, a human hand or liquid inside a plastic bottle were detectable but insignificant (see figure 6.4). When a human body was in the LOS, the computed distances doubled.

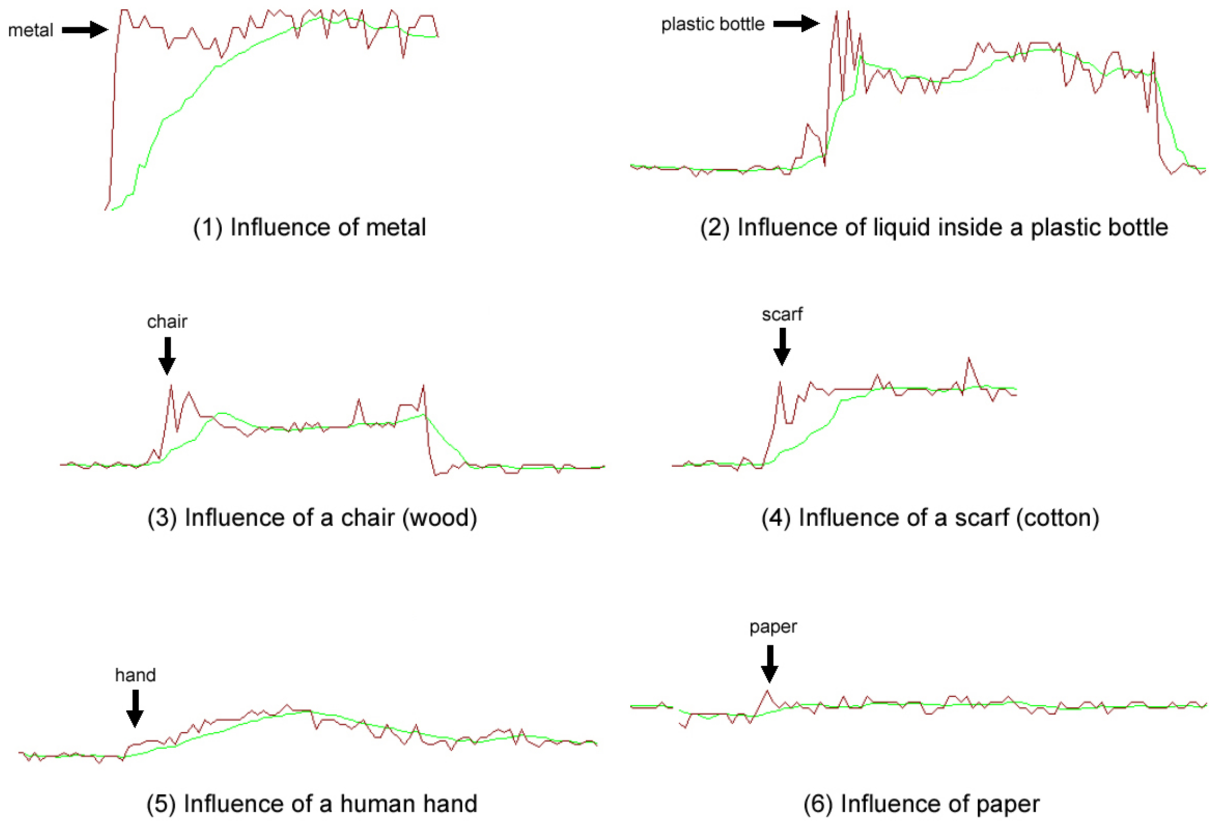


Figure 6.4: The results of the second test where different objects were placed between the tag and the anchor. The distance between tag and anchor always stayed the same (2.5 meters). The red curve represents the raw signal measured by the anchor while the green curve is the computed moving average. All the objects have visible impact on the continuously computed distance with metal having the most significant interference. Figure taken from [Vog14].

First algorithm

Two algorithms were implemented with RFID. Ideas and approaches such as [NHNV12] (take metal planes, mount them on the anchors' backs to use them as reflectors - for more details, see chapter 7.7) were taken and applied to the system to make it more stable and reliable regarding problems such as multipath effects and reflections. But there was still one problem with the signal strength values measured from the anchors. When actively moving the tag, the received signal strength indicator showed changes in the beginning but then went back to a certain constant level once the tag was stationary again (but not at the same spot). This prevented us from using any signal strength parameters for position calculation and instead, we had to solely rely on the distance values provided from the gateway reader.

The first algorithm was designed to use only one anchor mounted at the ceiling, looking downwards. Instead of signal strength measurements, a "valid distance argument" was put in the anchor's EEPROM. The "valid distance argument" should designate the range covered by the anchor where it could detect tags. The orientation of the anchor's as well as tag's antennas influenced the results heavily, either positively when both antennas were aligned or negatively when anything was obstructing the LOS. Looking at figure 6.5, the range/coverage represented an area around the OR table (which was positioned in the middle of the OR) where the medical staff was working with the mobile device. An expansion of this algorithm would be using two anchors in one room to create two “virtual” zones with consequently two OR tables.

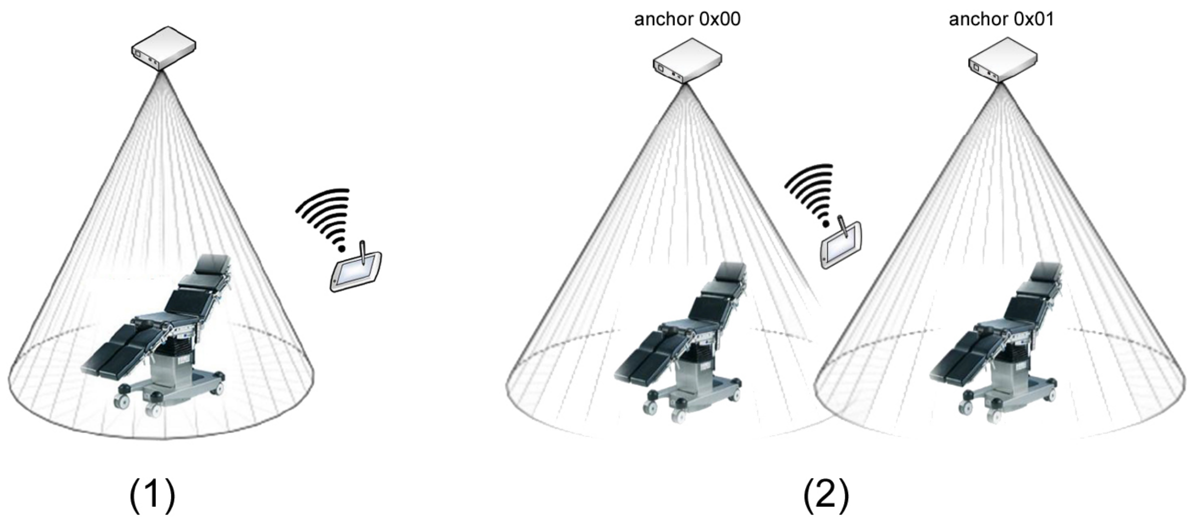


Figure 6.5: (1) shows the idea of the first algorithm with just one anchor above the OR table. The system recognizes a tag if it enters the anchor's range (which is specified by the “valid distance argument”). The same idea can be applied to multiple tables/anchors which, in the best case, are positioned in a way to avoid intersections of the anchors' ranges. If it comes to an intersection between two ranges/anchors (2) and a tag is placed in that region: The system takes the anchor which has received a message from the tag first as the final result.

Second algorithm

The second algorithm came with a total of four anchors where each of them was put into a corner of a square or rectangular room. Each anchor was mounted on a tripod with specific angle measurements to guarantee coverage of the area in front of the anchor directed to the center of the room (see figure 6.6). The room would be then split into quadrants with each anchor in the corners covering $\frac{1}{4}$ of the area. Two of the anchors had metal plates attached to their backs (see chapter 7.7). Since this algorithm made calculations according to the “valid distance argument”, there was a possibility that more than one anchor would detect the tag if the user stood in an unfavorable position. If, for example, the user would stay near one anchor with his tag, the anchor placed in the opposite quadrant would also detect the tag most of the times due to signal reflections. In these cases, a look-up table was used to assign the tag explicitly to one anchor (the anchor with the lowest measured distance to the tag). Table 6.1 shows the possible cases and their outcomes/decisions depending on how many anchors are active. An anchor being active is the equivalent of an anchor detecting a tag in its range. Through an iterative process, all the cases are considered and in the end, the quadrant with the tag's location is computed.

Both algorithms were tested in a mostly interference-free area for a duration of several weeks. Two test applications were developed for collecting the data and calculating the tag's location. Results showed that the system from Value-ID reached an accuracy of 85% when the tag was stationary and 88% when in movement. These results were calculated analytically and if applied to real data, would converge to the

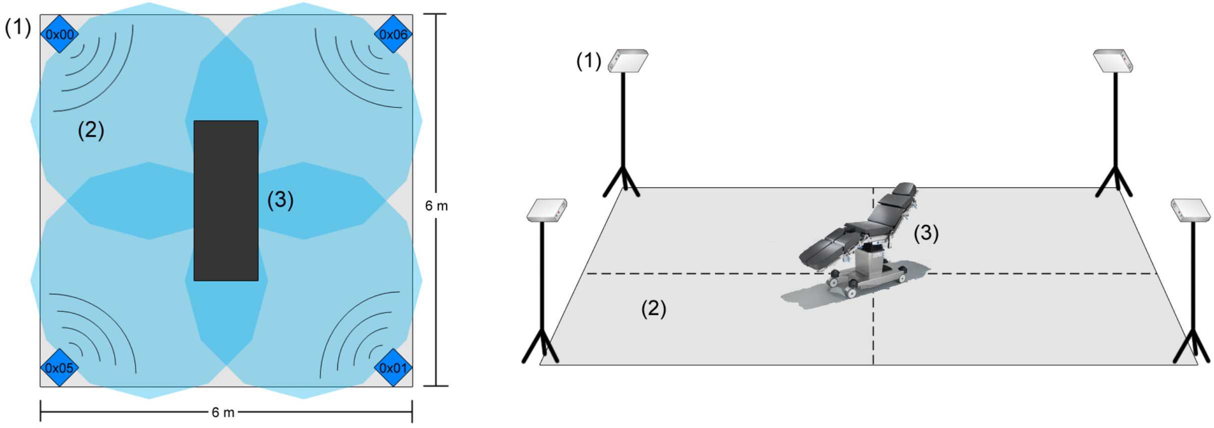


Figure 6.6: This figure shows the setup for the second RFID algorithm from two different views. The room dimensions were 6 x 6 meters and the tripods were set to a height of 2 meters. (1) represents the anchors mounted on the tripods. Each anchor covers a certain area (2) with the OR table (3) being in the center of the room.

percentages computed. Compared to other work and results from chapter 4.2, the accuracy we achieved was satisfactory, but also leaving a lot of room for improvements. Additional sensors on the tags could have been used and included in the position calculations to increase the system's reliability.

6.2 Tests with ZigBee

We bought another development kit from the company *Zigpos* (Dresden, Germany) consisting of four anchors, several tags and an Intel NUC to test it in the same area as the Active RFID system mentioned in the previous chapter (see figure 6.7). Similar to RFID, two algorithms were implemented here to locate tags. The task was to test, if the accuracies of up to 50 centimeters promised by the vendors could be reached with our setup.

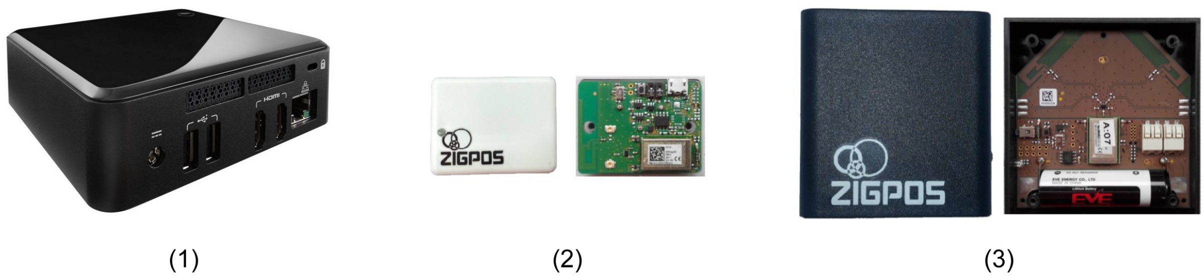


Figure 6.7: (1) is the Intel NUC computer, which serves as a gateway anchor for the Zigpos system. (2) and (3) are images of the tags and anchors.

Similar to the Value-ID system, the Zigpos system also uses a gateway reader (in this case, the Intel NUC) to communicate with the anchor modules. The communication process can be seen in figure 6.8.

Table 6.1: Look-up table with all possible outcomes for the second Active RFID algorithm with four anchors and one tag involved.

Case	Reader 1	Reader 2	Reader 3	Reader 4	Decisions taken
When no reader is active	x	x	x	x	The system assumes that the tag is out of range.
When only one reader is active	1	0	0	0	Look up previous value and then decide what to output. Initial stage when data is received.
	0	1	0	0	
	0	0	1	0	
	0	0	0	1	
When two readers are active	1	0	1	0	Look up previous value and then decide what to output. Second iteration step.
	1	0	0	1	
	1	1	0	0	
	0	1	0	1	
	0	1	1	0	
	0	0	1	1	
When three readers are active	1	1	1	0	Look up previous value and then decide what to output. Third iteration step.
	1	1	0	1	
	1	0	1	1	
	0	1	1	1	
When all readers are active	1	1	1	1	Look up previous value and then decide what to output. Final iteration step.

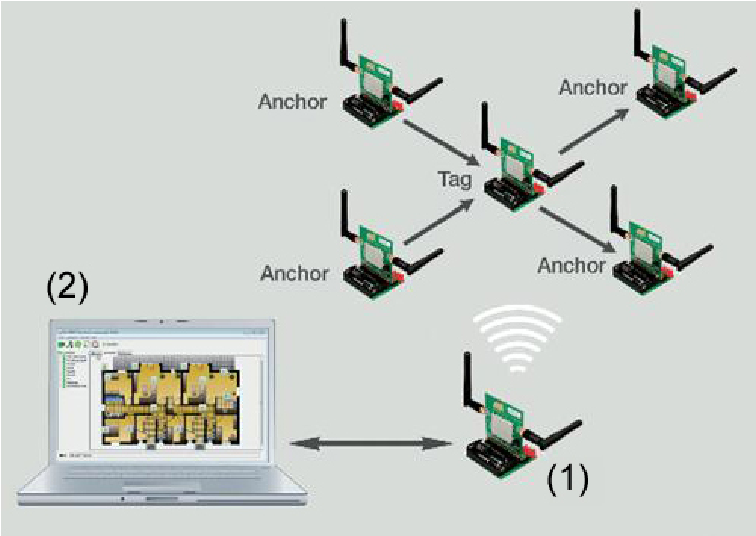


Figure 6.8: The gateway reader (1) is connected to a computer (2) with the installed location engine. All the measured data from the anchors is gathered by the gateway reader to compute the tag's position.

6.2.1 First algorithm

All four anchors were used similarly to the second algorithm of Active RFID (see section 6.1). The anchors were placed on tripods in the corners of the test room. This time, they were just put on the tripods with a specific rotation instead of inclining them (see figure 6.9). Different from the hardware setup of the Active RFID scenario, the ZigBee system has the capabilities to output reliable parameters such as the signal strength or even the calculated distance between anchors and a tag. With these parameters, a new test application was implemented for the first algorithm where the goal was to compute the location of a tag in the test room, split into even quadrants. The system should be accurate enough to tell, in which quadrant a tag was located with another look-up table. The look-up table was used to categorize the distance measurements into one of the quadrants depending on the x- and y-coordinates provided by the Zigpos anchors (for the detailed look-up table, see [Sal15]). According to [Sal15], the results were up to 50 centimeters accurate. This was calculated by measuring the coordinates of the tag at five different spots: at the center of each quadrant and at the center of the room. Then we looked at the minimum-maximum range of all the recorded values. For the x-coordinate, the highest value was 37 centimeters while for the y-coordinate, it was 48 centimeters. The maximum for the standard deviation of the x-coordinate was 12.11 and for the y-coordinate 13.62. These experiments showed that the accuracy provided by Zigpos could be achieved. A significant advantage over other development kits was the option to extract the estimated distances between the tags and the anchors and even an already calculated position in the two dimensional space directly from the system.

6.2.2 Second algorithm

The next approach was to make the system more scalable and to improve reliability. In the previous algorithm, we used a test room with the dimensions of 7 x 6 meters. We wanted to expand the dimensions to any size and layout while still achieving the same or even better accuracy with just three anchors (as compared to four anchors with algorithm 1).

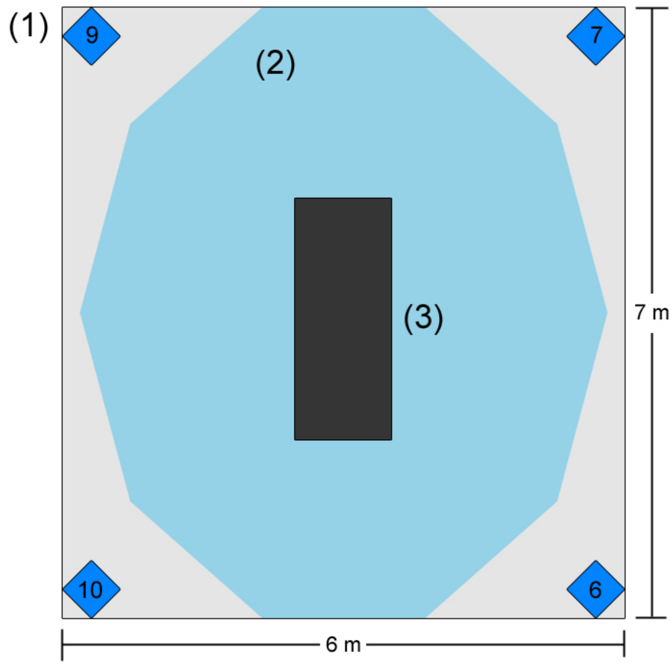


Figure 6.9: The anchors (1) are mounted on tripods and placed in the corners of the room. For this algorithm, the room dimensions were 7 x 6 meters. (2) designates the area covered by the ZigBee system and where tags can be located. (3) is the OR table, positioned in the center of the room.

The idea for the second algorithm was based again on the proximity-based method used for algorithm 1 of Active RFID. We mounted three anchors on the ceiling in the test area and tried to detect, if a tag was in their vicinity. By taking the calculated x- and y-coordinates as well as the parameters "signal strength" and "distance", we could get a more reliable location of the tag than with the Active RFID system. The setup can be seen in figure 6.10. We changed our test environment to be an "L"-shaped room. A look-up table similar to the one in algorithm 1 would then compute, in which area the tag was detected (see table 6.2). The look-up table worked with specific numerical values which designated the areas in the test environment (in meters). If the test environment would change, these values, since they were entered specifically for a certain setup, had to be changed as well.

Table 6.2: Look-up table, which assigns the computed x- and y-coordinates of the Zigpos system to a specific anchor/quadrant. The anchor IDs are taken from figure 6.10. Other cases (such as $x < 0$ and $y > 15$) are considered "out of range".

x-coordinate (in meters)	y-coordinate (in meters)	Anchor/Quadrant assigned
$0 \leq x \leq 8.5$	$0 \leq y \leq 5$	10
$0 \leq x \leq 8.5$	$10 < y \leq 15$	9
$8.5 < x \leq 15$	$10 < y \leq 15$	6

For this algorithm, it was interesting to see, how accurate a proximity-based method with three anchors in one room would work. The tag was positioned right underneath the anchors where its coordinates were recorded and compared against the real position. For each anchor, we reached an accuracy of up to 30 centimeters. The worst cases for the standard deviation of the measured x- and y-coordinates were 3.64 and 10.54 respectively.

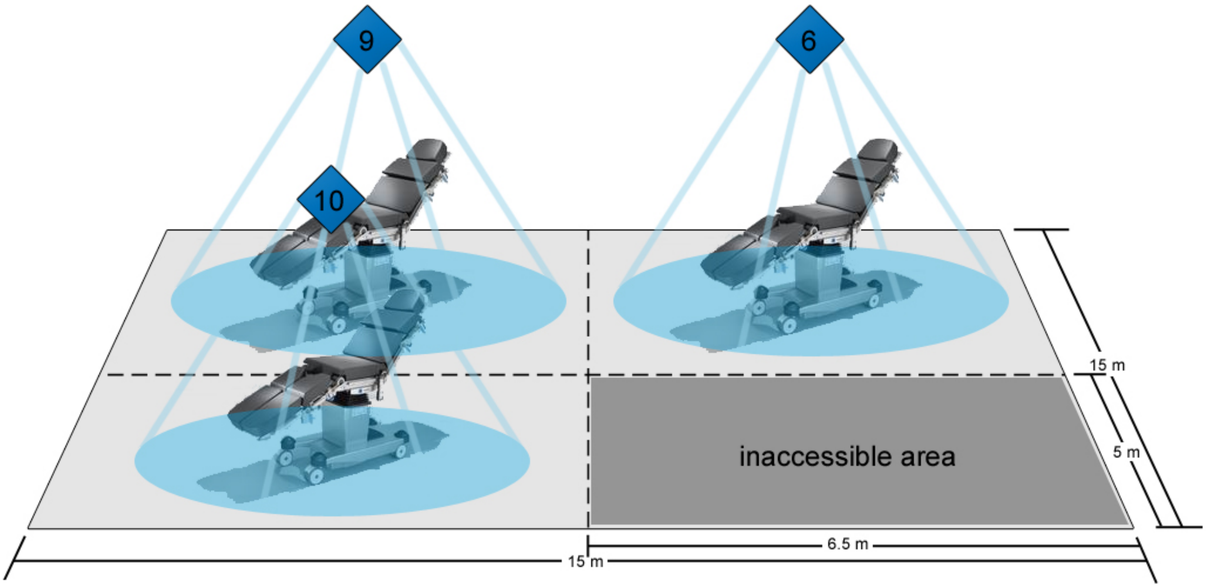


Figure 6.10: Setup for the second ZigBee algorithm. In each quadrant (except for the inaccessible area), an anchor was mounted on the ceiling above the OR table. The Zigpos system calculated the x- and y-coordinates of a tag in the environment which we then took to isolate the user's position in one of the quadrants.

A nice feature of the Zigpos system was the forward-compatibility to ultra-wide band for their anchors. With a software-update for the anchors, they would be able to detect ultra-wide band sender modules.

6.3 Tests with WiFi

Different to all the other development kits which were used as outside-in systems, we decided to use the WiFi location tracking system as inside-out. That meant that we obtained information about the user's or object's position through an anchor mounted on the user/object. The anchor received data from tags which were stationary and distributed in various spots throughout the environment (see figure 6.11).

We used proprietary components such as the small business access point WAP200 from *Cisco* (San Francisco, United States) as "tags". They were all configured to create the same wireless network with a common SSID and password. An advantage by using the system as inside-out was that the access points could be positioned anywhere as they served as tags and only required power to work. As anchor, we used the High Power Wireless USB Adapter TL-WN7200ND from *TP-Link* (Shenzhen, China), which was connected to a computer via a USB cable. All components can be seen in figure 6.12. Through a test application, a connection with one of the existing wireless networks was established through the USB adapter and data such as the signal strength values for all the access points could be read. Different from the methods used for RFID or ZigBee, we implemented fingerprinting for WiFi (see chapter 3.3 for details about fingerprinting). We decided against using the RSSI and distance estimations through propagation

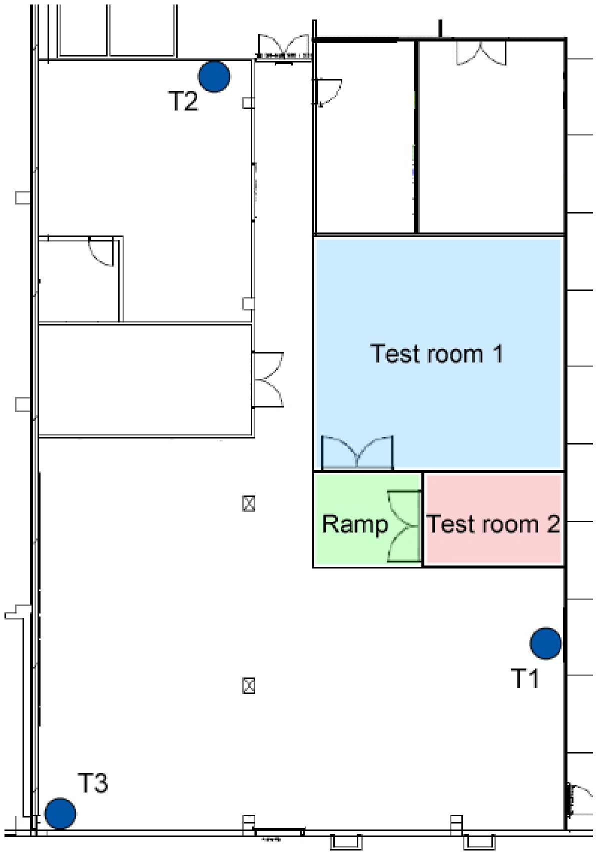


Figure 6.11: The setup for the WiFi tests. T1-T3 are the tags/access points distributed in the area. Three locations were essential for the tests: test room 1 (blue), the ramp connecting both rooms (green) and test room 2 (red).

models since we already investigated these methods with the technologies in the previous sections. The high probability of access points being already deployed in healthcare facilities (according to [Cis08], the number of access points varies but in most cases, 1 access point is installed in corridors and additional ones are deployed in adjacent rooms) leads to more possibilities of measuring fingerprints which is a big advantage of using this method and would increase the position accuracy in the end. In figure 6.11, you can see the setup and test environment with three access points placed at positions (T1), (T2) and (T3).

Figure 6.12: (1) is the WiFi USB adapter by TP-Link and (2) the access point by Cisco.

6.3.1 Experiments

For the tests, an application was programmed to record fingerprints for any given map in the offline phase and for measuring, computing and displaying the calculated position in the online phase. All the measured fingerprints were saved in a Microsoft SQL Server 2008 R2 database.
Three factors, which would all have an effect on the accuracy in the computed position, were considered in the tests:

- The density of the recorded fingerprints in the map
- The amount of measurements done at one fingerprint position
- The orientation of the anchor and its antenna

For the last factor, we would conduct tests where measurements done in all four orientations would be 1. averaged and stored in the database and 2. stored separately in the database for each of the orientations. All these factors would be used to apply the kNN and kML (see chapter 3.3). In the first stage of the experiment, we only recorded fingerprints for a closed room (see figure 6.13) to investigate the mentioned factors above and later on, in the second stage, the fingerprint map was expanded to other areas as well as refined to be more dense with additional fingerprints.

At each position and for each orientation, signal strength values were recorded for 10 seconds which equaled 10 RSSI values. Later, fingerprints were recorded at the same positions but for a longer time span of 15 and 25 seconds. Some fingerprints were also added to the map/database later to see if they would have an effect on the accuracy when measured and saved at different times. In summary, the following factors had to be measured, computed and stored:

- A fingerprint map with 2 x 2 and 4 x 4 meter maps
- Measurements done in time spans of 10, 15 and 25 seconds for each orientation
- Average value of all orientations at a position which results in one fingerprint
- Average value of each orientation at a position which results in four fingerprints
- A histogram for each position

Regarding the weights for kNN and kML, the following formula was used:

$$w_i = \frac{1}{distance(RSSI\_online_i - RSSI\_offline_i)} \tag{6.1}$$

For testing purposes, a programmed robot was used (see section 7.6) which would drive a specified route in the test area repeatedly and autonomously. The robot would stop at certain points for 60 seconds, then turn in other directions and continue driving. Using the robot saved effort and time since all the testing was done automatically.

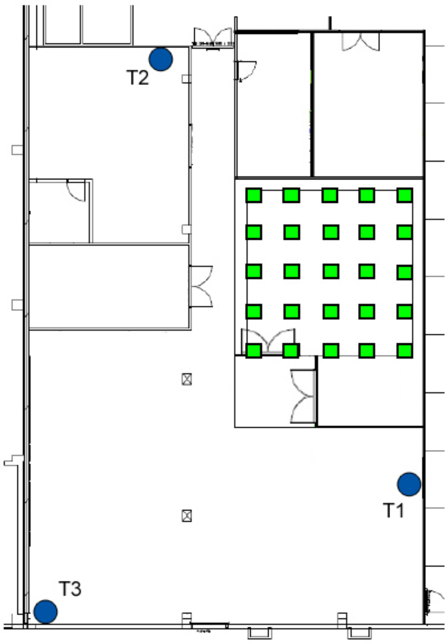


Figure 6.13: Fingerprints recorded in test room 1.

6.3.2 Results

Figure 6.14 shows two RSSI histograms measured at the exact same position (at the center of the room) but saved at different dates. While the average signal strength value of anchor 1 measured on March 27th was -49.0 dBm, it was -41.1 dBm on the 31st. The measurements on the 27th were performed at around 2:00 PM while measurements on the 31st were recorded in the morning (around 9:00 AM). Besides the time, other factors such as the parameters of the anchors or the activity in and around the room were similar for both days.

For our tests, using more dense maps (the 2 x 2 instead of the 4 x 4 meter map) increased the accuracy by approximately 12 percent while using 9 and in the end 25 fingerprints (which is almost three times the original amount). While the effort to calibrate and record the additional fingerprints is high, it is debatable if the improvement is enough to justify the effort. The results show that measuring fingerprints for 10-15 seconds led to a radial error of 4 meters while with 25 seconds for each orientation, the error was just 3 meters.

Taking the average values of each orientation for a position would not result in increased accuracy. If we calculate and save the average values separately, we automatically have fewer values included for each orientation. Having one average value consisting of all the measurements in each orientation taken at one position led to better results. In general and as we already showed in the paragraph before, the accuracy would improve when more signal strength values are taken into account when computing the average. Figure 6.15 shows that the computed radial error is less for the average value over all 100 RSSI measurements for a fingerprint than for taking the average values for just the 25 RSSI measurements for each orientation.

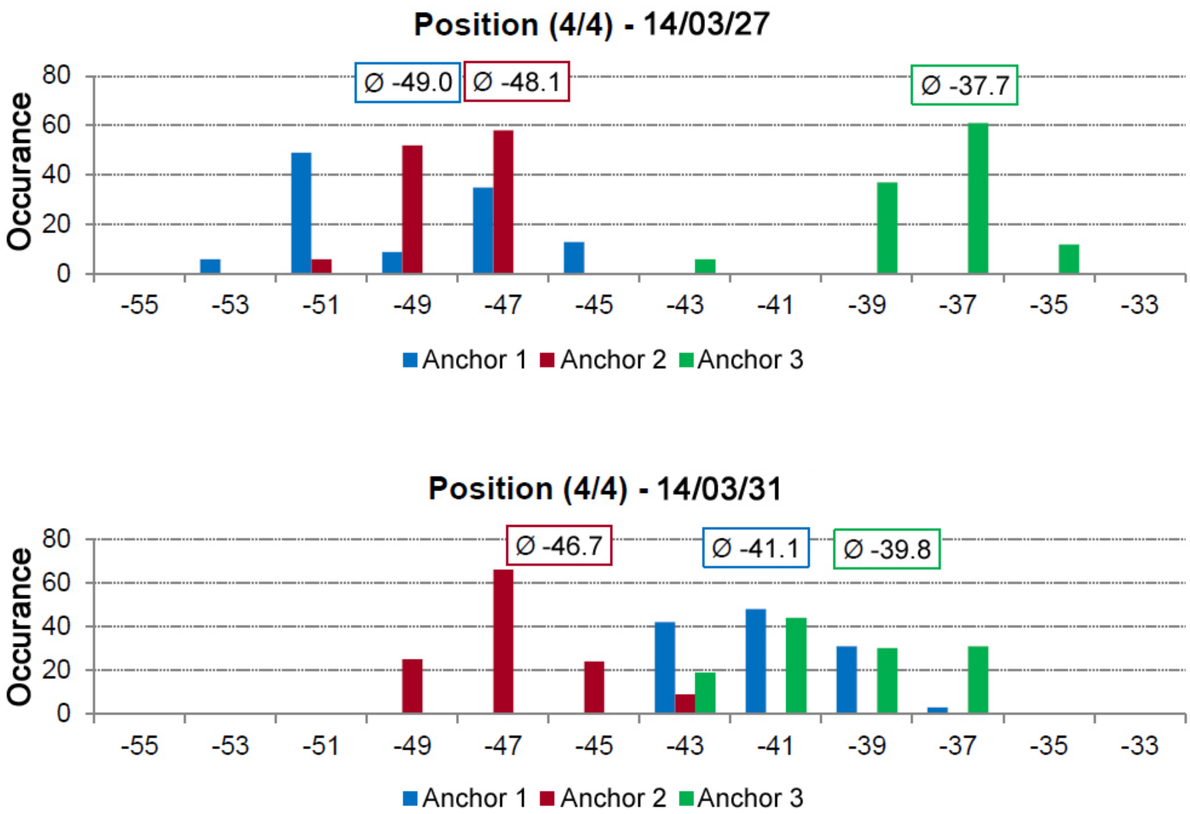


Figure 6.14: Two histograms taken at the same position in the test area but measured on different days. Graphs from [Mei14].

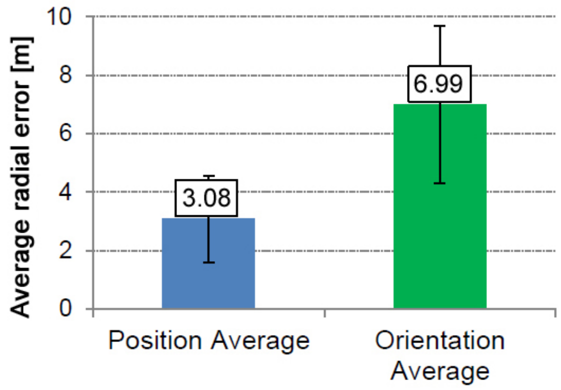


Figure 6.15: The average radial error for the position average (over all RSSI measurements) and the orientation average (for each orientation). Figure from [Mei14].

Results with kNN

For the factor k, we rely on [WDGN05]. Looking at our tests, a bigger k results in a decreased radial error by $\frac{1}{4}$. Using weights for the kNN or a moving average for the live signal strength values did not have significant effects on the radial error. The results for kNN in the test room can be seen in figure 6.16. The percentages of correctly assigned rooms (true positives) ranged from 30% to 70%.

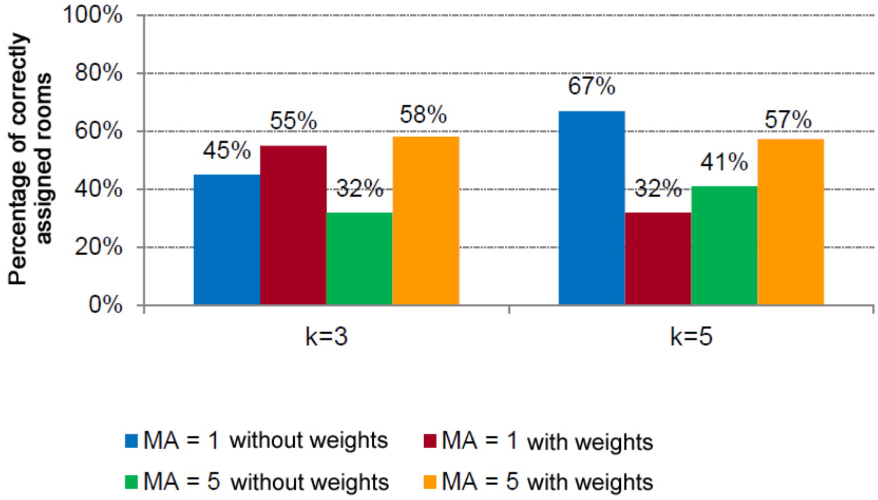


Figure 6.16: This graph shows the percentage of correctly assigned rooms with different k's for the kNN, moving average parameters as well as with and without weights. Graph from [Mei14].

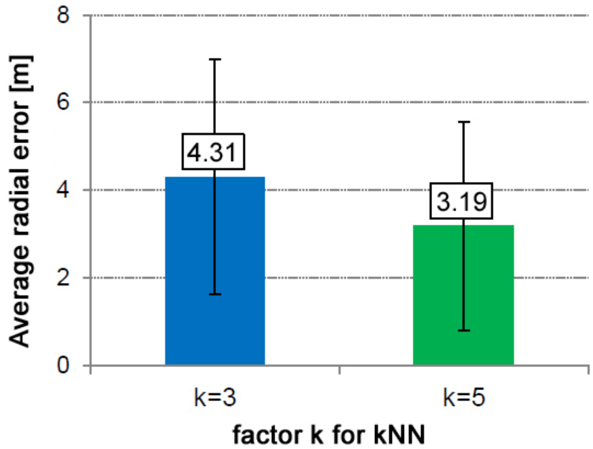


Figure 6.17: The average radial error when using $k = 3$ and $k = 5$ with the kNN. Figure taken from [Mei14].

If we look at figure 6.18, the percentages of how many times the tag was detected in each of the rooms are displayed. While in all three rooms, the percentage count of true positives is higher than the rest, the false positives are still too high to ignore. The tag was detected correctly in the test room 70% of the time but for 19% of the time on the ramp and 11% in the second test room. When the tag was positioned on the ramp, it was correctly detected there 56% of the time while being detected falsely 43% of the time. For the second test room, the true positive rate was 79% but the tag was found 21% of the time on the ramp. The high true positive rate for the second test room can be attributed to the small dimensions of the room and the anchor module on the ceiling covering the whole room optimally.

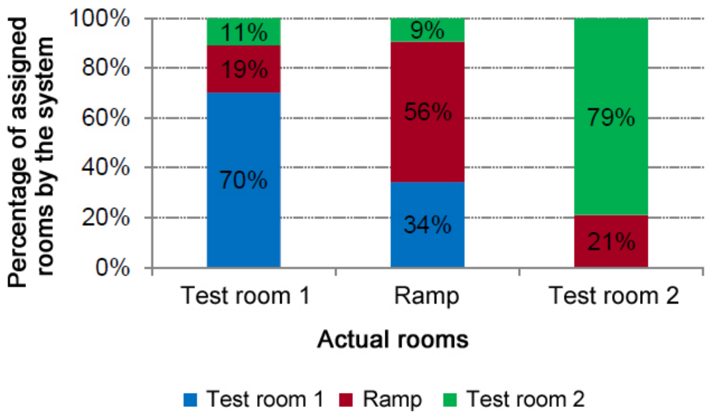


Figure 6.18: With kNN: the percentage of assigned rooms by the location tracking system compared to the actual ones. Graph from [Mei14].

Results with kML

Since the computation of the position with kML is done via comparison of histograms, we just took the raw signal strength value instead of the average. We tested, if weights (see equation 6.3.1) would have any influence on the accuracy of the calculated position in the end. Different than with the kNN, where a bigger k improved the results, a bigger k with the kML increased the average radial error. Also, weights had a more significant effect on the results with the kML than with the kNN.

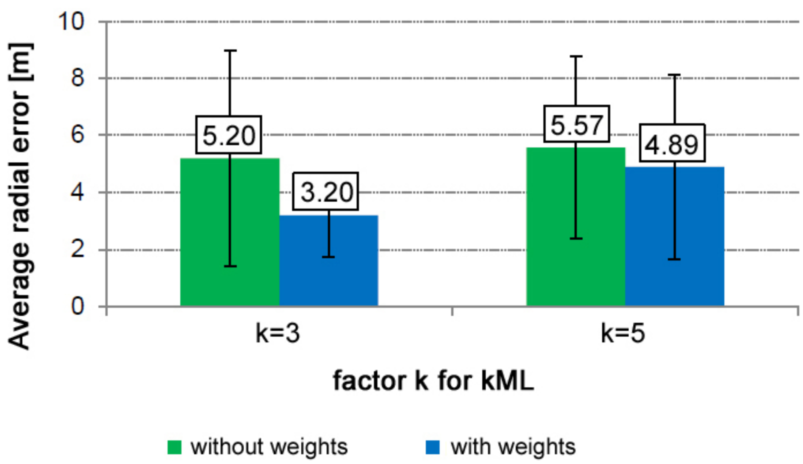


Figure 6.19: The average radial error when using $k = 3$ and $k = 5$ with the kML, also with and without weights. Figure from [Mei14].

The average radial error with the kML was around 2 to 6 meters. When looking at figure 6.19, we can see that with weights and $k = 3$, the error was 3.20 meters but increased with $k = 5$. Regarding the tests which check the room level accuracy of the WiFi system with kML, the following can be said: in the best case, the tag was detected for 55% in the correct room ($k = 3$ with weights, see figure 6.20) while for the worst, the rate was 29% ($k = 5$, without weights). For the individual rooms, the tag was found correctly 55% in the test room, 79% on the ramp and 100% in test room 2. The true positive result of 55% was reached because of the result from test room 2. The results (especially the 100%) have to be taken with a grain of salt. The count of readings where the tag was not found in test room 2 was very high but whenever the tag was found, it was found in the correct room. The true positive rate for the test room (55%) was not satisfying for our requirements.

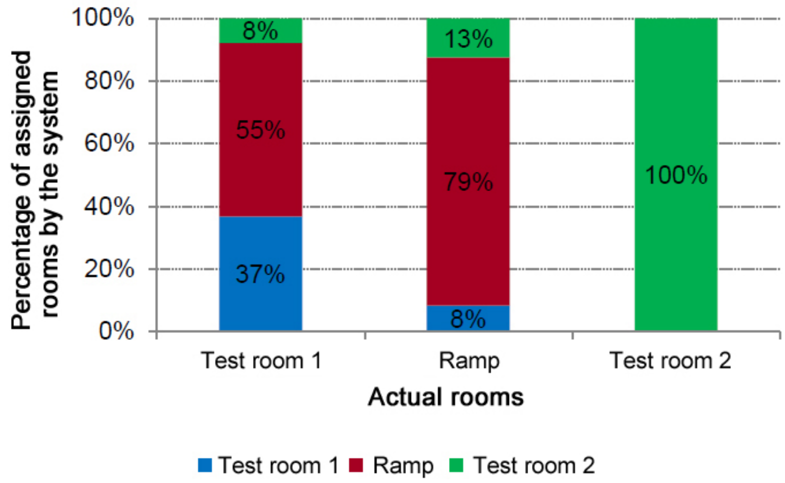


Figure 6.20: With kML: the percentages of assigned rooms by the location tracking system compared to the actual ones. Figure from [Mei14].

6.3.3 Discussion

We can confirm through our tests that making the fingerprinting map more dense and increasing the amount of fingerprints leads to improved accuracy ([Hon09] achieved an improvement of 20 percent in accuracy with doubling the amount of fingerprints). But [TSFC10] concluded that using fingerprinting in a hospital would come with difficulties and inaccuracies due to other hardware causing interferences and a constantly changing environment.

Looking at the results, the kML did not show any improvements in the results compared to the kNN algorithm but required more processing power and preparation in the offline phase (computing the histograms, saving a lot more data). For correctly assigning the rooms, the kNN achieved a true positive rate of 60% while for kML, it was only around 50%. In both cases, the results showed that a minimal radial error of approximately 3 meters could be reached for calculating a position. These results would not fulfill the requirements set in chapter 2.1 for stable working conditions of a tracked mobile device in the OR.

Overall, the experiments with Fingerprinting show that satisfying results can not be reached without extensive calibration effort. The fingerprinting maps are only a snapshot of a certain environment at a specific time but with time progressing and a changing setting, the maps would include outdated measurements. Another problem is that in many cases, signal strength combinations are not unique enough for their position on the map (see [BP] [LSDR] [RMT02] for references to other work with similar experiences and problems). [Hon09] said that using a Kalman filter with kML improved the accuracy and according to [TEP06], complementing the kML with Fuzzy Logic also had a positive effect on the radial error.

6.4 Tests with Bluetooth

First tests with Bluetooth began in 2013 when a development kit consisting of several anchors and sender modules by the company *connectBlue* (Malmö, Sweden) was acquired. At that time, proximity detection using low powered modules was an up and coming topic in the tracking market with huge potential [Mub13]. The Bluetooth anchor modules were configured to scan for Bluetooth Low Energy modules while the sender modules (tags) were set to send out BLE-specific advertisements in a periodic time interval. First tests (see chapter 7.3) confirmed, that the modules could be used for a simple proximity-based location tracking system. This is when we decided to base the location tracking system completely on Bluetooth (Low Energy) and use a rather simple approach: install an anchor per room and detect tags if they are nearby or far away. The tags would be integrated in the TruConnect mobile devices and depending on the measured signal strength values, the devices would enter a "virtual room", allowing the user to control other medical equipment or exit the room, subsequently disabling all controls. But this method came with some (known) issues as well (see chapter 7.7). All the different and important phases in developing and testing the system will be described in the next chapter.

6.5 Tests with a Hybrid RTLS

The company CenTrak provided us with a demo system for testing purposes. The RTLS works on a combination of infrared and 900 MHz RF to track people or equipment and should reach room or sub-room level accuracy. Four different anchors as well as three tags were included in the package to test. These and the conduction of a brief experiment to check the promised accuracy by the vendors are described in the following chapter.

6.5.1 Components

The system consists of various types of anchors and tags which complement each other in their functionality and also communicate with each other. The anchors send out unique IDs through the built-in infrared LEDs in periodic intervals which are then received by the tags and forwarded to the "Stars" via RF. The Star collects all the data from the anchors and forwards it to a computer in the back end to compute the position of the tags. The components which were used in the experiments will be explained briefly in the following.

Anchors

Figure 6.21: The anchors used in the CenTrak RTLS: (1) the Star, (2) the Virtual Wall Monitor, (3) the Monitor and (4) the LF Exciter.

- **Star**
  The Star is connected to a computer which is running the location engine. Its main task is to communicate with all the other components such as the Virtual Wall Monitor, Monitor and LF Exciter to gather all the data through 900 MHz RF.

- **Virtual Wall Monitor**
  The Virtual Wall Monitor is used to virtually restrict an area where tags should be found. It is generally mounted on the ceiling and looks downwards, creating a barrier. It houses 32 infrared LEDs, which emit infrared signals every 3 seconds in certain directions.

- **Monitor**
  The Monitor has the same functionality as the Virtual Wall Monitor except it emits the infrared pulses more uniformly.

- **LF Exciter**
  The LF Exciter extends the range of the RF communication between the Stars and other components. It is installed for example in corridors to connect the components of two rooms separated by a larger distance.

Tags

Figure 6.22: There are various tags, each with its own use case: (1) the asset tag, (2) the alert tag and (3) the patient tag.

We were provided with three different tags, each for a different use case:

- Asset tag (1)
- Alert tag (2)
- Patient tag (3)

All these tags come with power-saving sensors which detect, if they are moving or not. When placed at a fixed spot for a longer time period, the interval of communicating with the anchors decreases steadily (up to once every half an hour). Usually, when in motion, the tags report data to the anchors every 12 seconds. The alert tag has an additional feature where it communicates with "Dispenser Modules" (DIM) to notify them that the user wearing the tag is currently in its proximity. The range for when the DIMs register the tag is specified to be about 3.5 feet (which translates to around 1 meter). An event for hand washing is registered by the RTLS whenever a staff member is in vicinity of a DIM and concurrently washes his hands. The tags have different form factors and also come equipped with different batteries. Patient and alert tags can last for 12 months while asset tags last around 6 to 12 months.

6.5.2 Experiment

Two experiments were conducted with the three tags at different positions in each test. The focus was on testing borderline cases such as placing tags in the area between two rooms to see how reliable the system would behave in difficult conditions and environments. In figure 6.23, both setups from the top view can be seen.

Figure 6.23: An overview of the two setups for the experiments. The anchors were placed in spots according to the guidelines provided by CenTrak. The position of the tags can be seen in the figure as well. We put at least one of the tags in a "borderline" position to check the reliability and precision of the RTLS.

The anchors were placed in certain spots according to the manual provided by CenTrak. In setup 1, the tags were left on their positions for 24 hours and after that, the logs were exported from the location engine to analyze. The system stored the information about when and where a tag was found and if it left the room. In setup 2, we left the tags for 48 hours on assigned locations.

6.5.3 Results

Setup 1

The test ran from September 16th, 8:00 PM until September 17th, 8:00 PM. The tracking history for all three tags can be seen in table 6.3. For two of three tags, the locations could not be determined reliably for the entire test duration. The third tag was detected in the correct room (test room 2) for over 24 hours.

Table 6.3: Movement history of each tag for setup 1, directly exported from the CenTrak RTLS.

Setup 1 Tag 1	Found in	From	Until	Duration
	Hallway	September 16, 05:34 AM	September 16, 05:49 AM	15 minutes
	?	September 16, 05:49 AM	September 17, 12:22 PM	31 hours
	Test room 1	September 17, 12:22 PM	-	-

Setup 1 Tag 2	Found in	From	Until	Duration
	Hallway	September 15, 11:51 AM	September 16, 05:56 AM	18 hours
	?	September 16, 05:56 AM	September 17, 12:18 PM	30 hours
	Test room 1	September 17, 12:18 PM	-	-

Setup 1 Tag 3	Found in	From	Until	Duration
	Test room 2	September 15, 06:57 AM	September 17, 08:31 AM	2 days

Setup 2

The second test ran from September 18th, 11:00 AM until September 21st, 3:00 AM. The results can be seen in table 6.4. While tag 1 was not detected in the hallway nor in test room 1 as it was supposed to be, tag 2 and 3 were detected in test room 1 for a fraction of the test duration. Still, the results prove to be unsatisfactory and the RTLS seems to have trouble dealing with borderline cases.

6.5.4 Discussion

The infrastructure of the test environment could have been part of the reasons why the tags were not found in their rooms during the tests. Test room 1 lacks a ceiling and therefore, infrared signals, which were supposed to stay in room 1, could have leaked or could have been reflected into the hallway. Also, the doors leading to test room 1 are always open. In test room 2, we had more reliable results which could be attributed to the room having a ceiling and the doors being closed most of the time.

Table 6.4: The movement history of the three tags for setup 2.

Setup 2 Tag 1	Found in	From	Until	Duration
	Test room 2	September 15, 06:57 AM	September 17, 08:31 AM	2 days
	?	September 17, 08:31 AM	September 21, 04:27 AM	91 hours
	Test room 2	September 21, 04:27 AM	-	-

Setup 2 Tag 2	Found in	From	Until	Duration
	Test room 1	September 16, 05:49 AM	September 18, 11:30 AM	2 days
	Test room 2	September 18, 11:30 AM	September 18, 11:30 AM	31 seconds
	?	September 18, 11:30 AM	September 21, 04:28 AM	65 hours
	Hallway	September 21, 04:28 AM	-	-

Setup 2 Tag 3	Found in	From	Until	Duration
	Test room 1	September 16, 05:56 AM	September 18, 11:30 AM	2 days
	Hallway	September 18, 11:30 AM	September 18, 11:31 AM	59 seconds
	Test room 1	September 18, 11:31 AM	September 18, 11:31 AM	4 seconds
	Storage	September 18, 11:31 AM	September 18, 11:32 AM	48 seconds
	Test room 1	September 18, 11:32 AM	September 19, 11:09 PM	36 hours
	?	September 19, 11:09 PM	September 21, 04:20 AM	29 hours
	Hallway	September 21, 04:20 AM	-	-

But it is interesting to see that in setup 2, although no tag was actually in test room 2, the RTLS detected tag 1 in that room for most of the test duration. This contradicts the assumption that infrared would make the RTLS more stable for room level accuracy since only tags with LOS would be considered in the vicinity of an anchor.

It is also not clear why the tags were not found in any of the designated areas for as long as 91 hours (setup 2). According to CenTrak's installation manual, stationary tags would gradually decrease their advertising interval until they send out data only every 30 minutes. But it seemed like the tags stopped communicating with the anchors altogether and did not report any new positions.

7 Developing a location tracking system

After several evaluations of different radio-based technologies, we decided to go with Bluetooth Low Energy as our primary technology for our location tracking system (see section 6.4). This chapter describes the development and goes into detail about the parts of the system we used, such as hardware, software as well as the calibration process.

7.1 General

When developing an RTLS from scratch, the first idea was to look into WiFi. The reason for that was simple: since every operating room, where TruConnect would be installed, already came with WiFi access points, a wide area would be covered with a 5 GHz WiFi network. This network would be primarily used for transferring data from A to B but could also be used for location tracking with methods such as fingerprinting. But after evaluating WiFi (see section 6.3), a location tracking system based on that technology was deemed inadequate due to the high amount of effort for calibration and maintenance needed and the uncertainty of at least three of the installed access points being visible and reachable.
In 2013, Bluetooth Low Energy was an up and coming technology and a few companies were already offering products with embedded modules inside, using it for example as key finders or remote controls for the garage. The technology's biggest advantage is its low power consumption compared to others such as ZigBee or WiFi. However, there are also downsides such as the low update-rate, low data rate/speed and the limited option of setting up only 7 parallel connections to tags in the vicinity. All the applications available at that time worked on the same principle: a tag is detected when it comes close to an anchor and depending on the distance, a certain event is triggered. Because of its hardware restrictions (partly because of the official Bluetooth specifications), there are no real opportunities for modifications on the tags or anchors concerning the software without requiring a new certification for the altered product. One of the reasons why we chose to continue with Bluetooth was its value for money. A Bluetooth tag costs around 30 to 50 Euro and an anchor costs between 40 to 60 Euro.

The tracking of the tags is done via Bluetooth Low Energy signal strength measurements. As already mentioned, an anchor is installed in each room where tags should be detected. We can assume that the anchor, which finds a tag and records its highest value is the one, where the tag is in its immediate vicinity.

7.2 Hardware

This section describes the hardware used for the tag and anchor modules. We go into the specifications and explain the existing issues as well as the configuration for the modules.

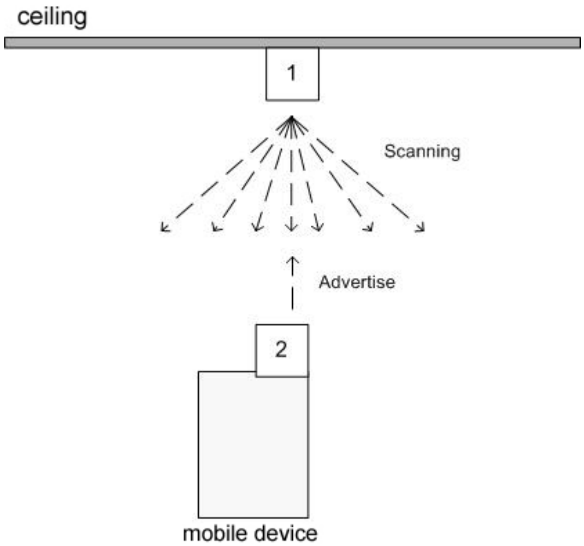


Figure 7.1: The anchor on the ceiling (1) scans the vicinity for mobile devices with embedded tags (2). The tags send out advertisements in a periodic time interval.

7.2.1 Tag and anchor module

For the tags and anchors, two hardware vendors were evaluated: *Bluegiga* (Espoo, Finland) and *connect-Blue* (Malmö, Sweden). At first, we started with the DKBLE112 development kit by the company Bluegiga. It included a board equipped with the Bluetooth Low Energy module BLE112. We used the board as anchor while using another module of the same type as tag. But unfortunately, the module did not offer predefined commands for the serial interface that we could use to extract the signal strength readings. Both providers were offering products with similar features and in the same price range but in the end, the modules from connectBlue were chosen for the location tracking system. We evaluated the OLS425 module to be used as tag and the OBS421 module as anchor (see figure 7.2).

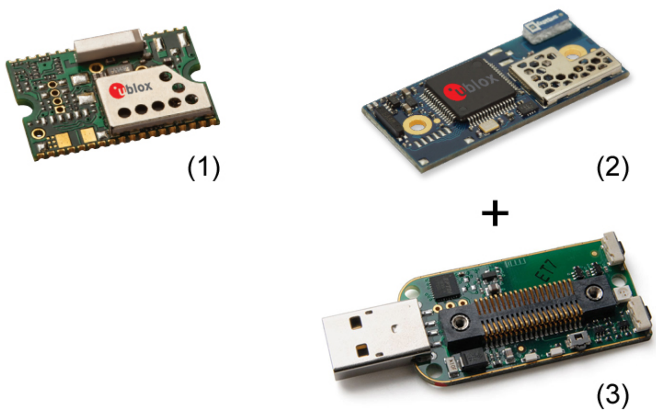


Figure 7.2: Images of the used hardware components. (1) is the OLS425 BLE module which is used as the tag in our system. The anchor module is composed of the OBS421 Bluetooth module (2) and the cB-ACC34 USB adapter (3).

Different from Bluegiga, connectBlue was offering simple USB boards with FTDI-chips for a very easy way to communicate with the modules over a virtual COM port. The OBS421 modules were mounted on the USB boards and then plugged into an USB-to-RJ485-converter to be powered (through Power over Ethernet, short PoE) and for covering long distances. These three components formed an anchor. The USB-to-RJ485 converter was necessary since the cable lengths of USB were limited to 2.5 meters. With RJ485/network-cables, distances of up to 100 meters could be covered. The OLS425 module represents the tag, which is mounted on an external PCB and is constantly sending BLE advertisements (see figure 7.3). The OLS425 module does not have an extension board as it is directly soldered onto the PCB which is then built into the mobile device's case. A rechargeable battery (VL2320) with 30 mAh capacity is powering the OLS425 module and whenever the mobile device is charged on a docking station, the battery for the tag is charged too.

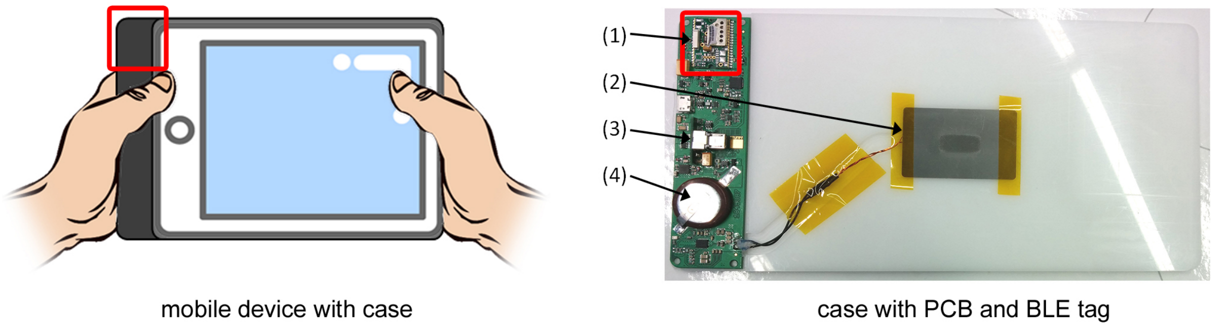


Figure 7.3: On the left: The mobile device with the case and how the user is supposed to hold the device. We purposely put the BLE module on the PCB in the upper left corner (1). The user, when holding it correctly, should not cover the tag with his hands. (2) depicts the induction spool to charge the battery for the tablet and the battery for the tag (4). (3) is the connector to the tablet.

For the use case of tracking people and equipment other than the mobile devices, different sender modules from companies such as *Conrad Electronic SE* (Hirschau, Germany) and *Texas Instruments* (Dallas, United States) were evaluated as well. The tests and results with these tags are presented in chapter 8.1.

7.2.2 Issues and points to consider

In the following section, some issues with the connectBlue modules are discussed. As with every off-the-shelf hardware, there are advantages as well as disadvantages. Buying and using these modules means a lot of room for modifications but they are also mostly intended for professional use or experts.

Connection

It is important to note that we are just sending inquiries from the anchor module and scanning the environment for any Bluetooth Low Energy tags. We do not establish a connection to the tags because of the existing limitation that we can only have a connection to 7 sender modules simultaneously per anchor. It would be difficult to manage the existing and new connections if we were to implement the pairing process between tags and anchors. But this would benefit us in having more and continuous data from the sender modules (for example the RSSI feed, accelerometer data or battery statistics) which can be obtained far more often with an established connection. One disadvantage when trying to establish connections to tags is the higher power consumption of the sender. Otherwise, the tags would be in a so-called “stop mode” to reduce battery consumption.

Antennas

Both modules have internal ceramic antennas mounted on their boards. Figure 7.4 displays the antenna and its propagation for the OLS425. The propagation characteristic for the tag shows a directivity going towards the x/y-axis. The signal propagation for the anchor module OBS421 as seen in figure 7.5 is more uniform. This implies that if we want to improve signal stability and have uniform range, we have to modify the propagation characteristic for the tag by using other, more uniform antennas.

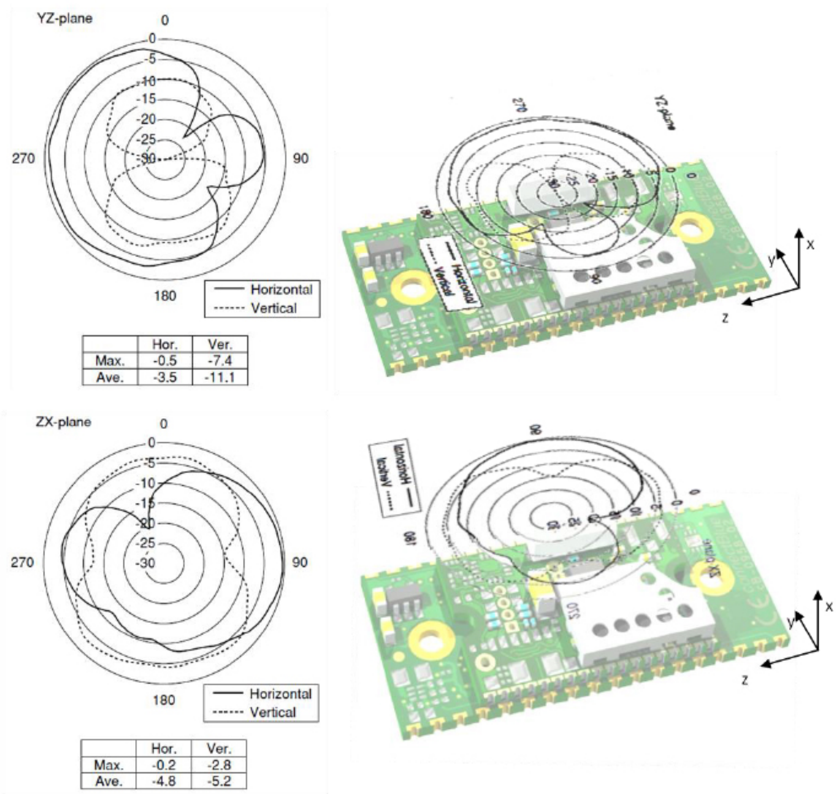


Figure 7.4: The signal propagation for the OLS425 module which is used as the tag. A more uniform propagation can be seen in the X and Y direction. Figures taken from [FCC].

For the anchor modules, external antennas were tested. Since the antenna gains of the external antennas are higher by 1-3 dBi, the results also showed increased signal strength values compared to the ones measured with the internal antenna. Also, the average standard deviation of measured RSSI values was lower than when tested with an internal antenna. This also led to minimally reduced fluctuations in the measured signal strength. Because of the external antenna, the RSSI values increased by an average of 39.6 dBm, implying that the range also expanded. Due to these results, it is highly recommended to test the sender modules with external antennas.

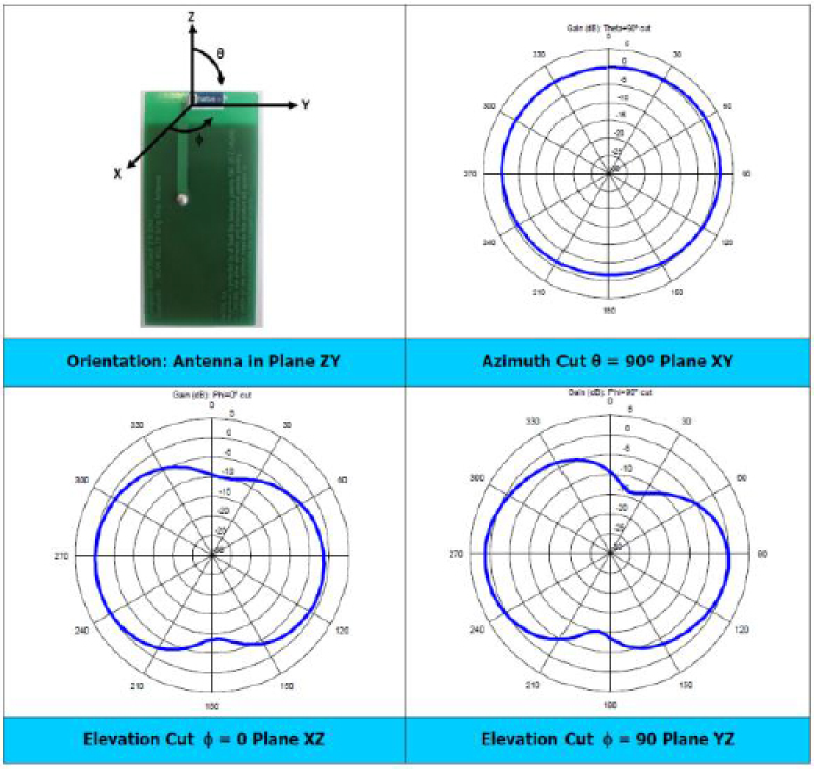


Figure 7.5: The signal propagation for the OBS421 anchor module. Compared to the OLS425 module, the propagation is more uniform in all directions. Due to the propagation, we decided on using this module as anchor. Figures from [Fra].

The accuracy of the BLE location tracking system would improve drastically, if an external antenna could reduce the signal strength fluctuations and provide a better, more uniform propagation.

The electrical mechanical data sheet of the OBS421 and OLS425 states that a minimum clearance of 5 millimeters between the antenna and any metal should be kept. It is also recommended to have no metal at least 10 millimeters around the antenna. Metal could influence the radio propagation and lead to unwanted effects such as signal reflections.

Firmware

For both modules, connectBlue is providing an SDK for modifying the firmware. One of the most interesting parameters for the OBS21 module/the anchor is the scan interval, which is set to 1.28 seconds by default. Typically, after a scan inquiry from the anchor module, we would get a response within 1.28 seconds depending on the amount of tags found in the vicinity (if more are found, the response lasts for the entire 1.28 seconds and otherwise, the response would come much faster). But we assume that the maximum number of tags in the same room at the same time is 10. With that assumption and knowing, that a response could come faster, we could also scan the environment faster than every 1.28 seconds. Also, due to high “not-found” rates, we considered reducing the scan interval from 1.28 seconds to a lower value. Through many exchanges with the connectBlue developers, we came to know that it was not a good idea to change the scan interval (nor was it recommended by the developers). If we scanned faster, we could unintentionally skip channels and, as a consequence, not find all the tags.

It is important to note that the signal strength values from all the detected BLE tags we are receiving through an inquiry scan have an offset of +128 dBm. So if we get a value of 43 for one tag, that translates to -85 dBm.

To lower the power consumption of the OLS425 module on the PCB, it is set to “stop mode” through the firmware. According to the specification of the module (see [cona]), the tag can still accept incoming connections and data over Bluetooth when in “stop mode”. But the UART is disabled which means that data sent to the tag over the Serial Port Adapter is lost. To activate that interface again, the DSR (Data Set Ready) pin on the module has to be enabled. A table with a few calculations of the tag’s power consumption at different steps can be seen in [conb].

7.3 Evaluation

7.3.1 Experiments

Various tests with the hardware were conducted to check if the results would be comprehensible, mathematically correct/provable and match the findings of other authors in their work. A simple setup with the previously mentioned modules was used (see figure 7.6) to get an understanding of the RSSI-distance relation.

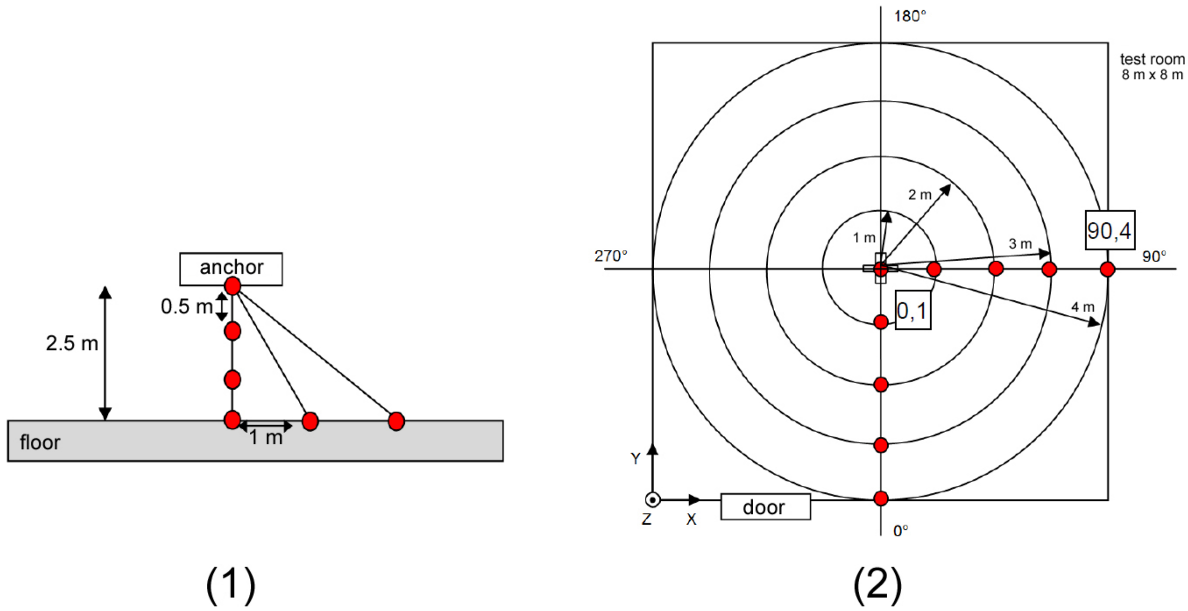


Figure 7.6: The setup for the RSSI measurement tests. (1) shows the side view with the anchor mounted on the tripod with the measurement positions in 0.5 meters distance. (2) depicts the top view with 8 measurement spots on the floor. Figure taken from [Mei14].

The tag was placed at the positions marked as red dots in figure 7.6. In total, 12 positions were determined for measurement with 4 positions being directly underneath the anchor at different heights (placed vertically with gaps of 0.5 meters, see figure 7.6 (1)) and 8 being distributed between 1 to 4 meters radially on the floor (see figure 7.6 (2)). To check if the orientation/angle of the anchor as well as the tag influenced the results, 4 out of 8 positions on the floor were perpendicular to the anchor. This was necessary because of the internal antennas integrated in both modules which did not come with uniform signal propagation characteristics. The first experiment was conducted along the 0 degree axis and after that, the second test was done on the axis rotated by 90 degrees. At each position, three measurements were made with the tag being orientated along its x-, y- and z-axis. While the figure shows the projected distance from the origin of the anchor on the floor to the position where the tag was placed, the actual distance was represented by the LOS. In addition to the measured signal strength values, the intervals, where no advertisements of the tag were detected, were stored too to determine the "not-found" rate.

7.3.2 Results

Figure 7.7 shows the average signal strength values of all three orientations of the tag as well as their deviations at different positions. The measured RSSI values at the positions can be used to calculate the distance according to the model from chapter 3.2 and compare the result to the actual distance (see table 7.1). For d_0 which was set to 1 meter, the measured RSSI value was -87.28 dBm and subsequently taken as P_r. The attenuation factor γ was set to 2 (free space). For each position, we had a deviation of less than 1 meter but this was also attributed to having an accumulation of several RSSI values taken at one position with different orientations. Less values would have resulted in a higher deviation.

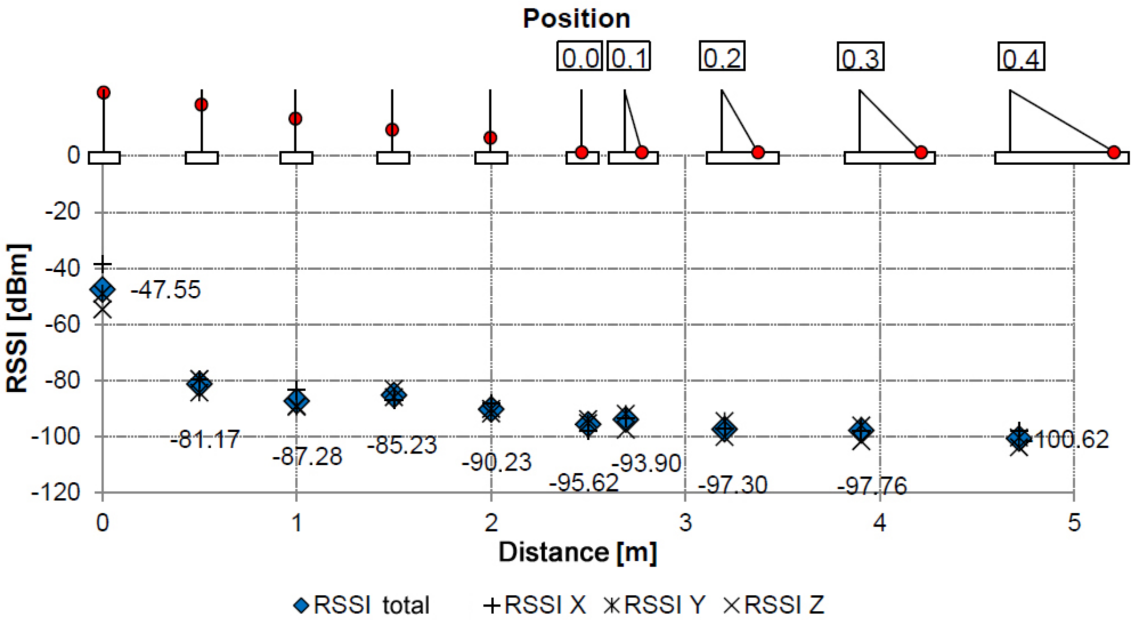


Figure 7.7: Results of the RSSI measurements at different positions. The x axis represents the position/the increasing distance to the right. The Y axis shows the RSSI value, spanning from 0 (highest) to -120 (lowest). The further the distance, the lower the measured RSSI value. Figure from [Mei14].

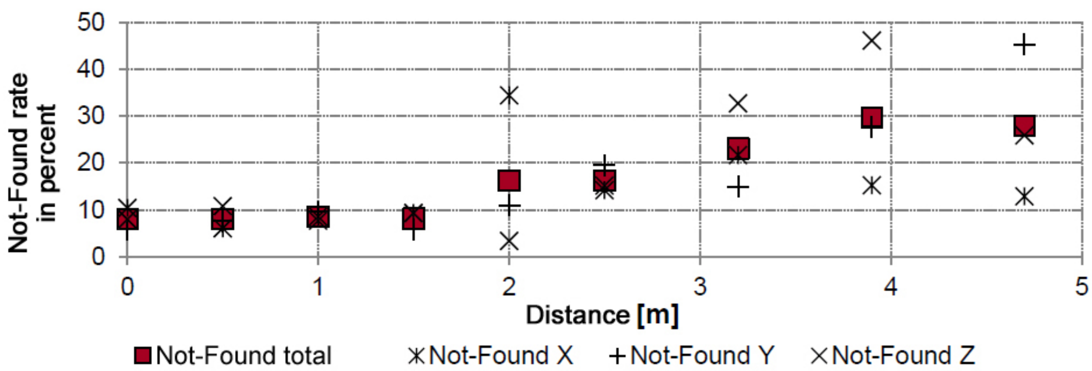


Figure 7.8: This graph shows that the further away the tag, the higher the Not-Found rate. Graph from [Mei14].

Figure 7.8 shows the Not-Found values which increase and fluctuate with increasing distance between tag and anchor. At distance 0, the percentage of Not-Founds was just below 10% while at 4.7 meters, it almost reached an average of 30%. Also, depending on the orientation of the antennas, the difference in the Not-Found rate could be up to 30%.

Table 7.1: Results of the RSSI measurements at different distances. Column 2 and 3 show the actual and the calculated distance respectively. The last column shows the difference between the actual and calculated distance. It can be seen that the deviation stays below 1 meter.

measured RSSI (dBm)	**actual distance (meters)**	**calculated distance (meters)**	**deviation (meters)**
-47.55	0	0.010	0.010
-81.17	0.5	0.495	0.005
-87.28	1	1	0
-85.23	1.5	0.790	0.710
-90.23	2	1.404	0.596
-95.62	2.5	2.612	0.112
-97.30	3.2	3.170	0.030
-97.76	3.9	3.342	0.558
-100.62	4.7	4.645	0.055

When looking at the average values of the x-, y- and z-orientations of the tag positioned at distance 0, a clear difference between the values is visible (see figure 7.9). The RSSI values were recorded for 3 minutes and the maximum difference between the orientations was around 16 dBm. Issues like the antenna orientation and how to properly consider/solve them are discussed in chapter 7.2 and 7.7.

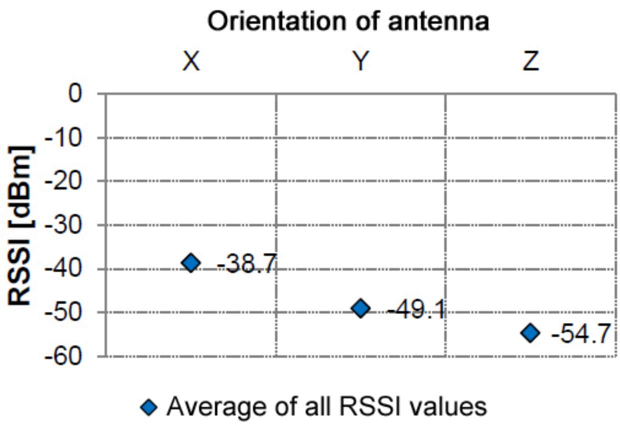


Figure 7.9: We can see that different orientations of the tag/antenna have an impact on the RSSI measurements. The biggest difference can be seen between the result of the x and z axis. Figure from [Mei14].

7.4 Software

The location engine for the BLE location tracking system was programmed in C# (.NET 4.0) for computers running Microsoft's Windows Server 2012 operating system. After installing the engine with a setup file, it is registered as Windows service and starts automatically with the computer. All the static variables such as COM ports or IP addresses are stored in a Microsoft SQL 2008 R2 database. The communication to the database is handled by stored procedures. For every query (create, read, update, delete), one specific stored procedure was created which could be executed by the location engine with certain input parameters.

We purposely decided to have a clear separation between the location engine and other software, which might use a predefined interface to communicate with it (such as the TruConnect Server service). When the interface of the location engine is implemented by another application, information such as the tags' locations can be received. That information is always updated by the engine in a periodic interval.

In every room covered by the location tracking system and where tags should be detected, a Bluetooth anchor module is installed. The communication with the anchors is established via a virtual serial port between the reader module and a computer (the server) in the back end. There are six layers with different components/modules which work together to compute a position of a tag (see figure 7.10).

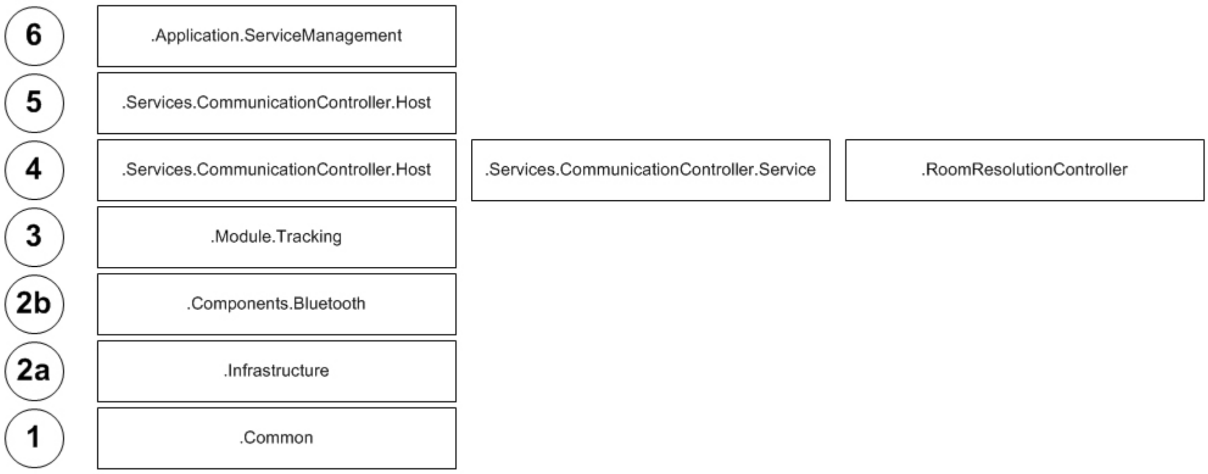


Figure 7.10: The six layers with its components and modules for the location engine. The modules are represented by their namespace in the software. Layer 1 consists of the .Common classes which deal with basic functionality and are considered low level. The upper layers represent the high level architecture of the software.

7.4.1 Layers and model

In the software, the components **.Module.Tracking** and **.Components.Bluetooth** represent the rooms with installed location tracking. These components work autonomously and are responsible for the serial communication with the Bluetooth anchor module in each of the rooms, forwarding the parsed messages to another component, the **.RoomResolutionController** via the **.CommunicationController**. A specified "Windows Communication Foundation" (WCF) interface is provided by the **.CommunicationController**, where any module can register/unregister itself and send messages to other subscribed modules. In case, a module such as .Module.Tracking or .Components.Bluetooth crashes because of errors, it is restarted by the **.ApplicationServiceManagement**. This process monitors all the other modules and is responsible for starting all the components when the server is booted. The .RoomResolutionController gathers all the parsed messages from each of the room components and calculates the position of the detected tags. Figure 7.10 shows all the software layers of the location tracking system. The layer on top consists of the .Application.ServiceManagement, which starts all the components below.

The location engine is based on a modular concept. In the following, each of the modules is explained in detail:

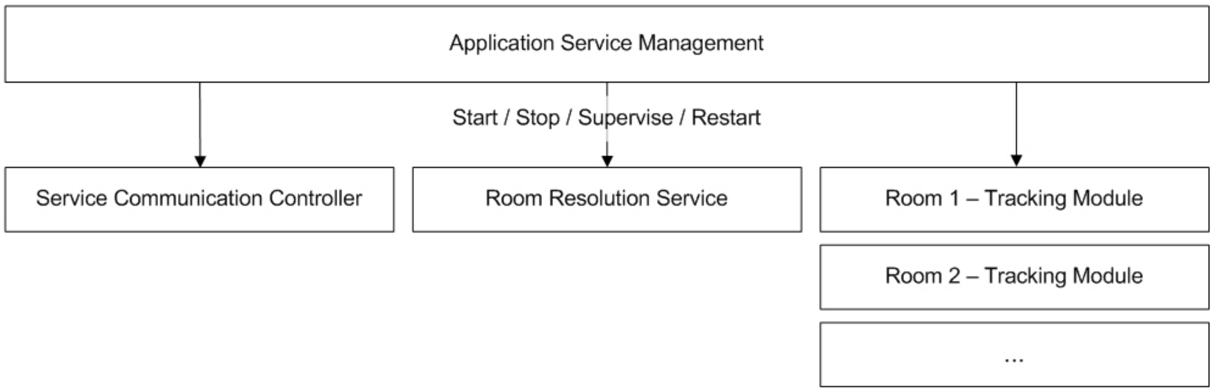


Figure 7.11: The modules of the location engine. The Application Service Management starts, stops, supervises and restarts the other modules.

- **Application Service Management (ASM):**
  This module represents the main method of an application. It is implemented as Windows service and starts when the OS boots. Its task is to monitor, start and shut down the other components.
- **Service Communication Controller (SCC):**
  The Service Communication Controller is written as a WCF interface service. It establishes the communication between the subscribed components, mainly the Room Tracking Modules with the Room Resolution Service.
- **Room Resolution Service / Room Resolution Controller (RRC):**
  This module gathers all the data from the Room Tracking Modules and calculates a location for all the detected tags.
- **Room Tracking Modules (RTM):**
  For each room, one Room Tracking Module component is started. It consists of all the Bluetooth components actually installed in each of the rooms. For example, if two anchors are installed in room 1, then the Room Tracking Module starts two Component Bluetooth, handling and synchronizing the communication with both anchors.
- **Component Bluetooth (CB):**
  This is where the serial communication between the Bluetooth Low Energy modules and the software/hardware happens. The module parses the messages it receives from the connected anchors

(which include data for all the detected tags) and sends the results to the Room Resolution Service via the Room Tracking Module and the Communication Controller.

7.4.2 Workflow

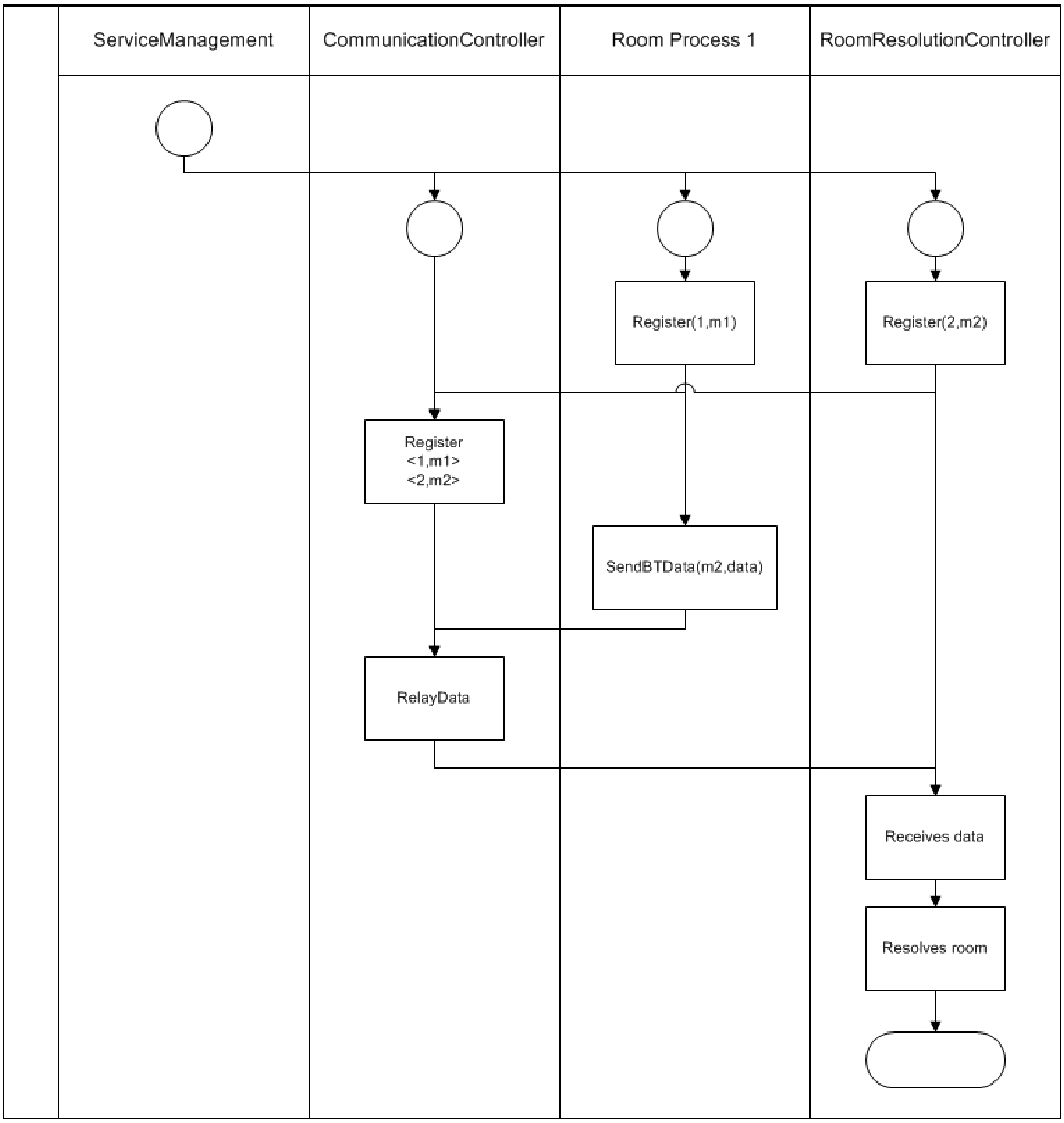
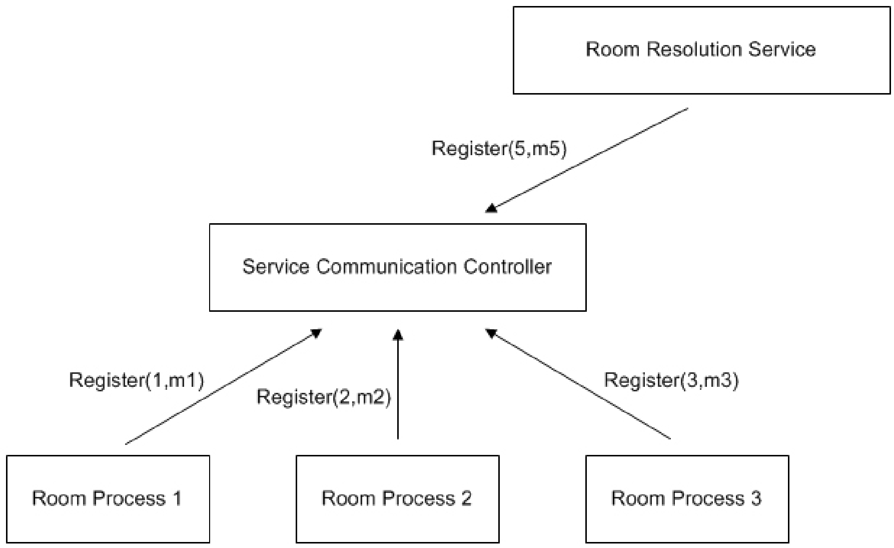


Figure 7.12: A workflow diagram showing the process on when which component registers, sends and receives messages.

In the beginning, the ASM starts all the components including the SCC, RRC, RTM and CB. All components subscribe themselves to the SCC and specify the message IDs they want to receive from other components. The room components (RTM and CB) send messages in periodic time intervals from the

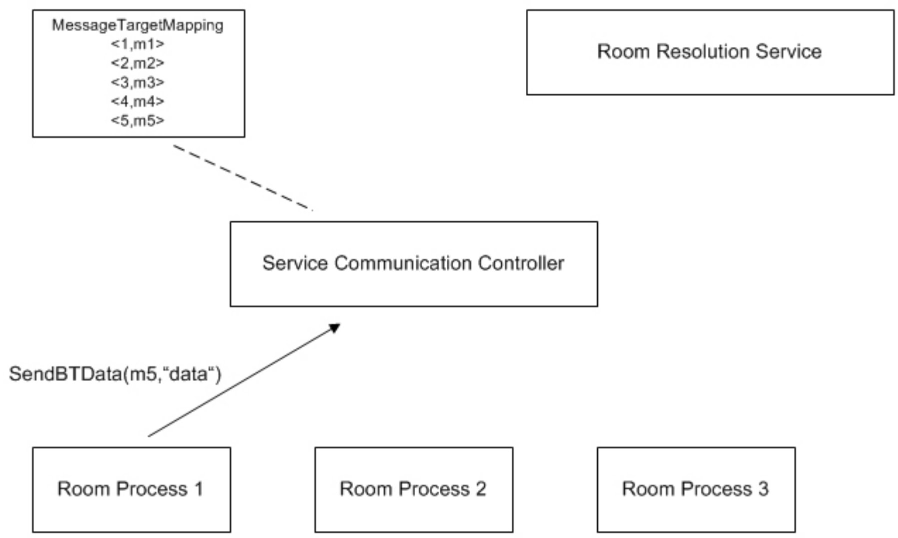
Bluetooth modules with a specific message ID m_2 to the SCC. The messages are then forwarded to the component which subscribed itself to the SCC with the message ID m_2, in our case the RRC.
The process in detail:

- **Step 1:**



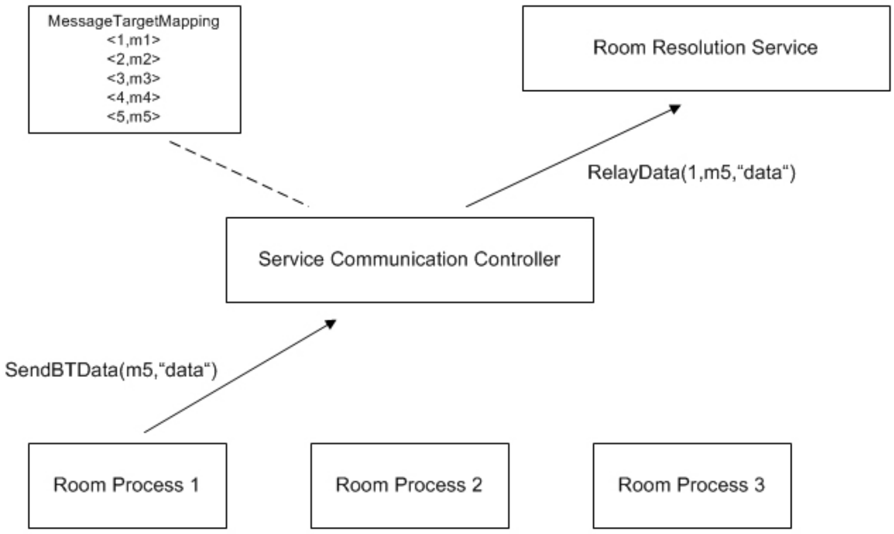
The room components and the RRC register themselves with their ID and the message ID they want to receive from the SCC.

- **Step 2:**



The SCC knows, where specific messages have to be forwarded due to the message IDs. If one of the room processes sends a message with the ID "m5", then the SCC/WCF service looks for the subscribed component with the exact same ID in its dictionary.

- **Step 3:**



The messages are then forwarded to the right component.

7.4.3 Components

.Components.Bluetooth

Each of the Bluetooth components tries to establish a serial connection to the actual modules via the assigned COM ports. Once connected to the COM ports, the components send an escape sequence to the modules. The escape sequence consists of the bytes `0x2f 0x2f 0x2f` (in ASCII: `///`). Then, a message is sent to the module to start inquiries for other Bluetooth Low Energy modules (in ASCII: `AT*AGI=6,1,0`). If a BLE tag is found, its MAC-address, name, signal strength and other parameters are returned as ASCII strings on the serial port. These strings are forwarded to a parser, where they are split into blocks. The parser goes through each of the blocks and filters the detected tags through the MAC addresses. The MAC addresses and signal strength values of the sender modules are then sent to the RTM. Every inquiry sent to the reader module is finished with either an "OK" or "ERROR". If there is no connection to the module or if the parser encounters an error, a counter is increased and once reaching a certain limit, a message to the RRC is forwarded that the component is not reachable anymore. Consequently, the component is then shut down and restarted. The interval, in which the anchor module scans the area, is set to 1400 milliseconds but it can be increased/decreased to a certain minimum and maximum value. The minimum time interval is 1 which translates to 1.28 seconds. This interval is also specified in the inquiry message `AT*AGI=6,`**`1`**`,0`. The first parameter of the inquiry represents the inquiry type and `AT*AGI=`**`6`**`,1,0` tells the OBS421 module to look specifically for BLE tags (6 = General extended inquiry with RSSI and device name for Bluetooth Low Energy).

.Module.Tracking

The RTM sends out synchronized commands to all its CB components in regular time intervals. The CB then executes these commands on a lower level (such as inquiry commands on the serial port) and gets messages as response, which are parsed and returned to the RTM in the end. If more than one CB is running and a tag is detected by more than one, the RTM would take the tag detected by the CB with the highest signal strength recorded for the room as result and relay it to the SCC with the RRC as its destination.

.RoomResolutionController

The component creates a new dictionary for each of the RTMs and fills them with the forwarded messages, which include the MAC addresses and the signal strength values of the detected tags. The RRC autonomously checks, if there are any new incoming messages from the room components every 1500 milliseconds (synchronized with CB). Once all messages from the components are collected for one cycle, the signal strength values of the detected tag in the rooms are compared to each other. The RRC then picks out the rooms with the highest recorded signal strength value for each of the tags, looks at predefined thresholds and if they apply, puts them into a new dictionary and sends them to the TruConnect Server service. The dictionary is sent continuously in regular intervals to ensure that changes in detecting tags are immediately forwarded to other services. The interval is closely related to the update-rate of the location tracking system, which is currently set to 1.5 seconds.

The RRC assigns sender modules to rooms by looking at the signal strength values and comparing them with stored thresholds. If the measured signal strength value is lower than a so-called "lower threshold", the sender module is put into the virtual room "no room". If the signal strength value exceeds the "upper threshold", the tag is put into that specific room. All the threshold-pairs (lower & upper) for each room are calibrated separately when installing the system (see chapter 7.8 for the calibration procedure).

7.4.4 Security mechanisms and settings

Sender modules in database

Before starting the system, we define, which tags should be detected for TruConnect (to prevent that any arbitrary BLE tag is recognized as a mobile device) and to which mobile devices they are related to in the SQL database. Then the CB as well as the RRC check, if the MAC addresses of the newly detected sender modules exist in the database. If they exist, the IDs of the sender modules from the database are used instead of the MAC addresses to communicate with the other components. Also, the component tries to read a list of all the stored tags from the database in a regular interval to check for any newly added or deleted mobile devices/tags.

Rooms

When starting the RRC, all the created rooms in the database are read and put in a new dictionary. If new rooms are created, the RRC, RTM and CB have to be restarted to also include them. The RRC computes the location/room for each of the tags and sends a message with a dictionary to the TruConnect Server service. A new UUID is created and also attached to that message. The TruConnect Server service checks, if the UUIDs are different for each message and in case they are not, the Server service assumes that the RRC is broken and as a consequence removes all the tags currently located in rooms. As a result, all the related mobile devices are logged out.

The RRC checks every 1.5 seconds if new messages from the RTMs are received. Additionally, a "keep alive" message is sent back and forth from the RTM to the CBs via the SCC.

7.4.5 Thresholds and calculating a location

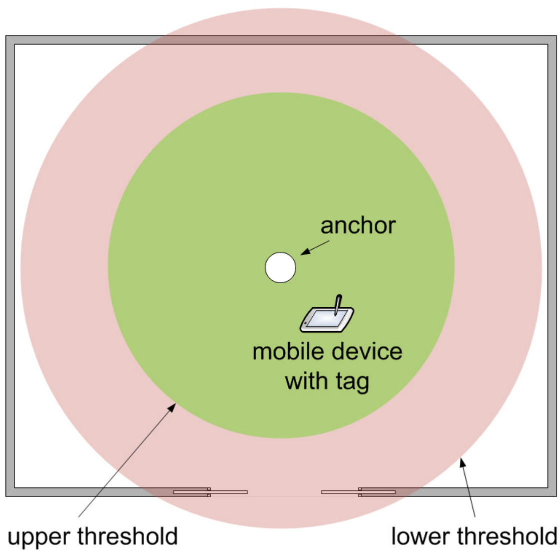
The engine requires two threshold values for each room: an upper threshold and a lower threshold. Both values have to be measured and stored in the database. The RRC checks, if the necessary values exist in the database. If a value is missing, its corresponding room is ignored by the RRC when calculating the locations. There are some requirements for storing thresholds:

- Upper threshold value must be bigger than lower threshold value
- The difference between upper and lower threshold must be bigger than 5 dBm
- Upper threshold value must be smaller than -28 dBm
- Lower threshold value must be bigger than -107 dBm

The measured thresholds are stored in the database if they fulfill all these requirements. Otherwise, the user needs to recalibrate the room.

The RRC collects all the detected tags for each room in a dictionary when the system is running. It is possible, that a sender module is detected in more than one room with different signal strength values, for instance if the rooms are located close to each other and have thin, penetrable walls. A tag can have 2 states: to be in a room or not. The decision making of a tag entering these states is described in the following:

Entering a room

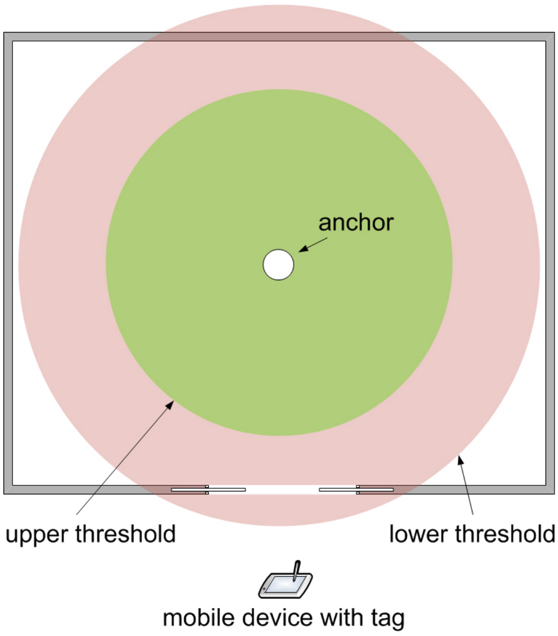


We assume that the tag has not been detected in a room:

- If the tag is found in a room r_1 and the measured signal strength value exceeds the upper threshold of r_1, then the sender module is assigned to r_1 and sent to the TruConnect Server service.

- If a sender module is found in more than one room, the signal strength values are sorted and we take the room with the tag's highest recorded value as its location. The RRC then checks if the highest signal strength value exceeds the upper threshold for that room. If it does, the sender module is assigned to the room.

Exiting a room



We assume that the tag has been detected in a room:

- The RRC removes the tag from a room, if the measured signal strength value falls below the lower threshold of the current room. The RRC also stops sending updates of that specific tag to the Tru-Connect Server service until it is found again.

7.4.6 Filtering the signals

Because of interferences caused by moving objects, certain material or people being present, the measured signal strength values are going to fluctuate over time. To reduce fluctuations, filters can be used to smooth the signal. All the filtering is done in the CBs and only the adjusted values are then transferred to the RTM and RRC. In addition to just taking the unfiltered, raw signal strength values, the following filters were tested:

- **Average**
  Take the average of the previous and current signal strength value.

- **Difference**
  If the difference between the previous and current signal strength value is bigger than 10, then take $rssi_o + \frac{rssi_n - rssi_o}{2}$ as the new signal strength value.

- **Gauss filter**
  Apply the Gaussian filter with $\sigma = 1$ and the kernel size $n = 5$ on the signal strength values.
- **Moving average without weights**
  Take the average of the last 3/5 values as new signal strength value.
- **Moving average with weights**
  Include weights to the average of the last 3/5 values to put more emphasis on newer values.
- **Kalman filter**
  Apply the Kalman filter using default matrices/values for state transition, measurement and covariance on the 2 parameters x (time in seconds) and y (signal strength in dBm).

For a more detailed description of these filters, see chapter 3.3.

7.4.7 Challenges and issues

As mentioned before, the anchor modules are continuously scanning for sender modules and are measuring their signal strengths. Since the engine is calculating the tags' rooms based on the signal strength values, they have to be measured reliably. But it is possible (with very low probability) that the firmware of a tag or anchor module is broken and sends or reads wrong values which are then incorrectly taken as valid measurements. This problem can not be detected in the current state of the system. One solution to know, if advertisements are unwillingly repeated or come with incorrect data is the inclusion of a counter or time stamps in the anchor-tag communication. If the counter stops or the time stamp is not updated, the engine assumes that something is wrong and stops to accept any messages from that anchor or tag.

7.5 Installation

Looking at the manual of CenTrak's RTLS (see chapter 6.5), we can see that extensive information on how the system behaves in difficult environments is provided and guidelines to place anchors at the right spots are given. It is interesting to see that the functionality of each anchor is explained in detail and how the system has to be configured to work under optimal conditions. The development of the location tracking system with Bluetooth Low Energy was in its advanced stages when we received the demo system by CenTrak. When developing the BLE system, we also created tutorials and instructions for correct deployment: how anchors should be installed and mounted to operate as intended. The detailed instructions by CenTrak found in the installation manuals supported our approach of documenting and describing the installation process in the best and most detailed way possible with examples, use cases, best practices and figures. In the following section, recommendations and examples on how to install the location tracking system with all its components are presented. Optimal results can only be obtained when these guidelines are met.

7.5.1 Things to consider

The operating room where the system is being installed should have the following characteristics:

Form factor and size:

- Minimum size: 5 x 5 meters
- Recommended size: 6 x 6 meters
- Form factor: Square or rectangle, viable until: length x (length + length / 2)
- Problems with long, narrow rooms, with the dimensions length x (length x 2) → usage of additional anchors has to be considered

Material and consistency of walls and ceiling:

- The tracking system works better if the walls are thick and consist of shielding material. If walls are composed of reinforced concrete, signals cannot penetrate them and therefore will not be detected in adjacent rooms.

Is there enough space to mount the anchor on the ceiling?

- The position of the anchor varies and is strongly dependent on the case, if "Laminar Air Flow" is built into the ceiling or not. See figure 7.13. Laminar Air Flow is a ventilation system used to provide a germ-free environment during the surgery.

Where are other ORs in relation to the current one?

- This information is important for positioning the anchor on the ceiling. Depending on where the adjacent operating rooms are, the anchor can be placed differently to avoid having overlapping signals.

- Also, the location and amount of doors is important and needs to be incorporated into the decision, where the anchors are mounted.

7.5.2 Recommendation for mounting the anchors

Requirements for the ceiling:

- Material and consistency of the ceiling must absorb signals penetrating it to avoid having high signal strength values in the room above. This case requires signal strength measurements in the room above.
- If no Laminar Air Flow is installed in the ceiling, the anchor can be mounted behind the OR light canopy.
- If Laminar Air Flow is installed, the anchor has to be mounted so that the radius of the reader module covers most of the room.

Requirements for the wall:

- Mount the anchor vertically on the wall only if there are no options for installing it on the ceiling.
- Material and consistency of the wall must absorb signals penetrating it to avoid having high signal strength values in the adjacent rooms. This case requires signal strength measurements in the adjacent rooms.

Scenarios which are difficult to assess:

- The location tracking system is difficult to use and poor results are expected when the operating rooms are only separated by thin walls, simple room dividers or not at all.
- Another difficult case includes large ORs which house several smaller areas with OR tables and OR lights. In this case, it is difficult to foretell if the tracking system would work reliably for every area.

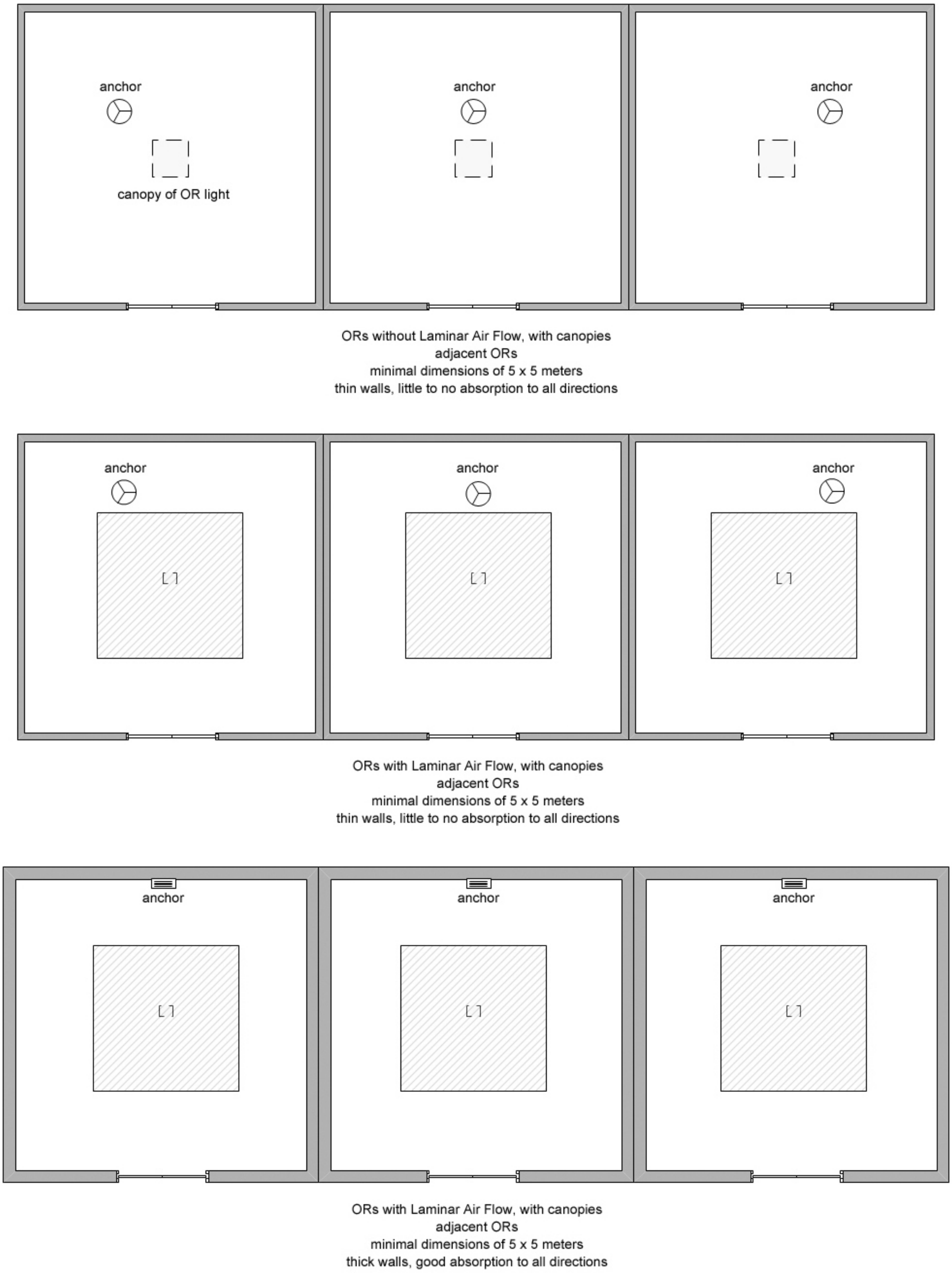


Figure 7.13: Three different scenarios, where anchors have to be installed. Depending on the case, it is recommended to mount the anchors as shown to achieve optimal results.

7.6 Testing

Test specifications and protocols were created which describe in detail, what a user has to do and how he has to do it to conduct the tests with the location tracking system. The tests included several scenarios:

- Check, if a mobile device, which is actually located outside of a room, is not registered inside.
- Test, if a mobile device enters and exits a room in less than 10 seconds.
- Check, if a mobile device, which is placed in a corridor between two rooms, is not registered in neither of them.
- Check, if a mobile device, which is placed and registered in a room, is not registered in another room ("no room" is an exception).

Besides these scenarios, various critical issues such as the communication through the interface provided by the location tracking system are also examined. We check if the system sends the correct information of rooms and located mobile devices to other services. Another case which is also checked with the protocol is, if thresholds were correctly calibrated and stored for all the rooms.

Usually, testing and evaluating an RTLS is time-consuming and in most cases, the results from the tests have to be taken with a grain of salt for instance due to human factors. Inaccurate logging of positions by test users can lead to skewed results. Therefore, an automatic test procedure was developed to repeat a routine over and over again with the test user being replaced by a robot. Developing the procedure was part of the master thesis by [Noe14]. Parts of the thesis were submitted and consequently published at the "Deutsche Gesellschaft für Computer- und Roboterassistierte Chirurgie e.V. (CURAC)" in Munich in 2014 [HNM+14]. We used an optical tracking system based on markers to get the ground truth positions of the robot. The optical system was chosen because it offered the highest accuracy for the job. At the same time, a location tracking system was set up.

Research showed that in the past, to measure accuracy for location tracking systems, tests were performed by either a person or robots. [BNTS+12] used a robot to check the accuracy of an optical tracking system with another optical system. [WSH+13] worked with a model railway to automatically evaluate the accuracy of an RFID location tracking system. [CZM10] were evaluating a location tracking system based on WiFi for the healthcare sector where 300 manual measurements had to be taken. Previous work shows that most test procedures are tailored for a specific location tracking system and setup. It is difficult to simply replace one system based on a certain technology with another one. Furthermore, there are still many procedures which take up a lot of time for the user, either because of manually checking and logging positions or because of crosschecking the measurements from the two used systems. Therefore, we proposed a procedure where a robot and an optical tracking system could autonomously and automatically test any location tracking system. To check, whether the combination of a programmed robot and an optical tracking system can achieve the desired results by being accurate and repeatable, we have set up some requirements:

- The radial error for measurements needs to be smaller than 1 meter
- The test system has to cover more than 1 room

- It should be possible to test any location tracking system
- Automatic procedure → spare the user from any required interaction
- Generate a protocol at the end with the ground truth (optical tracking) and computed (location tracking) positions

Hardware

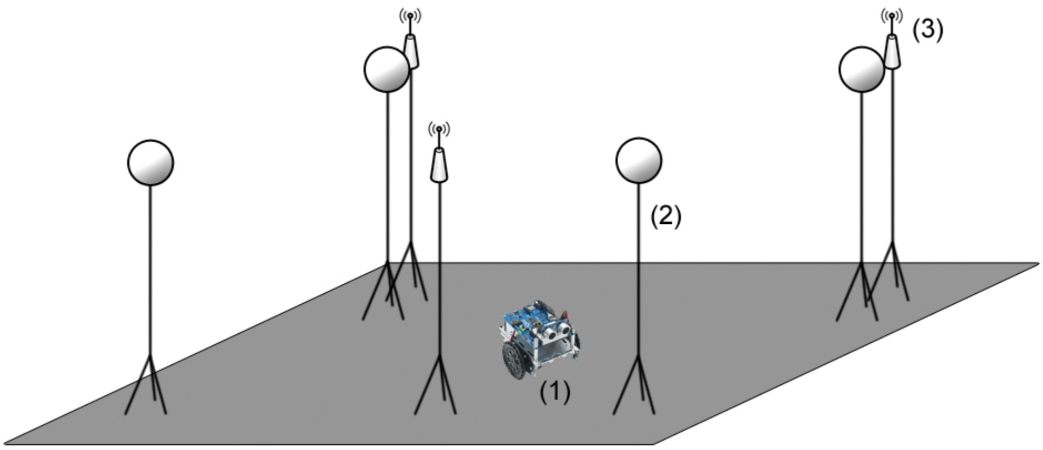


Figure 7.14: All the components for the test procedure: (1) the programmable robot, (2) the infrared cameras of the optical tracking system and (3) the anchors of the location tracking system.

The system with all its components and the physical arrangement can be seen in figure 7.14. In the following, these components will be described more in detail:

- **The robot:**
  Various robots were evaluated (see [Noe14]) but in the end, we chose the ActivityBot made by the company *Parallax* (Rocklin, United States). It is programmable and powered by five AA-batteries (1,2 V). The user provides instructions, what movements (forward, back, turn left, turn right, stop) the robot should perform in a C-file which is uploaded to the robot. When the user turns the robot on, it should run through the file and drive the programmed route. An attachment to the robot was built to place different tags as well as the retro-reflecting balls for optical tracking on top of the robot. The balls and sender modules had to be on top to guarantee LOS and to have enough space between the senders and other metallic objects on the robot. To ensure that the robot always started from the same position, a ramp was constructed where the robot could be parked inside and where tests could be started from. All the mentioned parts can be seen in figure 7.15.

- **The optical tracking system:**
  To obtain the ground truth positions of the robot, very accurate and precise tracking systems were needed. That is why we rented the "ARTTRACK2" optical tracking system from the company *Advanced Realtime Tracking (ART)* (Weilheim, Germany) for several weeks. Multiple infrared cameras

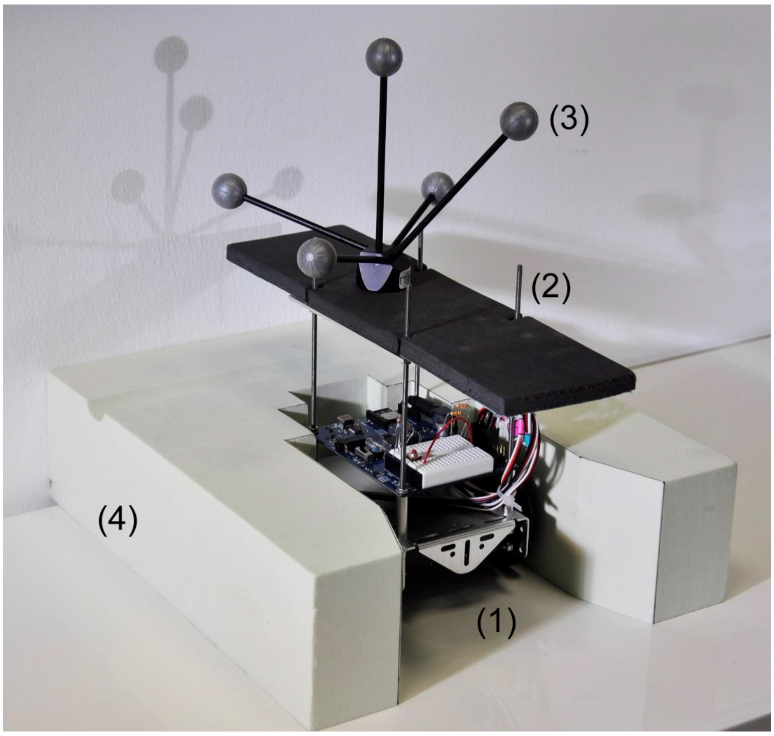


Figure 7.15: The attachment (2) on top of the robot (1) with the retro-reflective balls (3) mounted on it. The robot is parked in the ramp (4) to guarantee the same starting position every time at the beginning of a test procedure. Image from [Noe14].

were mounted on tripods, rotated and tilted to look at the center of the room covering the test environment in their field of vision. These cameras send out infrared signals, which are reflected back by so called tracking targets (such as retro-reflecting balls), and then picked up by the cameras. To get all 6 degrees of freedom, the tracking targets need to have a unique design and structure to differentiate all the axis. With the reflected signals, the optical tracking system then calculates a 3D position of the tracking target. For a test environment of 8 x 8 meters, four infrared cameras were required.

- **The location tracking system:**
  Two location tracking systems based on different technologies were tested. The first test included the developed Bluetooth Low Energy solution while the second test was conducted with a WiFi-based location tracking system. The idea was to test the automatic procedure in one room first and then see if the test procedure could be expanded to more than one room.

The procedure

An application was programmed to support the testing process, where the user could draw routes on a map which would then be converted into a C-file including all the movements the robot should perform. The user could select which location tracking system (BLE or WiFi) to use for testing and all the settings for each of the systems could be changed. All the measurements from both, the optical and location tracking system, were stored in a Microsoft SQL Server 2008 R2 database on the computer in the back end. An overview of the system can be seen in figure 7.16.

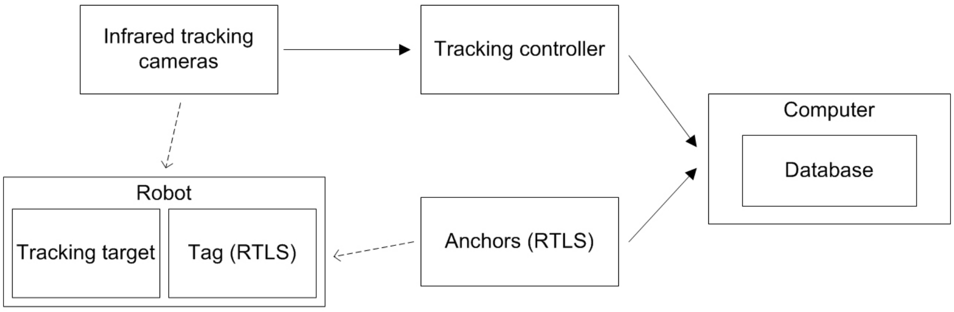


Figure 7.16: All the components of the automatic test procedure. The infrared cameras and the anchors are scanning the environment for the robot with the tag and tracking target attached. The measurements are forwarded to a computer, which computes two positions, one for the optical and one for the location tracking system, and stores them into a database.

Tests and results

First, we wanted to check the precision of the robot's movement with the optical tracking system. As already mentioned, the user could define the route the robot should drive. These routes could include rotations, pauses as well as a start- and an endpoint. For six routes (see figure 7.18), the deviation in both x- and y-coordinates between the actual to the measured positions of the robot was below 1 meter. The difference between the computed position and the position determined by the optical tracking system was always compared at the spots where the robot had to turn, pause, start and stop. The standard deviation at all the measuring spots was smaller than 10 centimeters with the maximum deviation being 51.01 centimeters for the y-coordinate for route 4.

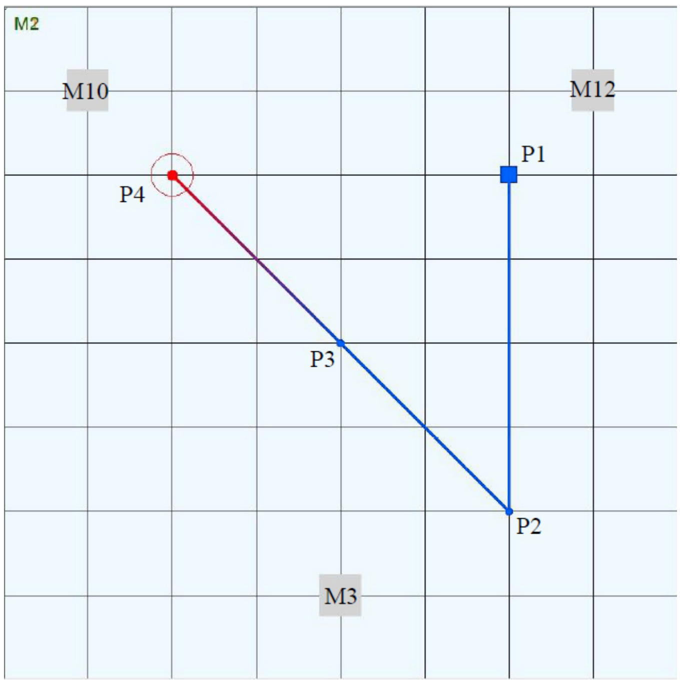


Figure 7.17: The test room with the dimensions of 8 x 8 meters. M3, M10 and M12 represent the anchors in the room and P1 to P4 the positions where the robot pauses for 60 seconds. Figure from [Noe14].

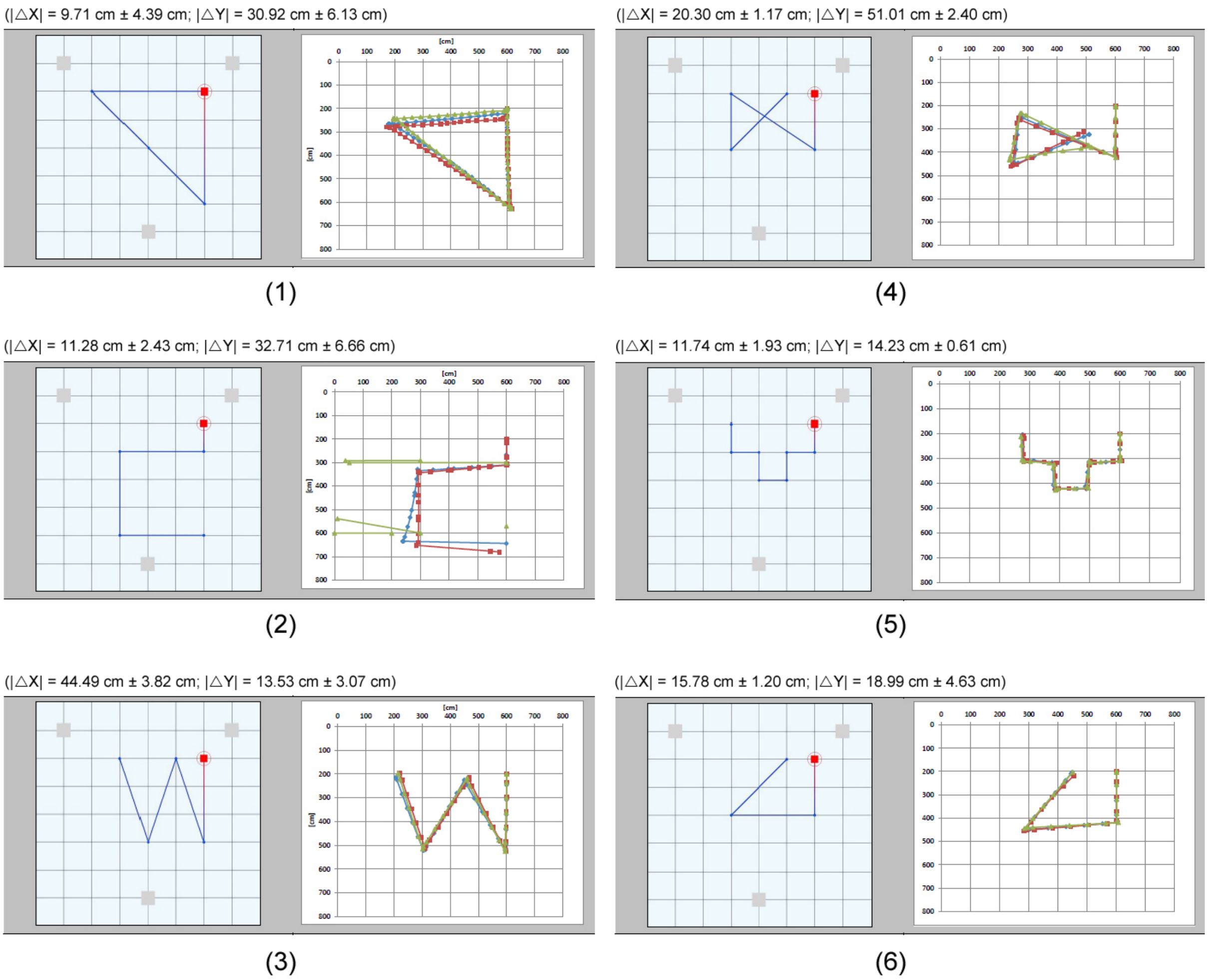


Figure 7.18: Six routes which were drawn by the user and tested with the robot multiple times. The deviations in x- and y-coordinates as well as the standard deviations are specified for each route. Figure from [Noe14].

Scenario 1:
Two methods with the Bluetooth Low Energy location tracking system were examined: Trilateration and proximity-based location tracking, both with RSSI measurements. Figure 7.17 shows the route used for trilateration in one room with the starting point being in the upper right corner.

Using the measured signal strength values of the three anchors, equation 3.2 provided us the radii to get the intersecting point which would represent the current position of the robot. We used P1 as our d_0 and calculated P_t and γ for M3, M10 and M12. The calculated values can be seen in table 7.2.

Table 7.2: The parameters for each anchor which were calibrated for the starting position P1 of the robot.

	M3	**M10**	**M12**
Position $(x/y/z)$ in cm	400/700/300	100/100/300	700/100/300
P_t in dBm	-93	-92	-87
γ	3	2.8	2.8

To guarantee a better coverage of the room for the optical tracking system, the defined positions of the robot P1-P4 were shifted by 20 centimeters so that d_0 would be at (620/180) centimeters.

Four tests with different settings were conducted and each test was repeated three times.

- **Trilateration without any filter**
  The optical tracking system determined an average deviation of 0.42 meters ($\pm$0.06 meters) in x- and 0.69 meters ($\pm$0.41 meters) in y-direction of the robot between the actual and the measured positions. The BLE location tracking system computed the position with an average deviation of 231.06 centimeters for the x- and 99.06 centimeters for the y-direction.
- **Trilateration with moving average of the previous 5 values, without additional filters**
  The difference between tracked and actual position was on average 0.51 meters in x- and 1.07 meters in y-direction. The standard deviation stayed below 12 centimeters. With a moving average of the previous 5 values, the computed positions of the location tracking system had a deviation of 154.46 centimeters in x- and 161.34 centimeters in y-direction.
- **Trilateration without moving average but with Kalman filtering**
  The maximum radial error between the actual and the measured positions added up to 0.82 meters. The computed positions with the Kalman filter had a deviation of 149.70 centimeters in the x- and 160.16 centimeters in the y-direction.
- **Trilateration with moving average of the previous 5 values, with Kalman filtering**
  In both directions, the maximum deviation of the robot from the actual to the tracked positions was 93.27 centimeters ($\pm$42.37 centimeters). The results from the location tracking system with both filters activated unfortunately did not show any significant improvements. The calculated deviation was 117.30 centimeters in the x- and 146.11 centimeters in the y-direction.

In all test runs, some of the computed positions had either minimal or significantly large deviations from the tracked positions. The large deviations could have come from objects occluding the direct LOS between tag and anchor.

For the second method, the proximity-based location tracking, we expanded the test area. The anchors were positioned at the center of each room (see figure 7.19). A specific route was provided to the robot so that one room would be exited and another would be entered. At positions P1 to P6, the robot would halt and pause for 60 seconds. Two test runs were conducted with these methods: one without filtering and the second one with a moving average of 5. Each test was repeated three times. For the "upper" and "lower" thresholds for both rooms, the following values were manually calibrated and used for the tests:

Table 7.3: The thresholds determined beforehand for both rooms.

	Threshold for room 1 (dBm)	**Threshold for room 2 (dBm)**
Entering	-92	-81
Exiting	-96	-88

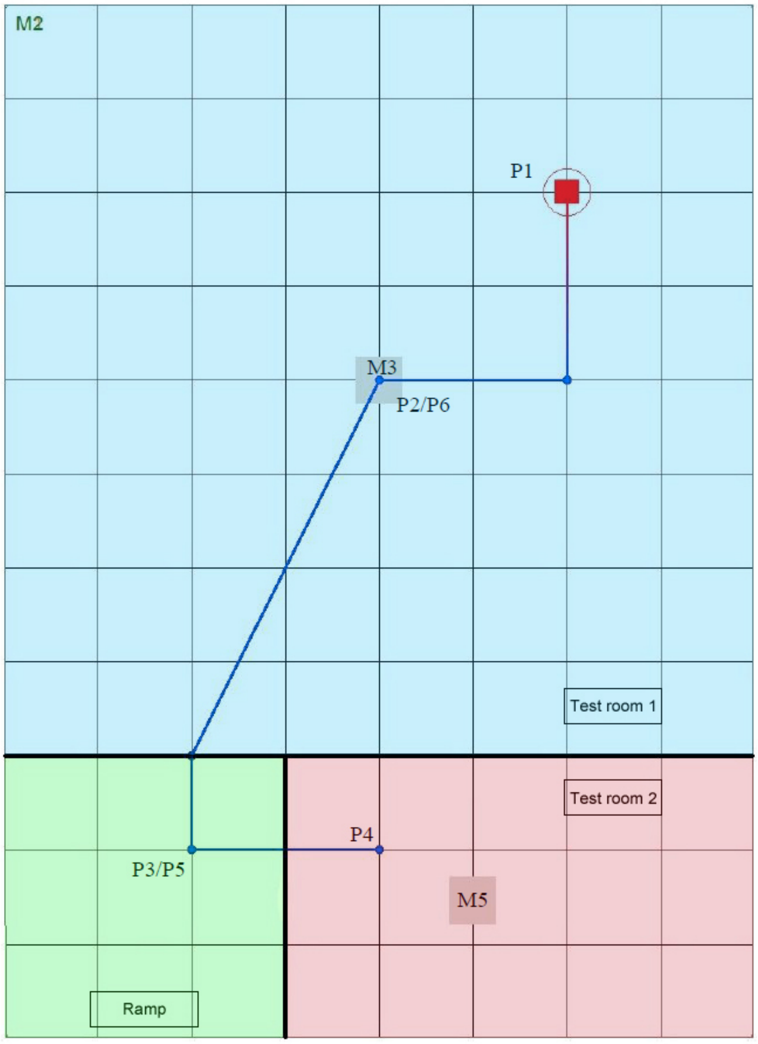


Figure 7.19: The planned path: The robot was programmed to drive from test room 1 (blue) to the ramp (green), then to test room 2 (red) and back. There is one anchor positioned at M3 in test room 1 and another one at M5 in test room 2. The robot stops at the positions P1-P6 for measurements. Figure taken from [Noe14].

- **Proximity-based without any filter**
  Through the optical tracking system, a deviation of 24.80 centimeters (±16.02 centimeters) in the x- and 19.67 centimeters (±12.79 centimeters) in the y-direction was determined. Figure 7.20 shows the results of the optical tracking system with the route taken by the robot three times. The gap between the rooms resulted from the limited coverage of the optical tracking system in the area near the doors. Figure 7.21 shows the number of measurements made for the rooms along the route (in order in which the robot would drive). In the beginning, the robot was found 50% of the time in room 1 (60 measurements say that it was in room 1 while 61 say that it was not) but that percentage decreased while the robot drove to the ramp and back to room 1 where the value increased again. On average, the robot was only found for 53% of all measurements in the correct room (for all three test runs). It is interesting to note that for all three test runs, the results were very different. For instance, while the true positive (correctly assigned room) percentage for room 1 in the first test run was 89%, it decreased to 23% and was at 32% in the final test runs. All tests

were conducted in a time span of 40 minutes which meant that the previously calibrated and stored threshold values at the beginning of the first test were not applicable for the later tests. This implies that measured signal strength values would be different depending on the time (and possibly the state of the environment).

- **Proximity-based with moving average of the previous 5 values**
  The average deviations from the actual to the measured positions were 34.54 centimeters in x- and 14.75 centimeters in y-direction. The results of the location tracking system were worse compared to the tests without a filter. The robot was correctly found in the respective room only in 48% (average) of all three test runs. Again, when looking at each test separately, we can see that due to the varying signal strength and threshold values over time, the true positive percentage decreases.

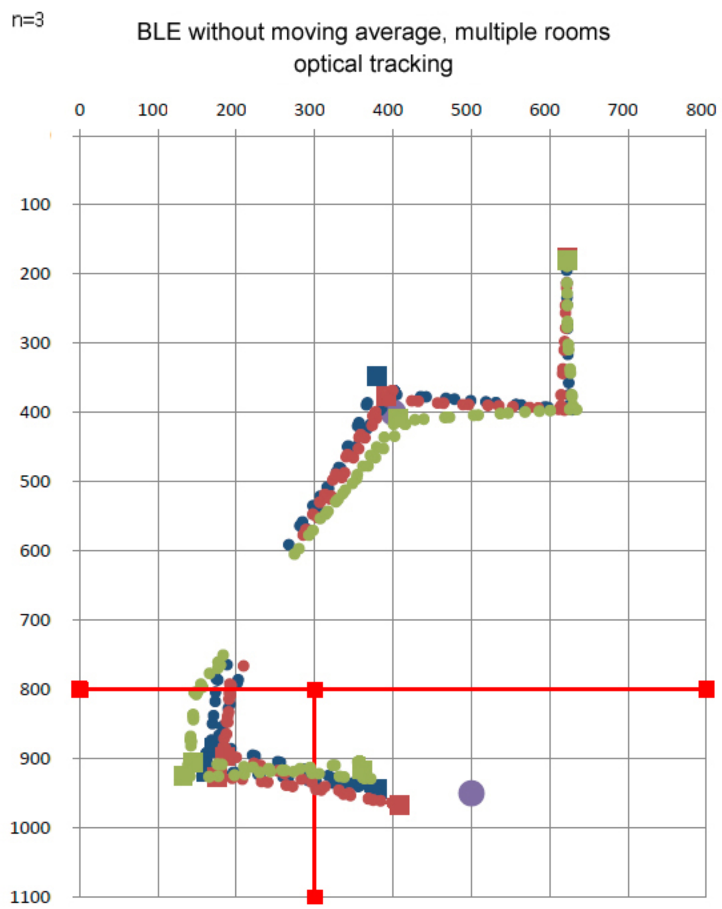


Figure 7.20: The actual paths the robot drove: The measurements done by the optical tracking system for both test rooms and the ramp. The test runs are depicted by the three colors in the measured positions. Figure from [Noe14].

Scenario 2:
After the tests with BLE, we proceeded with testing a location tracking system based on WiFi and the method "Fingerprinting". We placed three anchors in the area and recorded fingerprints in all the locations where the system should recognize the tag (see figure 6.11). The tests were first conducted in

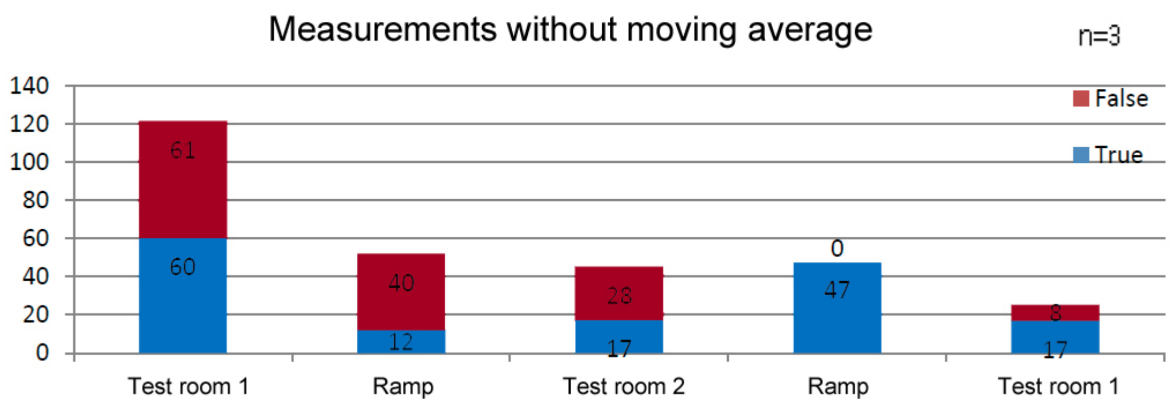


Figure 7.21: This graph shows the positions computed by the location tracking system for each room along the test path taken by the robot. The red bars represent the number of false positives while the blue ones show the true positive rate for each room. Graph from [Noe14].

room 1 to check the sub-room level accuracy and then expanded to a larger area for evaluation of room level accuracy. In the following, we want to look at how well the automatic test procedure with the robot worked in combination with the WiFi location tracking system. The detailed results of the experiments with the computed accuracies and deviations can be seen in chapter 6.3.

As described in section 6.3, the WiFi location tracking system was designed to be an inside-out system. The WiFi antenna, which was connected to the computer in the back end and acted as an anchor for collecting RSSI measurements, was mounted on top of the robot. Multiple USB extension cables were used to ensure the possible range, the robot could drive without being held back by the cable. But this also led to problems: sometimes, the motor of the robot was not strong enough to carry and pull the weight of the connected cables. That resulted in larger deviations regarding the measured positions compared to the actual ones. For the first experiment with just test room 1, the same route as in figure 7.17 was programmed and loaded onto the robot.

- Fingerprinting with kNN = 5, without any filter
  The average deviations for three test runs between actual and tracked positions were 15.76 centimeters ($\pm$4.10 centimeters) in x- and 11.71 centimeters ($\pm$4.97 centimeters) in the y-direction.
- Fingerprinting with kNN = 3, without any filter
  Here, the average deviations were 23.42 centimeters ($\pm$5.20 centimeters) in x- and 15.71 centimeters ($\pm$4.37 centimeters) in the y-direction.
- Fingerprinting with kML = 3, without and with weights
  The robot had a positional error of 30.11 centimeters ($\pm$13.59 centimeters) in x- and 14.35 centimeters ($\pm$8.42 centimeters) in y-direction.

In all the tests within room 1, accuracies of under 1 meter could be reached with the robot and the optical tracking system. For the second experiment, the same test layout with the robot entering and exiting the rooms as in figure 7.19 was used. The average deviations for all the tests were 37.03 centimeters ($\pm$10.79 centimeters) for both directions.

Discussion

The results show that the developed automatic test procedure fulfills most of the requirements defined at the beginning of section 7.6. It also guarantees a repeatability of the test (the radial error stayed below the 1 meter mark). The optical tracking system provided satisfactory results for the tests with multiple rooms involved. We can also verify that the tests were performed autonomously without people being present. One problem though was that the tracked positions of the robot deviated less from the actual ones on shorter paths than on longer ones. This usually happened when the robot had to turn and drive a distance longer than 5 meters. Also, errors and deviations would accumulate over time while driving the route.

The results show that both location tracking systems are prone to environmental influences. In addition, depending on when the calibration measurements were made, the results deteriorated over time. This led to inaccurate position calculations for the location tracking systems.

We used an out-of-the-box optical tracking system from the company Advanced Realtime Tracking which was easy and fast to set up and install. Various test applications were programmed in C# to connect all the components of the automatic test procedure. While accurate optical tracking systems are of great help to test location tracking systems for sub-room level accuracy (such as UWB), a simpler and cheaper system would have satisfied our needs for testing room level accuracy. Depending on the promised accuracy of the location tracking system, the optical tracking system should be replaced with a more appropriate one regarding the conditions and requirements. Also, instead of using the retro-reflective balls, active markers which send out signals could be used to extend the detection range of the optical tracking system.

A very practical application for the automatic test procedure would be the creation of fingerprint maps in the offline phase (calibration) of a location tracking system using Fingerprinting. We showed that the accuracies, which could be achieved with the programmed robot driving around autonomously, were always below 1 meter. The user could attach a tag on the robot and let 1. the optical tracking system measure the route the robot actually drives and 2. at the same time record RSSI fingerprints through the installed location tracking system. With the provided tools such as the test program to draw routes including pauses and turns for the robot, the calibration could be done easier, faster and automatically.

7.7 Discussion and improvements

Most of the following changes and improvements were examined by students with the task to make the existing location tracking system more stable. [Mei14] in particular contributed greatly to the following sections.

7.7.1 Not-Found rate

Not-Found is defined by us as the number of times when an advertisement of a tag is not detected during the inquiry scan of an anchor. If several Not-Founds occur sequentially, the tracking system can not state, where the tag is currently located. Figure 7.8 shows, that the Not-Found rate increases the larger the distance between anchor and tag becomes. This can be caused by two things: the timing of both the sender and reader module when they are sending and scanning on two different channels at the same time and/or environmental conditions causing scattering, shadowing and reflections which attenuate the output power below the scan level of the anchor. Also, looking at figure 7.7, we can see that when the tag was placed directly underneath the anchor (0 meters), the Not-Found rate was under 10 percent but increased to 20 percent at a distance of 2.5 meters. The results show that at 4.7 meters, the Not-Found rate was near 50 percent with the minimal signal strength value detected being -107 dBm. Another factor, which influenced the Not-Found rate was the orientation of the tag's antenna. At 3.9 meters, the tag in x-orientation had a Not-Found rate of 16 percent while it was almost three times higher for its z-orientation.

How BLE advertisements work

- **Tags sending advertisements**
  The advertising packets are sent by the tags in a periodic time interval (also called the advertising/advertisement interval, see figure 7.22). Normally, during the advertisement phase, packets are sent sequentially on the three channels 37, 38 and 39. To avoid collisions with other tags, which are sending at the same time, a random variable (between 0 and 10 milliseconds) is added to each interval. The advertising interval can be set to a minimum of 20 milliseconds and to a maximum of 10.24 seconds. By default, it is configured to send an advertising message every 1 second.

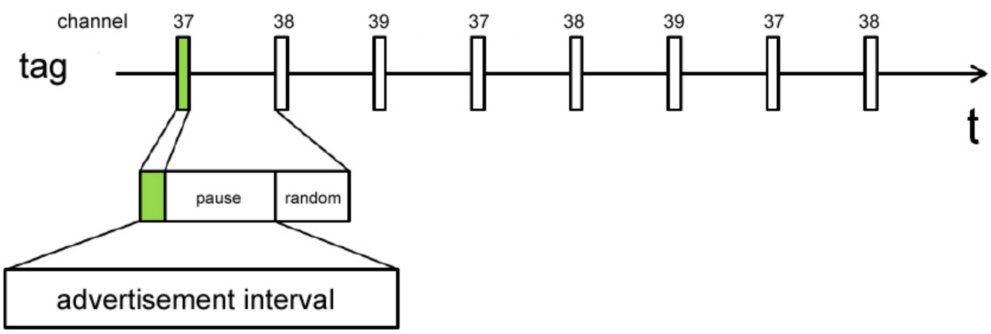


Figure 7.22: The figure shows the advertisements sent from a tag on a time line. The advertisement interval can be configured to a minimum of 20 milliseconds and to a maximum of 10.24 seconds. The random variable ranges from 0 to 10 milliseconds. By default, the tags send the advertisements on the channels 37, 38 and 39. Figure from [Mei14].

- **Anchors scanning for advertisements**
  The Bluetooth and Bluetooth Low Energy specifications state that the minimum time interval for a Bluetooth module to scan for others is 1.28 seconds (see figure 7.23). In these 1.28 seconds (the scan interval), all three advertising channels are scanned for a specific amount of time (defined as the scan window). Both, the scan interval and the scan window can be modified. 1.28 seconds is also the default scan interval set for the anchor modules we use.

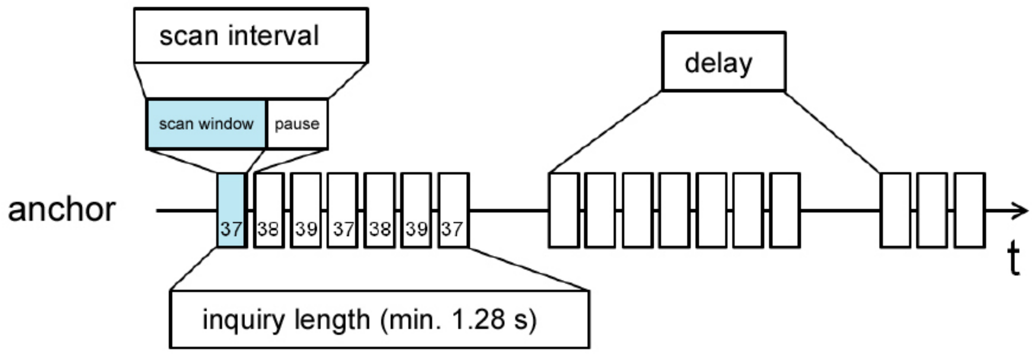


Figure 7.23: The intervals for the anchor on a time line. The inquiry length is set to 1.28 seconds by default. Some of the variables such as the scan interval or the scan window are configurable by the user. By default, the scan interval and the scan window are set to 10 milliseconds each. Figure from [Mei14].

Looking at the settings for both modules: When the advertising interval for tags is increased to 1.28 seconds, the reader modules should not be able to find them anymore. On the other hand, decreasing the advertising intervals to the minimum value should lead to the anchor detecting the sender module more frequently. The probability increases with a quicker advertising interval, as it should fit into the scan interval more often. Tests also confirmed the assumption and led to very good results, when the tags were sending advertisements for instance 10 times more often in one scan interval.

The requirements set at 2.1 state that the system should be highly reactive and reliable. These criteria can be met with a Not-Found rate lower than 20%. We reached that percentage with an advertising interval of 250 milliseconds. [FREI07] came to a similar conclusion, stating that 240-250 milliseconds was a good trade-off between finding the tag most of the time and energy consumption. Table 7.4 shows the calculated power consumption for different intervals and how long a CR2032 coin cell battery (with a capacity of 240 mAh) would last.

Installing more than one anchor in a room also reduced the Not-Found rate. While tests showed that with just one reader module, the Not-Found rate was almost 40%, the combined results would reach 6% if two anchors were scanning the environment periodically. In that particular case, it was sufficient to say that a tag was found, when at least one of the anchors in the room detected it.

Table 7.4: This table shows the power consumption for different advertising intervals and what effects they have on a CR2032 battery with 240 mAh capacity. The Bluetooth module was configured to be in the "stop mode" and the formula to calculate the current consumption was taken from [conb].

Advertising interval (ms)	Current consumption (μA)	Estimated hours	Estimated days
10	5.0412	33.33	1
50	1.0092	166.47	7
100	0.5052	332.54	14
200	0.2532	663.51	28
250	0.2028	828.40	35
500	0.102	1647.06	69
750	0.0684	2456.14	102
1000	0.0516	3255.81	136
5000	0.01128	14893.62	621
10000	0.00624	26923.08	1122

7.7.2 Signal strength fluctuations

During various tests, the signal strength fluctuations were analyzed more thoroughly. The results always showed three value levels even with different tags, anchors and in multiple locations (factory hall, office, etc.) to eliminate the environmental influences as cause. When looking at one experiment (see figure 7.24), we can clearly see three signal strength levels with deviations of 3 to 5 dBm.

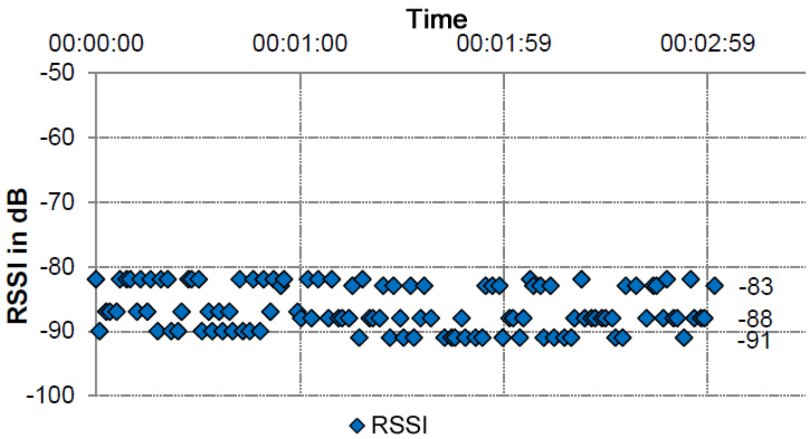


Figure 7.24: Three RSSI levels with different averages (-83, -88 and -91 dBm) can be seen over time. Figure from [Mei14].

Since the levels were not dependent on the used hardware or the environment, we looked at the settings of the modules, specifically the channel map to see if it was the cause of the fluctuations. As mentioned in chapter 3.4, by default, Bluetooth Low Energy sends advertisements on the channels 37, 38 and 39. Channel 37 represents the frequency 2.402 GHz, channel 38 the frequency 2.426 GHz and channel 39 the frequency 2.480 GHz used by BLE. To evaluate, if the levels were actually caused by the different channels, we deactivated two of them and tested only with channel 37 if the levels would disappear or become less apparent. If all channels were activated, the signal would reach the anchor with different frequencies/wavelengths, thus causing the three different levels of signal strengths. With only one active channel, the signal was always sent on the same frequency and consequently, the three signal levels disappeared.

By deactivating two of the three advertising channels, the Not-Found rate increased dramatically (see figure 7.25). While in difficult conditions, the tag could advertise on all three channels with different frequencies, it was hard to compensate the bad connection/signal with just one activated channel. Additionally, the anchor would miss the sender module just advertising on one channel more often since it was still scanning all three channels for modules. To change this, the firmware of the anchor modules would require modifications (and in the worst case, we would loose the certification/license of the third-party module). We also tested which channel we should leave activated. The result showed us that it made no significant difference, which channel out of 37, 38 and 39 we would use.

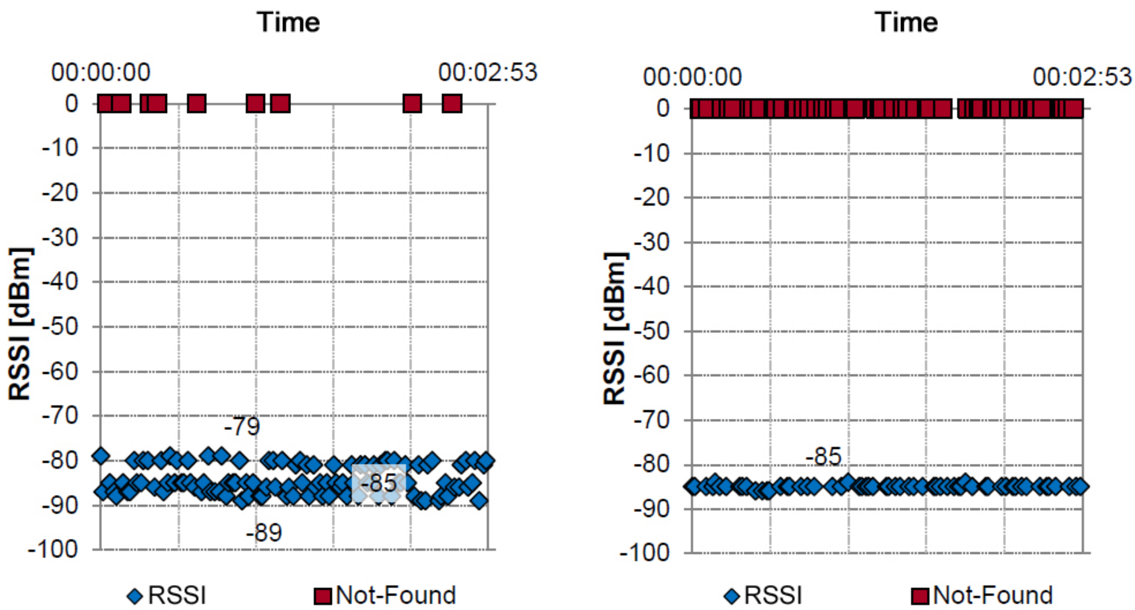


Figure 7.25: Both RSSI measurements (left and right graphs) were recorded over a time span of 3 minutes. The anchor and the tag were 50 centimeters apart. On the left: the signal strength levels with all three channels activated, different averages (blue squares) and the “not-founds” at the top as red squares. On the right: only one signal strength level with just one channel (37) activated, but with an increased number of “not-founds” at the top (red squares). Figure from [Mei14].

Furthermore, experiments showed us that the system suffered from signal strength fluctuations through influences such as people being present or metallic objects and items obstructing the LOS. Figure 7.26 shows us clearly that people had an influence on the signal of a stationary tag being 3.9 meters (LOS distance) away from the anchor. After 6:15 PM (the red line (1) in figure 7.26), the signal stabilized when nobody was present anymore. [FREI07] also ran similar experiments over a time span of 24 hours with the signal strength fluctuations being in the range of 10 dBm. These fluctuations were attributed to present/non-present people and other influences in the environment. We also tested if other Bluetooth

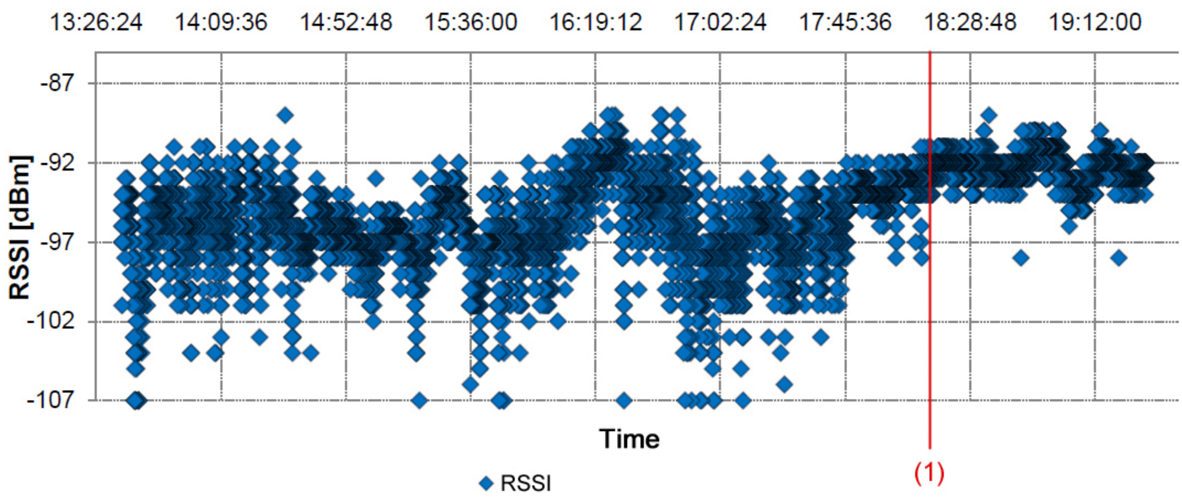


Figure 7.26: RSSI measurements of a stationary tag over a long time span to show that small changes in the environment have a significant impact on the signal strength. Before 6:15 PM (1), the signal fluctuated because of people being present and moving in the area. After 6:15 PM, they left and consequently, the signal stabilized. Figure taken from [Mei14].

modules (such as anchors or sender modules) could cause signal fluctuations in two experiments with a Bluetooth module being placed as interfering module in varying distances to the anchor. The results indicated that there were minimal signal strength fluctuations and these were mainly caused by the changing environment rather than through the additional Bluetooth module.

7.7.3 Orientation of the sender modules

To get a better understanding of how the antenna orientation of the sender module would change the signal strength values measured by the anchor, we set up a test with a tag being placed directly underneath an anchor in a distance of 2.5 meters. The tag was rotated around all three axis and 100 measurements were recorded for each orientation. The average values with their standard deviations can be seen in figure 7.9. It is clearly visible, that the anchor measured the highest signal values with the tag lying on the x-axis (-38.6 dBm average). The lowest value was recorded in its z-orientation (-54.6 dBm average) with the maximum difference being 16 dBm. [CnSE+04] also experimented with Bluetooth modules and they found out that depending on the antenna orientation, the signal strength values differed with the maximum deviation being 11 dBm.

Looking at the signal propagation characteristics of the sender module, it makes sense that depending on its orientation, the measured values differ (see figure 7.4 for the characteristics of the antenna). The antenna is linearly polarized and has a clear directivity for propagating the signal (in contrast to a uniform propagation like a sphere). Unfortunately, it was difficult to modify the antennas of the tags as they were already mounted on the modules. One option would have been to use external antennas but this would have affected the housing/case of the mobile device. An external antenna would need more space and therefore, would be mounted on the outside of the casing. Compared to the tags, the propagation of the anchor's antenna is more uniform (see figure 7.5).

One small change to the orientation of the sender module can be made in the mobile device: we can rotate the module clock-wise by 90 degrees so that the antenna/signal propagation faces the opposite direction of the user holding the mobile device (see figure 7.27). This change has to be evaluated, however we assume that this would bring improvements concerning the stability of the signal strength readings.

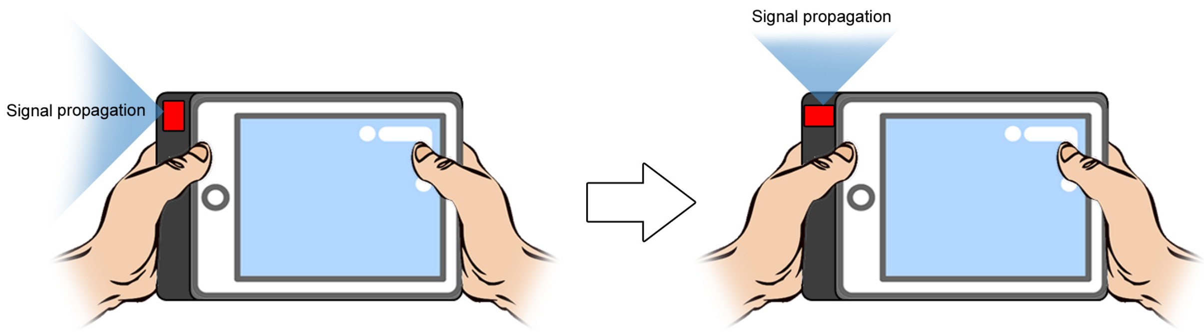


Figure 7.27: On the left: the tag (red) with the antenna sending its signals to the left. On the right: the antenna is rotated clockwise by 90 degrees so that the signals are sent in the direction opposite of the user.

We also tested another approach where we used an array of tags similar to [RFIE07]. We tried to use an array of modules and then calculate the average of the different RSSI values to reduce the fluctuations and get a more stable result combining all orientations. Figure 7.28 shows, how the three sender modules were arranged to cover the orientations.

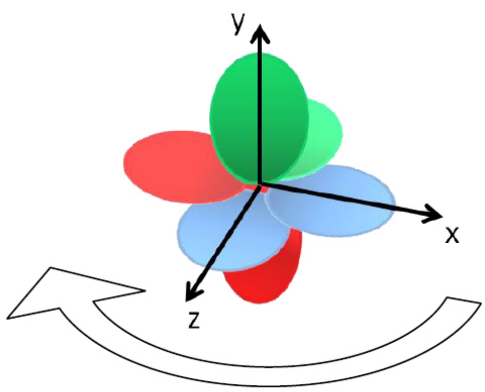


Figure 7.28: The three colors depict how the tags are oriented for the array. One tag covers two directions which means that three are sufficient to cover all orientations. Figure from [Mei14].

This array was mounted on a tripod in 50 centimeters height and rotated in 40°steps around its own vertical axis. Three anchors measured all the signal strength values of the tags during its rotation. Then, three different methods were applied to the collected data to see if any would bring improvements to the signal. The methods are described in [Mei14]. Other than expected, the results (see figure 7.29) showed us that the array did not bring any improvements to the signal by making it more reliable independent of the antennas' orientation. Instead of using an array of sender modules, experimenting with antennas which come with a uniform propagation seemed more promising. The direction of the polarization (linear or circular) could also increase the stability of the signal. [BKRG+14] described how using a circular polarized antenna could result in less fluctuations than a linearly polarized one.

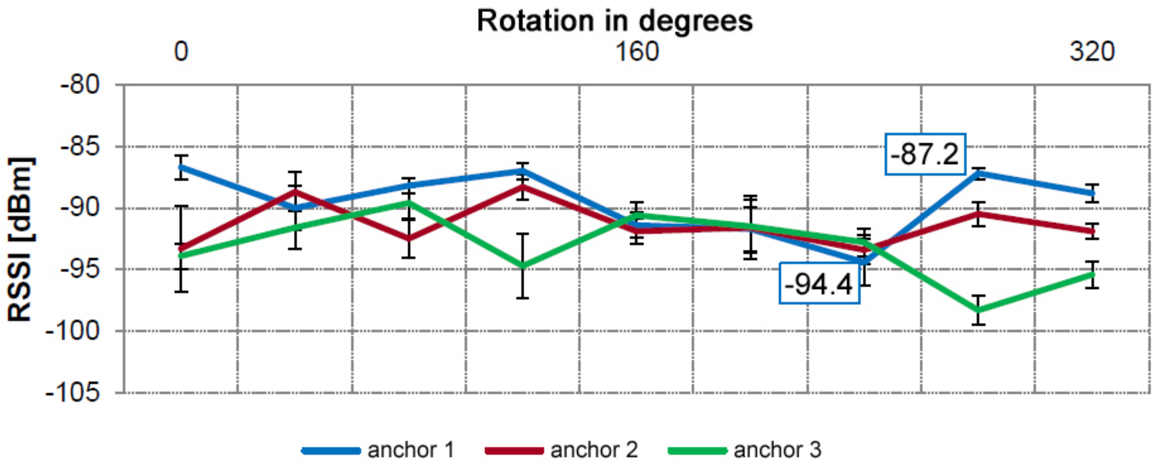


Figure 7.29: The RSSI measurements of the three anchors when the array is rotated by 320°. Differences of approximately 7 dBm and poor results with the three methods described by [Mei14] led us to believe that the array did not hold any improvements. Graph from [Mei14].

7.7.4 Metal back reflectors for anchors

[NHNV12] determined that using a metallic plane as reflector enhances the radiation pattern of an anchor module. The metal plane was mounted between the wall/ceiling and the anchor to reduce effects such as reflections from the walls and also to block signals emitted through the back side. They tested with modules which were also working in the 2.4 GHz frequency band but used the 802.15.4 standard (which implies that a variation of ZigBee was used). Similar to our case, an internal ceramic chip antenna was built into the module. We applied the results of that work to ours since complex modifications to the module or other components were not necessary.

We already mentioned in chapter 7.5, that we place the anchors for the BLE location tracking system on the ceiling at the center of each room (if possible, otherwise there is an offset to the position). Figure 7.30 shows the components for the anchor. For the same purpose as [NHNV12], we put metal reflectors behind the anchor to block outgoing signals and to also help with the propagation pattern. In our case, it is even more important that the anchor mounted on the ceiling on one floor can not detect any tags sending out advertisements on another floor above or below. If that happened, the user would be able to ineligibly control other highly sensitive medical devices. The walls (especially those made out of reinforced concrete) help attenuate the signal and also with path loss, the probability of detecting tags on other floors should be low. With the metal reflectors, the probability should be close to 0.

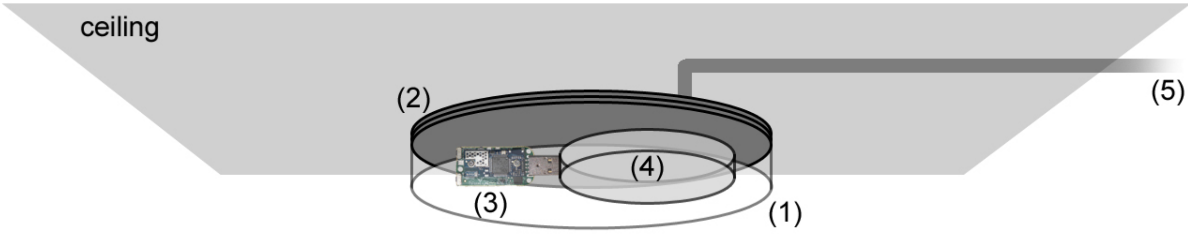


Figure 7.30: The anchor module (3) is attached to a USB-to-RJ45 converter (4). Both are inside a ceiling-mounted case (1) which has two metal planes (2) on its back for signal reflection. A RJ45 cable (5) leads inside of the case and is plugged into the converter (4).

7.7.5 Using more than one anchor per room

We decided to include the option of having more than one anchor installed per room in case the location tracking system was deployed in areas with an irregularly shaped layout. The anchors would have to be mounted symmetrically to each other as well as the room to sufficiently cover the area where the mobile device/tag should be tracked. Up to 3 anchors can be installed if the requirements as mentioned in section 7.5 are not met by the room dimensions. Figure 7.31 shows how the anchors have to be installed for different room layouts. Calibration needs to be done with just one of the anchors even if more are installed. The tripod with the mobile device attached to it has to be placed towards the anchor which is positioned nearest to all the doors in the room. The location engine would then try to measure the signal strength of the mobile device from all the installed anchors but since the tripod is inevitably closer to one specific anchor, its measured RSSI values would be the highest among all the others. Consequently, they would be taken to calculate the thresholds as described in chapter 7.8. Once calibration is finished, the computed threshold values are applied to all the existing anchors in the room. Therefore, it is very important to have a symmetrical placement of the anchors.

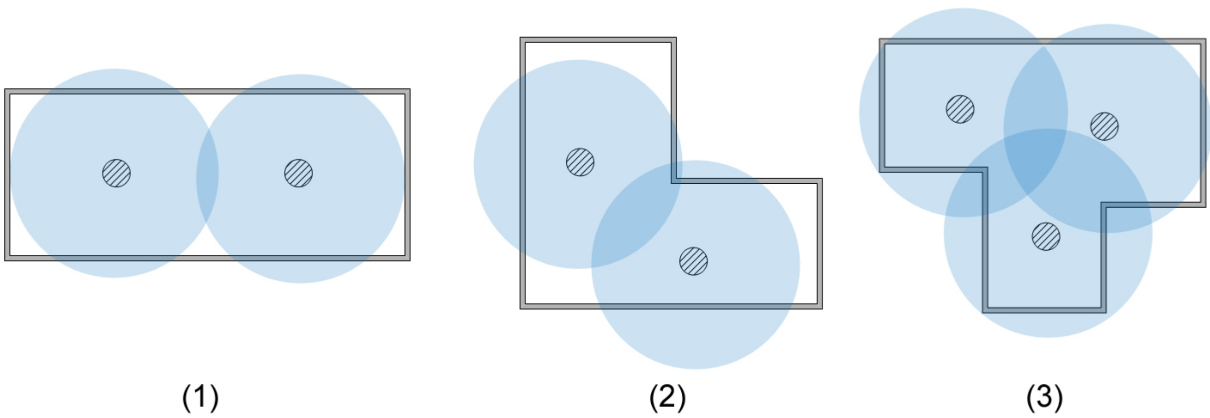


Figure 7.31: Various room sizes and their optimal anchor placements. For (1) and (2), two anchors are recommended to cover a majority of the area while (3) requires three anchors.

Algorithm for optimal placement of anchors

The Trumpf Medical sales team received the instructions and guidelines where and how many anchors to place for optimal conditions. However, we were still asked about certain placements when given a map of a facility, also to make sure that the sales people were following all the specific considerations. Since all these instructions and requirements can be declared in detail, it is also possible to have these set as initial conditions for an algorithm to automatically compute, how many anchors are needed and where they need to be placed. In the following, the algorithm is described in pseudo-code:

Algorithm 1 Algorithm for placing 1-3 anchors in a given room layout to cover the area

s_i = shape with s_1 being the original shape
c_i = centroid for shape s_i
a_i = anchor with range r
α = 95% for coverage
for $i = 1, i \leq 3, i++$ **do**
  for $l = 1, l \leq i, l++$ **do**
    calculate centroid c_l for s_l
    if a_l does not cover s_l to α when placed at c_l **then**
      if $l < 3$ **then**
        split s_1 into $i+1$ with placing $i+1$ lines at c_1 so that $i+1$ shapes result with equal areas and declare as s_{i+1}
        break
      else
        break $\rightarrow$ no solution for 3 anchors
      end if
    else
      break $\rightarrow$ all s_l are covered with i anchors used
    end if
  end for
end for

We declare s_0 as the original shape of the room and $n = \{1, 2, 3\}$ as the number of anchors, each with range r. We calculate the centroid of s_0 and see, if placing $n = 1$ anchor with r covers α of s_0. If it does, then we have the optimal position for the room with shape s_0 and just 1 anchor. If the placement of the anchor does not cover 95%, then divide s_0 into two shapes s_1 and s_2 so that both areas are 50% of the area of s_0. To do so, we place two lines with their origin at the centroid so that s_0 is divided into two equal shapes. Then take each shape and calculate its centroid and see if placing the anchor there covers α of its area. If it does not, we divide s_0 into three shapes with equal area sizes. We draw 3 lines with their origin at the centroid of s_0 and subsequently try to divide it in 3 symmetric shapes. If the shapes s_1, s_2 and s_3 are found, then calculate their centroids and see if $n = 3$ anchors cover most of the area.
Right now, only 3 anchors can be installed for one room but in the future, this could be expanded to any count of anchors. Also, it is not recommended to install and use the location tracking system if 3 anchors do not cover the majority of the area. Figure 7.32 shows three examples with the circle-shaped room as the "worst case" scenario.

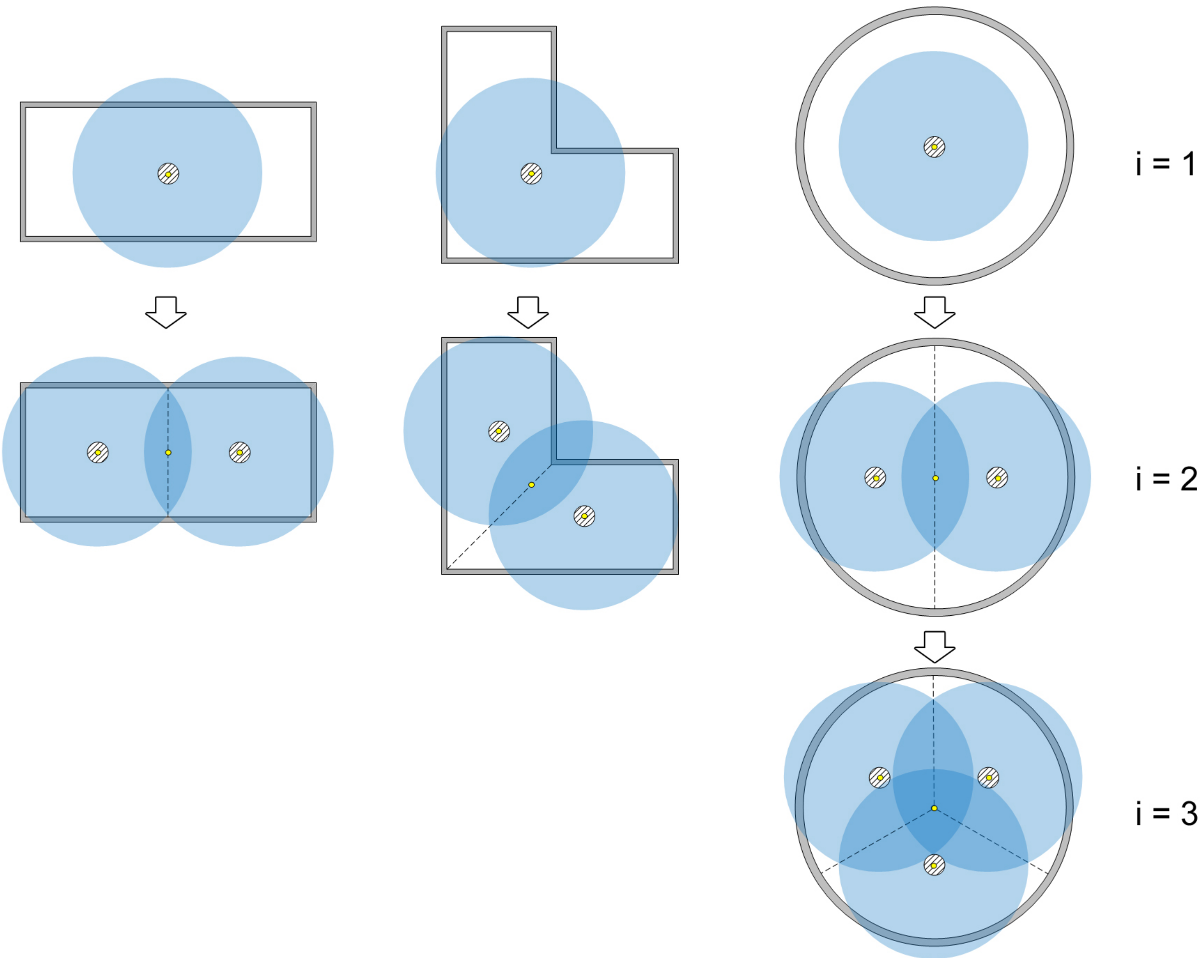


Figure 7.32: Three examples and their iterations with the proposed algorithm from $i = 1$ to $i = 3$.

7.8 Calibration

This chapter describes how the rooms are calibrated for the location tracking system. The main approach is to get two threshold values which define an area where the mobile device should enter or exit a room. We describe two possibilities on how the values can be obtained: a manual calibration process and one which is more sophisticated, does not require much user input and in the end, is more reliable.

7.8.1 Manual calibration

The first idea was to let the user record signal strength values at designated positions (at least eight) in a room to calculate two threshold values. A minimum of four of these eight positions should be at spots where the location tracking system should remove the tag from its current room. This means that the person calibrating these points had to stand at the border of the room with his back against the walls. He had to choose the calibrating spots wisely, so that the sides of the room would be the farthest away from its center. The user would stand at each position holding the mobile device in his hands and press a button in the calibration software to start the signal strength measurements. The location tracking system would record the signal values of the mobile device and respond with a message for a successful or failed calibration. If the calibration for that spot was not successful, the user would have to repeat the procedure. Otherwise, he could move on to the next position. After collecting the signal strength values for the first four spots, they were converted from dBm to milliwatt for linearity with equation 7.1.

$$P\,[\mathrm{mW}] = 1\,[\mathrm{mW}]\,10^{\frac{P\,[\mathrm{dBm}]}{10}} \tag{7.1}$$

Then, depending on the normal distribution (calculated through a "Kolmogorov-Smirnov" function which tests for normality) either the mean or the median was computed to get the lower threshold. Because of the potentially small sample size, the Kolmogorov-Smirnov test was used. Other, more efficient normality tests include the "Shapiro-Wilk", "Anderson-Darling" or the "Shapiro Francia" test (see [GZ12]). The same procedure was repeated but for an area closer to the center of the room, representing the region where the location tracking system would register the mobile device for the room. The calibration of these four positions would lead to an upper threshold value. Since a signal strength value is measured and stored every 1.4 to 1.5 seconds, the calibration process for 60 values takes around 1.5 to 2 minutes for each position (if we account for the Not-Found values as well). The total count of measurements adds up to 240 values for the inner area (entering) and 240 values for the outer area (exiting) to calculate the upper and lower threshold. In the end, the whole calibration process took around 12 minutes, computing the upper and lower threshold values. Figure 7.33 visualizes the idea for the manual calibration process. We borrowed the idea for manual calibration from the fingerprinting method. We took the orientation of the tag into account assuming that the user would always operate the mobile device while facing the OR table positioned in the center of the room. Taking fingerprints at the specified spots would give us a benchmark regarding the RSSI values while the system was running.

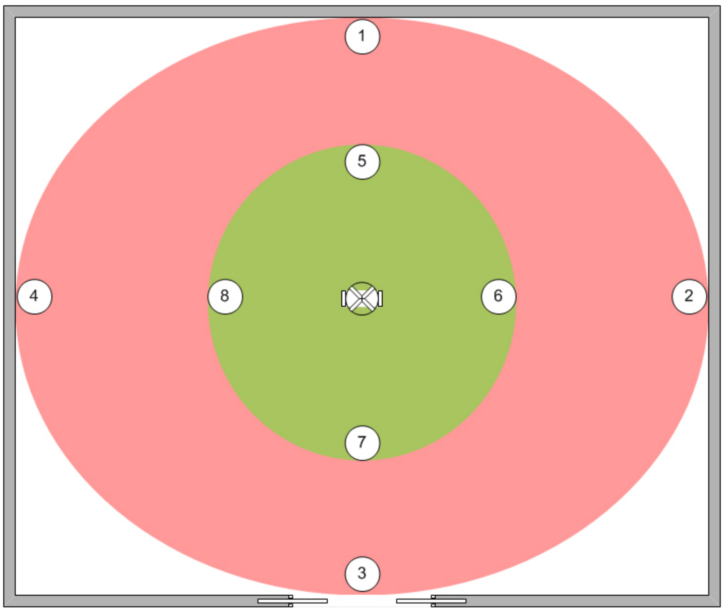


Figure 7.33: The manual calibration procedure with 8 measurements, 4 for the outer area (positions 1-4) and 4 for the inner area (positions 5-8).

7.8.2 With tripod

The first idea (see previous section) was to let the user choose eight positions for calibration: four positions representing the inner area (upper threshold) for entering the room and four positions for the outer area at the walls of the OR (lower threshold) for exiting the room. There were two problems with this method:

1. The user could choose any position for the eight calibration points. He could also choose to stand at unsuitable locations during the calibration and therefore get signal strengths much higher or lower than intended.
2. Since there are signal strength fluctuations happening all the time, there was no guarantee given that the user would get the same values when repeating the calibration procedure.

This led to the second idea of a more controlled calibration procedure where only one position p was needed for measurements (see figure 7.34).

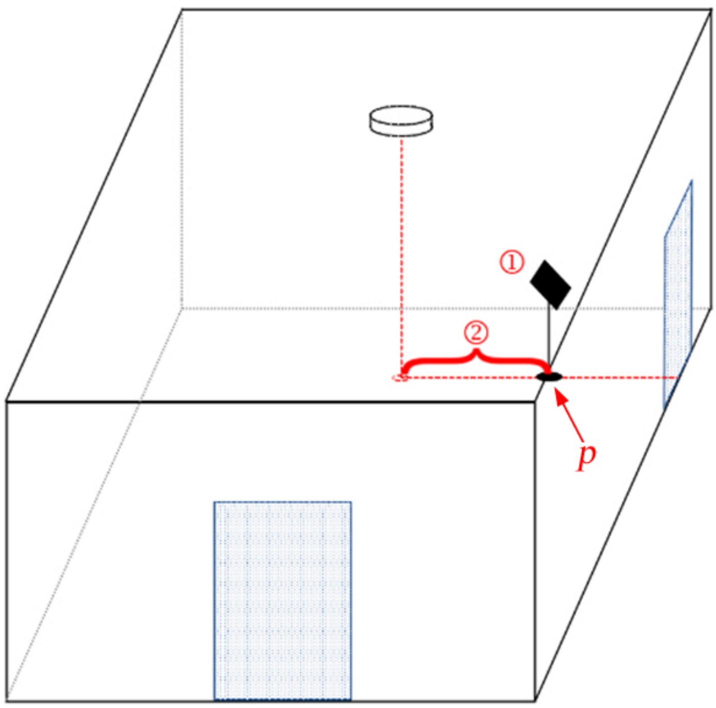


Figure 7.34: A tripod (1) with the mobile device mounted 1.3 meters above the ground is put at $p = \frac{d}{2}$ (2). 600 signal strength values are measured and from these, an upper and lower threshold is computed.

The process is taking longer than the previous one since there are more measurements taken at p. A tripod located 1.3 meters above the ground was chosen to replace the user standing at p holding the mobile device in the hand for longer than 10 minutes. For this procedure, the following parameters were used to compute the two threshold values:

1. Height of the room where the calibration is taking place.

2. Distance to the nearest door in the OR taken from the projected position of the anchor module on the floor.

3. Path Loss Exponent for calculating the two threshold values (upper and lower threshold).

Equation 3.2 is used to calculate the thresholds from the measured signal strength values at p. The upper threshold is computed as follows: Given the distance d from the projected position of the anchor on the floor to the nearest door, $\frac{d}{2}$ is used as d_0 and as the range, where the mobile device should enter the room when exceeding the upper threshold. Signal strength measurements with the mobile device mounted on the tripod are taken at $p = \frac{d}{2}$ and stored in the database. The values are then converted to milliwatt for linearity with equation 7.1 and then, depending on the normal distribution (Kolmogorov-Smirnov) either the mean or the median is determined to be the upper threshold value.

The lower threshold is then calculated as follows: The RSSI value for the upper threshold is taken as P_t. All other values for the formula such as d or d_0 are known except for the Path Loss Exponent, which we set to the constant value 3.5. According to [Gol05], the used PLE describes an office building with line of sight obstructions which in our case is partially true. An office building would not have reinforced concrete walls and therefore be less absorbent than the walls of an OR corridor. From our experience, we can say that due to the dynamic environment and influences, a PLE value of 3 to 4 is a sufficient representation of the environment.

With the same measurement interval as with the manual calibration (every 1.4 to 1.5 seconds), at least 600 signal strength values are stored in the database. The whole procedure to measure and calculate the two thresholds should take around 15 minutes.

7.9 Use cases

This section describes three use cases where the developed location tracking system was tested. We will also mention problems, anomalies as well as present our approach on how to solve them.

7.9.1 Hospital in Munich, Germany

In a hospital in Munich, two operating rooms were fully equipped with state-of-the-art technology consisting of new OR lights, OR tables and the OR integration system "TruConnect". The two ORs were a good place for testing the whole system and for gathering data/information regarding workflow and operation processes. Also, the medical staff helped us in providing feedback related to all the installed products. Figure 7.35 shows the ORs (OR 7 and OR 8) and the corridor connecting the two rooms. There is also a small corridor between the two rooms which directly connects OR 7 and OR 8. Most of the time, the two doors adjacent to the ORs are held open so that the scrub nurses can assist in both rooms when necessary. With the two ORs having a size of 43 square meters each, they fulfill the requirements set in chapter 7.5 for installing and using the location tracking system. But having two rooms with the installed location tracking system right next to each other and even with possible LOS spots, it was difficult to foresee if everything would work without problems. For instance, with an open door, signals from tags in OR 7 might be detected in OR 8 and vice versa. The challenge was to set the upper thresholds optimally so that the sender modules would only enter the correct rooms.

At first, the OR integration system was installed separately in both rooms. As a result, the user could not enter a "virtual room" with a mobile device which was not specifically designated to it. The location tracking system in OR 7 would only allow certain mobile devices to enter. The same applied to OR 8 and both rooms would work independently from each other. Later, with a software update, both ORs were merged to one system and then, users could move from one room to another with their mobile devices and get registered for the respective area they were located at.
The software was updated after all planned surgeries for both rooms had finished and with the medical staff as well as the medical equipment either turned off or not present (for example, the OR table with the patient was not present in the room anymore). When the initial calibrations were performed, only a few members of the Trumpf Medical team were present. Most of the large devices such as the OR booms and the OR lights were positioned as they would be during surgery. While the two ORs have almost the same dimensions, the calibration was still done in both and in the following, the upper and lower thresholds are presented:

Thresholds for OR 7

- Upper threshold: -90 dBm
- Lower threshold: -101 dBm

Thresholds for OR 8

- Upper threshold: -91 dBm
- Lower threshold: -102 dBm

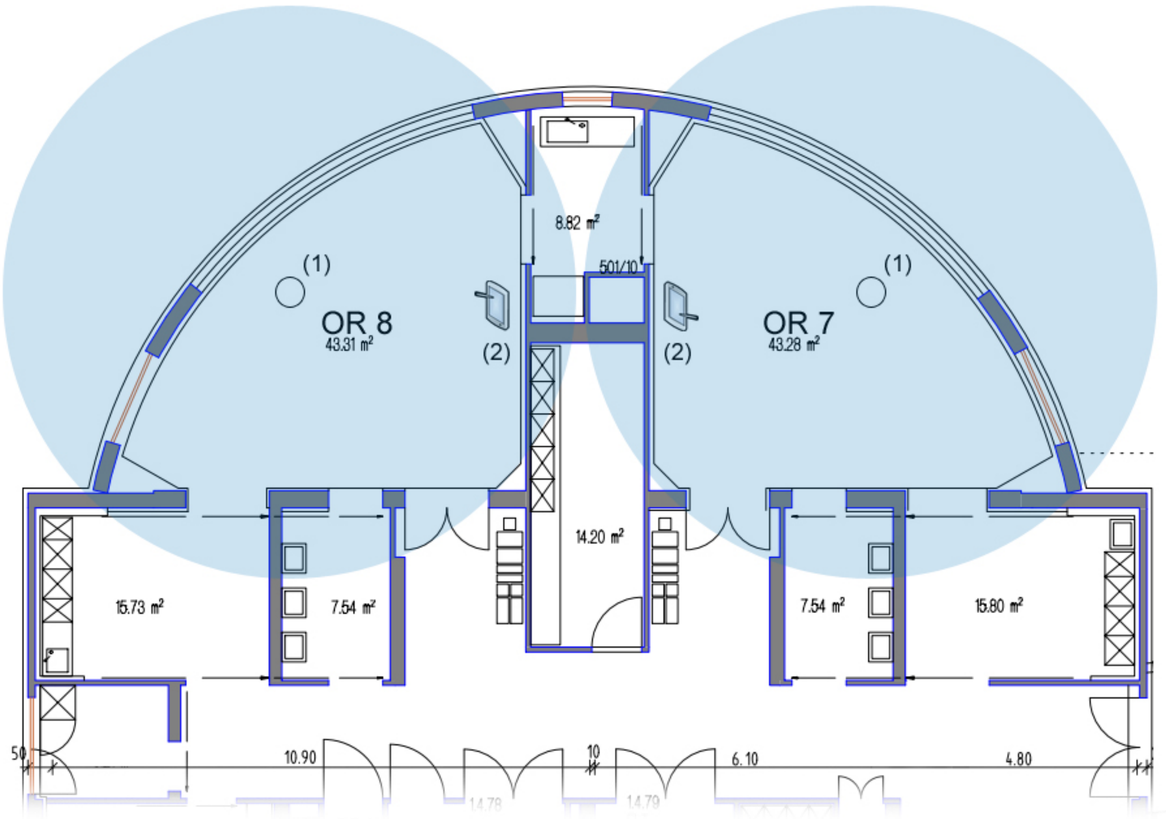


Figure 7.35: Top view of the corridors of the hospital in Munich with its two ORs, OR 8 on the left and OR 7 on the right. The anchors (1) had to be positioned with an offset due to the OR light canopies in each room. Most of the time, the mobile devices were placed on their respective docking stations (2) for charging.

A few weeks after the location tracking system was deployed at the hospital, we were notified that mobile devices would enter the wrong rooms. This was immediately analyzed and according to the event logs of the OR integration system, it was revealed that recorded signal strength values from the adjacent room were higher than those from the actual room. That was one of the reasons why the mobile devices kept leaving the current room. Then, they entered the room next door due to the higher RSSI values. The main reason for entering the wrong room was that the upper thresholds for both rooms were set too low. The spots from where the mobile devices would be operated were also unfavorable for the location tracking system (see figure 7.35 for the position of the docking stations, where the mobile devices would be placed most of the time). The following describes two cases where the mobile devices could enter the wrong room due to the low thresholds:

1. The anchor in the room where the mobile device is currently located does not detect a signal from the tag but the anchor in the next room detects it with a signal above the room's upper threshold.
2. The anchor in the room where the mobile device is currently located is in a faulty state where it does not find any sender modules. As a result, the anchor next door finds the mobile device with a signal above the room's upper threshold.

To solve this problem, the upper thresholds for the rooms were increased from -91/-90 to -83 dBm. After that, the mobile devices did not enter the wrong rooms when placed at their respective docking stations. The dynamic environment and the fact that during operations, at least 5 people are always present in each of the ORs could also contribute to signal fluctuations and consequently to mobile devices leaving the room.

7.9.2 Hospital in Berlin, Germany

One of the ORs in a hospital in Berlin was also equipped with the OR integration system “TruConnect”. Here, the system was only installed in one room (see figure 7.36). With its size of approximately 28 m^2 (7 x 4 meters), it was narrow and in general, too small. Due to an existing Laminar Air Flow ceiling, the anchor had to be installed with an offset of 1 meter to the center of the room. Various medical devices as well as people working in the small room led to frequent fluctuations of the recorded RSSI values which in turn led to many situations where the mobile device would leave its “virtual room”. Later, the lower threshold was lowered twice so that the mobile device would stay in the room for a longer time period than before.

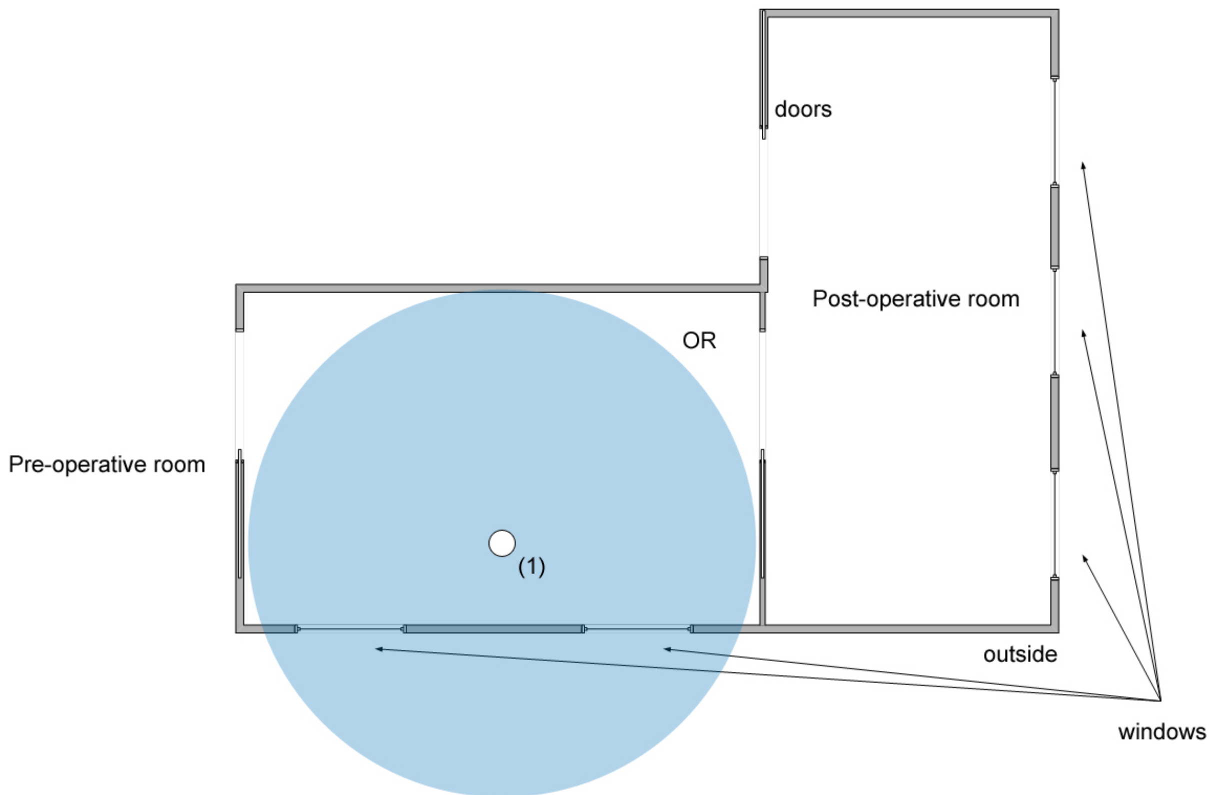


Figure 7.36: Top view of the OR as well as the pre- and post-operative rooms in a hospital in Berlin. The anchor (1) was mounted on the ceiling with an offset due to the existing Laminar Air Flow and OR light canopy being installed in the center.

7.9.3 MEDICA 2014 Trade Fair in Düsseldorf, Germany

In 2014, Trumpf Medical presented its products on a large booth at the MEDICA trade fair in Düsseldorf, Germany. The booth featured two areas which were designed to work independently: the OR area and the zones (see figure 7.37). In the middle of the booth, a large room representing an OR was constructed with TruConnect and also the location tracking system installed. One anchor was mounted on the ceiling of that room and only certain mobile devices intended for the OR were registered from the location tracking system. Outside of the OR, four zones were set up: two to present OR lights and two for OR tables. The visitors could take any of the mobile devices outside and go from zone to zone which would cause the mobile device to leave and enter a room once they were in close vicinity of one of the zones. Despite initial problems with the zones being too loose (the lower thresholds were set too low), after adjusting the thresholds, the tracking system worked satisfactory. After a time-out of 10 seconds, the mobile devices would leave their current rooms/zones if the users would move away from the site.

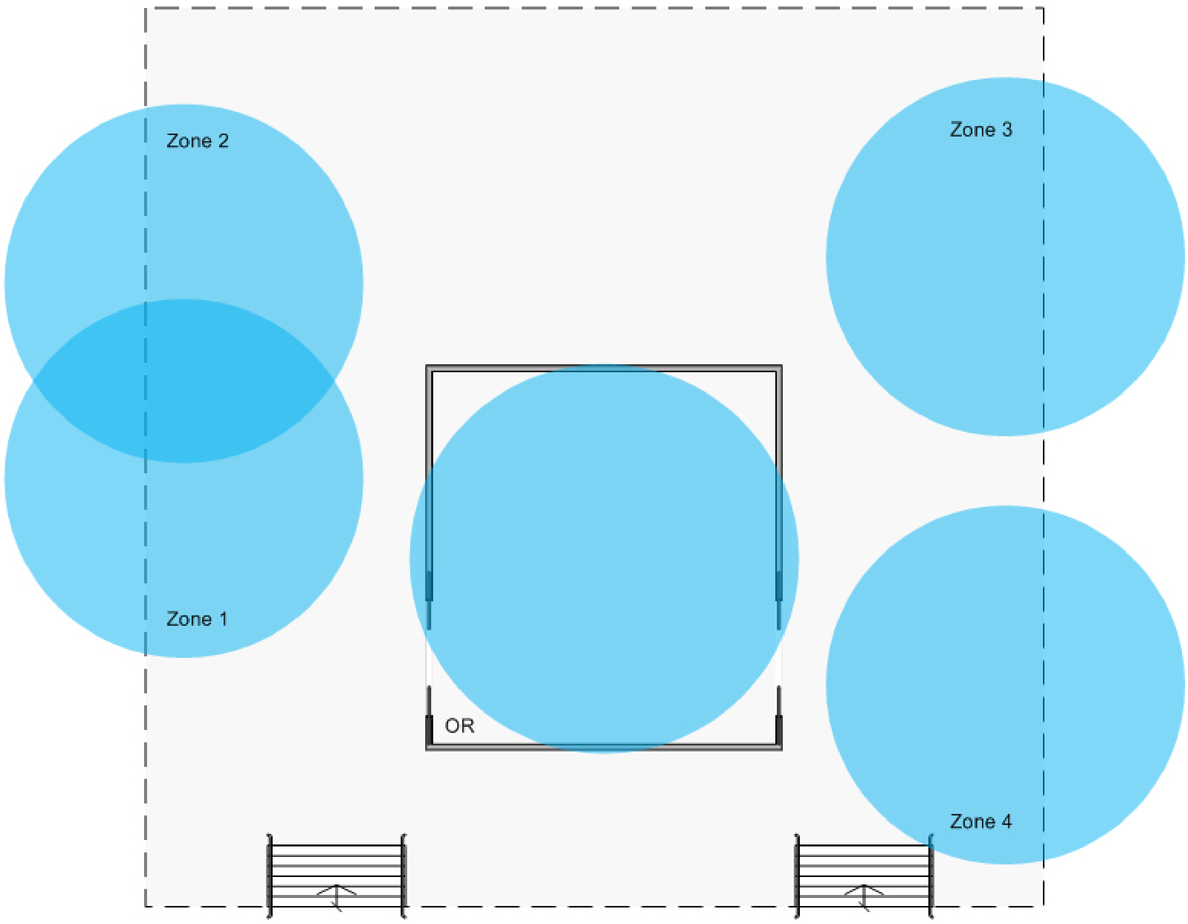


Figure 7.37: The Trumpf Medical booth at the MEDICA 2014 trade fair with the 4 zones and the OR in the middle.

Users with mobile devices had to be aware that standing between zone 1 and 2 could result in entering or exiting room 1 or 2 quite randomly and often. Since both anchors were put so closely together, two high threshold values had to be set. However, this did not separate the zones clear enough, which meant for the user that he could not remain in his desired area for a longer period of time. That is the reason why everyone with a mobile device was instructed to stay at the far edges of the zones for reliable tracking.

7.10 Using additional sensors for stability

7.10.1 Motion data of mobile device

The mobile device used for TruConnect includes sensors such as a gyroscope and accelerometer. A chip inside the device collects all the motion data and provides an interface where parameters can be retrieved. The following parameters are provided by the interface to predict whether the mobile device is moving or not:

- Cycling
- Automotive
- Walking
- Unknown

Either one of these parameters can be 0 or 1 and there is also the option that multiple parameters are set to 1 simultaneously. This is one of the reasons why we combined these to declare that if one of the parameters is bigger than 0, then the device is moving. Otherwise, the device is stationary (all parameters are 0). Besides those variables, the device gives us a “confidence” value, describing how certain the mobile device is in one of these states. The “confidence” value ranges from 0 to 2, with 2 representing “very certain”.

There are four scenarios where these two variables, “stationary” and “confidence”, can be used to make the tracking system more reliable:

- Measured signal strength is stable, mobile device reports “stationary”:

signal strength (dBm)	**stationary**
...	...
-94	yes
-93	yes
-93	yes
-95	yes
-93	yes
...	...

  This scenario reflects one of the two normal cases where the measured signal strength value and the motion variables correlate. If the mobile device stays at a fixed location, the recorded signal strength value should not deviate too much from one level. If this is the case, then the measured signal strength is taken as it is without any modifications.

- Measured signal strength is stable, mobile device reports “moving”:

signal strength (dBm)	stationary
...	...
-93	yes
-94	yes
-93	no
-93	no
-93	no
...	...

We can use this case to detect if the tags are still “alive” since we do not get this information through time stamps or counters yet. If the recorded signal strength is stable for a defined time span but the mobile device reports that it is moving, we declare that the Bluetooth tag is broken. We can then show a warning message to the user and omit the mobile device with the faulty tag from the location tracking system as long as the sender module is replaced and the signal strength value changes again. We could also detect if an anchor module on the ceiling was faulty and read the same signal strength values over and over again while the actual ones varied. To solve this problem, the anchor could be restarted to see if the newly measured values differed and if they did not, the user would receive a message to replace the anchor module.

- Measured signal strength fluctuates, mobile device reports “stationary”:

signal strength (dBm)	stationary
...	...
-93	yes
-94	yes
-106	yes
-98	yes
-93	yes
...	...

Since the mobile device states that it is staying at the same position, we have to assume that the signal strength fluctuations are caused by environmental influences. If the location tracking system takes the signal strength fluctuations just as they are, it could happen that the mobile device is removed from its current room (even if it physically stayed at the same location). In this case, we have to calculate the difference between the previous signal strength value and the new one. If the difference is bigger than x, we could correct the new value according to the following formula:

$$rssi_n = rssi_o + \frac{rssi_n - rssi_o}{2} \tag{7.2}$$

- Measured signal strength fluctuates, mobile device reports “moving”:

signal strength (dBm)	stationary
...	...
-93	yes
-94	yes
-106	no
-98	no
-93	yes
...	...

This scenario is also one of the default cases, where everything behaves as it should and the signal strength values are taken as they are.

7.10.2 Tests

We set up the BLE location tracking system with a mobile device including an activated motion sensor. Every 1-2 seconds, the status of the motion sensor was transmitted to a computer in the back end and then stored into a database. Figure 7.38 shows the setup from the top view. The mobile device was not moved for 2 days, from August 4th 11:23 AM until August 5th 1:02 PM. During that time, 91011 signal strength measurements of the BLE tag were logged.

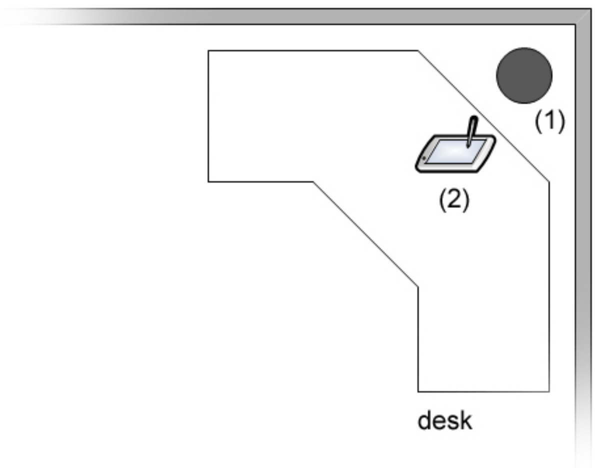


Figure 7.38: Top view of the setup for the test with the motion sensors in the mobile device (2). The anchor (1) was mounted on top of a tripod, 3 meters above the ground and the mobile device was positioned on a desk right in front of the anchor. The mobile device on the desk was 0.75 meters above the ground.

The upper threshold value was set to -88 dBm and the lower one to -96 dBm. The tag was close enough to the anchor that it should have stayed in the room the whole time with a measured signal strength value higher than -96 dBm but out of the 91011 measurements, the tag was detected 24918 times outside of the room. That gives us a false positive rate of 27%. Now, let $rssi_{i-1}$ and $rssi_i$ be the signal strength values measured for tag t. Since we only have one room in our test setup (and theoretically, one additional virtual room depicting "no room"), we have r_i which can be 1 for the test room and 0 otherwise. Also, we have the Boolean value of the motion sensor s which returns "true" if the tag would be stationary and "false" if it was moving. With all these parameters, we can determine if the tag has left the room because of signal strength fluctuations despite being stationary. The following query returns "true" if the tag was removed falsely from its designated room:

Algorithm 2 detects if the tag was falsely removed from the room

1: **if** $(|rssi_i - rssi_{i-1}| > \alpha \wedge r_{i-1} \neq r_i \wedge s_i = true \wedge r_{i-1} = 1 \wedge r_i = 0)$ **then**
2: let tag remain in room 1 until a) it is detected again in the room or b) the motion sensor returns "false" implying the tag is moving
3: **end if**

Through the algorithm above, all of the 24918 values where the tag was detected to be outside of the room could have been classified as false positives. Out of the 91011 Boolean values for the motion sensor (stationary or moving), 18 were set to "false" with the measured signal strength values actually varying from the previous ones. Most of the 18 values followed after each other in sequential order which implies that at that time, the mobile device was really moved.

7.10.3 Discussion

The results when applying the algorithm from the previous section are very satisfactory and optimistic. The experiment only lasted for two days and consisted of one simple scenario where the tag remained stationary the whole time. To see a significant, positive effect, the algorithm has to be tested throughout a longer period of time and in borderline areas where the tag would normally enter and exit the room frequently.

Another issue, which needs to be analyzed, is the sensitivity of the motion sensor built into the mobile device. Depending on the configured sensitivity, if a user places the mobile device on a cart and moves it around, the sensor would return different Boolean values due to very fine vibrations caused by the cart's wheels. An optimal value for sensitivity, which helps to distinguish between actual movement of the device (also counting acceleration) and placing it stationary, has to be found.

7.11 Dynamically adjusting thresholds

The proposed idea to adjust the static thresholds dynamically was tested, submitted and published as paper at the IEEE IWCMC 2015 conference in Dubrovnik, Croatia [HK15]. Some parts of this section have been taken straight out of this paper.

7.11.1 General

A common problem with radio-based technologies (such as Bluetooth) is that signal strength fluctuations are recorded even when tags are placed at fixed locations. The environmental influences, multipath effects and shadowing mentioned in chapter 3.2 lead to such fluctuations, therefore causing problems when comparing the current signal strength value to static thresholds (see figure 7.39). In case the RSSI value increases because of fluctuations while the static threshold stays the same, the region defined by the threshold increases too as the tag exceeds certain thresholds faster than intended.

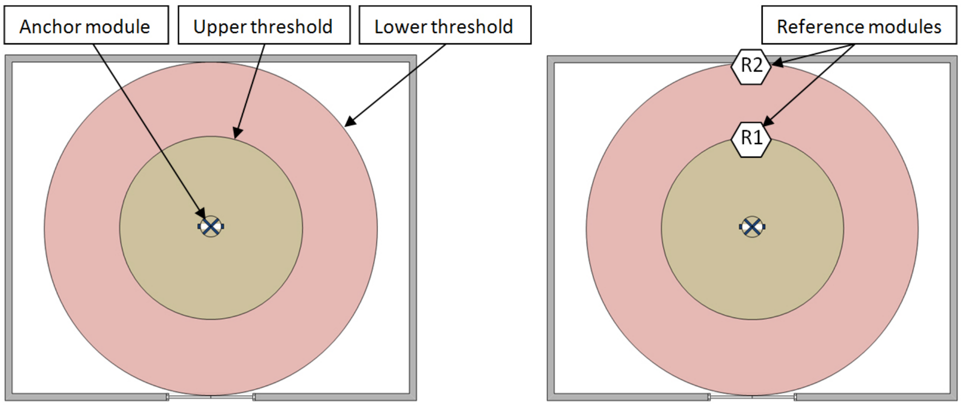


Figure 7.39: On the left: Initial setup with an anchor module mounted on the ceiling in the center of the room. Two threshold values (one for "nearby"/upper threshold and one for "far away"/lower threshold) from previous measurements are stored on a computer used for the calculation of the location. On the right: The proposed setup with two reference modules mounted on the ceiling in specific ranges to define the two regions.

Instead of static thresholds, we could use dynamic values which adjust themselves automatically. The adjustments are done by measuring the signals of an additional reference module placed at a fixed spot periodically. If fluctuations are detected and if they correlate with other signal strength values of tags nearby, the static thresholds are adjusted. If the fluctuations are positive, the thresholds need to be increased and if the fluctuations are negative, they have to be decreased. By placing two reference modules on the ceiling, both thresholds could be measured by an anchor and the two defined regions for the upper and lower threshold would stay similar over time.

We set up some hypotheses to show if reference modules can improve the stability of a proximity-based location tracking system:

- Hypothesis 1: Reference module 1 (R1) records fluctuations caused by environmental influences, multipath effects and shadowing

- Hypothesis 2: The fluctuations recorded by R1 are comparable to the fluctuations recorded by another sender module (S1)
- Hypothesis 3: Through the measured signal strength of R1, the static value depicting the region can be adjusted to stay similar despite fluctuations

7.11.2 The setup and the algorithm to adjust the threshold

Three different setups were tested (see figure 7.40) in an office with the size of approximately 10 x 10 x 3 meters.

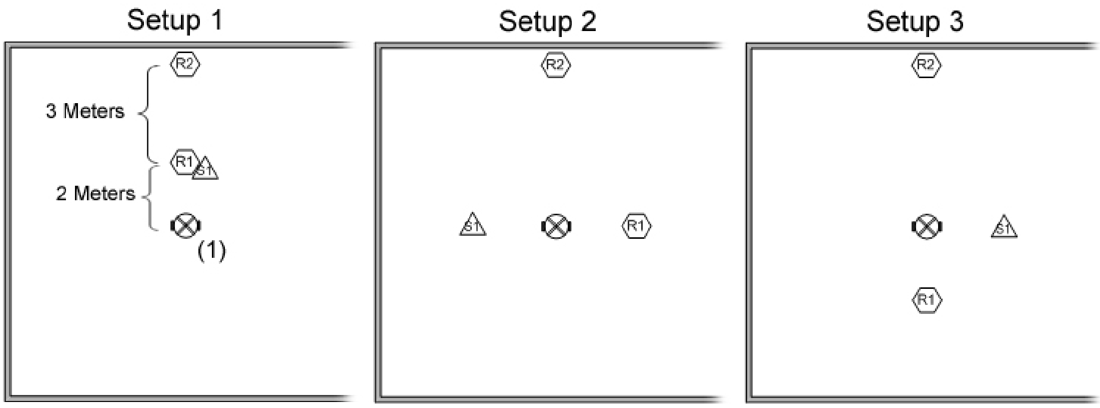


Figure 7.40: Overview of the three different setups with the location tracking anchor (1), the two reference modules R1, R2 as well as the sender module S1 placed at their respective positions. R1 and S1 were always placed 2 meters away from the anchor. R2 was placed at a distance of 5 meters from the anchor.

R1 was placed 2 meters and R2 5 meters next to the anchor (see figure 7.41).

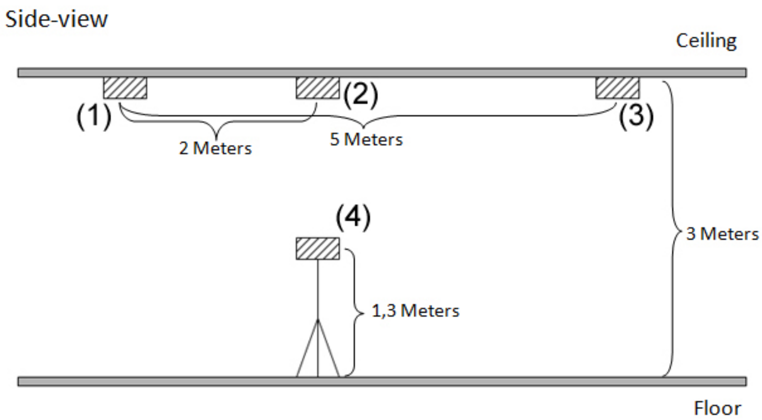


Figure 7.41: Side view of setup 1 with the location tracking anchor (1), module R1 (2), module R2 (3) and module S1 (4). S1 was mounted on a tripod. The other modules were attached to the ceiling with tape.

In each test run, we observed that people in the office were either moving, therefore causing fluctuations or the office was empty (over the weekend). Another aspect, which was important when planning the experiments was the orientation of the modules since the receiver and sender modules used different antennas (see chapter 7.2). To calculate if there was any correlation between the data of each module, we used "Pearson's R" correlation coefficient. The correlations for all three setups can be seen in table 7.5. Only setup 1 was interesting for further investigation since in all the other tests, the correlations were never significantly high enough. We then repeated the tests with just setup 1 two more times for a total of three test runs (see table 7.6 for T2 and T3).

In all the test runs, the modules were placed at the exact same location on the ceiling and every test began in the afternoon and continued over night. The selected time frame should show significant differences when people were still in the office during the day and when the office was empty at night. Four values for each of the located sender modules were written into the database: the signal strength, the moving average of the signal strength, the estimated Kalman filter value and the standard deviation of the signal strength.

With these values at hand, there were two options to dynamically adjust the threshold:

- Option 1: Calculate the moving average as well as the standard deviation from the stored signal strength values up to now and depending on the later, the threshold is adjusted (increased or decreased).
- Option 2: Use the standard deviation of the estimated Kalman filter value to decide if the threshold should be adjusted or not.

The algorithm of dynamically adjusting the thresholds can be seen in figure 7.42.

Let x_1 be the raw signal for R1 and x_2 the raw signal for S1. $f(x)$ is the filter (moving average, Kalman, ...) which is applied to the raw signal and $g(x)$ is the current standard deviation for all the previous signal strength values. $h(x_1, x_2)$ calculates β, the correlation coefficient. The threshold is represented by y. m_1 and m_2 are the current moving average values of R1 and S1. The query on the raw signal strength values can be seen in algorithm 3. For the experiments, α was set to 0.5 for the first test run and then 0.3 for the later ones. γ was always set to 0.5.

Algorithm 3 adjusts threshold

1: **if** $h(x_1, x_2) > \gamma \wedge g(f(x_1)) > \alpha \wedge g(f(x_2)) > \alpha \wedge ((|f(x_1) - m_1| > 0 \wedge |f(x_2) - m_2| > 0) \vee$
$(|f(x_1) - m_1| < 0 \wedge |f(x_2) - m_2| < 0))$ **then**
2: $\quad y = y + \frac{(m_1 - f(x_1)) + (m_2 - f(x_2))}{2}$
3: **end if**

First, the algorithm depicts if the correlation coefficient is greater than γ and second, the standard deviations of both signals from R1 and S1 are calculated to check the fluctuations in the data. Then the absolute

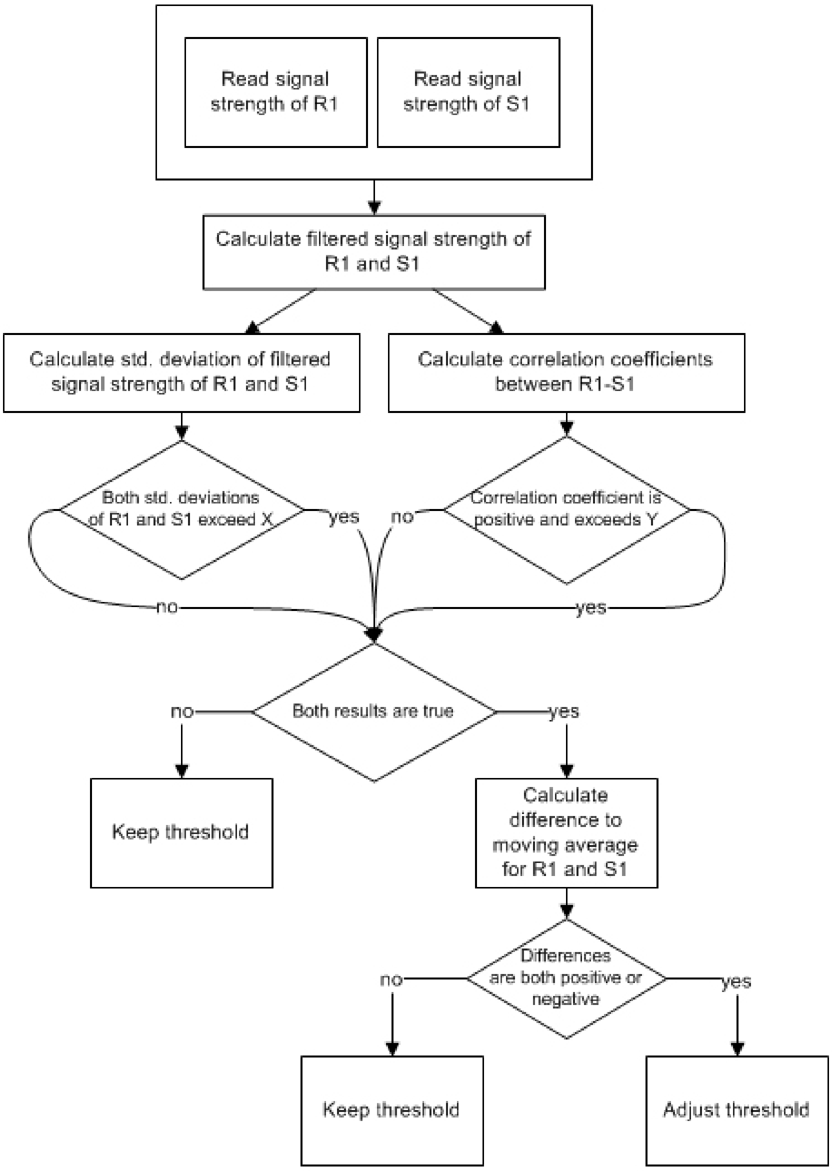


Figure 7.42: The process behind the dynamic threshold adjustment. The raw signal strengths of R1/R2 and S1 are the inputs while the output decides whether the threshold should be adjusted or not.

difference between the moving average and the filtered signal strength value is calculated for each module. The threshold y is adjusted if the differences are either both positive or negative and the rest of the factors are true. The adjustment itself is being done with the mean value of the added differences from both modules.

We calculated the expected signal strengths via the Log Distance Path Loss model (see equation 3.2) since the distances between the modules in the test setup could be measured beforehand. In addition, calculating the PLE value of each module and comparing them would provide insight into the influences (people, objects obstructing the line of sight etc.) in a test environment if the values would be significantly different over time.

7.11.3 Results and discussion

The correlation between the modules was checked and calculated for the following combinations:

- Reference module 1 (R1) - Reference module 2 (R2)
- Reference module 2 (R2) - Sender module 1 (S1)
- Reference module 1 (R1) - Sender module 1 (S1)

The results can be seen in table 7.5. A value between +1 and 0 represents a positive correlation whereas a value between 0 and -1 indicates a negative correlation (and 0 for no correlation).

Table 7.5: Correlation between the modules for each setup.

Setup 1 Test run 1 (T1)	**Raw**	**Moving average**	**Kalman**
R1 and R2	0.19	0.25	0.23
R2 and S1	-0.04	-0.15	-0.05
R1 and S1	0.08	0.46	0.11

Setup 2 Test run 1 (T1)	**Raw**	**Moving average**	**Kalman**
R1 and R2	0.20	0.77	0.24
R2 and S1	0.0	-0.20	0.0
R1 and S1	-0.12	-0.58	-0.16

Setup 3 Test run 1 (T1)	**Raw**	**Moving average**	**Kalman**
R1 and R2	-0.52	-0.93	-0.54
R2 and S1	0.09	-0.13	0.09
R1 and S1	-0.28	-0.09	-0.29

A positive correlation between R1 and R2 as well as R1 and S1 can be seen in the first two test runs. For the first two test runs of R2 and S1, we got negative correlations. Setup 1 was the only test run with a positive correlation between R1 and S1. If we take the moving average and calculate all coefficients with the current signals for each tag, the correlations become more apparent (see table 7.5). The gray rows depict the values with correlations greater than 0. We decided to conduct two more test runs with setup 1 since it was showing promising results regarding the correlation of R1-S1. The results of T2 and T3 can be seen in table 7.6. In the following, we are only discussing the three tests (T1, T2 and T3) of setup 1.

As for taking the measured signal strength values of the reference modules as thresholds: The minimum value of T1-R1 was -75 dBm and the maximum value of T1-R2 was -73 dBm. Assuming that we take the value of R1 as dynamically changing upper threshold and R2 as dynamically changing lower threshold, it would have been problematic if these values were read continuously since the lower threshold was at times higher than the upper threshold. However, there was no entry of R1 measuring the value -75 dBm and R2 measuring the value -73 dBm at the same time in the recorded data.

For the second test run, the minimum value of R1 was -77 dBm and the maximum value of R2 was -83 dBm. Looking at the data, there was no overlap of the values from R1 and R2 so taking the values from R1 as upper threshold and the values from R2 as lower threshold seemed unproblematic. It is remarkable that the signal from T2-R2 is considerably lower than the signal from T1-R2. This can be explained by a slight correction of the module placement after test run 1. The minimum value of R1 (-74 dBm) in test run 3 and the maximum value of R2 (-83 dBm) do not overlap either and therefore can be used as upper threshold and lower threshold respectively.

The mean values for T1 to T3 were taken as initial thresholds and were then adjusted with the averaged difference between the moving average and the estimated Kalman value of the respective test runs.

Table 7.6: Summary of all correlations, means, standard deviations and calculated Path Loss Exponents for each module and test run.

Setup 1 Test run 2 (T2)	**Raw**	**Moving average**	**Kalman**
R1 and R2	0.33	0.32	0.37
R2 and S1	-0.25	-0.12	-0.27
R1 and S1	0.08	0.36	0.16

Setup 1 Test run 3 (T3)	**Raw**	**Moving average**	**Kalman**
R1 and R2	0.07	0.75	0.17
R2 and S1	-0.12	-0.83	-0.15
R1 and S1	-0.18	-0.64	-0.19

Test run 1 (T1)	**R1**	**R2**	**S1**
Mean (dBm)	-71.84	-77.92	-79.17
Standard deviation	0.49	1.17	1.28
PLE	1.54	1.46	2.74

Test run 2 (T2)	**R1**	**R2**	**S1**
Mean (dBm)	-75.42	-92.90	-81.09
Standard deviation	0.71	1.67	0.72
PLE	2.65	3.59	3.26

Test run 3 (T3)	**R1**	**R2**	**S1**
Mean (dBm)	-71.09	-90.06	-91.71
Standard deviation	0.47	2.11	6.59
PLE	1.3	3.18	5.68

Table 7.6 shows all the mean and standard deviation values of the test runs with the Path Loss Exponents describing how people, shadowing, multipath effects and other influences led to a decrease in signal strength during the tests. A person moving the tripod with the module S1 explains why the Path Loss Exponent value was so surprisingly high at T3-S1.

A summary of the amount of threshold adjustments in all three test runs:

- T1: 4459 adjustments out of 9900 signal values
- T2: 264 adjustments out of 670 signal values
- T3: 1078 adjustments out of 26000 signal values

The results from table 7.5 show only positive correlations for the signal measurements where S1 is placed underneath R1. This suggests that the same could happen when S1 was placed underneath R1 in setup 2 and 3. Also, this indicates that the possibility of detecting a correlation when the sender module is moving increases if more reference modules are placed around the anchor. These cases need to be examined in future work.

The first hypothesis can be proven with all test runs for setup 1 (see figure 7.43). In the first two graphs, fluctuations of the signal strengths can be seen at the beginning when people were still in the office. Then the signal stabilizes while on the third graph, towards the end, people were entering the office and moving the tripod (S1). The second hypothesis can be proven with the test runs T1 and T2 (the correlation coefficients for raw signals as well as filtered signals are positive). The third hypothesis can be proven with all test runs since none of the adjusted thresholds overlapped during the experiments. For the first test run, the signal peak in the middle was recorded on both modules, R1 and S1, and the correlation was positive at that point which caused the threshold adjustment. For the third test run, the correlation at the end was not positive for both modules. Therefore, the threshold was not adjusted for the remaining test run.

For now, the only adjustment made to the threshold was to either add or subtract the difference of the moving average and the filtered signal. Adjustments were only made if the standard deviations crossed a certain value which was static in most cases (0.5).

Furthermore, an initial static value has to be measured and inserted into the current system. This is done by taking the average of a measurement which usually contains at least 500 signal values. Instead of taking a static value (the mean), the live signal value of R1 could be used. Considering the data from test run 1 and 2, this would work fine as both signal values from R1 and S1 would always be apart with sufficient space between each other. Only the third test run would prove to be problematic since both adjusted and filtered values would converge and be apart for only 2.5 dBm.

A more thorough examination of the correlation between the modules at different locations and various test environments has to be done to specify if the threshold adjustment would also work under difficult conditions.

The Path Loss Exponent values in table 7.6 were similar for the first and second test run while the third test included higher values due to changes in the environment and the movement of S1 itself. In addition to the factors in our proposed method, a change in the Path Loss Exponent could also be included in the query to make the system more responsive. The current signal strength of R1 could be used as a reference signal strength and R2 could be measured for the expected signal strength at the known distance

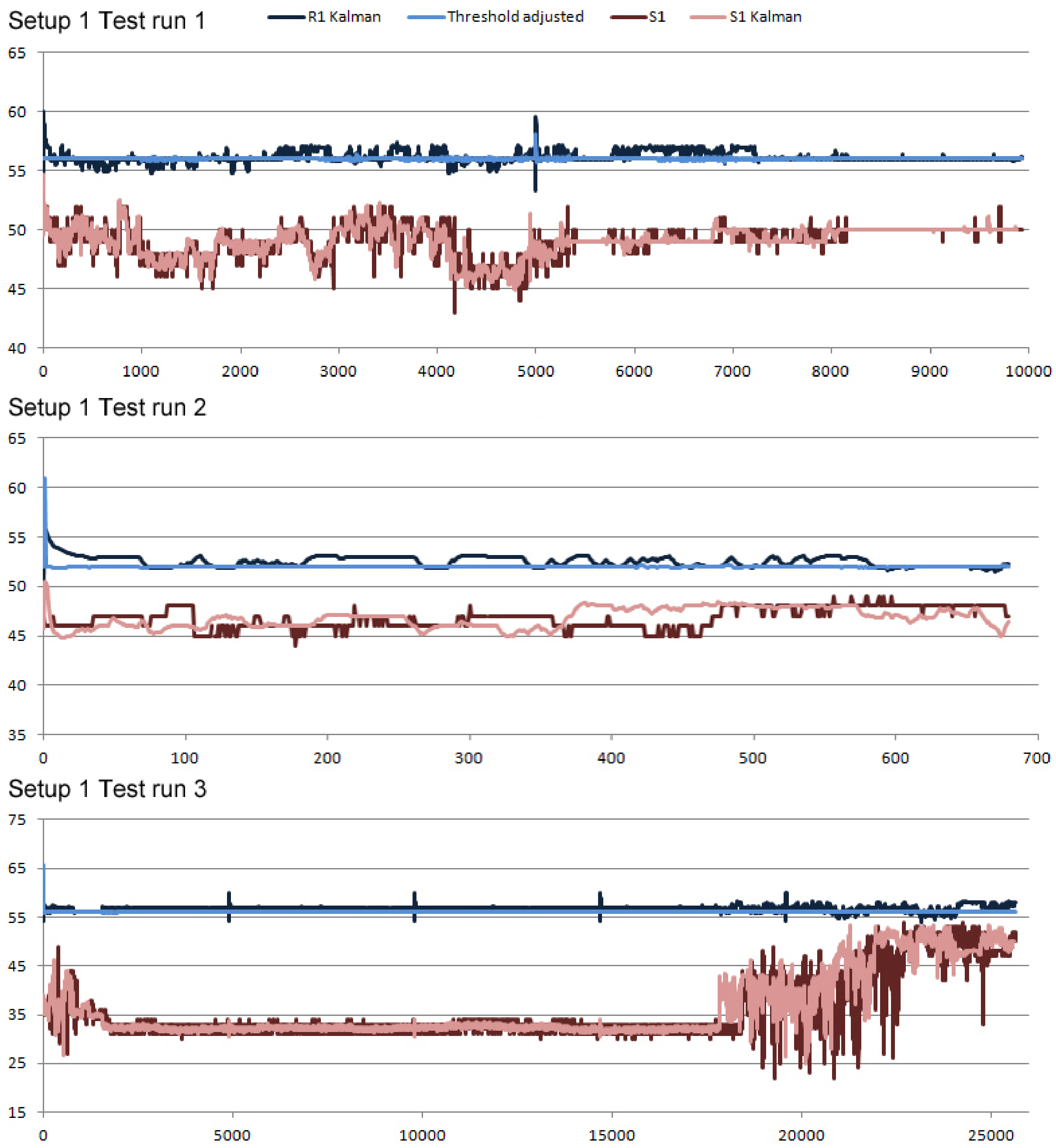


Figure 7.43: The results from each test run visualized with the adjusted threshold drawn in light blue. The raw signal strength values were recorded with an offset of +128 dBm. The values seen in the figure are the filtered/adjusted ones. An adjustment of the threshold can be seen in the first test run at time stamp 5000.

d to calculate the PLE. The correlations between R1 and R2 were not significantly high in our tests but this needs to be examined in further experiments with the modules placed at various positions. An example of including the updated PLE value when calculating the user's position can be seen in [GPWZ14].

Overall, the results suggest that the location tracking system would react better to fluctuations compared to a system without any adjustments but this has to be investigated more thoroughly.

8 Applications

This chapter presents three use cases and applications where the developed BLE location tracking system is being used. Some of these are for improving the user experience when working with the mobile device and others for expanding the system with additional features. Due to time constraints, only the first application was evaluated and tested. The other two are only described still with all their specifications, requirements and issues. In the following, a short summary is given for the upcoming sections:

Section 8.1. Tracking people and other devices
While we only discussed tracking the embedded tag in the case of the mobile device, here, we use the BLE tags to track people and other medical devices such as C-arms and OR table accessories. Tests are carried out with off-the-shelf BLE tags and the results are presented.

Section 8.2. Tag to unlock mobile device
The mobile device detects nearby users with tags and supports them, for example by automatically logging them in.

Section 8.3. Dynamic screens depending on the user's position
Depending on the user's position, the screen on the mobile device should change the arrangement of displayed objects.

8.1 Tracking people and other devices

The content and results of this section were published at the IEEE Healthcom 2015 conference in Boston, USA [HKOS15]. Some parts of this section are taken directly from this paper.

For our developed BLE location tracking system, the OBS421 modules by connectBlue were used as anchors. These modules can, when an inquiry is sent, detect any arbitrary tag which supports the Bluetooth Low Energy 4.0 specifications. So instead of just tracking tags for mobile devices, the follow up application was to track people and other medical devices with separate, mobile BLE tags. We evaluated a few stand-alone, consumer products which could be used as key chains or come with an attachable back (in form of stickers). These tags could be used in a procedure called "team time-out", which usually takes place before the surgery starts (see chapter 4.2). If the medical staff members were to wear a tag, an installed location tracking system would always check if the team was complete or not. The locations of the members could be logged during surgery and in addition, the system would automatically notify absent members if they were needed.

Figure 8.1: From left to right: (1) the *Conrad Electronic SE* Bluetooth Low Energy key chain, (2) the OLP425-tag from the company *connectBlue* and (3) the TI CC2650 SensorTag from *Texas Instruments*.

8.1.1 Material and methods

Figure 8.1 shows the different tags we evaluated. In our first experiment, we chose to test the system with tags from the company *Conrad Electronic SE* (Hirschau, Germany). They are offering key chains with built-in BLE modules and a battery holder for CR2025 batteries. When the anchor scans for tags, we receive parameters such as the MAC address of the tag (which serves as their unique identification) and its measured signal strength value. All the parameters are forwarded to the location engine where, depending on the signal strength, the detected tags can be considered far away (low signal strength value) or nearby (higher signal strength value).

For testing purposes, we installed anchors in the two test rooms (see figure 8.2) and created three "virtual" rooms for the location engine: no room, room 1 and room 2. All the data was logged into a database on the location engine computer. There were two test users wearing BLE tags for three days. In the test area, users were occasionally moving from room 1 to room 2. Figure 8.2 shows how the test environment looks like and which rooms/corridors are adjacent. The layout of the rooms and the positions of the users' workplaces had a significant impact on the final results.

Looking at figure 8.2, the border of the green area represents the upper threshold for entering the room and if the user is located somewhere in the yellow area, chances are high that the signal strength value will fall below the lower threshold (depicted as the border of the yellow circle). Then, the system removes the user from the room he is currently registered in.

Currently, the location engine uses a moving average of the last 5 signal strength values to filter and to smooth out the fluctuating signal. The thresholds for the location tracking system in both rooms were calibrated as follows:

- Upper threshold for entering: -93 dBm
- Lower threshold for exiting: -105 dBm

The Conrad Electronic SE BLE tags are set to send out advertisements every 25 milliseconds and when inactive (not moving) for 180 seconds, they switch into a sleep mode where they stop advertising. The tags consume little to no power when they enter the sleep mode. The range of these tags is specified to be 15 meters and the coin cell battery lasts 3 months on average.

As mentioned above, the tags go inactive if the built-in motion sensor detects that they are stationary.

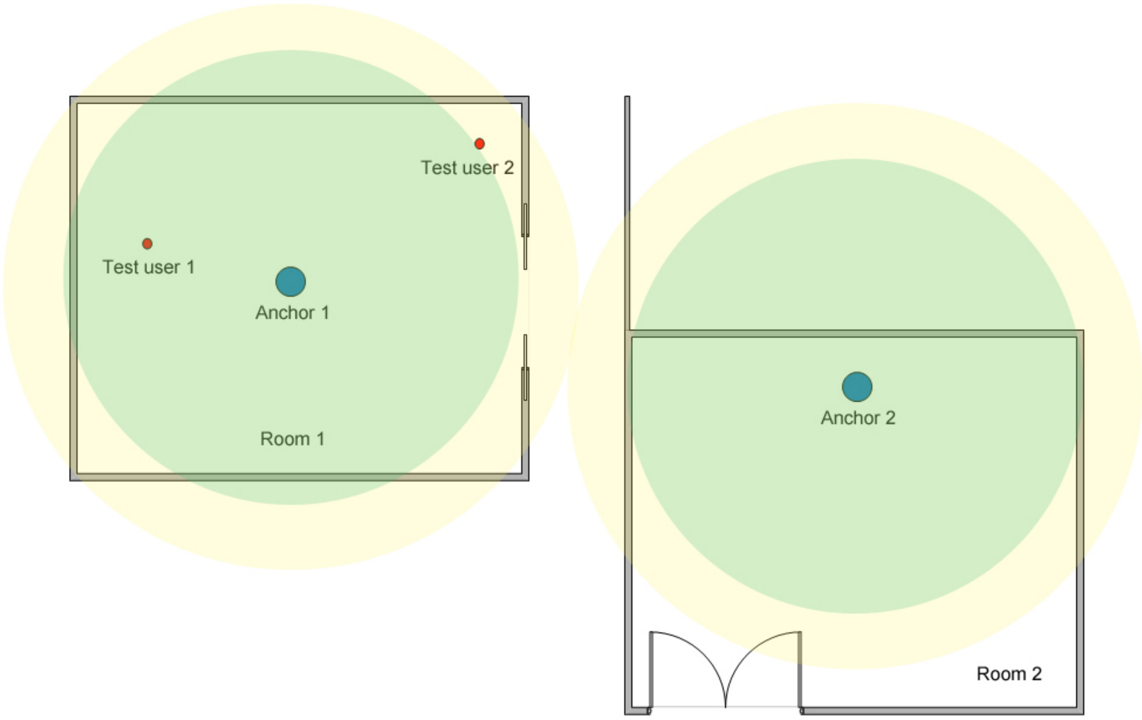


Figure 8.2: The setup from the top view with test user 1 and 2 working mostly in room 1. The borders of the yellow and green circles around the anchors represent the areas where the tags can enter or leave a room.

This is fundamentally different from the tags used in the mobile devices as they continue to send out advertisements in a periodic interval even when not moving and staying in a fixed position. With the Conrad Electronic SE BLE tags, the location engine has to compensate time spans where the module might be sleeping because of inactivity. We do this by waiting t minutes to look if a tag has been inactive and we have not received any new advertisements from it. In this case, the location engine removes the tag from its current room and puts it into the virtual "no room". For our experiment, we set t to 5 minutes. This value was stored in the database along with other values for mobile devices (10 seconds) and tags for medical equipment (also 5 minutes). Another issue was that when users were leaving room 1, it was possible that their tags were registered in room 2 due to the placement of the anchors in both rooms and the small distance between them (the signal attenuation through the corridor and the walls of the rooms was not high enough).

8.1.2 Results

The accumulated results can be seen in table 8.1. The columns are interpreted as follows:

- **#Time:** The amount of time, where measurements were made.
- **%Time:** The percentage of the total time where the measured and actual locations corresponded.
- **#Message:** The amount of messages recorded during the tests.
- **%Message:** The percentage of all the messages with correctly identified rooms.

Table 8.1: The results for both test users over the course of three days.

Test user	#Time	%Time	#Message	%Message
1	23h 21m	97%	229	63%
2	19h 48m	95%	257	55%

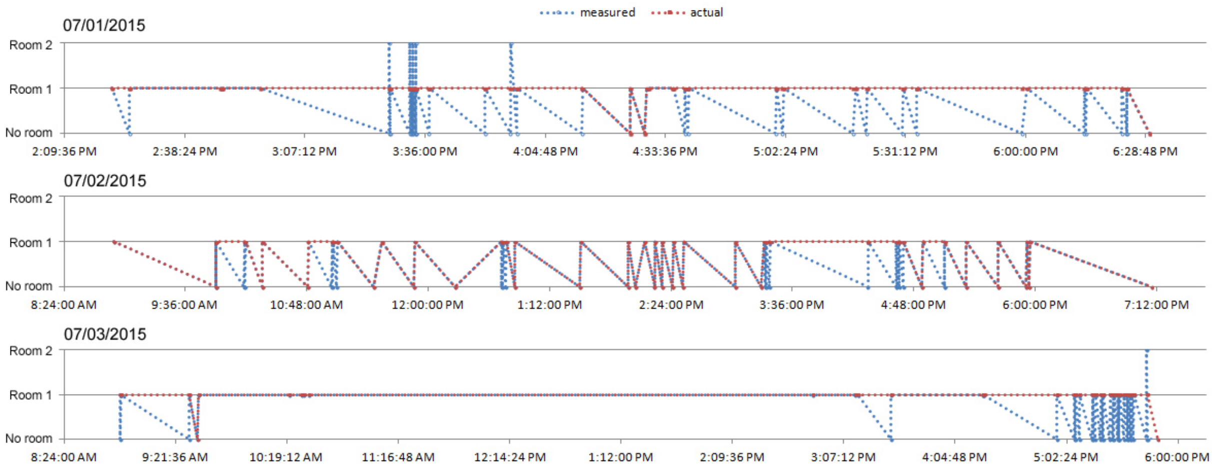


Figure 8.3: Measured data from test user 1 during three days (07/01 to 07/03). The blue dotted line depicts the rooms where the tag was detected while the red dotted line represents the actual room the test user was in. The y-axis is arranged as follows: 0 = no room; 1 = room 1; 2 = room 2. The x-axis represents the time, where measurements of the tag were made and saved in the database.

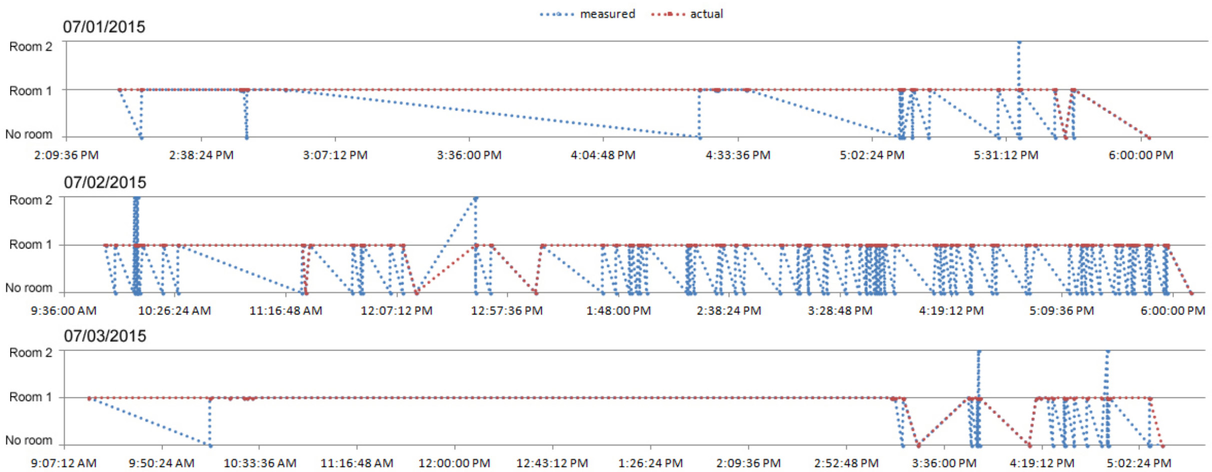


Figure 8.4: Measured data from test user 2 during three days (07/01 to 07/03).

For test user 1, a visual representation of all the test runs is given in figure 8.3, with time stamps on the x-axis and the rooms on the y-axis. Figure 8.4 shows the results for test user 2 for the same days. When looking at the data closely, it can be observed that the blue dotted line (the measured and calculated location) fluctuates quite a lot and differs from the actual position in many places for both users (especially for test user 2 on the second day). This can be explained with the locations of both test users' workplaces. Unlike test user 1, the second test user was sitting and working in close vicinity to room 2. The location as well as reflections and multipath effects caused the tag to leave room 1 quite often. Still, looking at the total test duration and the durations in which the users were registered in the right rooms, the results were satisfactory. Test user 1 was 97% of the total time in the correct room while the percentage for test user 2 was 95%.

When analyzing the results for the durations (see table 8.2), we can see that whenever tags were detected correctly in their rooms, they stayed longer in these than in the respective "wrong" rooms. While the true positive duration of test user 1 was at the maximum 4 hours and 20 minutes, the false positive duration was at one time 27 minutes. The location tracking system assumed that the tag of user 1 was in "no room" while it actually was in room 1. In this case, the module stopped advertising for 27 minutes because of inactivity. For user 2, the maximum duration where he was detected in the correct room was 4 hours 42 minutes while the false positive duration was 5 minutes and 34 seconds. Most of the false positives either happened because the tags fell "asleep" or they passed by room 2 when walking outside through the corridor. Because of the weak disjunction between the two rooms, passing by room 2 was sufficient to be registered for the respective room. On average, test user 1 was tracked for 6 minutes 43 seconds in the correct room while the value was 8 minutes 10 seconds for user 2. When the tags were detected in the wrong rooms, the average durations were 1 minute 50 seconds and 30 seconds respectively.

Table 8.2: Maximum and minimum of the durations when tags were detected in correct/incorrect rooms (in hh:mm:ss).

Test user	**Max. ✓**	**Min. ✓**	**Max. ✗**	**Min. ✗**
1	04:20:35	00:00:01	00:27:25	00:00:01
2	04:42:06	00:00:06	00:05:34	00:00:01

8.1.3 Discussion

Looking at the setup and the results, it is not surprising to see that test user 1 got a better percentage of correctly matched rooms than user 2. With the workplace of test user 2 being a borderline case in terms of its position in room 1, this outcome was expected. We already mentioned that the location engine worked with a time-out of 5 minutes to see if any of the tags worn by users had been inactive or not. If they were not detected any longer, they would be removed from their current rooms. We also had to subtract 5 minutes from all the data points in the figures where the tags left the rooms to acquire the correct times. All the instances where a tag supposedly left a room included an offset of +5 minutes. Entering the rooms was still measured and displayed with a latency of maximum 10 seconds.

Since these rooms were separated through thin walls and to some extent, did not offer a ceiling (with no signal attenuation happening), reflections and multipath effects are a valid explanation for the constant room changes for both users. To prevent such phenomena (and that is applicable to all radio-based technologies), it is recommended to deploy and install location tracking systems in environments which are controlled and built/designed for it. If the space between the two test rooms had been bigger, the lower threshold of room 1 could have been decreased to cover more of the area near the walls. This would have made the system more reliable when detecting the tags in the rooms. The guidelines and recommendations described in chapter 7.5 would have reduced the false positive rates.

Further research and tests regarding the other tags and their performance need to be done. Are they going into sleep mode faster than the Conrad Electronic SE BLE tag? It is possible to program and change the advertisement interval of the OLP425 tag? It would be interesting to remove the sleep mode altogether and instead of stopping the advertisements when being stationary, send them out in a lower frequency than normally. In addition to the different tags, the location engine has to be adjusted for more thorough tests. Is $t = 5$ a good value for the time-out counter of the tags? If the tags can be modified to continuously send advertisements, then the time-out counter can be set to a relatively low value such as 30 seconds. This would also make the tracking results more reactive and precise since the system would know with a maximum delay of 30 seconds, if tags have really left the vicinity of an anchor (instead of 5 minutes).

Moreover, we could also apply different algorithms to compute the position. A Kalman filter could make use of the measured signal strength values and the motion data of the tags to compute a new position. But since we do not establish connections between anchors and tags, this would require the tags to also advertise the status of their motion sensors which in turn could be read by any anchor.

8.2 Tag to unlock mobile device

8.2.1 General

Tags or badges are already used to lock/unlock doors or to find misplaced items such as keys. Currently, a user needs to login to the OR integration system TruConnect through the mobile device to control other medical devices. The application for TruConnect, when started on the mobile device, displays a list of users on a start screen. The user has to select his name from that list and then type in a 4-digit password to confirm (see figure 8.5).

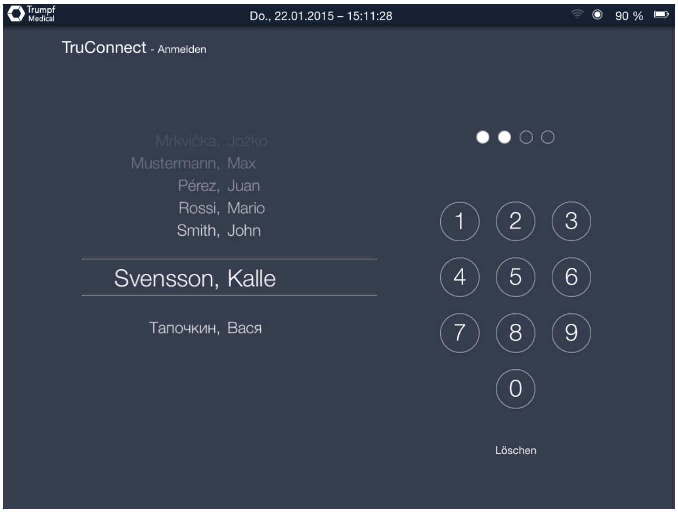


Figure 8.5: The start screen of the "TruConnect" application on the mobile device with the list of available users on the left and a keypad for entering a pin on the right. Image courtesy of Trumpf Medical.

Looking for the correct user name and entering his password can be time-consuming in case the list is very long and contains many names or the user could make errors when other users with similar names exist. Tags worn by the users can be used to speed up the login-procedure. The mobile device scans for tags in its surrounding and displays only the tags within a specified range. This leads to a shorter list of names to display. An additional input source could be used to replace the 4-digit password. In the following, some examples are listed:

- Voice sample from the user to compare to existing samples.
- A button on the tag which the user has to press to login.
- A fingerprint sensor on the mobile device to scan the user's fingerprint.
- The camera of the mobile device to identify the user by means of facial recognition.

An alternative would be to let the user login without doing any extra input. Having these input mechanisms would increase the security. But then the question arises what happens when multiple users are detected near the mobile device at the same time.

8.2.2 Issues to consider

Duration of scans for tags in the vicinity

The duration of scans has to be well-balanced for a satisfying user experience and also less power consumption for the mobile device. Once the user comes into a defined range of the mobile device, it should not take longer than 5 seconds to display his name in the list (the time is derived from [SSHR08]). The internal Bluetooth module of the mobile device scans the environment in a specific time interval and stores all the visible tags in a list (see figure 8.6). Since the range is usually greater than a few meters for Bluetooth, the tags are in most cases detected quite early. When users with their tags come near the scanning mobile device, the signal strength values of their tags increase. The signal strengths of all the detected tags are updated every 5 seconds as long as they stay in range. Once they leave the range, the modules are removed from the list. If the signal strength value of one module exceeds a certain threshold, it is eventually displayed in the login screen of the mobile device.

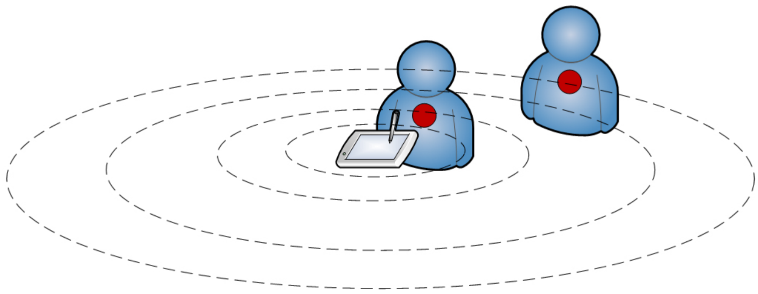


Figure 8.6: Depending on the proximity to the mobile device, the user (blue) associated with the tag (red) is included in the list of users authorized to log in. The dotted lines depict different signal strength levels, which are high near the mobile device and low when moving farther away.

Advertisement interval of the badges/tags

We look at the specifications of the OLP425 module from connectBlue rather than the Conrad Electronic SE tag from the previous section to have a comparison between these two. The interval in which the OLP425 tags send out their advertisements is set to 1 second. An accelerometer is mounted on the module to detect if it is moving or not. If the tag stays stationary for more than 30 seconds, the module transitions into a sleep-mode where it stops sending the periodic advertisements (similar to the Conrad Electronic SE tag). A slight nudge or small vibrations make the tag continue advertising again. There are two cases where the mobile device would not get any values from a tag:

1. When the tag's battery is dead.
2. When the tag has not moved for more than 30 seconds.

There are two options on how the battery status can be provided: 1. establish a connection from the mobile device to the tag to read the battery status or 2. attach the battery status to every advertisement packet sent from the tag so that the mobile device can pick it up through the inquiries/scans.
For case 2, the mobile device would again receive advertisements when the tag is moved. When the tag is resting, it does not send out any advertisements. Similar to the previous application from 8.1, a time out

counter for each tag is required to get information on when to remove it from the list. Otherwise, the tags would be removed immediately after going into a sleep-mode which consequently might have a negative effect on the user experience. When a tag is not detected anymore, the last received signal strength value is saved on the mobile device. This value is deleted after a certain period of time t (the time out value) to ensure that only tags which recently sent out advertisements are included. Tags which ran out of battery and stopped advertising would be then removed after t and subsequently, the user would be logged out automatically.

Range

At what range does the mobile device begin to display the user name in its login list? As already mentioned, a static threshold value has to be set for each mobile device and once a tag surpasses that value, it is known to be in a certain defined range. Taking equation 3.2, we could define 30 centimeters as an acceptable range (d) where the user with his tag is added to the list of names. That would give us -77 dBm as signal strength threshold ($d_0 = 1$ meter, $P_t = -87.28$ dBm, $\gamma = 2$).

Automatic or manual login/logout

Should a user be logged into a mobile device automatically if no one else was currently logged in? There are two cases where the mobile device has to log out someone or remove his name from the list: if the tag of the user falls below the set threshold (user leaves the vicinity of the mobile device) or the tag is not detected anymore for a time-span t (a timeout value, in seconds). What would be an appropriate value for the time-out? 5, 10 or 15 seconds? Should this value be configurable through the user settings?

These issues are still open and need to be tested with various configurations and user evaluations. This topic is part of the future work and could improve the user experience by actively supporting the user and making certain, repetitive procedures faster and smoother.

8.3 Dynamic screens depending on the user's position

When the user is logged in, he sees a schematic overview of the current OR on his mobile device. This overview contains 2D representations of elements in the real OR such as an OR table, multiple OR lights or monitors. There can be up to 3 OR lights and several monitors in one operating room. When having three lights of the same kind installed in one room, it is difficult to tell them apart. There are subtle difference such as one of the lights having a camera and others having a dummy-module attached to their light heads. In the end, the devices are identified by their position and currently configured settings. For example, a surgeon would tell the nurse to change the light intensity of the left OR light. If the nurse would have the mobile device in her hands, all the lights would be placed on the screen at specific, predefined positions. For the user, the positions would seem arbitrary and most of the time it is difficult to distinguish the lights due to their 2D representations on the screen.

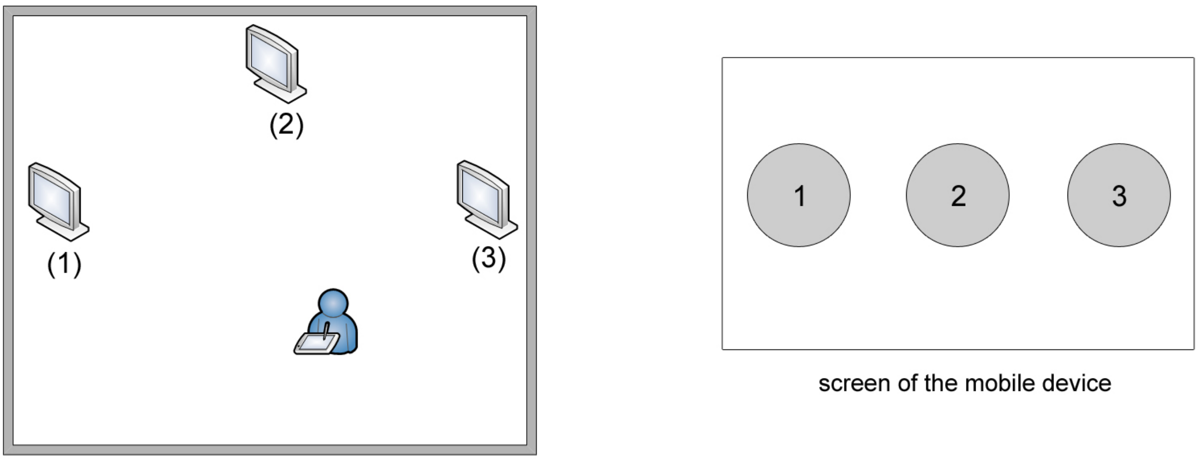


Figure 8.7: On the left: An OR with the user holding the mobile device in his hands, directed to the center of the room. Three similar devices (1)-(3) which can be selected and controlled by the user are placed in the OR. On the right: The screen of the mobile device, which shows an arrangement of the three devices. Depending on where the user is positioned, he should always see the correct order of devices from his point of view to safely select the right one at all times.

We want to dynamically arrange the screen on the mobile device depending on where the user is currently standing in the room. The OR lights should be displayed at their correct positions so that at all times, the user would select the correct device by associating the OR light in the room with its position on the screen. To solve this task, an accurate location tracking system which reaches sub-room level accuracy is needed. The location tracking system would compute the x- and y-coordinates of the tag inside the mobile device and the additional tags mounted on each of the light heads. Then, all the relations between the devices can be calculated and with the assumption that the user always faces the center of the room, the lights on the screen could be sorted and displayed in the correct order. The same use case could be applied to monitors or other devices which are difficult to differentiate (see figure 8.7).

9 Discussion and further work

In the following chapter, some of the previously mentioned issues and topics which are still open and need work will be discussed. Also, several aspects concerning further research will be pointed out.

All in all, it is surprising to see that with a very small budget, a good basis for a radio-based location tracking system can be built. Compared to other products, which cost at least 5 to 10 times more, the self-developed location tracking system fulfills most of the requirements satisfyingly. While the expenses are very low and the infrastructure is easy and simple to set up, the accuracy is currently just sub-par and could be improved to make the system more reliable.

9.1 The developed location tracking system

The tests show us that with our location tracking system, an accuracy of 1 to 3 meters can be achieved. While we set the accuracy to be “room level” in the requirements (see chapter 2.1), we make use of the building structure and walls to get more reliable results. If the location tracking system is installed according to the guidelines specified in chapter 7.5, the accuracy improves and reaches “room level” status. But fulfilling all the requirements is in most cases not possible due to monetary and infrastructural constraints.

Another challenge was to prevent excessive changing or interrupting of the existing workflows in the ORs. We had to make the system intuitive and user-friendly while achieving good tracking results. There were two factors which we assumed the users would do while using the mobile device: 1. take the mobile device and go in the vicinity of the medical device to control and 2. look at the device when the user is changing its settings from the mobile device to get an immediate feedback. The first factor would help us in registering the mobile device in the room since the signal strength measured from the installed anchor would increase. The transition of picking up the device from its docking station, walking towards the medical device, being registered in the room and then controlling it would be seamless. The second factor would help us verify that the user was indeed registered in the correct room, controlling the right medical device. In the manual for TruConnect, we specified that the user had to make sure the mobile device was registered in the right room (see figure 9.1). Also, depending on factors such as where the adjacent rooms are or what material the walls are made of, the “inner area” to get registered could be increased in radius. This would allow the mobile device to get registered faster and more frequent in the room in case it would be randomly removed. This in turn would affect the user experience positively. We had many cases where the tracking system would remove tags too often. In almost all of them, the measured signal was fluctuating and the calibrated thresholds were set too tightly given the conditions and circumstances of the environment.

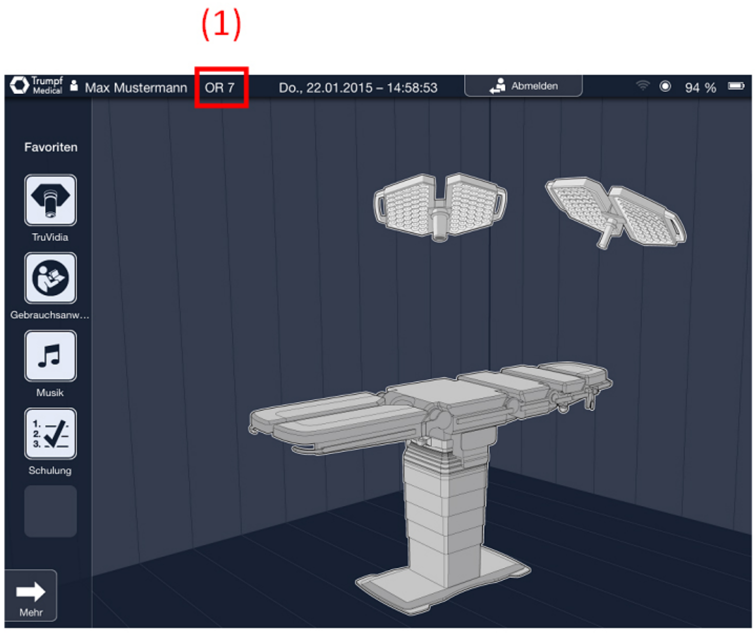


Figure 9.1: Screen of the mobile device which shows an overview of the current OR with all its controllable devices. In the upper left corner, the user name and the room (1), where the mobile device is currently located, are shown. Image courtesy of Trumpf Medical.

In the following, some ideas are presented to improve the existing system.

Fingerprinting with BLE

To test and use fingerprinting with BLE, we have one prerequisite: reduced signal strength fluctuations when measuring and storing the RSSI fingerprints. It is useless to look into fingerprinting if fluctuations in the ± 5 dBm range still happen. One thing we could do to make up for the fluctuations is filtering the signal during measurement (see chapter 6.3 for evaluation of WiFi fingerprinting).

As [BIG08] and [PCL+10] showed, fingerprinting is an alternative to achieve somewhat acceptable results with Bluetooth. One of the disadvantages is that because of building structures, materials and the small range of Bluetooth modules, several anchors have to be placed in a large-scale area so that at all times, at least three can detect a tag. Since walls can be made out of reinforced concrete or material which block signals, positioning of the anchors has to be well considered. Figure 9.2 shows a proposed layout for placing anchors in a hospital in Munich. We place at least three anchors in each of the operating rooms and distribute the rest on the corridors. In rooms such as the washroom, we only mount one anchor on the ceiling and in the offline phase, gather fingerprints with the doors of the room opened and closed to cover all cases.
When more than one anchor per room is utilized for tracking, we could also apply probabilistic approaches (similar to [RMT02]) or Trilateration (see [RASR10] and [Mei14]) for computing the position of a tag.

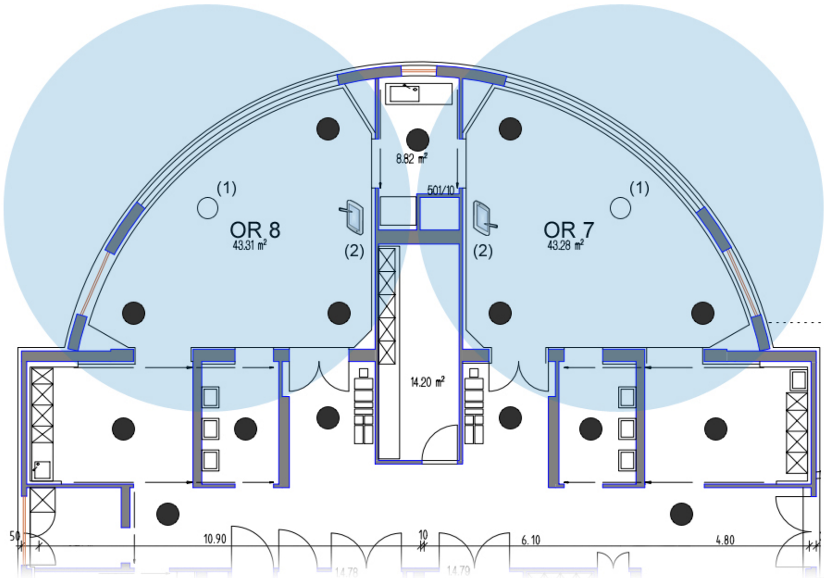


Figure 9.2: The black circles represent additional anchors which have to be placed in the hospital to test the fingerprinting method with BLE.

Orientation of tag and external, circular antennas

In chapter 7.2, we discussed the current placement of the tag with its internal ceramic antenna in the mobile device. Rotating the tag by 90°should bring improvements such as higher signal strength values (increased gain), less reflections and multipath effects due to better alignment of both antennas (anchor and tag) and LOS.

We already discussed that the orientation of the tags has a significant impact on the results. For further tests, an external, circular polarized antenna could be used to see if a more uniform signal propagation led to improved signal strength measurements and less fluctuations.

Motion sensor for tags to save battery life

We introduced two applications in our work which used tags with attached motion sensors, mainly to reduce energy consumption when the tags were not moving. But with the additional sensors, we could fuse the RSSI signal strength and the motion data to estimate the user's position more reliably, for instance with a Kalman filter. [BL13] and [YZKP15] already worked successfully on such a system as the inclusion of IMUs improved their results significantly.

Firmware modification

As described in chapter 7.2, the firmware of the Bluetooth anchor modules could be modified to scan only one designated BLE channel where the tags would be advertising (see figure 9.3). But this change would require a new certification and license for the module as modifications regarding the Bluetooth specification are not covered by the vendor.

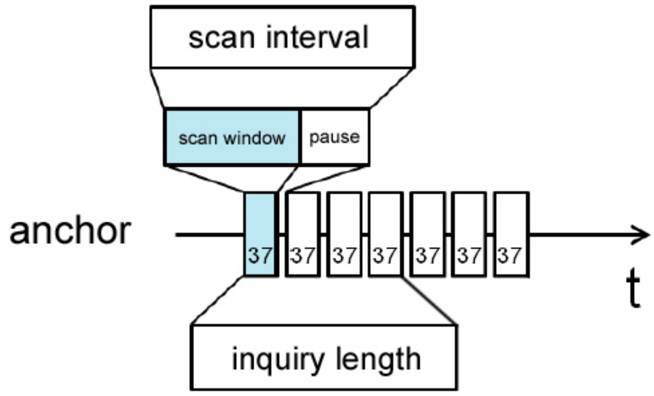


Figure 9.3: Usually, with the default firmware and the specifications of Bluetooth, the modules scan all three advertising channels for tags. Since we configured the tags to only send on one advertising channel (such as channel 37), we want to dismiss the other two and only scan on that one.

Combination with infrared

The OR tables by Trumpf Medical use the technologies infrared and 802.15.4 ZigBee to communicate with other components. These technologies could be incorporated into the BLE location tracking system. The OR table sends out infrared pulses intended for the wireless table remote control or the "Table Access Module" (TAM) in a periodic interval. The remote control is paired manually with an OR table t_1. If the remote control detects the infrared signals of t_1, it knows that the table is in its vicinity. Only then, controls are enabled. Messages to move the table are then sent over an established ZigBee connection. The TAM is installed in each room and works similar to the wireless remote control. The difference is that the TAM is connected to the TruConnect server which can read or send commands through the TAM to the OR table the same way the remote control does.

Our idea was to modify the BLE tags with infrared transceivers so that they could read infrared pulses emitted by an OR table or a TAM in their vicinity. The table or the TAM would send out messages with a room ID through infrared. Assume, that we have TAMs installed in OR 1 and OR 2. In each room, the TAM could send out a specific ID from its mounted location. Once the infrared transceiver receives the ID, it is placed into the advertisement message of the BLE tag. Since the advertisement is sent out periodically, the anchor would detect the tag and upon reading the advertisement message, the (room) ID of the TAM in the tag's vicinity would be known.

A problem arises when a door connecting two ORs is opened or stays open with two OR tables or TAMs being installed in each of the rooms. In this case, it could possibly happen that the BLE tag picks up infrared signals from both rooms through reflections. It is difficult to have both components, the OR table and the TAM, send their infrared signals in a specific direction (ideally, vertically and just covering a small area of the room). One very interesting approach would be to mount another module consisting of infrared transceivers on the ceiling (next to the location tracking anchor). The infrared module needs to be built so that it only covers the room radially and in a uniform shape. This could be achieved by arranging several infrared transceivers in a circle. Additionally, the signal strengths of the infrared pulses need to be adjusted and if necessary and depending on the height of the room, decreased as reflections are bound to happen.

(1) (2) (3)

Figure 9.4: (1) shows a BLE tag with a soldered infrared transceiver on its input pins. (2) shows the TAM which uses infrared and ZigBee to communicate with Trumpf Medical's OR tables. (3) represents the bottom part of an OR table with built-in infrared LEDs. These LEDs send out pulses which include data for communication with a table remote control or a TAM.

Dynamic threshold adjustment

We determined that in case a reference module r was installed on the ceiling, an anchor would detect fluctuations for r and a tag t, if t would be positioned right underneath r. This gave us the idea to put more reference modules on the ceiling to have a grid and detect fluctuations anywhere no matter where t would be (see figure 9.5). The algorithm for automatically adjusting the threshold could be modified as well. For now, the threshold is adjusted by the following equation:

$$y = y + \frac{(m_1 - f(x_1)) + (m_2 - f(x_2))}{2} \tag{9.1}$$

As already mentioned, another method would be to incorporate the PLE in the algorithm to improve responsiveness in terms of environmental changes.

Automatic test procedure

In chapter 7.6, an automatic procedure for testing arbitrary location tracking systems was presented. Some of the issues to follow up have already been described in that chapter: evaluate and use another robot with stronger motors and replace the current optical tracking system with a cheaper one. It would be sufficient if the new optical tracking system provided room level accuracy in centimeters. This could be supported by using active markers attached to the robot, which would also increase the detection range.

9.2 Further work

Tests with ultra-wide band

The tags from the company Zigpos (see section 6.2) came equipped with ultra-wide band hardware. We only evaluated the system with the modules being configured to ZigBee. Ultra-wide band was not supported by the software/internal firmware of the tags when we received the development kit. But the

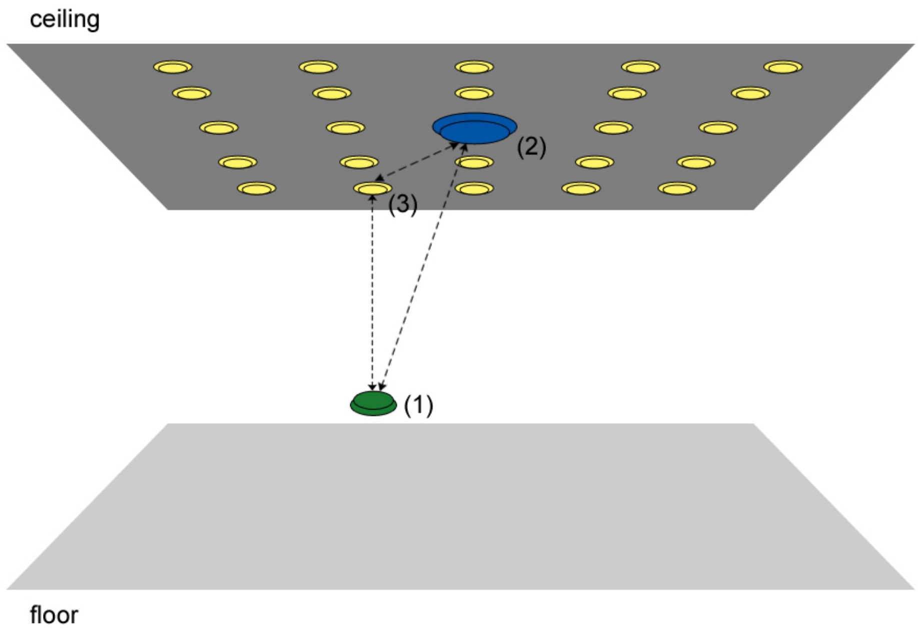


Figure 9.5: This figure shows a grid of tags (3) on the ceiling with an anchor (2) mounted in the center of the room. The anchor would measure the signal strength of the tag in the mobile device (1) and of all the reference tags on the ceiling. We assume that if fluctuations were to happen in the region of (1), they would be detected by the reference tag at (3).

providers announced that with just a firmware update, the tags could also be configured to be used in an ultra-wide band location tracking system. This implies that we also need compatible ultra-wide band anchors. Ultra-wide band, as mentioned in the previous chapters, is the most promising, modern technology to use for accurate and reliable location tracking. That is why tests with these modules would have been very interesting and informative. Can accuracies in the centimeter-range be really achieved with an ultra-wide band system? Another vendor known to be providing development kits for ultra-wide band modules is decaWave. UWB can be used in applications such as home networking, surveillance and Wireless Body Area Networks (WBAN) due to its accuracy and robustness [ABS+05].

The only downside of ultra-wide band is that the modules are still expensive and difficult to acquire. WiFi or Bluetooth modules can be bought at any well-sorted electronics retailer.

Other technologies

The idea by [JHP11] to use LED lamps for location tracking could also be applied to our use case since we have two types of lamps in each OR: the room lights and the OR lights. We could have them, through hardware modifications, emit a room-specific ID which is then caught by an ambient light sensor or an optical camera on the mobile device.

Also, ZigBee delivered very good results in our evaluations but compared to BLE, it was more expensive. The difference in price was so high that we compromised with Bluetooth's RSSI problems and other disadvantages. But ZigBee would be a viable option in the future next to ultra-wide band. The only issue we have to evaluate more thoroughly is if other devices working in the same 2.4 GHz band would be interfering with the signals of the ZigBee modules. Since we used channels specific for BLE, such problems would not occur with our current system.

In recent years, “Ultra Low Energy” (also known as ULE) caught the attention of the wireless and RTLS community. ULE is based on “DECT” (Digital Enhanced Cordless Telecommunications), which is used in cordless telephones around the world. DECT was established in 1993 and operates in the reserved 1.9 GHz frequency band. For applications such as home automation and security, a new specification for low power devices was introduced. ULE offers long range (100-300 meters), encryption, less interference problems and already integrated services such as RSSI readings. Also, according to [All], batteries in ULE devices last up to 4-10 years depending on the interval in which the devices communicate with a base station/anchor. Different from the usual maximum of 10 seconds in BLE, with ULE, it is possible to have longer pauses between two “advertisements”. The technology uses the frequencies from 1870 to 1930 MHz and although prices for modules seem moderate, it is difficult to get a hold of ULE modules at the moment. Taking all these points into consideration, ULE seems to be a very suitable technology for location tracking. However, further research has yet to determine if there are any problems with medical devices operating on similar frequencies.

10 Conclusion

Real time locating systems for use cases such as tracking equipment or patients remain a very exciting field with a lot of potential for improvements in factors such as accuracy or energy consumption. First and foremost, an RTLS tracks items and provides location as well as context-related data for people. Also, similar use cases, such as staff or patient tracking, support the workflow and help increase the patient throughput. Using an RTLS in the hospital brings advantages and additionally, in most cases, a guaranteed and immediate ROI. However, depending on the application, the RTLS has to be chosen carefully and configured accordingly to fit the customer's requirements. It is also important that every involved party has the same understanding and expectation on what an RTLS is able to achieve and what not. There are clear limits and often, a customized RTLS only works well in one use case but delivers poor results in others.

The task for this thesis was to evaluate technologies, choose one and develop a location tracking system for the use in the OR. The location tracking system was made part of an OR integration system called TruConnect where medical staff would control sensitive medical devices such as the OR table with a mobile device. To make sure that controls are only enabled in authorized rooms, the mobile devices had to be tracked. The user would only be allowed to control devices in the respective room where he is being tracked. A tag in the mobile device sends out advertisements which are detected by anchors. The anchors can measure the tag's signal strength and determine its proximity. If the mobile device would move into a certain region near the anchor, it would be registered and the user would then "enter" the room. If the user moves away from the anchor, the location tracking system would recognize the decreasing signal and consequently remove the mobile device from the previously registered room.

In the beginning, we determined conditions and requirements of the location tracking technology, which were essential for the usage in the OR. Building material, the location of other rooms as well as the dimensions of the room had to be considered. We then chose criteria such as accuracy, update-rate or price, according to which we could rate optical, radio-based and acoustic technologies. Through research and evaluation, we narrowed the focus to the type of technology most appropriate to our use case: radio-based. This had several reasons such as range, price or scalability which were all in favor for radio-based technologies. We evaluated most of the radio-based technologies such as RFID, WiFi or ZigBee and then went on to develop the location tracking system with Bluetooth (Low Energy). Bluetooth provided the best price-performance ratio and fulfilled most of the requirements we determined in the beginning. But we also had to deal with its issues such as fluctuating signals (common for radio-based technologies). The development process was documented, including the evaluation of hardware and software, calibration, installation, testing, issues and improvements. A location engine was developed to compute positions of BLE tags from the measured data of the anchors used in the proximity-based system. Two calibration procedures were developed and detailed recommendations were given on how to install the anchors for optimal results. We further investigated some issues of the system and succeeded in solving most of them.

These solutions already made the system more stable but there is still a lot of room for improvements.

Three applications were presented to further enhance the location tracking system. One feature would improve the user experience and with tags worn by staff members, make the login procedure easier and faster. Another improvement would be the following: The screen of the mobile device would adapt to the position of the user and the arrangement of the medical devices in the room. Since we were only tracking tags inside mobile devices, the third application would be to evaluate any arbitrary BLE tags to track assets or people (staff members or patients) with the existing location tracking system. The future prospect would be to have improvements for the workflow and therefore, an increased patient throughput and a better user experience with the tracking system. But to reach that point, the existing problems have to be solved first and the raised issues need to be dealt with. Although others have already worked on such solutions, they have to be applied to our system and tested thoroughly to see any improvements and consequences. The most ideal solution would be to have a combination of two technologies so that they could eliminate each others flaws.

This thesis contains all the steps for developing a location tracking system from scratch. It is also an accumulation of all the things which happened during my last 4 years at Trumpf Medical. Looking back at the development of the system, the tests as well as all the trade fairs, my wish of gaining experience (in the industry) was fulfilled and for that, I am truly grateful.

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