T.C.
ALTINBAŞ UNIVERSITY
Institute of Graduate Studies
Information Technologies

EVOLUTION OF INDOOR LOCALIZATION USING SEREVAL TECHNOLOGIES

TAREEF KHASHEA DAWOOD

Master Thesis

Supervisor
Asst. Prof. Dr. Sefer KURNAZ

Istanbul, 2021

EVOLUTION OF INDOOR LOCALIZATION USING SEVERAL TECHNOLOGIES

by

Tareef Khashea Dawood

Information Technologies

Submitted to the Institute of Graduate Studies in partial fulfillment of the requirements for the degree of Master of Science

ALTINBAŞ UNIVERSITY

2021

The thesis titled “Evolution of Indoor Localization Using Several Technologies “prepared and presented by “Tareef Khashea Dawood “was accepted as Master of Science Thesis in Information Technologies.

Asst. Prof. Dr. Sefer Kurnaz

Supervisor

Thesis Defense Jury Members:

Asst.Prof.Dr. Sefer KURNAZ	School of Engineering and Natural Sciences, Altınbaş University	
Prof. Dr. Osman UCAN	School of Engineering and Natural Sciences, Altınbaş University	
Prof. Dr. Mesut RAZBONYALI	School of Engineering, Istanbul Maltepe University	

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Approval Date of Institute of Graduate Studies

____/____/____

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Tareef Khashea Dawood

DEDICATION

First I would like to Allah Almighty for the power of mind, health, strength, guidance knowledge and skills to complete this study. This thesis is wholeheartedly dedicated to my beloved father, who have been my source of inspiration, he tells me that" every success in your life will be best gift for me". To my mother, who have been supporting me with the kind and purelove.

ACKNOWLEDGEMENTS

I would like to thank my supervisor professor Asst.Prof. Dr. Sefer Kurnaz for all support during my study. It’s great pleasure to express my deepest gratitude to my friends who have shared with me best moments during my study for the Master degree.

ABSTRACT

EVOLUTION OF INDOOR LOCALIZATION USING SEVERAL TECHNOLOGIES

DAWOOD,Tareef Khashea Dawood,

M.Sc, Information Technologies, Altınbaş University,

Supervisor: Asst.Prof.Dr. Sefer Kurnaz

Date: 04/2021

Pages: 55

The need for an efficient indoor navigation may be considered during the planning phase of the building process of modern buildings, thus allowing the use of more complicated, but also more accurate means of positioning and navigation. However, this is often not the situation of already built buildings, where there is already some kind of infrastructure and to build a new one costs additional resources. For these cases, there is the need of the positioning and navigation system, which could be deployed on an already existing infrastructure. Another possibility for the already standing buildings would be a navigation system, whose infrastructure is neither difficult nor expensive to create. This thesis presents and reviews the means of indoor positioning and navigation with the focus on their implementation on the Android platform. The focus on the Android platform is supported by the native support for the new WiFi standard (*IEEE 802.11mc*).

Keywords: Indoor Navigation, Positioning, Wifi, Comparison Analysis

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

eHealth	:	Electronic Health
CMS	:	Cloud Management Software
SaaS	:	Software as a Service
IaaS	:	Infrastructure as a Service
PaaS	:	Platform as a Service
iHealth	:	Intelligence Health
EHR	:	Electronic Health Recode

1. INTRODUCTION

1.1 MOTIVATION

Indoor navigation has been a much-discussed and interesting topic in recent years, and the industry does not focus only on the interior of buildings, but is used wherever the conventional GNSS method cannot be used. Experts from various fields are interested in the given topic and it can be solved in various ways. Whether physicists, programmers or surveyors and cartographers, their cooperation is often very important.

Wikipedia, defines navigation [**?**] as “the process of monitoring and controlling the movement of a craft or vehicle from one place to another.” The knowledge of the navigator’s own position is critical for the all the navigational techniques, however the process of finding a location relative to other reference locations or patterns is called localization. Sometimes the term navigation is used as totum pro parte when referring to the task of localization, though localization is only a subtask of the navigation process.

The word navigation comes from Latin and was created by combining two words - navis, which means "ship" and agere, which means "act". From time immemorial, people have had the need to determine direction, display the earth's surface in map works or find their location, for easier orientation and navigation. We find many definitions of the word navigation in the professional literature and often differ slightly in their conception, but we find common elements in all of them. In navigation, it is important to always identify the starting and destination point of either a person, object, vehicle or modern device and to obtain the information necessary to determine the best route or route between the two points, which can be obtained using appropriate technology and available technology. Thanks to these basic assumptions, we are able to successfully achieve our goal. [1] [2]

The need for an efficient indoor navigation may be considered during the planning phase of the building process of modern buildings, thus allowing the use of more complicated, but also more accurate means of positioning and navigation. However, this is often not the situation of already built buildings, where there is already some kind of infrastructure and to build a new one costs additional resources. For these cases, there is the need of the positioning and navigation system, which could be deployed on an already existing infrastructure. Another possibility for the already standing buildings would be a navigation system, whose infrastructure is neither difficult nor expensive to create.

1.2 THESIS GOALS

The main goal of this thesis is to evaluate a number of technologies and see if it can be used to create an indoor positioning/navigation system. To accomplish this goal, we evaluated and experimentally compared the technologies of positioning and navigation in terms of accuracy and precision.

2. BACKGROUND AND RELATED WORKS

2.1 LOCALIZATION

Merriam-Webster (an Encyclopedia Britannica Company) defines the localization as "to find or identify the location of something" (e.g., object or person) [6]. The localization can be thought of as the starting point of navigation in addition to the other location conscious services. Currently, the process of determining the localization of an object is an old problem. Many approaches and techniques were developed to overcome this problem. The current technology allowed the human being to localize and navigate by the use of many devices and software such as Astrolabe, Reflecting Circle, Traverse Board, Back-staff and The Sextant, Compass. The above devices have been invented to localize and navigate the ships in the sea and also some of them are used for many applications regarding navigation and localization in the land. For viewpoint in more modern time, tracking the position/location of vehicles can be seen similar to that of ships. The GPS system is the first device, which is developed for this issue. The rise of digitization and its entrance to our life require the needs of localization solutions for each person and not to be restricted to ships and cars only. The rules of this game have changed by the age of smartphones. Currently, the GPS technique is installed on most of our smartphones, and they are rapidly used in our daily life. The fact of existing a powerful mobile digital device in our hand allows us to personalize the context and location-aware applications. Figure 2.1 illustrates the flowchart of the localization types.

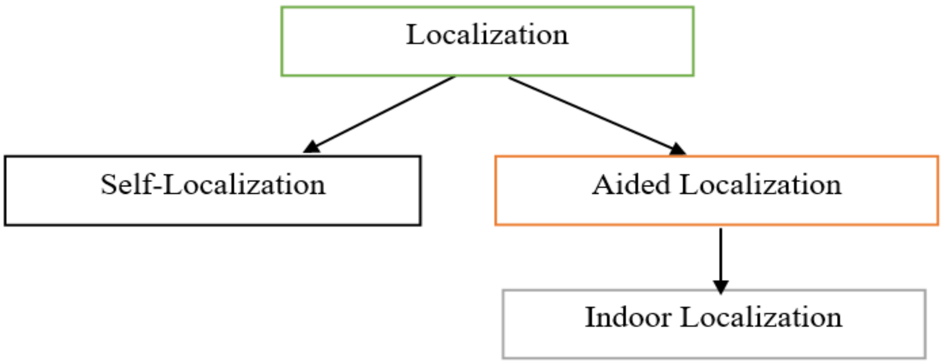


Figure 2.1: Localization types

An **indoor positioning system** (IPS) is a system that determines the position of an object in an indoor environment continuously and in real-time [6]. The Oxford Dictionary defines **navigation** as "The process or activity of accurately ascertaining one's position and planning and following a route" [7].

The **indoor navigation system** (INS) then can be defined as an ex- tension of indoor positioning. An extension that provides navigational capabilities atop the positioning provided by the IPS.

Besides the navigation, effective indoor positioning is applicable in many other fields. Indoor positioning may be used to track shipments in warehouses [8] or monitor patients in hospitals [6]. The INS can be used in malls [9] or other publicly accessible places or even in very specific use cases, for first responders [11].

This chapter provides the categorization of existing INSs with the description of each category, together with the examples of navigation systems conforming to those categories.

2.1 BLUETOOTH

One of the most popular and used technologies nowadays for wireless connection is Bluetooth. Bluetooth is a wireless technology that allows sending data or communication between devices in short distances. Bluetooth was mainly created to replace physical cables with wireless communication. User can create his Personal Area Network (PAN) with Bluetooth devices. Currently, the Bluetooth transfer rate is at 5The newest Bluetooth version is 5.1, which brings better battery life, larger message capacity or longer distance range than its older predecessor Bluetooth 4.2. Bluetooth is under control of the Bluetooth Special Interest Group (SIG), which is responsible for Bluetooth improvement, development and Bluetooth devices certification. Nowadays, Bluetooth finds its exploitation on the Internet of Things (IoT), for ex- ample, in Smart homes, where devices communicate with each other to deliver a better user experience. [6, 7]

Bluetooth technology operates in the 2.4 to 2.48 GHz frequency band known as the Industrial, Scientific and Medical (ISM) radio band. Bluetooth devices use Frequency Hopping for avoiding interference with other nearby Bluetooth devices. When the connection between devices is established, then devices periodically change communication channels multiple times per second. Frequency Hopping devices are on the particular channel only for a while; it reduces the interference possibilities. In Bluetooth Revision 1.2, Frequency Hopping is improved by avoiding channels that are in use.

Piconet is a combination of devices that are connected via Blue- tooth. In Piconet one device behaves as a master, that controls other connected devices, and up to seven slaves connected to one Master. Every Bluetooth device can act as a master or slave. Master is mainly the initiator of the connection. On the other hand, the roles can be changed during the communication. For example, headphones at the beginning act as a master, but when the connection is established to a mobile device, then the mobile device obtains the role of master.

2.2 BLUETOOTH LOW ENERGY (BLE)

Bluetooth low energy is a technology, that is developed by Bluetooth Special Interest Group and it is a subset of Bluetooth[8, 9]. BLE technology has started feature since the Bluetooth 4.0 specification. It promises improved energy consumption and easier integration into small form factors such as BLE Beacons. However, with small form factors and low energy consumption, it is a challenge for developers to obtain security. BLE is insecure because it works with low wireless bandwidth channels and small storage.

BLE discovery detection is based on broadcasting discovery packets in three discovery channels. These channels are used to minimize overlapping. Data channels apply Frequency Hopping for reducing interference and propagation errors, such as fading. After a device receives an advertisement packet, it may connect to a sender device. In BLE connection, there are two roles – slaves and master. Slaves can connect only for one master at a time. Thus, they create a network composed of master and slaves, which follows start network topology. Slaves are in sleep mode to save battery consumption. They periodically wake up and listen for packets from the master.

Master packets are advertised periodically to nearby slave devices, and this time is called advertising interval. The connection range is typically longer than a few tens of meters. Obstacles between slaves and master influence connection range also reflection from obstacles can cause multipath propagation problem.

2.3 BLE BEACON PROFILES

Bluetooth low energy beacons broadcast their packets to nearby de- vices. To be able to understand broadcasted information by a beacon to end-device, there needs to be a general specification or standards of the advertising packet. First well-known advertising packet stan- dard came from Apple with the name iBeacon. After 2 years Google announced their BLE advertising packet standard with the name Ed- dystone, which is open–source standard. The third best-known BLE packet specification is AltBeacon. More details about iBeacon, Eddys- tone and AltBeacon mechanisms and message formats are described down below.

iBeacon

iBeacon[10, 11] is a Bluetooth low energy beacon profile proposed by Apple, which introduced the beacon profile in the Apple World Wide developer conference in 2013. It is a communication protocol that controls communication between the BLE transmitter and receiver. Support for iBeacon profile has started in iOS 7, and since then it belongs to the CoreLocation library of the iOS mobile platform. During the communication beacon device, that supports iBeacon broadcast its packets to nearby devices. It is not supported only for iOS-based mobile devices, but iBeacon can be used in Android devices, which support Bluetooth 4.0. With iBeacon protocol developer can handle events when a user comes to a particular location or enters a specific region.

iBeacon packet holds specific information in its structure. The packet consists of five main fields: UUID, major and minor field, iBeacon prefix and TX power. UUID field is a 16 bytes size block, that identifies beacon, its region and multiple beacons can use the same UUID. UUID field sends beacon ID and mainly is associated with a specific application. The UUID's purpose is to distinguish beacons un- der your control from other application's beacons. There are major and minor fields to provide greater accuracy of identification inside your beacon network. Major and minor fields are two bytes long unsigned numbers, and they are required to be assigned in the packet. For ex- ample, you can use the same UUID for a complex building where are multiple blocks, and these blocks are further divided into single items. For blocks identification, you use major values, and for single items, there is a minor field value. The last field contains TX power, which is signal strength in one meter away from a beacon device. The distance approximation of a mobile device from the beacon uses TX power to calculate this distance. On a picture number 2.1 you can see a structure of iBeacon packet.

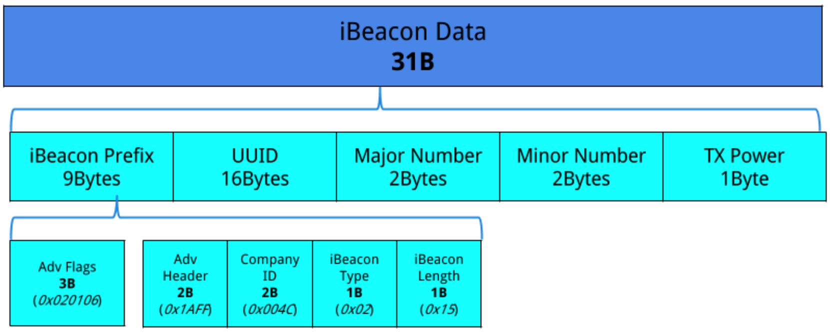


Figure 2.2: iBeacon packet structure [12]

Eddystone

Eddystone[13] is an open-source Bluetooth low energy protocol that defines message packet structure. Google introduced the standard in 2015, and it supports all Android devices with Android API 21 and above. The packet consists of prefix data and frame data. Prefixed data are used to secure and control packet's values. Frame data consists of 4 bytes of UUID – header of the frame and 20 bytes of the frame. There are four types of frame: Eddystone-UID, Eddystone-TLM, Eddystone- URL and Eddystone-EID. These four types are described below and visualization of Eddystone packet is on the picture number 2.2.

- Eddystone-UID

Eddystone UID is a 20 bytes long frame to identify beacons. It is composed of its type (1 byte), ranging data – calibrated Tx power at 0 meters (1 byte). There is also 10 bytes-long namespace that is equivalent to UUID in iBeacon protocol. It specifies beacon ID, and it may be used for filtering Eddystone beacons that belong only to the user's application. Six-bytes long instance component is a unique identifier within a namespace, equivalent to iBeacon's Major value.

- Eddystone-URL

URL frame holds URL of a website which is compressed by the encoding format. The frame includes its type (1 Byte), Tx power

is averaged signal strength power at 0 meters from a beacon (1 byte), URL scheme prefix (1 byte) and encoded URL (17 bytes)

- Eddystone-TLM

TLM frame provides supplement information about beacon de- vice state. It includes battery voltage, device's temperature or a number of broadcasted packets.

- Eddystone-EID

The ephemeral ID is a frame that enables encrypted configura- tion of beacon to broadcast information that can be read-only by authorized entities. It also supports cryptographically secured transmissions of TLM frames. With EID usage, the developer can ensure that only his application can read data from Eddystone beacon.

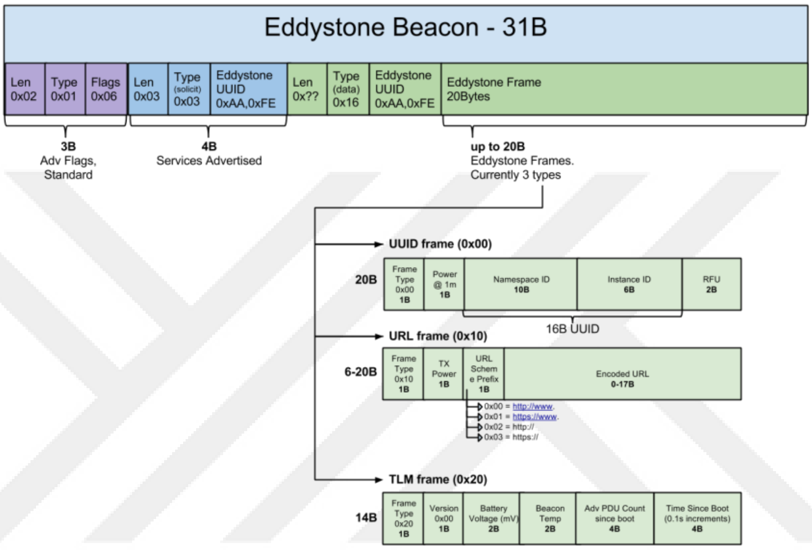


Figure 2.3: Eddystone packet structure [14]

Alt Beacon

AltBeacon[15] is a BLE protocol that defines an advertising message format. It is the open format published for everyone on their Github pages. The support of AltBeacon has started since Bluetooth 4.0. It is not suitable only for one-purpose devices, but AltBeacon can be used in any device, which supports BLE and is independent of Operating system.

2.4 BEACON DEVICES

Beacon [16] is a small device, which broadcast its universally unique identifier (UUID) within a packet to nearby receivers. The packet contains data written inside the beacon. In beacon, user can configure parameters such as packet broadcasting frequency in milliseconds or transmit power in decibel-milliwatts (dBm). It works with Bluetooth low energy, which is an extension of Bluetooth 4.1 protocol.

Beacon devices can be powered with small lithium coin batteries, because of that it can last longer than 2 years. Battery life depends on the broadcasting frequency and the strength of the Bluetooth sig- nal from the device. Another power supply option is via USB, but it decreases the portability of the device.

The way how packet from the beacon is broadcasted and how a receiving device processes the packet is defined in communication protocols. The beacon can support iBeacon, Eddystone and AltBeacon protocols. Below are some manufacturers that produce BLE beacons and also there is a small comparison table 2.1 between their products.

Kontakt.io

Kontakt.io is a company specialized in BLE beacon manufacturing [17]. They offer all kinds of beacons for a different way of usage. For every beacon they produced they provide software libraries for implementing localizations or beacon configuration. Also, they offer a variety of services for their product, where you can monitor used devices, set security rules for connection or configure beacons and set it up for retail. They offer tags for tagging goods in big warehouses for faster finding. Their Smart Beacon SB16-2 is a stationary beacon for localization. The furthest range of the beacon is 70 meters assuming nothing stands in the signal. It supports iBeacon and Eddystone, and its replaceable batteries can last longer than 5 years.

Estimote

Estimote is a Poland-based company [18], which is on the market since 2012. They produce the first beacon compatible with iBeacon. Their software cooperates with beacons a implements proximity marketing, automation or localization in a building. They offer seven beacon types in different form factors. For example, their Proximity beacon supports 5.0, that leads to a longer signal range, up to 100 meters and better battery life with 5 years of usage. The beacon is delivered with NFC support, which is used for pairing. Proximity beacon is fully configurable with their software. iBeacon and Eddystone beacon profile are supported in the device.

Em Microelectronic

Em Microelectronic is a company based in Switzerland and a semi- conductor manufacturer specialising in developing and designing low-power integrated circuits [19]. They also have three types of beacons – EMBC22, EMBC02, and EMBP0, which support all three BLE beacon profiles: Eddystone, iBeacon and AltBeacon. EMBC22 can last over four years. In the device's documentation is mentioned, that the range of the signal can be 200 meters at its maximum power output. The device also offers programmable parameters such as packet types, device name, address UUID, Beacon interval, transmitter power, and Accelerometer functionality.

Mobile application beacon simulator

Every device that supports BLE protocol and has the multi broadcast support can transmit or receive BLE data. This functionality can be used to simulate beacon's capabilities and functionalities on a mobile device. It is an excellent option for developers to learn how to interact with beacon's data and implement application without another device. For Android OS, there is Android simulator[4] application, that can simulate beacon. It is capable of configuring different beacon profiles such as iBeacon, Eddystone and AltBeacon. For every profile, you can set TxPower, frequency of packet transmitting, major and minor values or UUID. Another useful application for simulating beacon is Beacon Sim[5]. Beacon Sim app is compatible only with iOS devices. Thus it works only with iBeacon, and the main disadvantage is that user cannot configure anything – it leads to worse accuracy of calculating distance from the device.

Table 2.1: Comparison between different beacon devices.

Name	BT Version	Battery	Range	Support
SB16-2	4.2	5 years	70m	iBeacon, Eddystone
Proximity Beacon	5.0	5 years	100m	iBeacon, Eddystone
EMBC22	5.0	4 years	200m	iBeacon, Eddystone, AltBeacon

Beacon's use cases

Beacon is a small device which can create PAN and provide end de- vices with useful information. It finds multiple options in different market segments. Here are some of them:

- Retail industry

Shops use beacons to provide a better shopping experience for their customers. Beacons provide, for example, new goods dis- counts or promotions, which leads to an increased profit of the shop.

- Tourism

Beacons with their ability to hold data around physical locations are an excellent opportunity for cities, museums or restaurants to provide relevant data for customers when they approach an exact place. Museums or cities can use beacons to create a virtual guide, which shows user relevant information, for example, about the nearby statue.

- Indoor Positioning

One can easily get lost in complex building such as airports or malls. Beacons solve this problem by providing BLE signals to substitute Global positioning system (GPS) to position user in a building. Positioning can work with different positioning techniques like GPS, but accuracy is a little worse than GPS, on the other hand, good enough to show a user his likely position in a building.

3. LOCATION PROVIDERS AND TECHNOLOGIES

Nowadays, using a mobile phone as a localization device is very com- mon. Users may use this advantageous feature of a phone to check their precise location on a map, find the best routes, follow navigation in real-time or find nearest points like restaurants, gas stations, etc. Moreover, the possibilities of localization technology in mobile phones are still being explored. In addition to helpful ideas like tracking a lost phone or sharing your location with friends in chat, this technol- ogy can also be used in the entertainment industry. That includes, for instance, mobile games using the current position and movement in the real world to move a game character in a virtual world. Even though the aim of this thesis is to develop a mobile application using Bluetooth Low Energy and beacon technology, there are more ways to obtain and calculate a user's location. Few of them will be discussed and compared.

3.1 GPS

GPS is an abbreviation of a global positioning system. It is a satellite- based navigation system, which uses several satellites rotating over the earth. Existing for over twenty years, GPS has become broadly used in worldwide navigation. That means that modern navigations in cars, nautical navigation, land surveying, and flight transportation systems are often equipped with GPS modules. Moreover, GPS is also affecting many aspects of our personal lives because this technology can be found in various devices, from mobile phones to ATMs [16].

GPS is a part of GNSS (Global Navigation Satellite System) and other systems like GLONASS, Galileo, Beidou, and other regional systems. Devices can be equipped with navigation chips capable of receiving signals from more satellite systems and even combining them to improve satellite signals' accuracy and availability. However, in this chapter, we will discuss only the history and techniques used in GPS, as navigation systems are not the main topic of this thesis and will not be used in its practical part.

History of GPS

The Navstar Global Positioning System (GPS) started as a new nav- igation technology by the U.S Department of Defence in the early seventies to replace the first-generation satellite navigation system called Transit. The original purpose of this navigation system was to target nuclear missiles fired by submarines. The Navstar was also designed to create a single, global navigation system because they used more electronic systems mostly applied in particular areas for specific tasks [17]. The first four satellites were launched in 1978. However, GPS became fully operative in July 1995 since at least twenty-four satellites were needed to provide full functioning capacity.

Initially, there were two different services provided by the Depart- ment of Defense. The first one was the Precise Positioning Service (PPS), and the other one – the Standard Positioning Service (SPS). The difference between them was the accuracy of the measurement. PPS was more precise but served only for the U.S military. On the other hand, SPS was focused on civilian use but contained an intentional error that caused a measurement error of up to a hundred meters. The departure of Defense decided to protect the interests of the U.S., preventing possible enemies from misusing this technology against them. However, in 2000, president Bill Clinton ordered to remove this intentional error in SPS, making this public service five times more accurate.

How GPS works

Global Positioning System is based on the concept of trilateration, which is a technique to measure distances. It is based on the fact that if we know the distance between two points and the position of the first one, we know that the second point is somewhere on the circle with a radius equal to the distance between those two points. Nevertheless, to get the precise three-dimensional location, we need to know the distances between points we are looking for and the other four points with a known position.

As mentioned above, GPS uses satellites orbiting the earth as points with a known location. Each satellite works as a transmitter and reg- ularly broadcasts digital radio signals with information about the current time and actual position. The speed of this radio signal is equal to the speed of light. A device with a GPS module works as a receiver and can obtain those signals and decodes them to get the time sent by satellite. Substracting its own time from the time sent from the satellite, the receiver can compute the distance between itself and the satellite with the following equation:

$$Distance = Rate \times Time \text{ [18]}$$

Rate is the speed of the radio signal transmitted from orbiting GPS satellites. It is equal to the speed of light (299,792,458 meters per second). Time used in the equation is the time between sending the signal from the satellite and receiving this signal by GPS receiver on the earth.

Computing the distance between at least four satellites provides users with approximately 7.8-meter precision anywhere near the earth's surface, around 95% of the time [19].

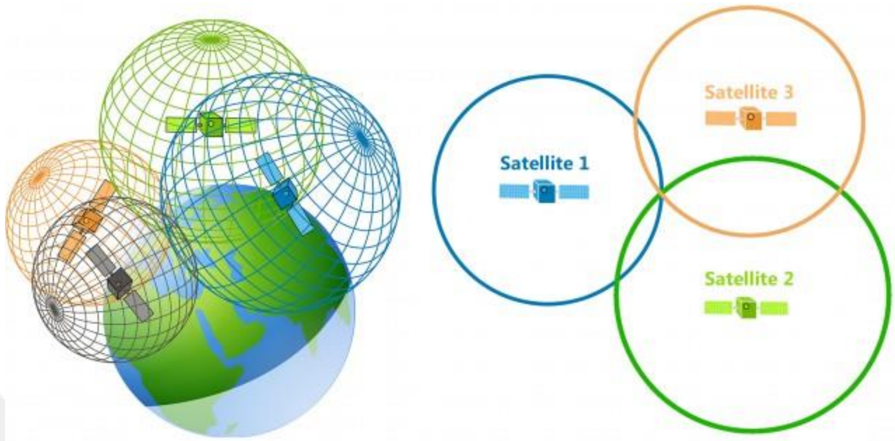


Figure 3.1: Illustration of trilateration

with three satellites and one intersection of its circles on the right and the same principle but with four satellites and precise tree-dimensional location on the left [20]

GPS and mobile phones

Probably every modern phone is obtained with a GPS module. That means that the phone can act as a receiver for radio signals from satellites. However, the technology used in mobile phones is not as accurate as professional GPS equipment. This equipment works with two GPS frequencies for improved accuracy and is usually used by the military, but it is also available for civilians [21].

Therefore, using a mobile phone as a localization device leads to measurement error caused by several factors, such as the error associated with space weather [22] or device surrounding. For example, the study by Krista Merry and Pete Bettinger shows "that the overall average horizontal position error of the iPhone 6 is in the 7–13 m range, depending on conditions, which is consistent with the general accu- racy levels observed of recreation-grade GPS receivers in potential high multipath environments [23]." We can consider that the error will be even more significant when the device is located indoors and hence is not in line-of-sight with satellites. It can be a problem because acquiring precise location in buildings is often more desirable than outdoors. Besides GPS, which is probably the most widely known technology in public, the location of a mobile phone can be obtained with more techniques.

3.2 WI-FI POSITIONING SYSTEM

Over recent years, Wi-Fi became a standard part of our lives. We have access to wireless networks throughout Wi-Fi in our homes, offices, cafes, restaurants, airports, or even public transport. The Wi-Fi positioning system is a geolocation system using a large number of Wi-Fi hotspots and other wireless access points around to find a device. Because of the problem with significant GPS error when used indoors, the Wi-Fi positioning system can be useful and find applications in indoor navigation.

History of Wi-Fi positioning system

An early project that uses a technique with a Wi-Fi signal was RADAR by Microsoft from 2001. According to its website, RADAR "is the world's first Wi-Fi signal-strength based indoor positioning system [24]." Nevertheless, new ways of using hotspot signals to discover and localize devices were developed over the years.

Ekahau used one such technology to create a small device with a button, lights, and motion sensors. This device worn by a person periodically transmits Wi-Fi packets as the person moves [25]. Later, with the rapid expansion of mobile phones capable of connecting to wireless networks, developers started to use mobile phones as devices to receive or transmit Wi-Fi packets. High penetration rate with the low cost and availability make smartphones have better applicability for every indoor positioning system using Wi-Fi. That created an opportunity to find even more ways how to use hotspots for localization.

How Wi-Fi positioning system works

As mentioned above, a Wi-Fi positioning system uses wireless access points to discover the device's location, making it one of the most cost- effective types of positioning systems. Currently, we can implement a Wi-Fi positioning system using more than one way. According to whether the user carries a particular device or not, we can divide it into two techniques – active positioning and passive positioning.

If the user needs to carry a mobile phone to collect signals from nearby access points and actively search for them, we are talking about active positioning. Information from access points is obtained and transmitted to the server. Using positioning algorithms, the system determines the location of the user.

On the other hand, the passive positioning technique does not need the user to carry any equipment at all. However, a signal transmitter and signal receiver must be deployed. The passive positioning technique works with changes in the signal. The receiver obtains different signals based on the user's position, and the system can process these changes and estimate the user's location [26].

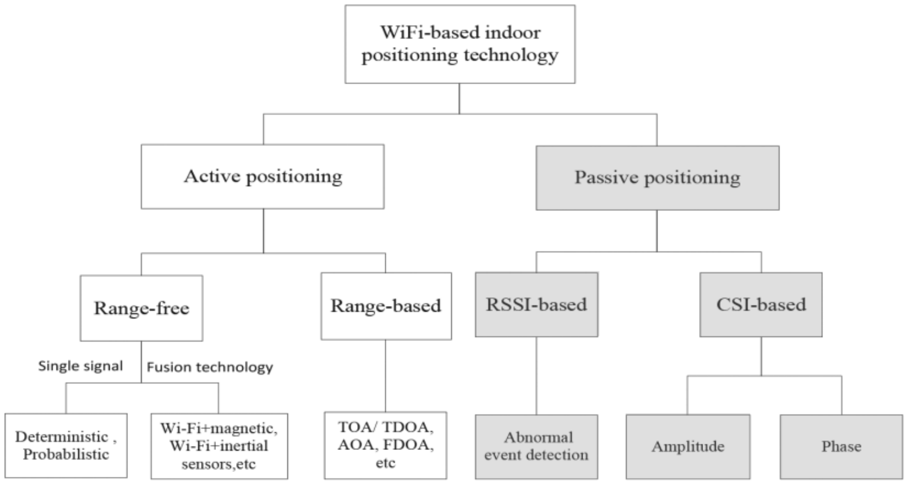


Figure 3.2: Category of the Wi-Fi positioning system [26]

Active positioning

Active positioning, using the user's device, can be divided into two types. The first one is called range-free, and the second one is range- based.

Range-free Active positioning

The implementation process of the active positioning technique is usually divided into two stages – offline and online phase. Both phases include signal strength measurements and work based on a finger- print.

The offline phase is necessary to create a radio map by sectioning the environment into a dense grid of locations, where signal strength is recorded from nearby access points to create a statistical model of the propagation environment at each location [27]. In practice, during the offline phase, it is necessary to estimate the probability of the distribution of signal strength in several orientations and combine them because physical barriers can disturb measurements. This problem can be even more significant in the areas where objects are occasionally moved.

In the online phase, the purpose is to localize the user by measuring the signal strengths of nearby detected access points. Those measurements are compared with the radio map to estimate the location and trajectory of the user.

Although the problem with a non-stable environment can be solved with a new measurement, the user's body also acts as a signal barrier. Therefore in crowded places, there can be measurement errors that cannot be solved so easily [28].

Range-based Active positioning

This family of positioning techniques uses various geometrical tech- niques such as received signal strength (RSS), time-of-arrival (TOA), or angle-of-arrival (AOA). The signal is received from an anchor, a unique node, or a network access point with a perfectly-known location. The location of the user is calculated using those geometrical techniques and received signals. However, because the received signal is corrupted by noise, does not come from an anchor in line of sight, or works differently on different models of mobile phones, a range-based technique can produce not minor errors in measuring location [29].

3.3 BLE POSITIONING

BLE stands for Bluetooth Low Energy, which is part of Bluetooth wire- less communication technology. It can be used to calculate a user's location using beacons - small Bluetooth radio transmitters. Bluetooth itself was designed for data exchange in short distances to create wire- less communication between two devices [25]. Bluetooth technology is nowadays supported by most modern mobile phones and is used daily to connect our smartphones with wireless headphones or speak- ers, smartwatches, and printers. Furthermore, even modern cars have an in-car entertainment system capable of pairing with a phone using Bluetooth to transfer music, calls, or mirror phone screen.

History of BLE

Bluetooth Low Energy, also called Bluetooth Smart, was announced as part of Bluetooth 4.0 in 2009 [30]. Compared to original Bluetooth, BLE was designed to transmit a small amount of data and be the lowest possible power technology for wireless communication. As a result, BLE devices can run on simple batteries for more than a few months or even years. Thanks to these characteristics, this technology is suitable for gadgets like sensors, wearable devices, or the Internet of Things in general [31]. One such device is a beacon.

The first beacons were introduced in 2013 by Apple during the Worldwide Developers Conference. They demonstrated transmitting data between a beacon and a receiver, using their protocol called iBeacon. Two years later, in 2015, Google released a new protocol, in response to Apple, called Eddystone BLE beacon. It was similar to iBeacon, but the protocol was focused on smartphones using An- droid OS [32]. Implementing into mobile phones led to the growth of Bluetooth Low Energy evidence of what is that over 50 of the top 100 retailers in the United States started to test beacons in their stores by 2014 [33].

How BLE positioning works

As mentioned above, BLE beacons are small battery-powered devices that transmit data over Bluetooth Low Energy communication channel. All Bluetooth 4.0 devices can obtain this data. Summarized in an article by Alexander Yohan and others: "the information broadcast by a Bluetooth beacon consists of a short and simple data format, e.g., the Universal Unique Identifier (UID) of the device, telemetry, and URL. In general, Bluetooth beacons take a broadcaster role in the Bluetooth environment [31]. "

Although beacons can not connect with other devices, they can launch specific actions on a mobile phone when a user receives a signal from a beacon. Based on the received information, the approximate location of the user can be calculated. However, beacons themselves cannot carry out any operations to proceed with the information or calculate the distance. Thus all calculations must be done on a mobile phone with a suitable application or on the server-side [34].

Several methods could be used to calculate the user's location with the received signal, as with Wi-Fi positioning.

Beacon Proximity

Beacon proximity is the way to calculate the distance between a device and a beacon, based on the Received Signal Strength Indicator (RSSI) of one beacon. It is used in a lot of other methods. A specific intensity of received signal strength is known to be transmitted by a beacon that is a certain distance away. This information is used for calibration and measuring a distance between a device and a specific beacon with received signal strength value. The calculated distance creates a circle at the boundary of which the device is located.

Trilateration method

Trilateration work thanks to beacon proximity, just like few meth- ods from both range-free and range-based Wi-Fi positioning active techniques, which use RSSI. It is one of the most common methods used for indoor positioning [31]. The calculation of an approximate location is based on the RSSI of at least three beacons. As mentioned above, received values can be converted to distances, which creates geometric shapes, like trilateration used in GPS, but circles are used in this case. The result location is the intersection of these circles.

Nonetheless, according to ChinKun Ke and others, the BLE beacon signal is based on a 2.4 GHz radio band, which is easily affected by multipath effect attenuation and shadowing effect due to external objects' influence [35]. The estimated intersection is then not one point, which is right what the actual location of a user is, rather than it is the whole area created by errors in the received signal.

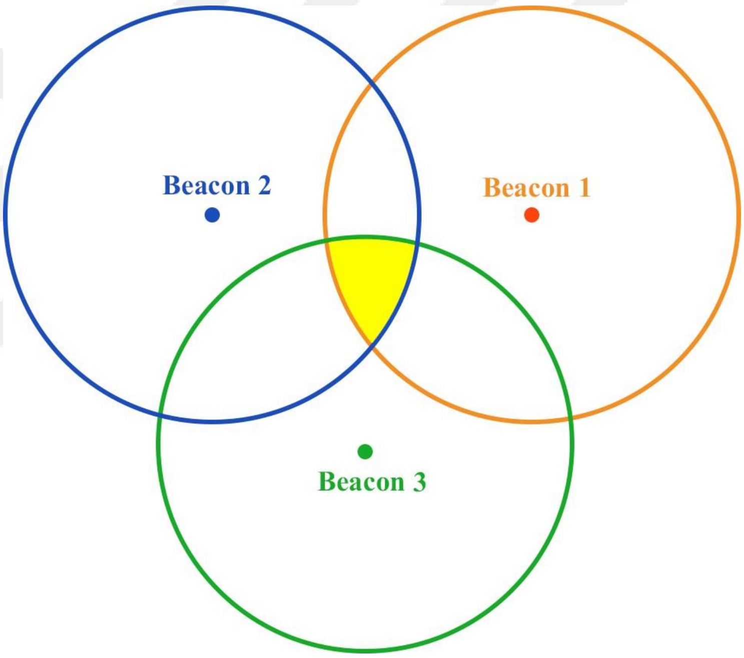


Figure 3.3: Trilateration error creates a yellow area

between 3 points of intersection and no single point with a user's real location

3.4 FINGERPRINT METHOD

Another technique to obtain a position using BLE beacons is a fin- gerprint. This method is similar to the range-free active positioning fingerprint method used with Wi-Fi access points, but a database is created with RSSI measurements of Bluetooth beacons. Fingerprint can be used with trilateration to improve results [34]. Drawbacks are the same as with the range-free active positioning technique used with Wi-Fi access points. Furthermore, beacons can run out of battery. Thus the database is out of date, which creates another measurement errors.

Comparison to other positioning systems

Compared to GPS, BLE Positioning undoubtedly offers better position accuracy for indoor positioning. According to Table 1 and Table 2 in *Survey on WiFi-based indoor positioning techniques* [26], with BLE, we can achieve approximately 2 meters accuracy, while GPS may have 10 meters accuracy. In the same tables, we can see that base Wi-Fi positioning systems can achieve results slightly more inaccurate than BLE.

In terms of deployment, GPS is the easiest method, as it does not need any special devices, just a regular mobile phone with a GPS module. In contrast, both BLE and Wi-Fi positioning systems may need special devices. BLE needs beacons, and Wi-Fi may require special access points.

Because this thesis aims to develop an android application, another important thing to compare is the battery usage of a mobile phone. Because BLE was designed to be the most power effective technology, in the test made by Shu Liu and Aaron Striegel [36], it is several times more efficient than GPS and more than one time more efficient than Wi-Fi.

3.4 WIFI ROUND-TRIP-TIME

WiFi Round-trip-time (RTT) technology utilizes the **Fine timing measurement (FTM)** protocol to measure time with the picoseconds resolution. The FTM protocol is part of the **IEEE 802.11mc** standard, which was ratified in 2016 (also 802.11-2016) [15]. The RTT measure- ment takes place in a *FTM session*. A *FTM session* is an instance of FTM protocol between the two communicating devices, an initiator and a responder. The initiator is usually a mobile phone. It sends the *FTM request frame* and receives the *FTM frame*. The responder, on the other hand is usually the access point. The AP sends the *FTM frame* and receives the *FTM request frame* [37].

A typical FTM session is depicted in Figure 3.1. The initiator is on the left-hand side and the responder is on the right-hand side. A FTM session is requested by the initiator sending a request. The responder responds with ACK frame. It marks *t1* which is the time-of-departure of the FTM frame *M* (ToD(M)) and sends the frame *M*. The initiator marks *t2* which is the time-of-arrival of the frame *M* (ToA(M)). It also marks *t3*, which is ToD(ACK) and responds with ACK frame. On arrival, the responder marks *t4*, which is ToA(ACK) and responder responds with the second FTM frame now containing times *t1* and *t4*. Upon receival, the initiator finally responds with *ACK*.

Now the initiator, knowing all four times (in seconds), computes the time-of-flight (ToF, also round-trip-time (RTT)) as *(t4-t1) - (t3-t2)*. With the ToF known, the initiator can then compute the distance to the responder. The distance is computed as *(ToF * c) / 2*, where *c* is the speed of light.

The difference between this approach and the one proposed in [22] is that times *t2* and *t3* are marked by the AP at the exact moment they are received with WiFi RTT, whereas in the mentioned paper, these

Figure 3.4: FTM session from [15] (edited)

times are marked by the initiator and the eventual delay is taken into account when computing the distance. In the result, WiFi RTT should be more accurate.

4. PRACTICAL PART AND ANALYSIS

This chapter describes the experimental evaluation of WiFi Round-trip- time (RTT). The chapter also contains the experimental comparison of selected technologies usable for indoor navigation such as Bluetooth Low Energy (BLE) and WiFi Received signal strength indicator (RSSI). These technologies are compared to WiFi RTT in terms of accuracy and precision.

The first part of the chapter describes testing environments and the experiment setup. It also provides the description of devices used for measurement. The next section describes the process of measurement for each selected method and each environment. Finally, the last section states the results of the experiments and presents the comparison result based on the measurement results.

4.1 EXPERIMENTS SETUP

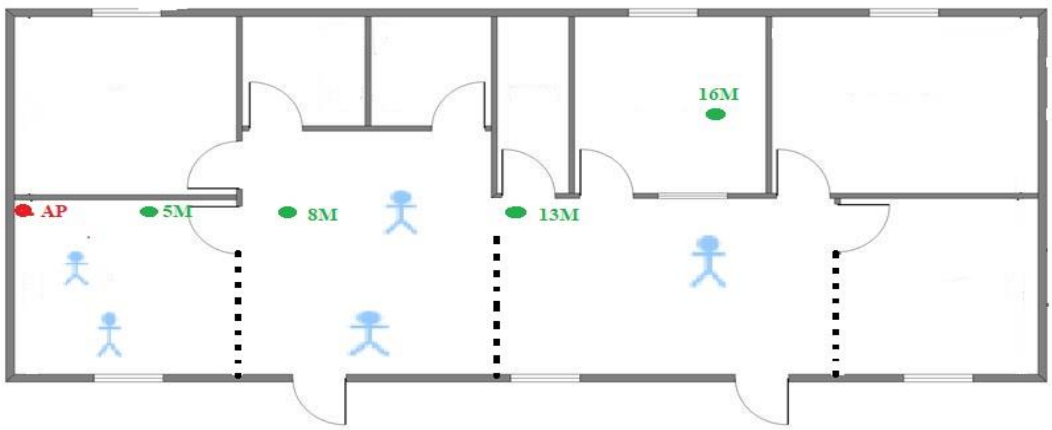
Two testing environments were set up for the experiments. Environment 1 (shown in Figure 4.1a) was represented by a three-room flat in an apartment building. The reference access points (APs) and BLE beacons were positioned in one corner of the apartment (drawn as a red circle labeled "AP") at the height of approximately one meter. The scheme illustrates the locations of measurements (drawn as green circles, labeled by their distance from the APs/beacon). The first environment was set up to test the behavior of technologies in places where the multipath effect may occur.

Environment 2 (shown in Figure 4.1b) was a small office with multiple rooms of different sizes. Gray-colored lines in the diagram represent the door made mostly of glass. Gray-black dashed lines represent the walls with aluminum struts and frames and the glass panels between them. The location of the reference APs/beacon is depicted by a red circle. The APs/beacons were located right next to the concrete wall at the height of 120*cm*. The close-to-the-wall location was chosen also to leverage the reflection provided by the wall, which could possibly increase the range (inspired by the metal reflectors in [11]). Green circles labeled with the distance from the AP represent the measurement positions. The red ellipse in the center part of the diagram represents a place with many wireless-enabled devices such as tablets, smartphones, computers, Bluetooth printers and WiFi access points. Finally, the blue icons of people represent the locations where the people were walking/sitting during the measurement. This environment was set up to test the technologies' behavior in the environment that is "polluted" by the wireless signal and where people move, which could lead to the signal interference.

For the receiver for all three tested technologies, Google Pixel 2 was selected. The selected device was an entry-level model with 4GB of RAM and 64GB of storage, running on the Qualcomm MSM8998 Snapdragon 835 chipset. The device was updated to the Android 9 prior to the testing. This exact device model was selected, because no other devices are known to be supporting the *IEEE 802.11mc* standard and therefore WiFi RTT.

As the transmitter for the Bluetooth Low Energy measurement, an I2 Max iBeacon BLE beacon by Social Retail was selected. The particular beacon was selected due to its low price (bought at Amazon.com for 11 euro) and compact dimensions (7*x*7*x*2*cm*).

(a) Environment 1



(b) Environment 2

Figure 4.1: The schemes of testing environments

The beacon supports the *iBeacon* protocol and multiple of its transmission parameters could be configured using the application. However, for the testing purposes, those parameters were left in the default state; the **transmission power** was set to the highest level; the **reference distance** (txPower) was set to $59dBm$ and the **broadcasting interval** set to $300ms$.

For the WiFi RSSI measurements, the D-Link N300 (DIR-605L)

access point was used. The access point supports the *802.11n* standard and transmits on the (*2.4GHz*) frequency. The signal strength measurements were conducted against the pre-configured WiFi network. No transmission parameters were modified before the experiments.

Finally, to test the WiFi RTT technology, Compulab Wifi Indoor Location Device (WILD) had to be purchased. The computer is the first access point with the RTT support [41]. The used model was configured with the Intel Celeron-J3455 processor, 4GB of RAM and 32GB SSD. The computer utilizes the Intel Wireless-AC 8260 SoC which is one of the WiFi Certified access points as per [40]. The operating system (OS) running on WILD was GNU/Linux Debian with RTT tools provided by Compulab. Prior to the testing, a new version of OS image had to be flashed onto WILD. The new version introduced the wild program. This program takes care of RTT handling and configures the system to run in either responder or initiator mode.

For the AP being the first supporting WiFi RTT, it has several disadvantages or problems. The first disadvantage lies within its con- figuration. The AP can be configured only using the terminal. A user without any experience with Linux would have a significant problem setting it up. Moreover, the process of OS update is poorly documented and had to be done manually, by installing the OS from a removable device. The next disadvantage is that without LAN connected, the AP does not allow wireless clients to connect. Although, this is a known issue documented in the wiki, it is not pleasant. Due to this issue, WILD could not be used for the WiFi RSS testing as the smartphone was unable to connect to the WILD's network.

4.2 THE PROCESS OF MEASUREMENT

A set of markers denoting the real distance from the AP was placed on the floor before the tests were conducted in the new environment. For Environment 1, together eight marks were placed. Most of the marks in Environment 1 were placed around the imaginary line connecting the AP (in the bottom right corner of Figure 4.1a) and the mark in the top left corner of the apartment. The positions of marks were chosen with respect to their surroundings. For example, one mark was positioned in the top left corner, near the wall to test whether the reflection provided by the wall would have some effect on the readings. Another marks were positioned randomly across the rooms. In the second environment (depicted in Figure 4.1b) most of the marks were placed in the line perpendicular to the bottom wall in the location of AP (red circle). Together seven marks were placed on this line, in the distances of 1, 2, 3, 5, 8, 10, and 13 meters. One more mark was placed the furthest from the AP to test the range of each technology as well as its accuracy in the bigger distance and in lots of walls in the way. This mark was placed at the distance of approximately 17 meters.

The testing device was held in hand in the natural height. The natural height is the height at which the smartphone could have been comfortably worked with. For the measurement, the application de- scribed in Appendix A was used. The overview of sampling rates selected can be seen in Table 4.1. The sampling rate for BLE measurement was set to $50ms$ because it was expected that the measured value would be scattered.

Table 4.1: Sampling rates used for the measurement.

Technology	Sampling rate (ms)
Bluetooth LE	50
WiFi RSS	500
WiFi RTT	800

In each environment, the measurements were performed in the same order. The first measurement was Bluetooth LE, followed by WiFi RSS and finally, WiFi RTT. The measurement was performed. A single measurement consisted of a set of value reads. When measuring the distance using WiFi RTT, the first measurements showcased negative values of distance. For example, at $3m$ real distance from WILD, the distance readings were around $4m$. As discovered by Horn in [16], the change of the bandwidth of the transmitter could help. By changing the bandwidth, the following was observed:

with the default bandwidth value ($80MHz$), the distance readings at $3m$ real distance were reaching $-4m$;

with bandwidth of $20MHz$, the distance readings in the close proximities showed negative values (for example, at $1m$, WiFi RTT reported the measured distance of $2m$

in average), how- ever, with a bigger real distance (about 5*m* and more), the re- ported values were close to the real distance; the 40*MHz* bandwidth showed relative good distance readings in both short and long real distances.

Because of negative readings in close proximities of 20*MHz* band- width, the bandwidth value of 40*MHz* was set for the measurements. After the measurements were gathered, the measurement values were exported from the application as *CSV* files. The exported files were processed in Google Sheets. The resulting spreadsheets in the *.xlsx* format are a part of the digital attachments to this thesis.

4.3 THE EVALUATION PROCESS

For the WiFi RTT measurements, no post-processing of the measured values was needed, as the output was already in millimeters. To express the measurement error, the root-mean-square-deviation (*RMSD*) was calculated for each of the measurements. The *RMSD* is the variant of the standard deviation. In contrary to the standard deviation (*SD*), the *RMSD* is based on the reference (or expected) value, rather than the mean. The *RMSD* is the square root of the mean-squared-error (*MSE*), which is in turn the variant of variance, but again, computed using the reference value, rather than the mean of measured values. The *MSE* and the *RMSD* for the measurement *X* can be computed using the following equations:

$$MSE(X) = \frac{1}{n}\sum_{i=1}^{n} \quad (x_i - x_0) \qquad (4.1)$$

$$RMSD(x) = \sqrt{MSE(X)} \qquad (4.2)$$

where x_0 is the reference value (distance) and n is the number of value reads in the measurement X.

Using this method, the measurement error (*ME*) for each measurement in each environment was calculated. The final average measurement error was computed as the average of the measurement errors of each measurement:

$$ME = \frac{1}{m}\sum_{i=1}^{m} \quad RMSD(X_i) \qquad (4.3)$$

Equations 4.1, 4.2, and 4.3 are also used to calculate the measurement error with both, WiFi RSS, and Bluetooth Low Energy.

Measurements results from WiFi RSS and Bluetooth LE measurements are in decibels referenced to $1mW$ (dBm). These values indicate the signal strength received from the transmitter device (RSSI). A suitable propagation formula had to be found to convert the RSSI value to distance. One possible choice could be the general Free-space- path-loss (FSPL) function. This propagation function is effective only in free space, because it does not take obstacles (usually walls) into account thus it may lead to inaccurate results in the typical indoor environment. Instead of the FSPL, an empirical propagation model from [21] was chosen:

$$RSSI[dBm] = txPower[dBm] - 10.n.log\ log\ d\ - l.WAF \qquad (4.4)$$

$RSSI$ in dBm, is the received signal strength. $txPower$, also in dBm, is the signal strength at the reference distance, which is $1m$ in this case.

The parameter n is the *exponent value*. The exponent value determines the rate of the signal fading in space. The parameter d is the distance at which the given $RSSI$ was measured. The value d is divided by the reference distance ($1m$) inside the logarithm. The parameter l describes the number of walls between the transmitter and the receiver. Each of these walls degrades the received signal by the so-called wall attenuation factor (*WAF*). The *WAF* is determined experimentally as the difference of the RSSI value observed with the Line-of-sight (LOS) to the transmitter and the RSSI in the non-line-of-sight(NLOS) environment:

$$WAF = RSSI_{LOS} - RSSI_{NLOS}. \tag{4.5}$$

Both measurements have to be done in the same distance from the transmitter.
To take the effect of walls into account, *WAF* was experimentally measured. The value of *WAF* for Bluetooth Low Energy was $10dBm$, while the value of *WAF* for WiFi RSS was $8dBm$. Next, to determine the distance from the received RSSI values observed by measurement, the parameter n had to be calculated. To determine n, Equation 4.4 was adjusted:

$$n = \frac{RSSI - txPower + l \cdot WAF}{-10 \log d}. \tag{4.6}$$

First of all, for each measurement (the measurement is a set of value readings at the same distance from the transmitter), the respective n value was computed. Then, to simulate the real-life deployment and calibration of a navigation system based on BLE and/or WiFi RSS, n for the given technology/environment combination was calculated as the average of the first half of the measurement performed with that technology in that environment. For Environment 1, n was calculated as the average n of measurements at $2m$, $3m$, $4m$, and $5m$, while for Environment 2, n was the average n of measurements at $2m$, $3m$, $5m$, and $8m$. The measurements at $1m$ were not taken into account because the reference values were measured at $1m$ from the transmitter, thus the logarithm would be equal to zero, which would result in the division by zero. The values of n for each technology/environment combination can be seen in Table 4.2. As can be seen from the table, Environment 1 showed a higher rate of the signal fading

Table 4.2: The exponent value in each technology/environment combination

	Environment 1	Environment 2
BLE	3.3883	1.0619
WiFi RSS	2.5254	0.5980

than Environment 2, where the tests were concluded in a straight line without walls (except for the last value).

With *n* calculated, the model was ready. To transform the received signal strength into the distance, the adjusted version of Equation 4.4 was used:

$$d = 10^{\frac{RSSI - txPower + l \cdot WAF}{-10.n}} \tag{4.7}$$

Using this equation, the approximate distance (columns labeled d_approx in the spreadsheets) was calculated for each value read for each measurement. As the next step, the *RMSD* was calculated from these values for each measurement. As stated above, the measurement error (*ME*) was then calculated as the average of all *RMSD*s. The results of these calculations can be found in the next section.

4.4 RESULTS

This section provides an overview of discovered results. The accuracy of each technology is described by the *average measurement error* which can be found in Table 4.5 at the end of this section. The table lists the errors by the environment and the technology used.

4.4.1 Environment 1

The aim of testing in Environment 1 was to examine the technologies' behavior in small areas with dense placement of walls. The measurement errors in Environment 1 are stated in table 4.3. The results are organized by the real distance and the technology used.

Table 4.3: Measurement errors (in meters) observed in Environment 1

	1m	2m	3m	4m	5m	6m	8m	9m
BLE	1.110	1.450	1.940	6.790	9.896	28.010	27.250	30.100
RSS	1.245	1.734	2.800	4.689	6.723	43.100	32.500	35.010
RTT	0.370	0.700	0.980	0.930	1.900	2.801	2.763	2.500

The chosen propagation model appeared to be suitable for WiFi RSS and Bluetooth LE only in short distances.

The measurements at 1*m*, 2*m*, and 3*m* were taken in the same room where the AP/beacon was positioned, thus without a wall. The measurements at 4*m* and 5*m* were positioned outside the room, with exactly one wall between them and the AP/beacon. Finally, the measurements at 6*m*, 8*m* and 9*m* were placed in the same room, with two walls between them and the AP/beacon. The respective increase of measurement error can be observed with the measurement at 6*m*, which was performed right behind the second wall.

The measurement error increased (compared to the foregone measurement) three times in the case of BLE and almost seven times in the case of WiFi RSS (for WiFi RSS, the error calculated at 6*m* is the largest of errors calculated in Environment 1). The bigger measurement error can be observed even in the case of WiFi RTT. However, the error is not as significant as with the other two technologies.

4.4.2 Environment 2

The testing in Environment 2 provided more interesting results. The errors calculated for BLE and WiFi RSS at 16*m* and 17*m* respectively reached millions meters in the case of BLE and even billions in the case of WiFi RSS. Because of this, these results were not put in the table. It is, however, important to note that at 17 meters distance, the signal of BLE device was very low, which lead to higher periods between the value reads and also to the high variance of the measurement. The interesting observation is that the measurement errors calculated

Table 4.4: Measurement errors (in meters) observed in Environment 2

	1m	2m	3m	5m	8m	10m	13m	17m
BLE	0.890	1.710	4.010	7.645	5.012	43.765	38.101	–
RSS	1.200	0.410	5.401	44.100	24.380	121.20	1250.4	–
RTT	1.166	0.910	1.10	0.959	1.102	0.902	0.720	3.426

for WiFi RSS are several times higher than the ones calculated for Bluetooth LE in the area with many interfering devices.

High error values were expected in the area, but not with this scale. The 5*m* mark was located near the area of interference which can be observed by the enormous increase of measurement error with WiFi RSS. The interference was expected to be the significant factor affecting the testing results as most of the devices in the area of interference were operating on Bluetooth or a 2.4*GHz* WiFi. Also the RSS testing was performed with the 2.4GHz WiFi network as stated in Section 4.1. The enormous average errors of BLE and WiFi RSS stated in Table 4.5 were caused mostly by the high variance (and the standard deviation) of measured signal strengths. For example, the WiFi RSS measurement at 8*m* reported the RSSI variance of 41*dBm* and the variance of 13*dBm* at the distance of 13*m*. Bluetooth Low Energy showed high variance in all measurements. The lowest variance, of $7dBm$ was observed at the distance of $1m$, whereas the highest, $33dBm$, was observed at the distance of $10m$. WiFi RTT, on the other hand, behaved as expected providing sub-meter accuracy for the most of the times. One significant peak is the calculated error of $3.342m$ at the distance of $17m$. This error is, however, tolerable, because there were five solid walls between the AP and the receiver device.

Table 4.5: Average measurement errors (in meters) by environment and technology used

	Environment 1	Environment 2
BLE	10.020	770312
RSS	11.625	410618030.8
RTT	1.700	1.240

First of all, Sadowski and Spachos in [1] reported the accuracy error of WiFi RSS positioning of only $0.5183m$ and the accuracy error measured for Bluetooth of 1.1143. Sadowski and Spachos used a simi- lar approach of determining the model parameters according to the measured values. Unfortunately, they did not provide the parameters that their model used. According to their results, WiFi RSS proved itself to be more accurate than Bluetooth LE. On the other hand, their testing environment differed dramatically. Their testing took place in an empty room with minimized interference. The study by Lanzisera, Zats, and Piste compared the RSS approach to their own developed time-of-flight (TOF) measurement implementation. They used the device with the $2.4GHz$ antenna to transmit the signal [24]. This approach is similar to the testing environment used in this thesis, as WiFi RSS measurements were conducted against the 2.4*GHz* WiFi AP. Their results showed the accuracy error of the RSS approach to be around 8*m*, while the accuracy error of their TOF implementation was 1 3*m*. Although the results of their RSS do not correspond with this thesis's results, it showed much higher error than the paper presented by Sadowski and Spachos. On the other hand, the accuracy error of their TOF implementation looks similar to the WiFi RTT results in this thesis.

The next compared study is the paper by Schauer, Dorfmeister, and Maie. Their suggested round-trip-time-of-flight (RTOF) approach showcased the accuracy error of 1.33*m* [22], which is also very close to the smallest average error observed with WiFi RTT (1.231*m*).

Finally, the results observed in this thesis are similar to the ones discovered by Cobb in [42] and also by Horn in [16]. The Cobb's report the standard deviation of 0.83*m*m while Horn observed the accuracy of "about meter or two", which is also in consensus with the observations discovered by this thesis.

5. CONCLUSION

The aim of this thesis was to compare the new *IEEE 802.11mc* WiFi standard to the existing means of indoor navigation and positioning. The thesis proved that WiFi RTT is more accurate than each of the compared technologies with the lowest measurement errors recorded. WiFi RTT was also proven to be suitable for the environments with high levels of interference caused either by other devices' signal or by people moving across the testing space. The technology achieved the measurement error of 3.342*m* with five solid walls between the transmitter and the receiver and the error of around 2.5*m* with two solid walls between the transmitter and the receiver. This thesis proved that with the use of WiFi RTT, the navigation systems on Android can achieve the sub-meter accuracy mentioned in [15].

5.1 FUTURE WORK

One possible direction of future work based on this thesis is by improving the accuracy even more. For example, when implementing an in- door positioning/navigation system, one can utilize the least-squares or gradient descent or even a particle filter to smooth the received values, which should result in more accurate positioning [16].

Another possible way of improving the positioning accuracy is by combining WiFi RTT with another means of navigation. The following work may review which of the existing means would be the most suitable to be used in combination with WiFi RTT, or it could even lead to an entirely new technology.

Another possible direction of further research could focus on the implementation of the intelligent scanning mentioned in Section 3.2.2. The section already proposes the possible solution to mitigate the limitations introduced by Android. Once the RTT will be extended with the information of the exact location of the AP (such as latitude, longitude and altitude) [37], it may result in an interesting research work, which could possibly lead to the development of a universal and self-sustained indoor navigation system. This indoor navigation system would be self-sustained because there will be no need to enter the location of APs manually, which will increase the robustness and the flexibility of such system.

REFERENCES

[1] S. Sadowski and P. Spachos, “Comparison of rssi-based indoor localization for smart buildings with internet of things”, in *2018 IEEE 9th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON)*, Nov. 2018, pp. 24–29. doi: 10.1109/IEMCON.2018.8614863.

[2] Techopedia Inc. (2019). Line of sight (los), [Online]. Available: https://www.techopedia.com/definition/5069/line-of-si ght-los.

[3] K. Taylor and L. Silver, “Smartphone ownership is growing rapidly around the world, but not always equally”.

[4] The Android Open Source Project. (2018). Wi-fi rtt (ieee 802.11mc), [Online]. Available: https://source.android.com/devices/t ech/connect/wifi-rtt .

[5] Android 9 features and apis, [Online]. Available: https ://developer.android.com/about/versions/pie/android-9.0

[6] M. A. Al-Ammar, S. Alhadhrami, A. Al-Salman, A. Alarifi, H. S. Al-Khalifa, A. Alnafessah, and M. Alsaleh, “Comparative survey of indoor positioning technologies, techniques, and algorithms”, in *2014 International Conference on Cyberworlds*, Oct. 2014, pp. 245– 252. doi: 10.1109/CW.2014.41.

[7] “Navigation”, in *Oxford dictionary*, Oxford University Press, Ed., 1st ed., 2019. [Online]. Available: https://en.oxforddictionar ies.com/definition/navigation.

[8] S. G. Obreja, T. Aboul-Hassna, F. D. Mocanu, and A. Vulpe, “In- door localization using radio beacon technology”, in *2018 Inter- national Symposium on Electronics and Telecommunications (ISETC)*, Nov. 2018, pp. 1–4. doi: 10.1109/ISETC.2018.8583888.

[9] Cisco, “Mall of America○R Assists and Engages Visitors with Cisco Wireless”, 2018. [Online]. Available: https://www.cisco

.com/c/en/us/about/case-studies-customer-success-stor ies/mall-of-america.html.

[10] A. McCullough. (Aug. 2014). Who is a first responder, [Online]. Available: http://www.usfra.org/notes/Who_is_a_First_Re sponder .

[11] J. R. Guerrieri, M. H. Francis, P. F. Wilson, T. Kos, L. E. Miller, N. P. Bryner, D. W. Stroup, and L. Klein-Berndt, “Rfid-assisted indoor localization and communication for first responders”, in *2006 First European Conference on Antennas and Propagation*, Nov. 2006, pp. 1–6. doi: 10.1109/EUCAP.2006.4584714.

[12] F. DVOŘÁČEK, “Navigace v budově s využitím mobilních za- řízení”, Master’s thesis, The Faculty of Informatics, Masaryk University, Brno, 2018. [Online]. Available: https://is.muni.c z/th/mlayw/ .

[13] M. HOLČÍK, “Indoor navigation for android”, Master’s thesis, The Faculty of Informatics, Masaryk University, Brno, 2012. [On- line]. Available: https://is.muni.cz/th/o4tfv/ .

[14] M. Kotaru, K. Joshi, D. Bharadia, and S. Katti, *SIGCOMM Com- put. Commun. Rev.*, vol. 45, no. 4, pp. 269–282, Aug. 2015, issn: 0146-4833. doi: 10.1145/2829988.2787487.

[15] R. W. Frank Van Diggelen and W. Wang. (Jul. 2018). How to achieve 1-meter accuracy in android, [Online]. Available: https:www.gpsworld.com/how-to-achieve-1-meter-accuracy-in -android/.

[16] B. K. Horn. (). Indoor positioning using time of flight with respect to wifi access points, [Online]. Available: http://people.csail.mit.edu/bkph/ftmrtt.shtml.

[17] J. A. Puertolas-Montañez, A. Mendoza-Rodriguez, and I. Sanz- Prieto, “Smart indoor positioning/location and navigation: A lightweight approach”, *International Journal of Interactive Multi- media and Artificial Intelligence*, vol. 2, no. 2, pp. 43–50, Jun. 2013, issn: 1989-1660. doi: 10.9781/ijimai.2013.225. [Online]. Available: http://www.ijimai.org/journal/sites/default/files/2013/06/ijimai20132_2_5_pdf_27975.pdf.

[18] J. H. Choo, S. N. Cheong, and Y. L. Lee, “Design and development of nfc smartphone indoor interactive navigation system”, *World Applied Sciences Journal*, vol. 29, pp. 738–742, Jan. 2014, issn: 1818- 4952. doi: 10.5829/idosi.wasj.2014.29.06.1553.

[19] Online QR Code Generator. (2012). Qr codes in museums, [Online]. Available:

http://onlineqrcodegenerator.com/223/qr- codes-in-museums/ .

[20] E. Costa-Montenegro, F. J. González-Castaño, D. Conde-Lagoa, A. B. Barragáns-Martínez, P. S. Rodríguez-Hernández, and F. Gil-Castiñeira, "Qr-maps: An efficient tool for indoor user location based on qr-codes and google maps", in *2011 IEEE Con- sumer Communications and Networking Conference (CCNC)*, Jan. 2011, pp. 928–932. doi: 10.1109/CCNC.2011.5766643.

[21] Y. Chen and H. Kobayashi, "Signal strength based indoor geolocation", in *2002 IEEE International Conference on Communications. Conference Proceedings. ICC 2002 (Cat. No.02CH37333)*, vol. 1, Apr. 2002, pp. 436–439. doi: 10.1109/ICC.2002.996891.

[22] L. Schauer, F. Dorfmeister, and M. Maier, "Potentials and limitations of wifi-positioning using time-of-flight", in *International Conference on Indoor Positioning and Indoor Navigation*, Oct. 2013, pp. 1–9. doi: 10.1109/IPIN.2013.6817861.

[23] ZigBee Standards Organization. (2012). Zigbee specification, [Online]. Available: https://www.zigbee.org/.

[24] S. Lanzisera, D. Zats, and K. S. J. Pister, "Radio frequency time- of-flight distance measurement for low-cost wireless sensor localization", *IEEE Sensors Journal*, vol. 11, no. 3, pp. 837–845, Mar. 2011, issn: 1530-437X. doi: 10.1109/JSEN.2010.2072496.

[25] O. J. Woodman, "An introduction to inertial navigation", University of Cambridge, Computer Laboratory, Tech. Rep. UCAM- CL-TR-696, Aug. 2007. [Online]. Available: https :// www . cl.cam.ac.uk/techreports/UCAM- CL- TR- 696.pdf

[26] UAV Navigation. (2019). Uav navigation in depth: Dead reckon- ing operations, [Online]. Available: https://www.uavnavigati on.com/company/blog/uav-navigation-depth-dead-reckoni ng-operations .

[27] B. Ozdenizci, K. Ok, V. Coskun, and M. Aydin, "Development of an indoor navigation system using nfc technology", May 2011, pp. 11–14. doi: 10.1109/ICIC.2011.53.

[28] Bluetooth SIG, Inc. (2019). Radio versions, [Online]. Available: https://www.bluetooth.com/bluetooth-technology/radio- versions.

[29] B. Ray. (Nov. 1, 2015). Bluetooth vs. bluetooth low energy: What's the difference?, [Online]. Available: https://www.link-labs.c om/blog/bluetooth-vs-bluetooth-low-energy.

[30] Bluetooth SIG, Inc. (). Bluetooth generic attributes, [Online]. Available: https ://www .bluetooth . com /specifications /g att/.

[31] The Android Open Source Project. (2018). Bluetooth low energy overview, [Online]. Available: https://developer.android.co m/guide/topics/connectivity/bluetooth-le.

[32] Z. Lin, C. Chang, N. Chou, and Y. Lin, "Bluetooth low energy (ble) based blood pressure monitoring system", in *2014 Inter- national Conference on Intelligent Green Building and Smart Grid (IGBSG)*, Apr. 2014, pp. 1–4. doi: 10.1109/IGBSG.2014.6835225
.

[33] H. H. Strey, P. Richman, R. Rozensky, S. Smith, and L. Endee, "Bluetooth low energy technologies for applications in health care: Proximity and physiological signals monitors", in *2013 10th International Conference and Expo on Emerging Technologies for a Smarter World (CEWIT)*, Oct. 2013, pp. 1–4. doi: 10 . 1109/CEWIT.2013.6851347.

[34] M. Ali, L. Albasha, and H. Al-Nashash, "A bluetooth low energy implantable glucose monitoring system", in *2011 8th European Radar Conference*, Oct. 2011, pp. 377–380.

[35] Y. W. Prakash, V. Biradar, S. Vincent, M. Martin, and A. Jadhav, "Smart bluetooth low energy security system", in *2017 Inter- national Conference on Wireless Communications, Signal Processing and Networking (WiSPNET)*, Mar. 2017, pp. 2141–2146. doi: 10.1 109/WiSPNET.2017.8300139.

[36] G. Ruiz-García, J. M. Flores-Arias, F. J. Bellido-Outeiriño, A. Moreno-Muñoz, E. J. Palacios-García, and M. A. Quero-Corrales, "Home lighting controller based on ble", in *2017 IEEE International Conference on Consumer Electronics (ICCE)*, Jan. 2017, pp. 340– 341. doi: 10.1109/ICCE.2017.7889346.

[37] Wi-Fi Alliance. (Nov. 2017). Wi-fi certified location$^{\mathrm{TM}}$ orientation, [Online]. Available: https://www.wi-fi.org/file/wi-fi-certified-location-orientation.

[38] N. Carey. (May 31, 2005). Establishing pedestrian walking speeds, [Online]. Available: https://www.westernite.org/datacollec tionfund/2005/psu_ped_summary.pdf .

[39] Healthline Media. (2019). How to calculate stride length and step length, [Online]. Available: https://www.healthline.com/hea lth/stride-length#step-length .

[40] Wi-Fi Alliance. (Feb. 22, 2017). Wi-fi certified location$^{\mathrm{TM}}$ brings wi-fi R indoor

positioning capabilities, [Online]. Available: http s://wi-fi.org/news-events/newsroom/wi-fi-certified-lo cation-brings-wi-fi-indoor-positioning-capabilities.

[41] Compulab Ltd. (2018). Wifi indoor location device, [Online]. Available: https://fit-iot.com/web/products/wild/.

[42] J. Cobb. (Sep. 13, 2018). Testing wifi rtt on android p for indoor positioning, [Online]. Available: https://www.crowdconnected.com/blog/testing-wifi-rtt-on-android-p-for-indoor-positioning/.