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HW module for indoor-tracking purposes

HW modul pro podporu indoor lokalizace

BACHELOR THESIS

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CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

BACHELOR'S THESIS ASSIGNMENT

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II. Bachelor's thesis details

Bachelor's thesis title in English:

HW module for indoor-tracking purposes

Bachelor's thesis title in Czech:

HW modul pro podporu indoor lokalizace

Guidelines:

Get familiar with the technologies of localization in the interior of buildings. Also known as indoor tracking. Implement a simple HW module for localization based on signal strength and discuss the issue of measuring the current of battery-powered devices with peak consumption. The task can be divided in more detail as follows:
-research state-of-art currently used radio technologies in indoor tracking (UWB ToF, UWB TDoA, RSSI), their comparison in terms of different parameters
-selection of adequate radio module for RSSI localization
- design schematic wiring of the module with regards to low power consumption and battery operation
- design of module's PCB
- PCB production and mounting, basic testing of individual HW blocks
Within the current measurement issues, verify the consumption and service life of the designed module, specifically, for example, using a digital oscilloscope, a multimeter with DAQ memory, Coulomb Counting technology. Compare the conclusions from the life estimation based on the current measurement with the real life of the module for different battery or other sources. Discuss the conclusions and possible differences.
In laboratory conditions, perform only basic analysis of the accuracy of the indoor localization of the selected radio type

Bibliography / sources:

[1] Position Calculation with Least Squares based on Distance Measurements (Mathias Pelka, Lübeck University of Applied Sciences: Technical Report 2015; 2)
[2] Problematika UWB - https://www.decawave.com/products/
[3] Problematika BLE - https://locatify.com/blog/indoor-positioning-systems-ble-beacons/
[4] Obvody coulomb counting napr. https://www.analog.com/en/products/ltc2943.html
[5] STM32L - https://www.st.com/en/microcontrollers-microprocessors/ stm32-ultra-low-power-mcsus.html

Name and workplace of bachelor's thesis supervisor:

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Date of bachelor's thesis assignment: **15.11.2021** Deadline for bachelor thesis submission: **20.05.2022**

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by the end of summer semester 2022/2023

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III. Assignment receipt

The student acknowledges that the bachelor’s thesis is an individual work. The student must produce her thesis without the assistance of others, with the exception of provided consultations. Within the bachelor’s thesis, the author must state the names of consultants and include a list of references.

.

Date of assignment receipt

Student’s signature

Declaration

I warrant that the thesis is my original work and that I have not received outside assistance. Only the sources cited have been used in this draft.

In Prague ....

Kateřina Poláková

Acknowledgements

I am grateful to my thesis supervisor Ing. Ján Tomlain, for his feedback and valuable advice regarding this work. Thanks should also go to my family and friends for their unconditional support.

Kateřina Poláková

Title:
HW module for indoor-tracking purposes

Author: Kateřina Poláková

Thesis supervisor: Ing. Ján Tomlain

Abstract: The thesis deals with the issue of indoor localization using the Bluetooth Low Energy. The possibilities of indoor localization are looked into. The appropriate method of localization is chosen an the HW module is completed.
This work also concentrates on SW for indoor localization in 3D. The algorithm for localization based on Received signal strength indicator (RSSI) is created and used. The calculated position is compared with the real position of localized module in a graph. Lastly the power consumption of module used in different modes is measured and used for calculation of expected battery life.

Key words: STM32, STM32F042F6P6, RN4870, LTC4150, indoor tracking, indoor localization, RSSI, trilateration, Bluetooth Low Energy, Radio localization.

Název práce:
HW modul pro podporu indoor lokalizace

Autor: Kateřina Poláková

Vedoucí práce: Ing. Ján Tomlain

Abstrakt: Tato práce se zabývá problémem lokalizace ve vnitřních prostorách. Možnosti lokalizace jsou rozebrány.
Je zvolena vhodná metoda lokalizace a vytvořen HW modul. Tato bakalářské práce se taktéž zabývá SW řešením indoor lokalizace ve 3D. Je vytvořen algoritmus určující polohu na základě Indikátoru intenzity signálu (RSSI). Očekávaná pozice modulu je v grafu porovnána s pozicí skutečnou. Na závěr je změřený odběr proudu u daného modulu a vypočtena očekávaná životnost baterie.

Klíčová slova: STM32, STM32F042F6P6, RN4870, LTC4150, indoor lokalizace, RSSI, trilaterace, Bluetooth Low Energy, Radio localizace

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Introduction

Motivation for this work is the fact that currently the indoor localization is relevant topic and used in different environments and various industries, for example museums, shopping malls, universities, hospitals, railways, resorts, etc. Localization itself can be separated into different subgroups based on technology used or location.[1] These are discussed in the thesis. The most easily accessible technology is based on radio frequency.
The goal of this thesis is to build HW module for indoor localization, perform localization with this module and verify its usability in the given environment. For this work the localization based on the BLE technology will be used as well as microcontroller from STM, specifically STM32F04F6P6.
Consumption measurements of technology used will be performed. Battery life expectancy in battery powered mode will be estimated. The consumption measurements will be performed by Coulomb counter or multimeter with DAQ memory.

Chapter 1

Types of localization

There are different ways how to localize an object or a person. Therefore localization technologies could be split into different categories based on the localization system they use. Another way how to distinguish between the types of localization is where the localization should take place.
We will discuss different approaches to localize object outdoors or indoors.

1.1 Types of localization based on technology used

1.1.1 Satellite based

Satellites used for localization, including Global Positioning System (GPS) satellites, orbit Earth in the so called "medium Earth orbit". The GPS satellites orbit at an altitude of 20,200km and broadcast radio signals which contain information about their position, status and precise time.

Figure 1.1: Orbit classification by altitude. (NASA illustration by Robert Simmon)[2]

Since the signal travels through the space at the speed of light, a GPS receiver is able to compute, based on the information received, its distance from transmitting satellite. Once the receiver has computed its distance from at least four satellites it is able to determine its position on Earth in 3D.[3]
The GPS signal is not able to penetrate walls, ground and similar materials. For this reason the GPS localization cannot be used in indoor spaces.
Other Global Navigation Satellite Systems (GNSS) are BeiDou Navigation Satellite System (BDS), Galileo and GLONASS. [4]

1.1.2 Magnetic based

Magnetic based localization uses magnetic field to determine position of objects. Its main advantage is the ability to function in harsh conditions. The results are not influenced by changes in temperature, pressure, radiation and other environmental factors.
It allows localization through non ferromagnetic mediums. This method is being tested for precise intra-body medical intervention, such as Nasogastric (NG) intubation.[5]

1.1.3 Inertia based

Inertia based localization uses gyroscope and accelerometer to determine position of localized objects. Inertia localization is used to support different types of underwater localization for AUVs (Autonomous Underwater Vehicles).[6] [7]

1.1.4 Sound based

Humans can hear sounds between 20 Hz and 20 kHz. Therefore sound based localization operates out of this range. One of the acoustic localization currently used is ultrasonic localization.
Ultrasonic localization uses ultrasonic pulses send by tags to localize them. It is similar to the Ultra Wide Band(UWB), which we will describe later on. This type of localization is used by some animals(e.g. bats)
The correctness of the result is surface dependent. Uneven surface may reflect the ultrasonic pulse in wrong direction, hence the receiver will not receive any signal.
Currently the possible use of sound based localization is being researched in regards of its use in healthcare.

1.1.5 Optical based

Optical based localization uses light pulses, usually in the infrared spectrum. The infrared (IR) light has a wavelength of 700 nm to 1 mm. Human eyes can see light with wavelength between 400 nm to 700 nm, therefore the infrared light is not visible to human eyes.
Since it is impossible for the light to travel through the walls, the light signal is limited to one room and cannot be picked up by reader, which is not in line of sight. In this aspect the infrared localization provides better results with smaller amount of false positives then the radio localization. One of the examples of infrared localization is the self-localization of robot in indoor setting. IR LEDs are installed in the ceiling and photodiodes are attached to the top part of the robot. The robot determines its position based on the IR LED signals it receives.[8]

1.1.6 Radio frequency based

Radio frequency(RF) is one of the most commonly used methods for localization. Its main advantages are the ability of radio waves to penetrate

materials (of different origins - walls, objects, humans, etc.). Correct results can be obtained even for objects that are not in line of sight. Another advantage is that the radio waves cannot be detected without proper equipment, therefore they are invisible to human senses.
Due to the advantages of RF localization this technology will be used in this thesis.

1.2 Types of localization according to location

1.2.1 Indoor localization

Indoor localization tracks objects in indoor spaces. In indoor localization the precision is important, since the difference of mere 30 centimeters may provide incorrect result in respect of in which room the object is located.
Other challenges to be dealt with are walls and presence of other objects.
The best results for indoor localization can be usually achieved by RF.

1.2.2 Outdoor localization

The best known example of outdoor localization is GNSS. Out of which the most known is the GPS.
Outdoor localization is less demanding in respect of precise results - it is not necessary for the localization to be exact.

Chapter 2

Radio frequency based localization

2.1 Different types of RF localization

Radio frequency based localization is mostly used for indoor spaces or compact outdoor spaces. Radio frequency based localization can be categorised based on the frequency it operates.
The most common types of RF localization are as follows.

2.1.1 Ultra-Wideband (UWB)

UWB is a short range wireless technology, which can be used to transmit data, detect accurate location and directions. It has a band width greater than 500 MHz and carrier frequency larger than 2.5 GHz; it commonly operates in frequency range from 3.1 to 10.6 GHz.
When transmitter and receiver are in close proximity, UWB's accuracy can be up to 10 cm.
The wide bandwidth allows it to have a low power spectral density which minimizes interference with other technologies operating in the same frequency band. Another advantage of the low power density is that transmissions using UWB technology are secure as they are very difficult to detect.
Since UWB signals do not interact with each other and other radio frequency components, the technology can be successfully applied for creating noise-resistant solutions for example in health care.

UWB technologies are used for:

- car keys localization in BMW[9]
- increases AirDrop precision (iPhone)[10]
- tracking ventilators, X-ray equipment, goods, stock, or vehicles
- navigation and positioning on the territory of airports or railway stations
- interactive maps with point-of-interest visualization

- staff monitoring in real time
- warning on a possible collision with a vehicle or an employee

[11] [1]

2.1.2 Bluetooth Low Energy(BLE)

Bluetooth low energy is wireless technology. In comparison with Bluetooth Classic, Bluetooth low energy is supposed to provide similar functionality while using considerably less power. Therefore it is used in applications which run on batteries for long periods of time (months, and even years).
Advantage of BLE is that it can communicate with large amount of mobile devices and computers and it is not as costly as other RF.[12]

BLE technologies are used for:

- indoor localization
- monitoring sensors

2.1.3 WiFi

WiFi operates in RF bands of 2.5 GHz and 5GHz. It is one of the most used technologies and is mostly used in WLAN(Wireless Local Area Networks). It has high privacy and security standards. Since WiFi networks are mainly used for communication their priority is good connectivity and data rate, not the localization. Another thing to consider when choosing this technology is that the number of devices using the WiFi will increase in near future with technological advancements. This may cause overload and interference problems.[13]

2.1.4 Radio Frequency Identification (RFID)

Radio Frequency Identification (RFID) is a system which is composed from two elements: readers and tags. Reader emits radio waves and receives signals from tags. Tags can be mobile; or static - mounted on a post or already built into the architecture of building (room). One of the uses for RFID is as barcode, when a "scanner" (receiver) does not have to be in line of sight of the barcode (tag).
RFID uses the following frequencies:

- Low Frequency (LF) 125 to 134 KHz band
- High Frequency (HF) 13.56 MHz
- Ultra High Frequency (UHF) 433 MHZ and 860 to 956 MHz band
- Microwave Frequency 2.45 to 5.8 GHz band

Tags are of two types: powered by batteries (active RFID tags) or powered by the reader itself (passive RFID tags). Tags communicate their identity to readers using radio waves at several different frequencies. The data stored in tags can be anything from serial number to multiple sheets of information.[14]

RFID technologies are often used for:

- inventory control
- equipment tracking
- out-of-bed detection and fall detection
- personnel tracking
- ensuring that patients receive the correct medications and medical devices
- preventing the distribution of counterfeit drugs and medical devices
- monitoring patients
- providing data for electronic medical records systems

Based on the information from FDA website, FDA is so far not aware of any adverse effects of RFID. However possible interference with electronic medical devices such as peacemakers or implantable cardioverter defibrillators (ICDs) is being researched. [15]

2.1.5 Frequency Modulation Technology

Frequency modulation operates on 87.5 - 108 MHz RF spectrum. It is used for regional radio transmission across the globe. Thanks to the high frequency on which it operates, its signal is less likely to be affected by obstacles.
In the frequency modulation the amplitude of the signal does not change, but the frequency does.[16]
This technology is usable for indoor localization, but since the wave length of signal is around 3 meters and the frequency modulation base station tends to be far away, the receiver signal strength does not really change significantly for short distances.

2.2 Comparison of BLE, UWB, WiFi

Table 2.1: Comparison of BLE, UWB and WiFi

Type	UWB	BLE	WiFi
Frequency[Hz]	3.1 -10.6G	2.4G	2.5, 5 G
Accuracy [m]	0.1-0.5	5	10
Range(optimal)[m]	0-50	0-25	0-50
Power consumption	Low	Very low	Moderate

For my indoor localization module I choose BLE, since it has good price to battery consumption ratio and relevant information regarding this technology is easily accessible online.

Chapter 3

Bluetooth Low Energy

In following chapter we will describe Bluetooth Low Energy and its architecture.

3.1 Differences and similarities betweeen Bluetooth Clasic and Bluetooth Low Energy

All information and data regarding BLE and Bluetooth Classic were extracted from [17]. The Bluetooth technology is differentiated into two categories. Bluetooth Classic (further on "BC"), also referred to as Bluetooth Basic Rate/Enhanced Data Rate (BR/EDR) and Bluetooth Low Energy, also known as BLE. Bluetooth versions lower than 4.0 do not include BLE, but consist only of Bluetooth Classic. Bluetooth versions 4.0, 4.1, 4.2, 5.0 include Bluetooth Classic as well as Bluetooth Low Energy.

Data streaming
Both BC and BLE transmit data in the 2.4GHz unlicensed industrial, scientific, and medical (ISM) frequency band (2.402 – 2.480 GHz Utilized). BC streams data over 79 1MHz channels while BLE streams over 40 2MHz channels only.

Applications: BC and BLE are used for data transfer. For the audio streaming BC is mainly used, though, acording to bluetooths official website[17] the audio streaming using BLE is under development. BLE is also used in location services and device network.

Communication topologies:
BLE as well as Bluetooth Classic support Point-to-Point (P2P) communication between devices. BLE also supports broadcast and mesh communication.

Positioning Features:
BC does not include any positioning features. On the other hand BLE has the following features: position (advertising), direction (RSSI) and distance (AoA, AoD) findings.[17]

The differences between BLE and BC are shown in Table 3.1.

Table 3.1: Comparison BLE and BC[17]

	BLE	Bluetooth Classic
Frequency Band	2.4 GHz ISM Band	2.4 GHz ISM Band
Channels	40	79
Channel spacing	2 MHz	1 MHz
Bit rates	125 Kb/s, 500 Kb/s, 1 Mb/s, 2 Mb/s	1 Mb/s, 2 Mb/s, 3 Mb/s
Communication	P2P, Broadcast, Mesh	P2P

3.2 BLE architecture

The architecture of BLE can be divided into three basic parts: controller, host and application (described in Figure 3.1).

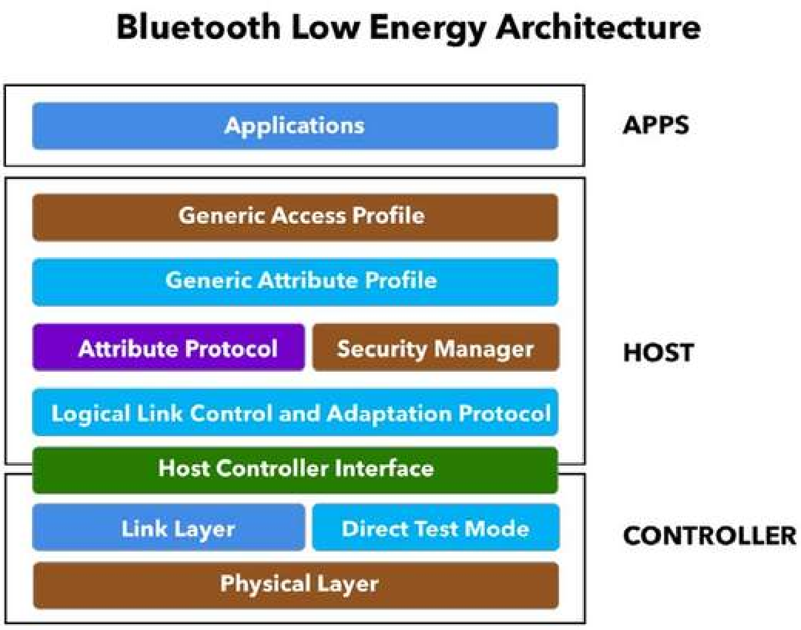

Figure 3.1: BLE Architecture [18]

3.2.1 Controller

Controller is composed of physical and link layer, as well as of direct test mode and the host/controller interface.
The Physical Layer is responsible for the bit transmission over radio at frequency 2.4GHz. The bits are coded into the radio signal using modulation scheme called Gaussian Frequency Shift Keying (GFSK). GFSK uses filter shaped as a Gaussian curve. In this modulation the ones and zeros have slightly shifted frequencies up for ones or down for zeros.
The purpose of the Direct Test Mode is to test function of the Physical Layer. It allows to analyze number of packets received or their content.
Link Layer is responsible for advertising, scanning, creating and maintaining connections as well as packets structure. Link Layer can be separated into two

types of channels: advertising channels and data channels. In BLE there are 40 channels, out of those 37 are data channels and 3 are advertising channels. Advertising channels are used to broadcast data, advertise the discoverability and connectability of BLE device, as well as to scan and initiate connections with other devices. Data channels on the other hand can be only used once the BLE device has been connected to other device and is ready to transmit data. The length of data transmission packets,is from 80μs to 376μs, with average at 144μs for data packets and at 128μs for advertising packets.
The Host Controller Interface allows communication with the controller through a standardized interface.

3.2.2 Host

The Host includes Logical Link Control and Adaptation Protocol (L2CAP), Security Manager, Attribute Protocol, Generic Attribute and Access Profiles. L2CAP is a multiplexing layer. L2CAP defines terms L2CAP channel and L2CAP signaling commands.
The Security Manager is used for pairing, which is usually followed by key distribution. Within role of Security Manager are generating hashes, confirmation values and short-term keys (used in pairing process).
In Attribute Protocol list of rules used for accessing data on peer device is defined as well as permissions to specific attributes. Attributes are addressed, labeled bits of data stored on an attribute server, which can be accessed or changed by attribute client. The Attribute Protocol defines six message types, but does not define the types of attributes.
The Generic Attribute Profile defines types of attributes used by Attribute Protocol.
The Generic Access Profile defines how are devices discoverable, connectable, bondable or how they present useful information to the users. It also defines grouping attributes for services and characteristics.

3.2.3 Application Layer

The Application Layer defines specifications which use the attribute groups defined by Generic Access Profile. Those specifications are characteristic, profile and service.
Characteristic are reusable bits of data with known format and labeled with Universally Unique Identifier (UUID).
Services can be primary or secondary and define behavior of characteristics, when read or written.
Profiles describe how devices should be discoverable and connectable.[19][20]

Chapter 4

Position determination in indoor localization

There are three basic ways how to determine position of transmitters and receivers. Two of them are time based - the receiver itself measures time between received signals (ToF, TDoA).The third one is based on the difference in strength of the signal at the receiver compared to signal strength at the proximity of the emitter.

4.1 Time of Flight (ToF)

Time of flight is a positioning method based on two way ranging. Two way ranging is when the tag needs to send and receive signal from anchor multiple times before the flight time between the anchor and the tag can be determined.[21]
The distance is calculated from the time of flight and speed of radio waves, which travel close to speed of light.

4.2 Time Difference of Arrival (TDoA)

Time Difference of Arrival is a strategy how to determine (estimate) location of a wireless emitter comparing the times, when signal from this emitter arrives at different receivers.
Since we use the difference in arrivals among the receivers to determine emitter's location, the inner clock of all the receivers have to be synchronised.[22]
One of the examples of TDoA usage is localization of cellular phone device from the time it takes for signal to reach surrounding cell towers.[21]

4.3 Received Signal Strength Indicator (RSSI)

RSSI is parameter that determines the strength of communication signals. The signal is measured in dBm. The higher the RSSI the stronger the signal is. Based on measuring the strength of the received signal in relation to its

original intensity the RSSI can be computed.
To calculate the value of RSSI following formula is used:

$$S(dBm) = P(dBm) - 10K \log d \tag{4.1}$$

Where d is estimated distance in meters. P is broadcasting power of the beacon in dBm at 1 m. S is measured signal value a.k.a RSSI in dBm and K is environmental factor, its commonly used value is between 2 and 4.
If we know the RSSI for the signal transmitted from beacon to receiver, we can calculate the distance of the receiver from the beacon by modifying equation 1 as follows:

$$d = 10^{\frac{P-S}{10 \cdot K}} \tag{4.2}$$

Knowing the RSSI value at the emitter and at the receiver, the approximate distance from each beacon can be determined and the position of the receiver calculated using following algorithm.[13][23]

4.3.1 Trilateration in 2D

If we have at least three beacons and we know their RSSI value, therefore their distance from the receiver, we can determine position of the receiver by the trilateration method.
Trilateration uses a fact that when we have four points (3 beacons and 1 receiver) and we know location of three of them (beacons) and distance of each of the three points from the fourth (receiver), we can determine the position of the remaining point by drawing 3 circles each of them with the center of each circle laying in the position of one beacon and the radius of each circle is corresponding with the distance of each beacon from the receiver. The intersection of all three circles marks the position of the receiver.

$$(x - x_1)^2 + (y - y_1)^2 = r_1^2 \tag{4.3}$$

$$(x - x_2)^2 + (y - y_2)^2 = r_2^2 \tag{4.4}$$

$$(x - x_3)^2 + (y - y_3)^2 = r_3^2 \tag{4.5}$$

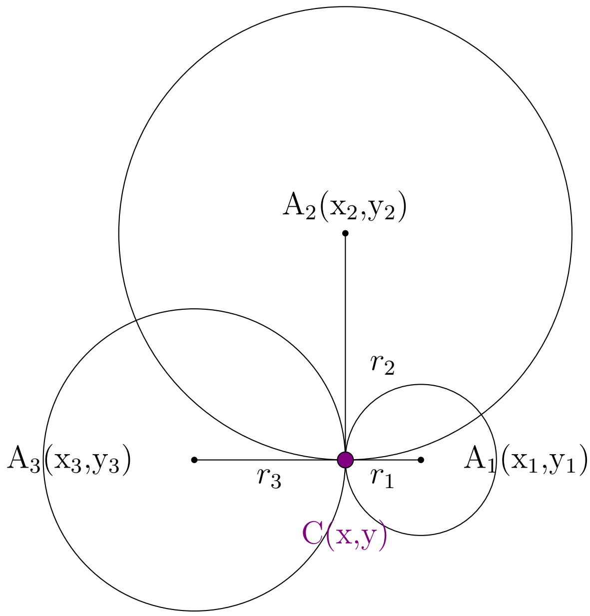

Figure 4.1: Trilateration in 2D

4.3.2 Multilateration

Trilateration can be further enhanced to multilateration, where more than three beacons are used. In comparison to trilateration multilateration increases computational complexity. The method is more resilient to errors and the precision is higher.

Chapter 5

HW solution for indoor localization module

In this chapter main components for the module schematic will be chosen, based on different requirements.
The key step in designing the schematic, and later on PCB, is choosing the main components. For my solution it means microcontroller and Bluetooth low energy module. Subsequently it is necessary to add to each component other components required by the data sheet. Later the main components have to be connected by correct pins in schematic.

5.1 Component Choice

Due to chip and semiconductor shortage the HW will be build from already preexisting modules. The best option is to have one kit with microcontroller and another with the BLE module.
The kits were chosen according to following criteria:

- **Availability** - whether it is possible to acquire kit in time with regards to a due date of the thesis
- **Cost**
- **Know-how**- whether I have ever used given component or module before or the datasheets are easily available and comprehensible.

5.1.1 Microcontroller

The microcontroller controls the bluetooth module and coulomb counter. It is responsible for communication with bluetooth module, which is bidirectional, as well as communication with the coulomb counter which could be either one directional or bidirectional - this depends on the type of coulomb counter chosen.
I decided to use one of the STM32 microcontrollers, because I have worked with them previously. Out of the STM32 line the ideal microocontroller would be one from the line of Ultra low power microcontrollers. This choice will allow for longer battery life should the device be battery powered. Due to worldwide shortage of semiconductors and long delivery time, that exceeded

the deadline of my thesis, buying a new microcontroller was not an option. For this reason I used kit I built during the Laboratories of Industrial Electronics and Sensors in summer semester 2021.[24] The kit uses the microcontroller STM32F042F6P6 in packaging TSSOP20 WITH 20 pins. The kit consists of the USB, microcontroller and voltage stabilizer. The microcontroller is not out of the Ultra low power line, therefore its power requirements are higher. Though it is not part of the ultra low power line, but of F04 line, it has another advantage. The main advantage of the F04 line is the cost, the F04 line includes one of the cheapest STM microcontrollers available.

5.1.2 Bluetooth module

The Bluetooth module is responsible for transmitting messages from microcontroller to the mobile phone and receiving signals from the beacons (emitters). To complete required tasks the module should be equipped with antenna. For easier communication with the microcontroller the existence of UART is preferable.
The RN4780 BLE module was chosen for its availability, its inclusion of antenna and ability to communicate over UART with ASCII commands.

5.2 Schematic

As a referential material for my proposed schematic and real connection of modules on breadboard the data sheets for BLE module RN4870[25] and microcontroller STM32F04F6P6[26].

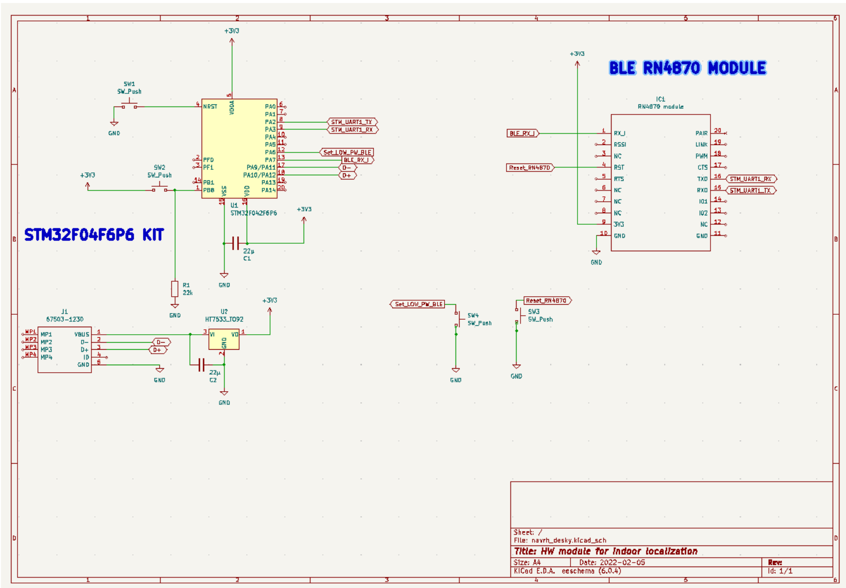

Figure 5.1: Schematic of HW module

Microcontroller STM32F04F6P6 The microcontrollers connection in schematics is based on following requirements:
For the correct voltage supply the pins VDD and VDDA have to be connected to the voltage source, and VSS connected to the ground.

To reset the microcontroller, pin NRST is pulled low.
To boot, pin PB1 has to be pulled high.
Pins PA2 and PA9 can be used as UART TX, while pins PA3 and PA10 as UART RX.[26]

BLE module RN4870
The module connection in schematics is based on following requirements:
Since the module will communicate with microcontroller over UART, it is necessary to connect module's UART RX to microcontrollers UART TX and vice versa.
To reset the module, the RST N pin has to be pulled low. This can be done by user pressing the button or, based on the data sheet of RN4870, by the power dropout protection.
To be in app mode, pin P2 0 is pulled high.
An indication LED can be connected to pin P0 2.[25]

5.3 Real module

The real module is build by connecting modules on breadboard.
For the microcontroller and the BLE module their final connection will be as in schematic. The connection of the Coulomb counter is described in following chapter, as in this case the coulomb counter is going to be an external measurement device which is not connected to the final module permanently, but only when the current usage measurement is required.

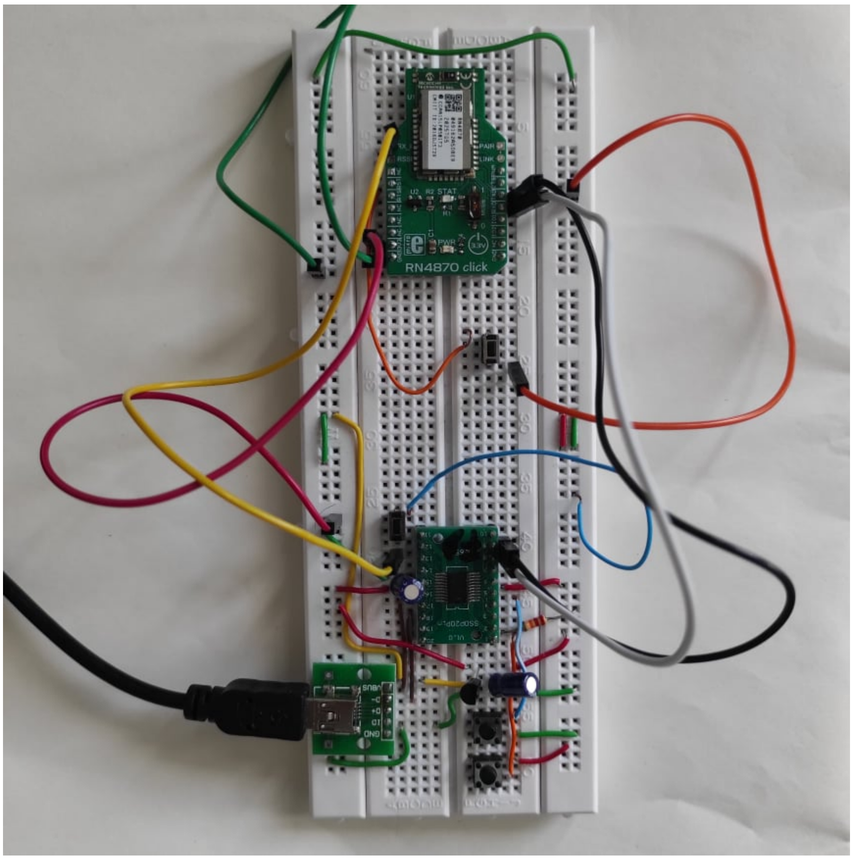

Figure 5.2: Realization of HW module

5.4 HW module Testing Environment

5.4.1 Beacons

The beacons were provided by thesis supervisor. Each beacon requires voltage supply of 24V, has its name and MAC address. When connected to power, beacons are sending advertisement packets in periodical intervals. Packet is specific to each beacon, therefore each packet identifies its sender. For further use and programming of the localization module it was necessary to find out address (name) of each beacon. To achieve that, the BLE module was connected over UART to PC with program RealTerm. Each beacon was connected to the power, the scanning was initialized on the BLE module and with resulting address each beacon was labeled. From here forward the beacons are going to be described by last two numbers in their addresses. The resulting beacons therefore are Beacon 13, Beacon 28, Beacon 43
and Beacon 48.
For testing purposes it was necessary to install beacons.

Beacons installation
To install the beacons I first measured the room and marked the points where the cables connecting the power source to the beacons will lead. After experimenting with the cable I decided to attach cable to a wall at least every 30 centimetres. The beacons were installed in corners of the laboratory all at same height of 2.30 meters. As there was only one 24 voltage adapter all beacons were connected to it in parallel. On Figure 5.3, 5.4, 5.5 and 5.6 all installed beacons are shown. The Figure 5.3 also shows the connection to the power socket using 24 V adapter.

Figure 5.3: Installation of beacon 13

Figure 5.4: Installation of beacon 28

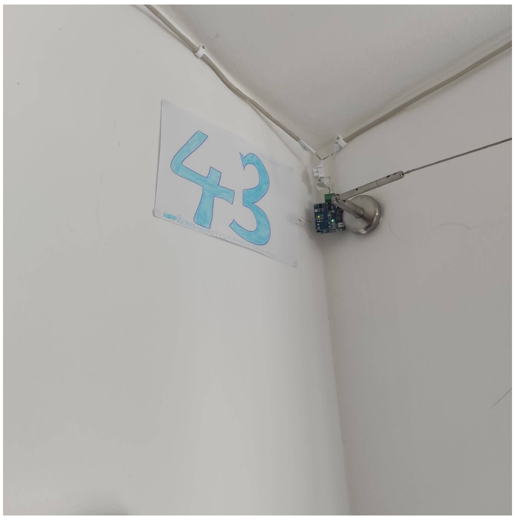

Figure 5.5: Installation of beacon 43

Figure 5.6: Installation of beacon 48

5.4.2 Laboratory conditions

The size of the laboratory is 5.80 meters long and 3.45 meters wide. It is surrounded by walls from plasterboard and it shares three out of four walls with other spaces with BLE devices, therefore the radio noise from the surrounding areas can be observed.
In following Figure 5.3 beacons are labelled as points B with index, which corresponds with their addresses.

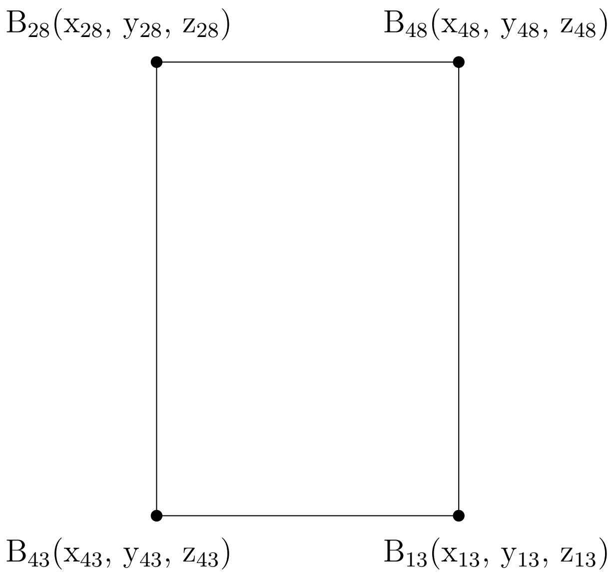

Figure 5.7: Laboratory layout top view

Values of the x, y, z coordinates were chosen based on the beacon location. One point in the coordinate system corresponds with one meter in reality.

$$z_{13} = z_{28} = z_{43} = z_{48} = 2.30\text{m} \tag{5.1}$$

$$x_{13} = x_{28} = 3.45\text{m} \tag{5.2}$$

$$x_{43} = x_{48} = 0\text{m} \tag{5.3}$$

$$y_{13} = y_{43} = 0\text{m} \tag{5.4}$$

$$y_{28} = x_{48} = 5.80\text{m} \tag{5.5}$$

Chapter 6

SW solution for indoor localization module

6.1 Communication with the RN4870

The RN4870 BLE module can communicate either over UART or I2C Serial bus. For this application the microcontroller and the BLE module communicate over the UART. The RN4870 can work in two modes: either in data mode or in command mode. In the data mode the RN4870 works as a pipeline - it receives data from paired device and sends them to microcontroller and receives data from the microcontroller and transmits them to the paired device. When in the Command mode the microcontroller can control or configure the RN4870 by sending valid ASCII commands over UART. The most relevant ASCII commands are as follows.

6.1.1 Common ASCII commands for communication with RN4870

"$$$" is send when the microcontroller requests the Module to exit Data Mode and enter Command Mode.

"—CR", where CR stands for Carriage return, is used to exit the Command Mode and enter the Data Mode.

Following commands can be only used when the BLE module is in the Command Mode and are followed by the CR. All commands are always responded to by RN4870 and the BLE module cannot receive any other commands until the previous command is responded to. The responses to Set or Action commands are **"AOK"**, which indicates success or **"ERR"** which indicates failure.

"S-,<string>" is used to set the name of the BLE module so it is easily recognized by user. To set the name of the RN4870 simply insert the required name instead of <string>.

"F" is used to scan for other devices in surroundings.

When scanning the BLE module scans for all visible devices. Since in every environment in residential area there are multiple bluetooth devices we might prefer to scan just for certain devices. To do so, we need to add devices' addresses to the white list. Once there is at least one address in the whitelist, everytime the RN4870 receives **"F"** command, it scans only for the devices whose addresses are on the white list.

"JA,<0,1>,<MAC>" is used to add device to the white list. MAC address is the address of device which is to be added to white list and 0 or 1 indicates whether the address is public(0) or private(1).

"JD" is used to display all devices currently on the white list.

"JC" deletes all addresses from the white list.

"X" is used to stop ongoing scanning. [27]

6.1.2 RSSI Constant

For the calculation of correct position in eq (4.1), it is necessary to know the value of K. K stands for environmental factor. It is a constant specific to each transmitter. To find the value of K, the eq (4.1) can be adapted into following:

$$K = \frac{P(dBm) - S(dBm)}{10 \log d} \tag{6.1}$$

The value of P is the value of RSSI one meter away from the transmitter. The BLE module was used to obtain the RSSI value. The module sends results of its scanning process to microcontroller in text form and the RSSI value is given in hexadecimal number, that shall be converted to number within range [-128,127] from two's complement. The functions for reading the whole information of received message, determination of which beacon is the sender of given message and translation of the RSSI value into decimal were implemented. The noise in the laboratory is quite high and therefore the values of RSSI keep changing, as can be seen on Figure 6.1, 6.2, 6.3, 6.4. From the figures it is also possible to determine, that the fluctuation of values is not limited to only one beacon, the noise affects all beacons. The measurements necessary to obtain those figures had been done between 1 a.m. and 3 a.m., to ensure they were less influenced by the RF interference from surrounding apartments.

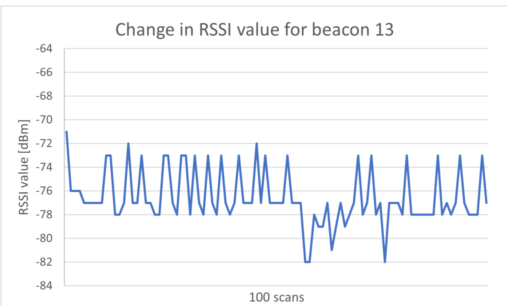

Figure 6.1: RSSI value for beacon 13 at chosen point during 100 scans

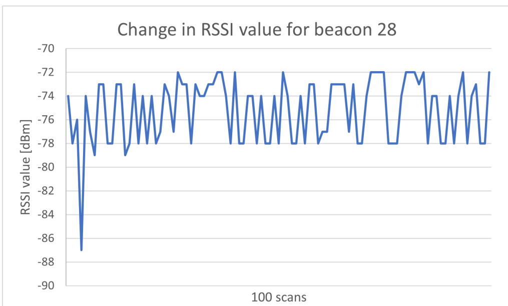

Figure 6.2: RSSI value for beacon 28 at chosen point during 100 scans

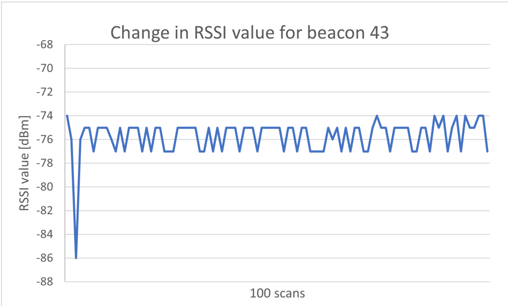

Figure 6.3: RSSI value for beacon 43 at chosen point during 100 scans

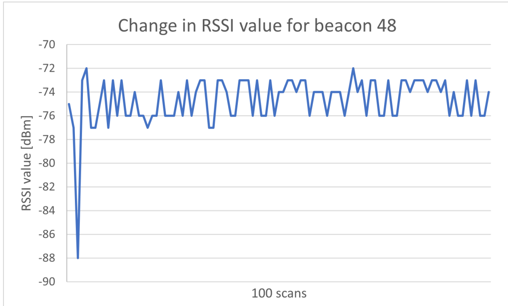

Figure 6.4: RSSI value for beacon 48 at chosen point during 100 scans

To minimize the noise interference the value of RSSI one meter away from the transmitter is going to be measured multiple times and then averaged. In Table 6.1 values of P for each transmitter are recorded.

Table 6.1: Values of P by each transmitter

Beacon	13	28	43	48
P(dBm)	-66	-67	-67	-66

When the value of P is known for each transmitter, the values of K can be computed for each transmitter as well. To do so, it is necessary to obtain multiple measurements of RSSI value at different positions (as many as possible) in the lab and measure the distance of each of those positions from each transmitter. For each position multiple measurements of RSSI will be conducted to minimalize the noise, out of those measurements the average is taken and used to calculate the constant K for each beacon for given position. The final K for given beacon is acquired by averaging the K values for given beacon at different positions. Final values of constant K are in the Table 6.2.

Table 6.2: Values of constant K for each transmitter

Beacon	13	28	43	48
K	2.477	2.196	2.375	2.341

6.1.3 Position from RSSI calculation

Firstly it was necessary to compute the approximate distance of the module from each beacon. For that the equation in 4.2 was used. The distance of each beacon from the HW module is labeled r_{13}, r_{28}, r_{43}, r_{48}, where the index number stands for the last two numbers of beacon from which the distance was calculated.
Statement that the HW module has distance r_{13} from beacon 13 is analogical to statement that the HW module is located on surface of sphere with radius r_{13} and centre in the beacon 13 position. This can be applied to all beacons. The final location of HW module should be at the intersection of all four spheres.

Trilateration method

When the distance from each beacon is known, the position of HW module can be determined by trilateration method mentioned in chapter 4 for 2D applied in 3D. We can edit eq. (4.3), eq. (4.4) and eq. (4.5) to include the z direction and add another equation for fourth beacon.

$$(x - x_{13})^2 + (y - y_{13})^2 + (z - z_{13})^2 = r_{13}^2 \tag{6.2}$$

$$(x - x_{28})^2 + (y - y_{28})^2 + (z - z_{28})^2 = r_{28}^2 \tag{6.3}$$

$$(x - x_{43})^2 + (y - y_{43})^2 + (z - z_{43})^2 = r_{43}^2 \tag{6.4}$$

$$(x - x_{48})^2 + (y - y_{48})^2 + (z - z_{48})^2 = r_{48}^2 \tag{6.5}$$

Due to defined positioning system we know the values of x_{13}, x_{28}, x_{43}, x_{48}, y_{13}, y_{28}, y_{43}, y_{48},z_{13}, z_{28}, z_{43}, z_{48}. Therefore we can edit the equations (6.2)-(6.5) into following form:

$$(x - 3.45)^2 + y^2 + (z - 2.30)^2 = r_{13}^2 \tag{6.6}$$

$$(x - 3.45)^2 + (y - 5.80)^2 + (z - 2.30)^2 = r_{28}^2 \tag{6.7}$$

$$x^2 + y^2 + (z - 2.30)^2 = r_{43}^2 \tag{6.8}$$

$$x^2 + (y - 5.80)^2 + (z - 2.30)^2 = r_{48}^2 \tag{6.9}$$

The intersection of three spheres does not usually give only one point but commonly two. This is due to the limitation of measuring environment, since the other intersection point would be above the plane which connects all beacons. The plane is at height 2.3 meters and at the ceiling level, therefore any point above the 2.3 meter mark would be out of the laboratory physical bounds.

Solution to those equation exists only when three (or four) of the spheres intersect in one point. Unfortunately due to the radio noise from other devices and the precision issues of RSSI counting it was not achievable in real conditions. Instead of intersecting at one point the spheres did intersect in more points and never all of them in the same point.

The spheres were either all overlapping, none overlapping or anything in between. To solve this I used the following strategies based on comparison of distance: neighbour comparison, diagonal comparison and the combination of neighbour diagonal comparison.

Neighbour comparison

To determine x,y coordinates by neighbour comparison method the values of each two beacons which are next to each other have their radius values compared based on the ratio of their radiuses. The points O, P, Q, R lay on the edges connecting the beacons and are defined as follows:

$$O_x = 0 \tag{6.10}$$

$$O_y = \frac{y_{28} \cdot r_{43}}{r_{43} + r_{48}} \tag{6.11}$$

$$P_x = \frac{x_{13} \cdot r_{48}}{r_{48} + r_{28}} \tag{6.12}$$

$$P_y = y_{28} \tag{6.13}$$

$$Q_x = x_{13} \tag{6.14}$$

$$Q_y = \frac{y_{28} \cdot r_{13}}{r_{28} + r_{13}} \tag{6.15}$$

$$R_x = \frac{x_{13} \cdot r_{43}}{r_{43} + r_{13}} \tag{6.16}$$

$$R_y = 0 \tag{6.17}$$

Points O, P, Q, R forms vertices of the rectangle. The localized module should be within the rectangle and its most probable position is in the centre of mass (point N) of rectangle $OPQR$.

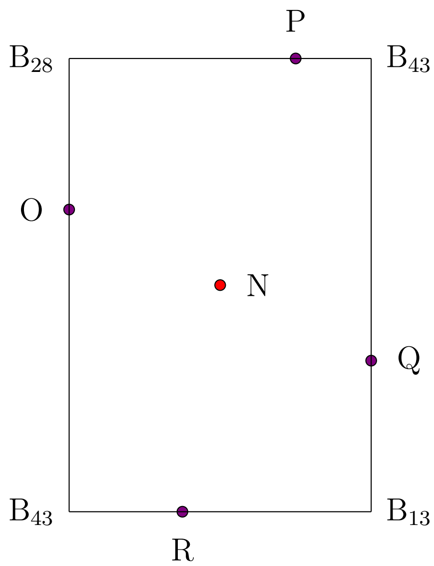

Figure 6.5: Neighbour comparison method

The centre of mass has following coordinates:

$$N_x = \frac{P_x + R_x}{2} \tag{6.18}$$

$$N_y = \frac{O_y + Q_y}{2} \tag{6.19}$$

To calculate z coordinate firstly I check whether the x, y coordinates correspond with surface of the sphere. If there is more than one solution the result is averaged. Calculation of z coordinate is identical for diagonal comparison and combination of diagonal and neighbour comparison. If the resulting point is out of the laboratory boundaries, the nearest point laying on the boundary is chosen instead.

Diagonal comparison

To determine x,y coordinates by diagonal comparison the values of beacons which share diagonal are compared and the ratio of their radiuses is calculated. Point C lays on the diagonal between beacon 43 and 28, and it divides the diagonal in the same ratio as is the ratio between radiuses r_3 and r_2. Point C lays in distance d_3 from the beacon 43. Analogically the point D lays on diagonal between beacon 48 and beacon 13. It also divides diagonal in given ratio and lays in distance d_4 from beacon 48. The size of the diagonal (d) is computed in eq. (6.13).

$$d = \sqrt{x_{13}^2 + y_{28}^2} \tag{6.20}$$

$$d_3 = \frac{d \cdot r_3}{r_3 + r_2} \tag{6.21}$$

$$d_4 = \frac{d \cdot r_4}{r_4 + r_1} \tag{6.22}$$

$$C_x = \frac{x_{13} \cdot d_{43}}{d} \tag{6.23}$$

$$C_y = \frac{y_{28} \cdot d_{43} \cdot y_{28}}{d} \tag{6.24}$$

$$D_x = \frac{x_{13} \cdot d_{48}}{d} \tag{6.25}$$

$$D_y = y_{28} - \frac{d_{48} \cdot y_{28}}{d} \tag{6.26}$$

All points which has the distance from beacons on the diagonal in same ratio lays on the parallel line to diagonal at points C and D. Intersection of those two lines (point M) is the most probable position of the HW module.

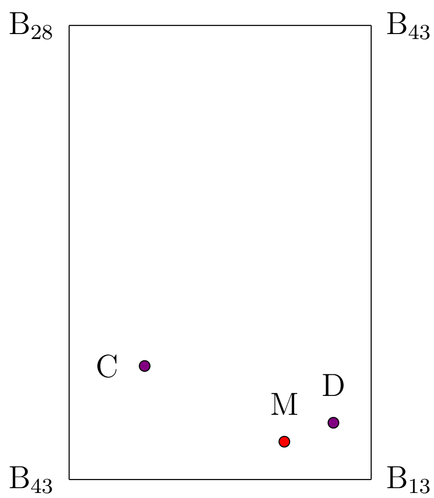

Figure 6.6: Diagonal comparison method

$$M_x = \frac{D_y + \frac{y_{28}}{x_{13}} \cdot D_x - C_y + \frac{x_{13}}{y_{28}} \cdot C_x}{\frac{y_{28}}{x_{13}} - \frac{x_{13}}{y_{28}}} \tag{6.27}$$

$$M_y = -\frac{x_{13}}{y_{28}} \cdot M_x + C_y + \frac{x_{13}}{y_{28}} \cdot C_x \tag{6.28}$$

Combination of diagonal and neighbour comparison

To calculate x,y coordinates, the above mentioned methods are used with small adjustment. If the point M created by diagonal comparison is within the bounds of rectangle created by neighbour comparison, the point created by diagonal comparison is chosen. If the point M is on the outside of this rectangle, the center of mass (N) of the rectangle is connected with point M. The final point lays in the center of the line defined by point M and point N.

6.1.4 Transmission of results to mobile device

Final position is calculated in form of x, y and z coordinates.
Everytime the position is calculated, it is send through UART to attached BLE module, which transmits it to the paired device. Paired device, in this case mobile phone, uses freely available app Serial Bluetooth Terminal to connect and communicate with BLE module.

6.2 Localization results

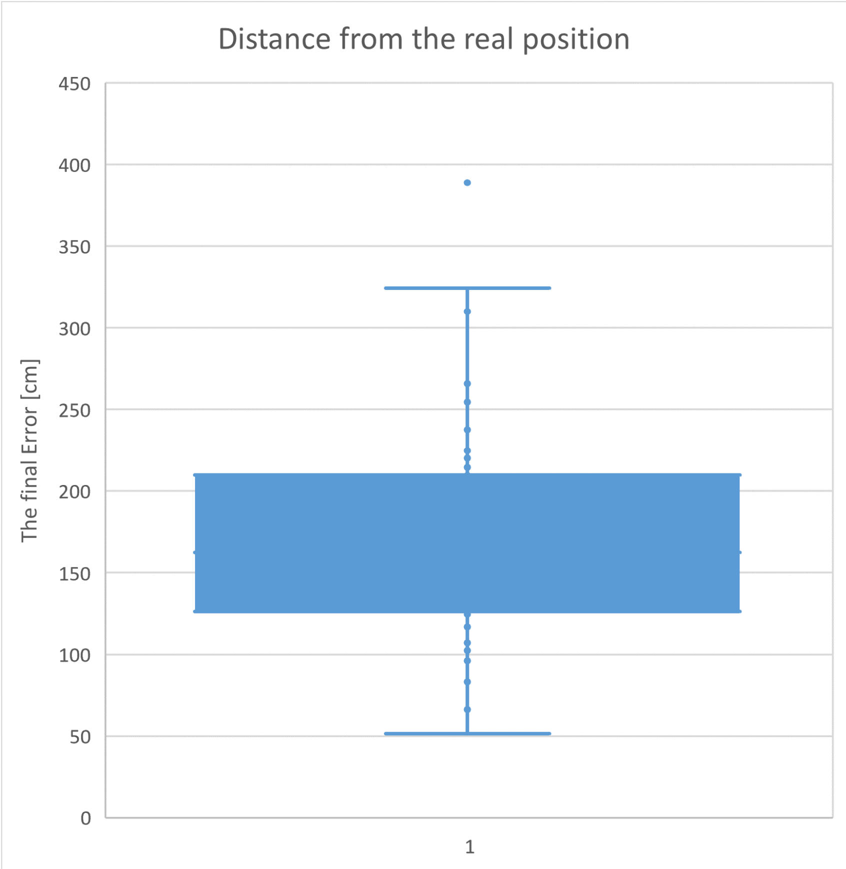

Figure 6.7: Measurement error

The Figure 6.7 depicts the distance in centimetres between the module's real and calculated position, using the neighbour comparison. It would seem that the localization error is reasonable, since the precision of BLE module should be in meters not centimeters, but the data set for this measurement consists only out of 50 measurements, therefore it is not significant. During the measuring process not all data sets had as promising error values. This packet was measured at night, which usually increases the precision of the localization, since there is less interference and noise.
In a day time it is less possible to determine the exact localization. I believe that this is caused by noise, which has variable values both in time and space. This variability and probably large fluctuations in the values of the noise have causes the measurement to be burdened with significant errors.

Chapter 7

Measurement of battery lifespan

In this chapter we will measure the current consumed by the BLE module to estimate life expectancy of 3V battery used as power source. For the measurement 2 different technologies will be used: multimeter with DAQ memory and Coulomb Counter. Measurements from each measuring device used will be compared.
First I measured the power consumption of the whole module with both a coulomb counter and a multimeter in all modes of the bluetooth module. In both measurement methods, when switching the bluetooth module to low energy mode, the power consumption was reduced, but only slightly. To lower the consumption further all LED diods were disconnected, but the current consumption was not reduced significantly. After disconnecting the bluetooth module and other peripherals, I found that the processor consumes an average of 10 mAh in idle mode. Since I do not put the processor to sleep in the program or switch it to power saving mode, the consumption never decreases. Thus, it is irrelevant to measure the processor's power consumption when its lower power capability is not used. Therefore I will only measure the power consumption of the BLE module.

7.0.1 BLE modes

During the run of the program, BLE module is always in one of the three modes: low power consumption mode, scanning mode or transmitting mode.
Low power consumption mode has to be enabled from the microcontroller by command **"SO, 1"**, before sending the command, the pin RX I has to be first pulled high. Afterwards the BLE module can be woken up by the pin RX I being pulled low. After exiting the low power mode it takes approximately 5 ms before the BLE module is able to respond to commands.

7.1 Multimeter with DAQ memory

In the current consumption measurement the KEYSIGHT 34465A digital multimeter was used. The PWC was set to 10 and firstly the current consumed by microcontroller was measured. The histogram of the measurement is in Figure 7.4 and the measured value is in Table 7.1. Subsequently the current consumption of BLE module was measured in different BLE modes, the histograms from those measurements are in Figure 7.1 to 7.3, and discussed in section 7.3, where they are compared with the coulomb counter measurements.

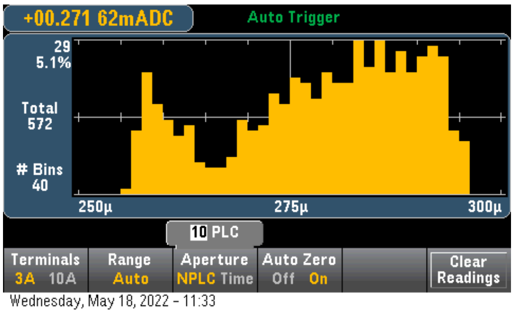

Figure 7.1: BLE in low power mode

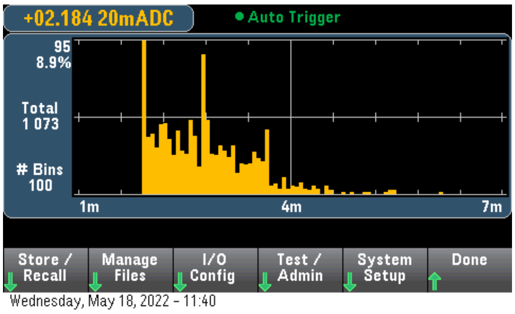

Figure 7.2: BLE in scanning mode

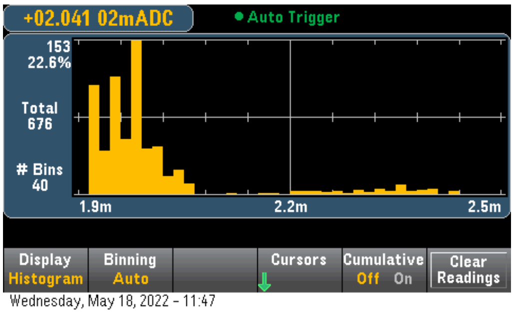

Figure 7.3: BLE transmitting mode

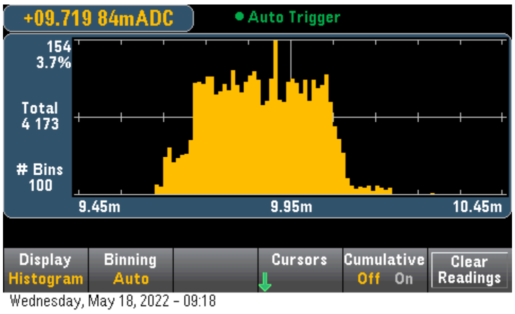

Figure 7.4: MCU idle

7.2 Coulomb Counter

Coulomb counter is a device, which measures the cumulative current used from the source by the load. It can also measure current transferred to the source, e.g. rechargeable batteries. Due to its ability to measure current used, the coulomb counter can be used to determine the state of charge of the battery, and therefore its lifespan.
Coulomb counters are quite useful with circuits which do not have constant current consumption due to their various functions which require different amount of current at different times.
Each time certain amount of coulombs passes through the coulomb counter it sends pulse to the connected device. The coulomb count causing this pulse can be modified by changing the resistor which the coulomb counter uses to measure coulombs. Coulomb is defined as:

$$1\text{C} = 1\text{A} \cdot 1\text{s} \tag{7.1}$$

Therefore one ampere hour is equal to 3600C.
Current is the amount of charge which is transferred over certain period of time. To calculate current from the charge used, following equation is applied:

$$i = \frac{\partial Q}{\partial t} \tag{7.2}$$

.

7.2.1 Choice of coulomb counter

Most common coulomb counters are the LTC coulomb counters, which are easily accessible, have well documented data sheets and are not overly expensive. When choosing the optimal coulomb counter for this project the key feature was its availability as well as simple use. The key requirement for the actual measurement was that the coulomb counter comes in a kit.
The coulomb counter LTC4150 comes in a kit with attachable headers. The headers were necessary to solder to the module. It has an input for battery and voltage output to the measured circuit (load) for which it serves as a power source, while counting how many coulombs have passed through it to the load. Other pins are: SHDN, CLR, POL,GND, VIO, INT.

7.2.2 Connection to the BLE module and processor

Connection of Coulomb counter LTC4150 is as follow:
firstly the pin headers have to be mounted to the module. In the kit pins SHDN and CLR needs to be left unconnected. When the CLR was pulled high as it is already connected in kit to pin INT the module never send out any interrupts, therefore the measurement was not possible.
The GND and the GND from input are connected, therefore, if the INT is connected to processor which shares GND with the coulomb counter this pin does not have to be connected.
For the same reason VIO was connected with soldering iron with the input VCC.
All SJ1, SJ2 a SJ3 had to be soldered shut.
By default the INT is high and pulled low when the the amount of charge passing through the coloumb counter reaches the value given by the sensing resistor. Since the original size of the resistor was 0.05Ω the INT reacted everytime 0.17067759 mAh passed. This number is too great for measurement of the power consumption in reasonable time on the BLE module. Therefore the sensing resistor was changed to firstly 0.5Ω, with INT reacting when 0.017067759 mAh passed. For measurement of power consumption of BLE in Low power mode the sensing resistor is changed to 11Ω, with INT reacting when 0.00075807 mAh passed.[28][29]

7.3 Comparison of the multimeter with DAQ memory and coulomb counter

All measured values from coulomb counter or multimeter were averaged. The average for each measuring device and each mode is in the Table 7.1.

Table 7.1: Current consumption by BLE module RN4870 in different modes

	LTC41503	multimeter 34465A
low power mode [mAh]	0.2955	0.2804
scanning mode [mAh]	2.9308	2.7193
transmitting mode [mAh]	2.0792	1.9976

The measurements above show slight difference in measured values by multimeter and coulomb counter. Since the difference in values is smaller than 10% I will assume both measuring devices measured correctly.
The difference in power consumption by BLE module is significant. If the BLE module is in the scanning mode and is sent into low power mode, its consumption lowers to approximately 10% of the power consumption in scanning mode.

7.4 Battery life expectancy

To properly estimate battery life expectancy, it was first necessary to measure average time of scanning, transmitting and low power consumption. The time varied based on the program used. The time of the low power mode was set for 0, 5, 15 and 60 seconds. The averaged time values are: for transmitting mode 1.34 seconds and for scanning mode 16.5 seconds.

Table 7.2: CR2032 battery life expectancy as a function of duration of low power mode in one cycle

Low power time	consumption per cycle	cycle length	length of life
0 s	0.0132 mAh	17.84 s	3.67 days
5 s	0.0135 mAh	22.84 s	4.57 days
15 s	0.0143 mAh	32.84 s	6.21 days
60 s	0.0178 mAh	77.84 s	11.84 days
120 s	0.0225 mAh	137.84 s	16.62 days
300 s	0.0365 mAh	317.84 s	23.64 days
600 s	0.0599 mAh	617.84 s	28.04 days

In the above Table 7.2 the length of life was computed for button battery with capacity 235 mAh. The values of current consumption measured by multimeter were used. As we can see with increasing length of sleep mode per cycle the life expectancy of the battery increases.

Conclusion

In this work we discussed different technologies commonly used for localization. For realisation the BLE technology was chosen due to its low power requirements and relatively optimal accuracy. The chosen BLE module is RN4870, its main advantage is communication over UART in ASCII commands and good documentation. To operate the BLE module microcontroller STM32F04F6P6 was chosen due to its availability and low price.
Due to chip shortage and other outside factors, it was obvious that realisation of the module itself using my own created PCB would not be possible in given time frame. Therefore the HW module realisation is based on connecting different already completed modules on a breadboard. The element of using the soldering iron was not omitted, since it was used to connect the headers to the coulomb counter.
For the implementation of the RSSI based position calculation different methods were used. The trilateration method in its original form was not sufficient, as it works well in ideal cases, but not in the reality. Therefore the trilateration method was enhanced with methods determining position based of the ratio between the values of RSSI received from different beacons.
The power consumption of BLE module was measured by coulomb counter and multimeter with DAQ memory. I found out that the main consumer of energy in my module is microcontroller STM32F04F6P6. Its power consumption depletes 3V battery in several days. Such a short battery lifetime is insufficient for practical use. One possible solution would be to switch the microcontroller to a lower power mode, or to choose a microcontroller that is directly designed for low-power applications. When measuring the power consumption of the BLE module, I found that in low power mode the BLE module consumes 10 times less power. Therefore the chosen BLE module is appropriate for low power applications.
The localization results were not as precise as expected. This was caused mainly by interference from other devices, which used the same technology or emitted signals in similar frequency range. From the result of my work it is obvious that Bluetooth technology can be used for localization, however for use in non laboratory conditions (such as apartment house), this technology would have to be further modified to be much more resistant to noise.

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