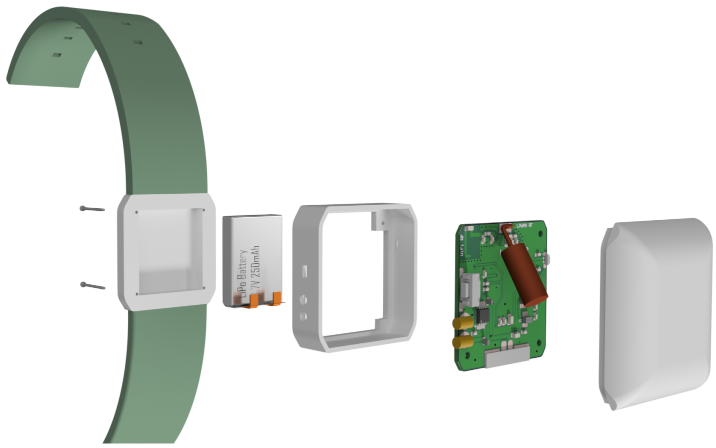

Wearable for Mixed Indoor/Outdoor Localisation

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Thesis to obtain the Master of Science Degree in

Electronics Engineering

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October 2019

Declaração

Declaro que o presente documento é um trabalho original da minha autoria e que cumpre todos os requisitos do Código de Conduta e Boas Práticas da Universidade de Lisboa.

Declaration

I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Acknowledgments

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Abstract

Dementia is the term used for diseases and conditions characterised by a decline in memory, language, problem-solving and other reasoning skills that affect a person's ability to perform everyday activities. These affect nearly 50 million people and is one of the major causes of disability and dependency among older people. One of the most worrisome problems dementia causes is to find them when there is no caretaker present. One solution to this problem, is restraining the movement to a safe confined space, where help is available. However, restraining their freedom puts in danger their well-being. Thus, it will be presented a new approach to wearable tracking device making it suitable for a person with dementia. The chosen tracking technology is Wi-Fi based geolocation, which, in an urban environment, can be used not only as an indoor positioning system but also as an outdoor positioning system. Moreover, the emerging Low Power Wide Area Network (LPWAN) are used to communicate with the cloud making it more affordable, when compared with devices with Global System for Mobile Communications (GSM), and independent from a smartphone. The proposed solution consists in a smartwatch-type device controlled with an ESP32 Micro Controller Unit (MCU) that has an embedded Wi-Fi module. The design, miniaturisation, power efficiency and the tracking software are the focus throughout this thesis.

Keywords

Geolocation, Internet of Things (IoT), Low Power Wide Area Network (LPWAN), Wi-Fi.

Resumo

Esta tese tem como principal objetivo encontrar um modo de melhorar a segurança de idosos, com demência, quando o cuidador não está presente. A demência é um termo que descreve um conjunto de sintomas associados a várias doenças que afectam aproximadamente 50 milhões de pessoas. Alguns destes sintomas, como a perda da memória ou perda da noção do espaço e tempo, levam a dependência da população idosa e quando não são devidamente controladas levam a situações perigosas. Uma solução comum é limitar o espaço em que estes podem circular, um local onde exista assistência disponível. No entanto, esta solução retira liberdade a estas pessoas e coloca em causa o seu bem-estar. Assim existe a necessidade de proteger os pacientes sem que existam restrições físicas. Neste sentido, esta tese apresentará uma nova abordagem a dispositivos de localização, tornando-o adequado estas pessoas. A tecnologia de geolocalização usada será Wi-Fi, que, em ambiente urbano, pode ser usada não só como um sistema de posicionamento interior, mas também como sistema de posicionamento exterior. Já a tecnologia de comunicação escolhida é uma Rede de Longo Alcance e Baixo Consumo (*LPWAN*) que traz as vantagens de ter um baixo custo, quando comparado ao Sistema Global para Comunicações Móveis (*GSM*), e não necessita de estar conectado a um telefone inteligente. A solução proposta consiste num dispositivo semelhante a um relógio inteligente controlado pelo microcontrolador ESP32 que já traz um módulo de Wi-Fi embebido. O design, miniaturização, a eficiência energética e o software que permite a localização dos pacientes são os focos principais deste trabalho.

Palavras Chave

Geolocalização, Internet das Coisas, Rede de Longo Alcance e Baixo Consumo, Wi-Fi.

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Acronyms

3GPP	3rd Generation Partnership Project
AoA	Angle of Arrival
AES	Advanced Encryption Standard
AP	Access Point
API	Application Programming Interface
BLE	Bluetooth Low Energy
CSS	Chirp Spread Spectrum
D-BPSK	Differential - Binary Phase Shift Keying
ETSI	European Telecommunications Standards Institute
FDMA	Frequency Division Multiple Access
GFSK	Gaussian Frequency Shift Keying
GPIO	General Purpose Input Output
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
HTTP	Hypertext Transfer Protocol
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial Science Medical
IST	Instituto Superior Técnico
ISR	Instituto de Sistemas e Robótica
IoT	Internet of Things

LATI	Liga dos Amigos da Terceira Idade
LDO	Low-Dropout
LED	Light Emitting Diode
LoRa	Long Range
LoRaWAN	LoRa Wide Area Network
LPWAN	Low Power Wide Area Network
LTE	Long-Term Evolution
MAC	Media Access Control
MCU	Micro Controller Unit
NB-IoT	NarrowBand IoT
OTDoA	Observed Time Difference of Arrival
PCB	Printed Circuit Board
RFID	Radio Frequency Identification
RGB	Red, Green and Blue
RPMA	Random Phase Multiple Access
RSSI	Radio Signal Strength Indication
SIM	Subscriber Identity Module
SSID	Service Set Identifier
TDoA	Time Difference of Arrival
ToA	Time of Arrival
UART	Universal Asynchronous Receiver/Transmitter
UNB	Ultra Narrow Band
USB	Universal Serial Bus
VNA	Vector Network Analyser

1

Introduction

Contents

Introduction

This thesis describes the development of a wearable device for mixed indoor outdoor localisation and supporting software.

1.1 Purpose and motivation

In the ever growing elderly population, mental health disorders are getting more and more frequent. These diseases can cause loss of memory, panic attacks, loss of perception of time/space and even of reality/imagination, etc. Some of these symptoms can lead to dangerous situations when a caretaker is not present, raising concerns on the well-being of the patient. One solution is constraining the space where they can walk freely, but this can cause more psychological damage. This work proposes another viable solution, using a tracking device that has the capabilities to alert the caretakers if, at any time, they go outside the allowed area or if they enter a dangerous area.

As described in Chapter 3, the elderly population is already served by some trackers that are a solution to a certain extent. However, the requirements established by Liga dos Amigos da Terceira Idade (LATI), the elder care institution that exposed to us the problem, are not fully met. Three of this requirements are: the device should have a low cost, should give a rough indoor and outdoor location and it should be difficult to detach itself from the user. Plus, this thesis will use a Low Power Wide Area Network (LPWAN) bringing further cost reduction and battery life improvements, as these networks are suitable to devices that transmit low amounts of data.

1.2 Goals and challenges

The main objective of this project is to develop the service that provides a solution to the proposed problem. This service includes: (i) the wearable device, capable of transmitting the information to locate the user, and (ii) the cloud application that will provide a Graphical User Interface (GUI) where the caretakers can see the status of each of the users. Thus, after the initial study of the state of the art, the goals set to this project are:

- Develop the prototype, applying miniaturisation techniques, and harmonise the hardware with its enclosure.
- Power consumption optimisation allowing update the location every ten minutes and maintain this rhythm without the need of a charge for two weeks.
- Guarantee tracking reliability;
- Testing the system and survey both users and caretakers in usability, comfort and suggested improvements.

Once chosen the technologies that will be used in the device, and tested their reliability and effectiveness in requirements compliance, the goal is to have a device that is ready to be in the market.

1.3 Document organisation

This report is organised as follows:

- Chapter 2 surveys the main technologies needed in the device. Aside from the basics of functionality of each technology, are presented the advantages and disadvantages that led to the choice of each technology, positioning method and LPWAN.
- Chapter 3 reviews the State of the Art, including how technologies are implemented and improved by companies and the scientific community to solve the problem in hand.
- Chapter 4 presents the design process and developed system prototype.
- Chapter 5 describes how the system performs.
- Chapter 6 gathers the conclusions of the work, and states the guideline for future work.

1.4 System Requirements

This system is developed to target the senior population with dementia. To have a better understanding of the users, both seniors and caretakers, some meetings and surveys took place. The institution, Figure 1.1, is divided in 2 parts, the main part where the patients live and most services are located, with roughly 1800 m^2 per floor area, and a daycare centre. Both resident and non resident patients have free movement in all spaces.

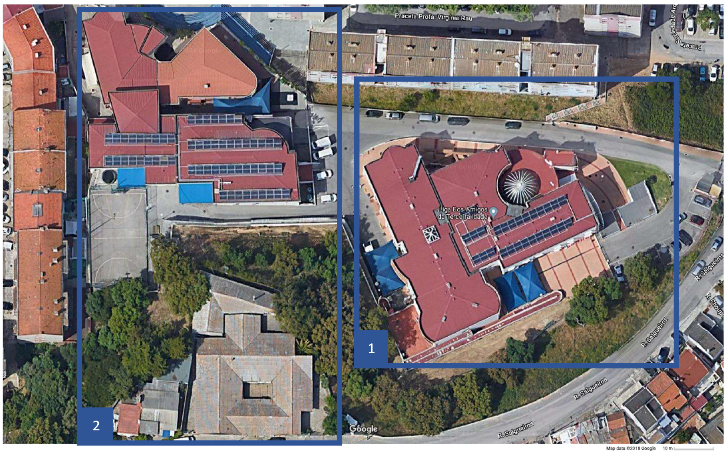


Figure 1.1: Area where the system will need to work. 1 - Indoor Location where the patients live. 2 - Daycare centre.

In the meetings, the caretakers from LATI described various real situations, however, two resume why the device is needed both are about two patients that lived in the facilities. The first, occurred during the daytime, the patient runoff from the premises getting to a train station, in a taxi. The driver recognised a special bracelet that identifies the patient and he safely returned to the institution. The second situation occurred inside the facilities, the patient hid in a room from another patient. It took hours of searching outside before they found out that he was inside the house.

The first situation is the most dangerous for the patient, if not for the driver, he may have hurt himself. The second situation caused distress and consumed unnecessary amount of time.

Furthermore, senior patients, from another institution (to avoid alienating the main target of the system), were enquired to understand their take on this problem. Figure 1.2, summarises the results. Also, in the same enquiry, they made suggestions such as, the inclusion of a display to show hours, personalisation possibility and monitoring hearth rate and sleep apnea.

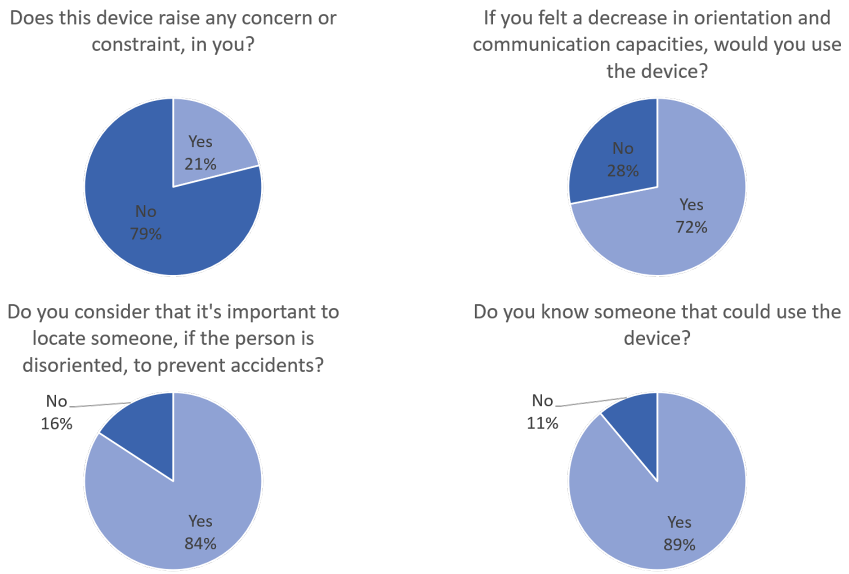


Figure 1.2: Patients feedback enquiries. (20 answers)

Finally, these are the requirements extracted from the enquiries results.

GUI for the caretakers:

- Map with patients Geolocation;
- Geofencing;
- Low battery alerts;
- Device management and configuration;
- User friendly.

Cloud application requirements:

- Rough Indoor Location Estimation: Depending on the Wi-Fi coverage of the target location it can have distinction between floors of the institution;
- Outdoor Location Estimation: Depending on the available nearby Wi-Fi ranging between 20 m and 50 m.

The device requirements:

- Reliable communication with the cloud, more than 80 % of messages delivered;
- Distress signal button;
- Low cost of device (<€ 50);

- Long Battery Life ($>$15 days);
- Water Proof;
- Design: Smartwatch type, ergonomic, small volume, lock mechanism and customisable.

The requirements in the device are a trade off between power consumption, functionality, cost and size. These represent the minimum requirements. Nevertheless, extra functionality such as a screen or sensors can be added, in the future, at the expense of cost and power consumption. The indoor localisation is also limited due to complexity and dimension of the space.

2

Theory and Background

Contents

Theory and Background

This chapter, introduces the most relevant positioning and LPWAN technologies, justifying their use on the solution proposed in this thesis.

2.1 Positioning Technologies

Technologies to track people and assets have been around for some time now, but their popularity had the biggest advance when the Global Positioning System (GPS) became fully operational, in 1995. From then, anyone with a device able to receive GPS signals could pinpoint its approximate latitude and longitude coordinates. Since then, this positioning method has improved and other positioning technologies have emerged. The miniaturisation and the decreasing cost of these technologies made possible embedding positioning systems to all sorts of devices and, thus, transmitting their location to anywhere on the world. However, GPS does not work very well in need indoor positioning systems, since it requires line of sight between satellites and devices. Many studies proposed alternative indoor tracking technologies and, in recent years, several commercial solutions became available in the market.

2.1.1 Cellular Wireless Network

A cellular network consists of many base stations distributed over land called cells. These cells offer network coverage to transmit voice, data and others. These networks normally operate under licensed spectrum frequencies, however, as mentioned, some also provide a network service in the unlicensed spectrum.

Cell Tower Triangulation uses the serving cell tower and neighbouring cell towers to obtain the location of the user. The accuracy of this method highly depends on the density of base stations and also city configurations. There are many methods to triangulate/trilaterate the position of a mobile device, for example:

- Time of Arrival (ToA) - This is the time that takes for the radio waves to propagate from the transmitter (cell towers) to the receiver (user). Thus, given the velocity of electromagnetic waves, it's possible to estimate the distance between the cell tower and the modem. The estimated distance yields a circle centred on the cell tower. If more cell towers are available, the intersection of the circles give a more accurate position. The main disadvantage of this method is the strict time synchronisation between the receiver and transmitter [1] [2].

- Time Difference of Arrival (TDoA) - This method uses the difference of time at which the transmitted signal, from the node, arrived at each of the receivers. This time is then recorded and transmitted to the localisation system that produces a range difference measurement. This defines a hyperbola of constant range difference with the base station at the foci. The intersection of multiple hyperbola gives the location estimate of the transmitter. Also, this method has the advantage that nodes do not need to be synchronised [3].
- Angle of Arrival (AoA) - To retrieve the AoA an array of antennas placed side-by-side, is needed. By measuring the phase difference between the received signals, in the array, it's possible to convert this measurement into the AoA. This allows to draw a line in the direction of the emitter. The intersection of the lines of multiple towers gives the location. The disadvantages are, besides the obvious problem of no line of site, the complexity and size of the antennas [4].
- Radio Signal Strength Indication (RSSI) - Relating the received signal strength with the travelled distance between the cell tower and the modem is another possible approach to position estimation. The main disadvantage of this method is the complexity of the propagation mechanisms [1].

Since the propagation environment is not ideal, there is path loss and shadowing effects on the electromagnetic waves, causing abnormalities and attenuating the signal power. Many models were developed to estimate how the received signal was affected therefore enhancing the estimated distance between base station and modem.

Although the accuracy has improved in certain networks, 3rd Generation Partnership Project (3GPP) claims that Long-Term Evolution (LTE) can achieve 150 m accuracy 97 % of the times [5].

2.1.2 Global Navigation Satellite System

The most commonly known Global Navigation Satellite System (GNSS) is GPS but there are already other competitors in place, such as, Glonass and the European Galileo. Galileo is controlled by civilian entities contrary to the military American GPS and Glonass Russian systems. Each of these GNSS are constituted by satellite constellations, ground control stations and receivers. Ground stations monitor the precise orbits of the satellites and the timings of their clocks so corrections can be made if needed. Satellites transmit the messages that enable the receivers to discover their positions.

The method used to position the receiver is trilateration, represented in Figure 2.1. Each of the available satellites transmits the precise time at which the message was transmitted and the location of the satellite. This is enough to estimate the distance to the satellite. However, the receiver needs an accurate and stable clock, which can't be assumed. This leads to an error on the calculation of the propagation time and, thus, an error on the distance between both. An error of 1 ns causes a 30 cm deviation in the sphere radius. This can be solved by calculating the correction of the receiver clock. In an ideal situation, three satellites would be enough to locate the receiver, although, due to errors between the actual position of the satellite and the one that is transmitted it is used all the available satellites and then applying least square fitting algorithm to discover the most likely position of the receiver [6].

Galileo will achieve the best open usage accuracy, close to 1 m, leaving the American GPS behind with an accuracy of 5 m. Due to the necessity of a line of sight between satellites and the receiver, this method is only suitable for outdoor tracking. The other disadvantage of this method it is the power consumption needed to acquire one infrequent localisation it is very high.

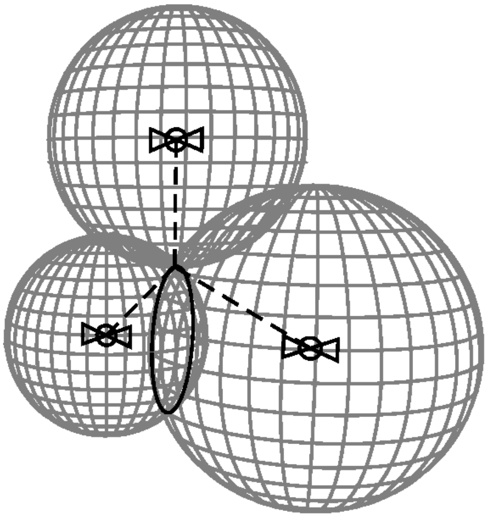


Figure 2.1: Trilateration [6].

2.1.3 Wi-Fi

Wi-Fi is a technology trademarked by the Wi-Fi Alliance. It is based on the Institute of Electrical and Electronics Engineers (IEEE) 802.11 standards and is used for wireless local area networking. This Alliance is what makes possible the interoperability between the billions of Wi-Fi enabled devices around the world [7].

Initially the term Wi-Fi was only used to denote the 802.11b standard. Only later this was expanded to all the networks based on any of 802.11 standards. Most of the standards work in the 2.4 GHz Industrial Science Medical (ISM) band achieving an indoor range up to 70 m. Despite this, the fastest growing standard is the 802.11ac, due to its astonishing stream data rate that can go up to 4 Gbit/s, while the indoor range can go up to 35 m [8].

There are obvious advantages on using Wi-Fi for indoor positioning systems such as a good signal coverage which significantly decreases the necessary infrastructure, when compared to other technologies. However, it is important to notice that a greater density of Access Points (APs) increases accuracy so investing in infrastructure may be necessary. Also, the infrastructure can be used to provide internet access. The most common technique to track devices is to use trilateration using the RSSI. However, deriving an accurate propagation model for each AP in an indoor situation is a complex task and usually leads to poor accuracy. Other common technique is Fingerprinting, that consists in mapping areas with RSSI measured at known locations. The position of the user device is then obtained by comparing the values measured in his location with the radio map [9].

Although Wi-Fi isn't perceived as an outdoor positioning system, it can be used as so, thanks to large databases that include the position of billions of Wi-Fi APs. Therefore, with a simple scan of the available APs, one is able to find its approximate location. However, this is only useful in an urban environment since it probably has a high APs density.

2.1.4 Radio Frequency Identification (RFID)

RFID is mainly used to identify assets with a tag compliant with a reader system. These tags can be subdivided in two categories: passive RFID, and active RFID. The main difference between both is the power source.

- Passive RFID tags are composed of two components: the antenna, and a microchip that stores and processes received and transmitted signals. They rely on the reader to wirelessly power the tag circuitry. They are small since there's no need of a battery. However, the harvested energy depends on the number of windings of the antenna. Therefore, if the device is small, so will be the available output power, which limits range to just a few centimetres.
- Active RFID tags also contain a battery which allows to include other components like a more powerful Micro Controller Unit (MCU) and sensors. Since it isn't powered by the reader, it has higher radio output power, achieving significantly more range, commonly up to 50 m.

Passive RFID tags are not commonly used to tracking due to their limited range. A high density of tag readers would be required, making the system expensive. On the other hand, active RFID has the capabilities to be used on indoor localisation. Using active RFID requires a fixed position tag that constantly beacons an identification message. In this case, the reader is mobile and, from time-to-time, wakes-up and scans available tags nearby. The position estimation uses conventional trilateration methods and the RSSI to calculate the distance between tag and reader.

2.1.5 Bluetooth

Bluetooth is another wireless technology standard managed by the Bluetooth Special Interest Group that's composed by more than 30 thousand companies. Bluetooth also operates in the 2.4 GHz ISM band and has 79 channels of 1 MHz each. Since its beginning, Bluetooth has seen many improvements, being the most relevant, to this work, the standardisation of Bluetooth Low Energy (BLE). As the name implies, the key difference is the low power consumption. Regular Bluetooth requires more energy since its designed to transfer much higher quantities of data continuously. On the other hand, BLE was designed to applications that only require to exchange small amounts of data periodically.

The active Bluetooth standard has an approximate range of 10 m, as a tracking technology is similar to active RFID.

2.2 Low Power Wide Area Network

It's expected that in 5 years the number of Internet of Things (IoT) enabled devices will double, achieving more than 50 billion. This market is growing rapidly and tech companies grabbed the opportunity to decrease costs and improve energy efficiency of newly designed devices. Most of these devices have the particularity that they don't need to be constantly streaming data nor they need to be listening to incoming data all the time. Thus, more suited protocols and networks have been developed, these have been named LPWAN.

2.2.1 Sigfox

The company Sigfox was founded in 2010 and marked the reemergence of the LPWAN concept. Prior to this, alarm companies developed networks with similar topologies. However, Sigfox network was only deployed in 2012. It offers an end-to-end solution to its subscribers from gateway coverage to back-end servers, the radio modules for the end nodes are developed by third party companies. The subscription fee, to access the network, can vary between €1 and €15 per year, depending on the number of devices being connected and also the number of message exchanged uplink/downlink.

The network uses a star topology that's similar to the cellular architecture. A wide deployment of base stations permits the edge-nodes to communicate the gathered data directly to Sigfox servers.

Sigfox operates in the sub-GHz ISM (regional) band and uses Ultra Narrow Band (UNB) modulation, in combination with simple modulation techniques, that grants it the advantage of transmitting signals over long distances. This allows Sigfox to cover entire countries with few base stations. Belgium, a country with a surface area of approximately 30 500 km^2, has Sigfox coverage with only seven base stations. Furthermore, Portugal, is almost fully covered with Sigfox network, as can be observed in Figure 2.2.

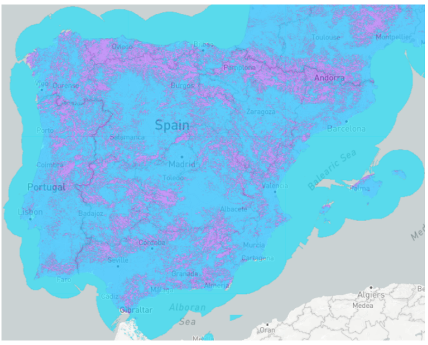


Figure 2.2: Sigfox Coverage in the Iberian Peninsula. (Blue represents live coverage) [10]

There are several reasons why UNB modulation is an effective way of increasing signal range. Sigfox claims that, the main advantage, compared with wide band, is the ability to concentrate the output power increasing the signal to noise ratio. The only disadvantage is the limited baud rate.

The modulation Differential - Binary Phase Shift Keying (D-BPSK) is used in the uplink. Due to its simplicity, only encoding 1 bit per transmitted symbol, the chance of being mistakenly decoded by the receiver decreases. Also, since the signal degrades over the travelled distance it can travel longer distances, without becoming undecipherable by the receiver. On the downlink, Gaussian Frequency Shift Keying (GFSK) is used, since there is no power constrain in the base stations it also uses a higher bandwidth. The number of messages to uplink are limited to 140 per day and the downlink are limited to 4 per day. The downlink message requires a request from the device and the limited message size doesn't allow firmware updates. For the moment, to ensure quality of service, it is mandatory to send three replicas of the message, in different frequencies, which, in the future it will be adaptive. There is no negotiating or acknowledging of the messages.

Sigfox doesn't perform optimally in moving environments, because of the doppler effect and multi-path propagation issues. Multi-path propagation can cause a corruption of the message sent, due to accumulation of the multiple received signals, as demonstrated in Figure 2.3. This problem is greatly solved by multiple replica transmission, which increases the chance of receiving the message successfully.

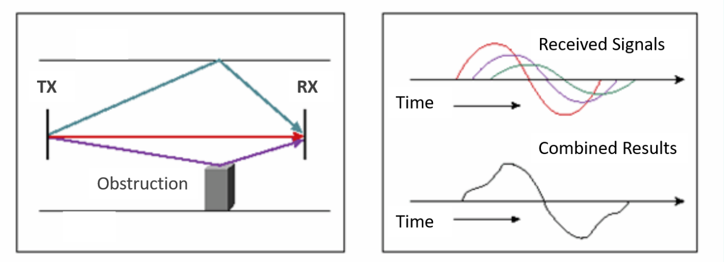


Figure 2.3: Multi-path propagation effect. [11]

In terms of security there is no encryption between end nodes and base stations, so any intercepted messages can be deciphered unless the application layer encrypts the message. Nevertheless, the messages are sent randomly in one of the 400 hundred channels available and it has the ability of having the messages encrypted in the application layer.

The question arises, why does such a minimalist approach makes sense? For most of the use cases, the cloud is harvesting data from the nodes, downlink is normally unnecessary although can be useful for some degree of control and configuration of the device.

2.2.2 Long Range (LoRa)

LoRa is a physical layer communication protocol, that operates in the sub-GHz and uses Chirp Spread Spectrum (CSS) modulation. When LoRa is used as a LPWAN it's common to refer to it as

LoRa Wide Area Network (LoRaWAN) that is, it defines the network layer in this LPWAN. Unlike the physical layer, the Media Access Control (MAC) layer is an open standard, maintained by the LoRa Alliance. This means, that other companies can develop their own MAC layer, e.g. Symphony Link. For a better understanding of the layers the protocol stack is represented in Figure 2.4.

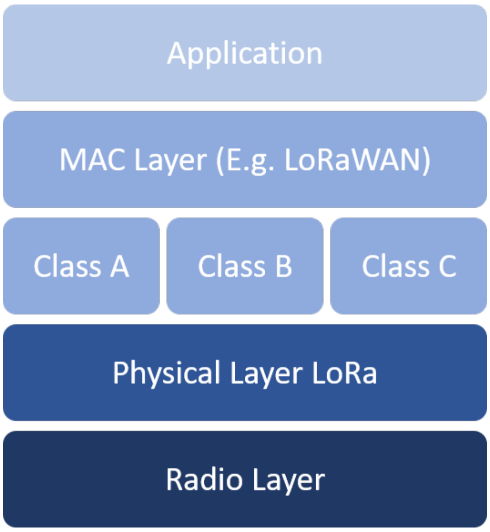


Figure 2.4: LoRaWAN Protocol Stack.

The payload and the data rate of each transmission depend on two factors: bandwidth and the spreading factor. Contrary to Sigfox, LoRaWAN uses channels with higher bandwidth of 125 kHz and 250 kHz. The spreading factor is the base-2 logarithm of the number of chirps per symbol, i.e. the number of bits encoded into each symbol. Having a higher bandwidth or a lower spreading factor increases the data rate and consequently a higher payload size, although at the expense of reduced range. The network manages this in order to maximise efficiency and network capacity. All the communications are secured with a Advanced Encryption Standard (AES)-128 encrypted link from nodes to gateways.

LoRaWAN provides 3 different classes of nodes, where each addresses different requirements of a wide range of applications. The first, Class A, has limited bidirectional capabilities, each uplink message is followed by two short downlink reception windows. It is directed to applications that have power limitations. Class B provides receiving time frames that are independent of the uplink traffic. To establish connection, the gateway sends a time synchronised beacon to the node. Finally, Class C is for applications that do not have power consumption limitations. The nodes are continuously listening, to receive downlink messages, except when they are transmitting.

Moreover, LoRa doesn't deploy its own network. It leaves this function to the end users, which sometimes can be cost prohibitive, depending on needed area coverage. Other times, this confers an advantage to the users because it gives them the possibility to manage the network on early stages of product development.

2.2.3 NarrowBand IoT (NB-IoT)

The 3GPP is a group that unites telecommunication standard development organisations. The latest standard, Release 13, included the specification of NB-IoT a LPWAN technology.

NB-IoT, is a stripped down version of the LTE protocol to enhance IoT applications, that generally require reduced costs and lower power consumption. Some examples of features that were removed from the standard are: measurements to monitor channel quality, carrier aggregation and dual connectivity (half duplex communication). On the contrary to the previous LPWANs, NB-IoT operates in licensed frequency bands, and employs quadrature phase-shift keying modulation. Each channel has a 180 kHz bandwidth, close to Global System for Mobile Communications (GSM) bandwidth (200 kHz). These channels can be used by multiple users simultaneously, since the network uses Frequency Division Multiple Access (FDMA) to divide it in multiple, non-overlapping, frequency bands.

NB-IoT, offers a quality of service (latency, speeds, reliability), that Sigfox and LoRa cannot give mostly because of the use of licensed frequencies and its synchronous protocol. However, this comes with some costs and buying the access to LTE licensed spectrum frequencies is very expensive, with costs around €500M per MHz.

In Germany, Deutsche Telekom, already offers a subscription that includes, 500 MB and 250 SMS, that can be spent through the course of a 10 years period and costs €10 for that same period. In Portugal, Altice already covers district capital, plans to have national coverage before the end of 2019. Still, there are no subscription plans available to the general public.

There are three operation modes, presented in Figure 2.5. First, is the standalone operation, that re-uses GSM frequencies that are no-longer used. This is the easiest option since both have almost the same bandwidth. Second, is the guard-band operation, that uses guard-bands in between LTE bands. Lastly, is the in-band operation, which utilises the LTE band. It is up to each network deployer to define the operation mode.

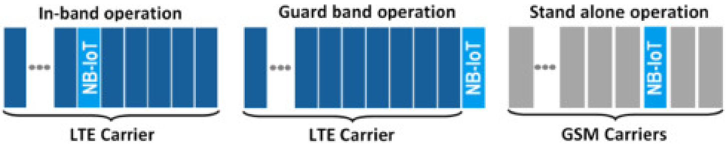


Figure 2.5: NB-IoT operation modes.

The biggest downside of NB-IoT is the power consumption, the peak current doubles, compared to Sigfox. However, if the data is not time sensitive, it can send bursts with more data less regularly, making it more efficient than Sigfox. Also, the hardware is more complex and expensive.

2.2.4 Ingenu

Ingenu is the company developing Random Phase Multiple Access (RPMA), a LPWAN technology that uses a spread spectrum modulation. Unlike the other mentioned LPWAN technologies, it operates on the 2.4 GHz ISM band. Operating in ultra high frequencies has the drawback of using smaller antenna (when comparing with Sigfox and LoRa that operate in the sub-GHz), which reduces the range of the communications (a larger antenna collects energy from a larger area). However, the regulations in this band are more relaxed and allow higher power outputs which, combined with a optimised sensitivity on the receivers, allows an extended coverage.

Furthermore, in terms of security, the messages are encrypted with a 128 bit key, and a two-way authentication is needed for the communication to be established.

Ingenu has a full acknowledgement of its messages and allows firmware updates over-the-air so it has ample downlink capacity, but this means a higher energy consumption. Also, it is worth mentioning that to send a uplink message there must be a request from the gateways. This request will then be used to evaluate the power needed to send the message [12].

2.2.5 Comparison

Finally, in Table 2.1 we present some of the essential specifications of the studied LPWAN. Ingenu is not available in Europe, thus is not a competitor in the choice of technology. The technology chosen to this project is Sigfox mostly due to the almost total coverage of Europe and also the low cost of the modules. However, there are drawbacks for using this technology. First we have the data download and upload limitations. Download is very small since only 4 messages per day can be received. Hence, a firmware update is impossible, only minor configurations. Anyway, this may be accomplished through other available connectivity, for instance Wi-Fi. The uplink limitation is not so constraining since it enables the device to update the position every 10 minutes without going over the limit. NB-IoT is in test phase in Portugal but still not available. Furthermore, it requires Subscriber Identity Module (SIM) cards which, in a miniaturisation perspective, is a drawback. LoRaWAN would be a great choice if outdoor tracking wasn't a requirement, as the coverage in Portugal is provided by private communities and companies, and it doesn't cover even a quarter of the country.

Table 2.1: LPWAN specifications comparison.

	Sigfox	LoRaWAN	NB-IoT	Ingenu
Spectrum	Unlicensed	Unlicensed	Licensed	Unlicensed
Frequency Band (Europe)	868 MHz	868 MHz	LTE frequency bands e.g. 700 MHz	2.4 GHz
Bandwidth	100 Hz	125 kHz and 250 kHz	180 kHz	80 MHz
Packet Size Uplink/Downlink	12 B/8 B	51 B–243 B	1600 B	6 B - 10 kB
Range Urban/Rural	10 km/40 km	5 km/20 km	1 km/10 km	5 km/30 km
Maximum Data Rate Uplink/Downlink	100 bit s^{-1}	50 kbit s^{-1}	200 kbit s^{-1}	624 kbit s^{-1} / 156 kbit s^{-1}
Transmit Power & Power Consumption	14 dBm/ 66 mW [13]	14 dBm/ 84.15 mW [14]	13 dBm/ 330 mW [15]	22 dBm/ 1 W [16]
Scalability	●●	●●	●●●	●●●
End-Device Price	●	●●	●●●	●●●
Coverage in Portugal	●	●	●	-

3

State of the Art

Contents

State of the Art

This chapter presents the state-of-the-art on indoor and outdoor localisation systems using the technologies described in the previous chapter.

3.1 Prototype/Research Solutions

Most of the previously studied technologies are currently used for tracking/positioning systems. Besides presenting some prototypes developed by the scientific community, this section will also demonstrate how existing research can provide better reliability and accuracy from the same technologies.

3.1.1 Cellular Wireless Network

One of the few tracker prototypes that solely rely on cellular networks was developed in India to improve safety for women. Two researchers developed the prototype, a GSM enabled wristwatch that provides the location to the police or relatives whenever the wearer is in distress. The system is composed of a 8-bit microcontroller (Attiny84), a GSM module (Quectel M66) and a switch. The algorithm uses linearly weighted localisation technique based on the RSSI of up to 6 available cell towers. In urban environment they achieve an average accuracy of 50 m [17].

Cellular mobile communication systems such as the 3GPP LTE have evolved not only optimising communication performance, through wide band signals, but also tight synchronisation among base stations, which makes them more suitable for positioning systems [18]. One of the improvements was the inclusion of the LTE Positioning Protocol that includes Observed Time Difference of Arrival (OTDoA), a mobile service positioning method, and the Positioning Reference Signal. This method uses TDoA observed at the user equipment from cell towers (the serving cell tower plus two or more surrounding towers), to obtain longitude and latitude coordinates. This is mostly studied and applied to serve as a fall back method of positioning when no GNSS is available. Furthermore, this method requires an algorithm to solve the navigation equation such as the Kalman filter or particle filter. Depending on the radio environment, the filter should take into account errors introduced by the environment [19] [18].

There are scenarios where the user equipment can't find enough servicing cell towers which leads to an imprecise location. To address this problem, some researches suggest a cooperative localisation technique for LTE systems, in which the user equipment communicates not only with the cell towers but also with other user equipment. Due to the lack of synchronisation between user equipments, the method cannot be OTDoA. In alternative it can be measured the round-trip time. Although most of the research is only based on simulations, all the results, point to improvements in the positioning performance claiming that a single collaborator can improve, positioning accuracy, to up to 30 % [20] [21].

3.1.2 GNSS

The greatest advantage, of GNSS, is the reliability since the probability of having 4 satellites in line of sight, while being outdoor, is 90 % and it has 5 m accuracy. Also, receivers decreased in size and price making it possible to incorporate them in many other technologies. GNSS trackers are so common that everyone carries one in the pocket (the smartphone). Nonetheless there are applications where smartphones are not suitable.

One project in Vila Real - Portugal developed a pet tracker with GPS and GSM technology. The whole concept was constructed as a service in which the service provider would update the device software, cover the use of GSM costs and maintain the web application that provided the pet location remotely to the pet owner. Geofencing is one of its main features. It creates an area where the pet is able to roam freely and, as soon as it steps out, the sleeping GSM module is activated and the position of the pet is updated more frequently. Enabling the sleep mode on the GSM module, grants a lower power consumption [22]. Several similar projects also rely on GPS and GSM, and add other functionalities for example hearth-rate monitoring, a screen to display time and even wandering detection [23] [24].

This last functionality, wandering detection, is able to detect outdoor wandering behavior in real-time, based on individuals' GPS traces. They define wandering trace as a continuous sequence of partial traces, with each partial trace clamped by two adjacent sharp points. Each of the processed point is then fed into the detection algorithm to find the partial traces. A trace with partial traces exceeding a given threshold is recognised as wandering. [25].

Other GNSS trackers discarded GSM communication altogether by replacing it with a LPWAN, acknowledging the obvious advantages such as the power consumption and cost. A prototype that used LoRa LPWAN, achieves an autonomy of up to 40 hours with continuous GPS tracking, contrary to most of the GSM trackers that achieve a 10 hour autonomy. However, the LoRaWAN base station only covers about 2 km and the amount of messages delivered decreased with distance, making it unreliable [26].

3.1.3 Wi-Fi

In the previous chapter this technology is introduced as one of the most versatile, since it can be used as both outdoor and indoor positioning system. The main approaches used in Wi-Fi based positioning, as already mentioned, are based on the strongest RSSI method or on RSSI triangulation. Others, such as AoA or ToA, will not be subject of further discussion since they require line-of-sight and the special hardware required to support them is expensive [27] [28].

The first method, Cell-Id, obtains the position by scanning the available Wi-Fi APs and the one with the strongest signal determines the device's position. The advantages of this method is that it only needs a database with the location of each AP. The disadvantage is the existence of high relative errors in the indoor environment. The approach based on the signal strength also relies on a Wi-Fi APs scan. However, instead of relying only on the strongest signal, it processes the data of more APs to give more accurate positioning. One method is based on a radio propagation model that, in an ideal situation, would only be affected by the signal path loss,

$$P(d) = P_0 - 10n\log_{10}\left(\frac{d}{d_0}\right) \tag{3.1}$$

where n is the path loss exponent, $P(d)$ is the received power in dBW at a d distance and P_0 is the received power in dBW at a reference distance d_0. This can be further improved, for indoor environments, by adding the effect of obstructions such as walls or doors,

$$P(d) = P_0 - 10n\log_{10}\left(\frac{d}{d_0}\right) - m \times WAF \tag{3.2}$$

where $P(d)$, P_0, n, d, d_0 have the same meaning as in (3.1) while m (the number of walls between transmitter and emitter) and WAF (the attenuation factor) can be derived empirically. Finally, using trilateration with the extracted distances, is possible to position the user [29]. The work [30] applied these methods for indoor tracking in a hospital and results gave a 5 m accuracy.

Other method, Location Fingerprinting, is divided in two phases: offline training and online positioning. The offline phase consists in creating a radio map where the space is divided in cells, and each division is defined by Wi-Fi APs scan samples. The database will store the RSSI and MAC addresses and also the position where the sample was taken. A filtering technique is applied on the samples to decrease the number of APs RSSI that represent the fingerprint, that leads to a decrease in the computation time in the online phase [31] [32]. The process of collecting the samples can be difficult and time consuming. So, after an initial setup, it can be crowd-sourced through the development of an application that automatically logs the Wi-Fi scans and the user position, thus improving the database and the positioning accuracy [33]. The online positioning phase is the positioning system itself, assuming a database already exists. The device obtains its location by comparing the results from a Wi-fi RSSI scan with the samples in the database. However, there's still a need for a matching algorithm to achieve better positioning accuracy, such as the Nearest Neighbours method or a Neural Network method [31] [32] [34]. So far these studies have only used this method in an indoor environment. In [35] fingerprinting is used in an outdoor environment. The algorithm accuracy is dependent on a high number of samples which is difficult in a high mobility environment.

Google owns one of the biggest Wi-Fi databases and it is dynamically updated with gathered data from Android phone users. Periodically, Android phones collect its GPS, Cell-ID and Wi-Fi location and send back the publicly broadcast Wi-Fi APs data, their Service Set Identifier (SSID) and MAC data. This is how the database knows the location of each AP. Figure 3.1, illustrates how the process unrolls to obtain the location. The device scans available Wi-Fi APs, uploads the RSSI and the MAC address and sends them to a remote server that has access to the database. This information is then transformed in latitude and longitude coordinates and displayed in some GUI. As such, the device never knows its own position, unless the GUI is accessible in the device (uncommon since these are battery powered devices).

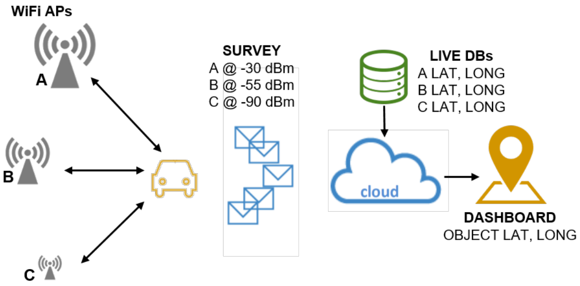


Figure 3.1: Process of discovering the device location through Wi-Fi.

3.1.4 Other Technologies and Hybrid systems

Some studies explore ways to improve positioning methods using more than one radio technology since each one has its strengths and weaknesses. Most of them rely on the higher transmission power of Wi-Fi, that gives a significant coverage over large spaces, for the rough positioning and Bluetooth to divide the space in more small sections although in most the Bluetooth doesn't cover the entire of the space because it would increase costs.

A team from an engineering university in Malaysia developed a prototype that has a similar goal as this thesis i.e., tracking elderly people in an indoor environment. However, they do not consider the outdoors environment. This system consists in a BLE wearable device with embedded sensors and BLE scanner nodes. The wearable device has a three-axis accelerometer and a three-axis gyroscope and with the data from these sensors they determine the motion type and broadcast it to the server. The BLE scanner nodes are used to scan the RSSI values of the beacons and broadcast them to the server. Once the values are received they are processed, with the trained model, to identify the location [36]. Similar to this study there is FIND an open-source framework that allows a client of this system to be able to pinpoint location in indoor environments with Wi-Fi and BLE sensor data. Since it is open source anyone can clone the system code and run it on its own server, it is also fully configurable to the specific use case. Once the service is running, it is accessible with an Hypertext Transfer Protocol (HTTP) Application Programming Interface (API) that allows the user to train the algorithms that predict the locations and to make the estimations after the training. The accuracy of this system is dependent on Wi-Fi AP and BLE beacon density [37].

The work [38], proposes a hybrid indoor positioning method employing both BLE and Wi-Fi. There are two actors in this method the cooperating mobile devices (e.g. staff of a hospital with BLE/Wi-Fi smartphones) and the searched asset (something equiped with a BLE beacon). In the first stage both are roughly positioned with a Wi-Fi fingerprinting map. The second stage, enters in action when the cooperating users approach the rough location of the asset, in this stage BLE gives a more accurate and live position of the asset using trilateration. The trilateration uses the distances between each of the cooperating users and the asset to calculate the exact asset position. To improve accuracy the map is constantly updated by the new fingerprints received by the user scan. In [39] it is used the smartphone inertial sensors data to predict the next user position, based on travelled distance and walking direction. In addition to Wi-Fi fingerprinting, there's also geomagnetic fingerprinting. This data provides extra reliability and accuracy. All the methods are able to give a prediction independently as fallback.

3.2 Commercial Solutions

In this section we present commercial solutions available in Portugal, that can, to some extent, solve the problem proposed on this thesis.

3.2.1 V-Bag

V-Bag is a tracker developed by Alcatel, that costs €50. The tracker relies on GPS to position the ”bag” and the communication technology is GSM that requires a SIM card with a monthly fee of €3. Battery life goes up to 4 days and it is resistant to rain and dust. It’s possible to set safe zones through the application (geofencing). The hardware is involved in a silicone case that has a clipper to attach to the bag or to attach to a person.

Figure 3.2: V-Bag device.

3.2.2 Prosegur *Sempre Consigo*

This device is developed by the security company Prosegur and was specifically developed to give a 24/7 assistance to the elderly. In its essence is very similar to the V-Bag. It has a GPS tracker and it allows to create safe zones but it has other features such as an emergency button and 4 other buttons that connect to the security company or to other 3 number previously configured. However, the device is considerably more expensive €300, and it assumes the user is a subscriber to other security services from the company. The device itself is not very comfortable to transport.

Figure 3.3: Prosegur *Sempre Consigo*.

3.2.3 Geolokator

This device has the same functionality as the device from Prosegur, although it doesn't have the proximity service from the company. The price of the device is €99 and the communication method is through a cellular carrier. The company recommends a service that costs €5 per month with 1 GB of data, more than enough for tracking 24/7. The battery has 360 mA capacity and only lasts 3 to 4 days. However, it updates the location with a 1 minute interval.

Figure 3.4: Geolokator for kids.

4

System Development

Contents

System Development

The design process of this system begins with identifying what it must do and what the relevant inputs and outputs are. In principle, the system needs to continuously collect data and send it so it can be processed and give an approximate location of the patient to the caretaker. To simplify we can divide these in two subsystems one that is responsible for the data collection and a second where data is processed and displayed.

An overall view of the proposed system in this thesis is shown in Figure 4.1. The first subsystem is a tracking device that will accompany the patients and its function will be to collect the data and send it. The key technologies that enable these functions are Wi-Fi, used to estimate the patient location and transmit data, and Sigfox used to transmit data when Wi-Fi is not available. To fast track part of the hardware development, a module that contains a microcontroller and a radio transceiver will be embedded, in the first subsystem.

The second subsystem is where the collected data will be transformed into locations and displayed to the caretaker. The database stores all relevant data such as configurations of the device and the Wi-Fi scans that will be delivered to the localisation methods. The localisation methods are different for indoor and outdoor and the servers that compute these make the third block. Lastly there is the GUI, a smartphone application, that enables the caretaker to configure the device and track the patient.

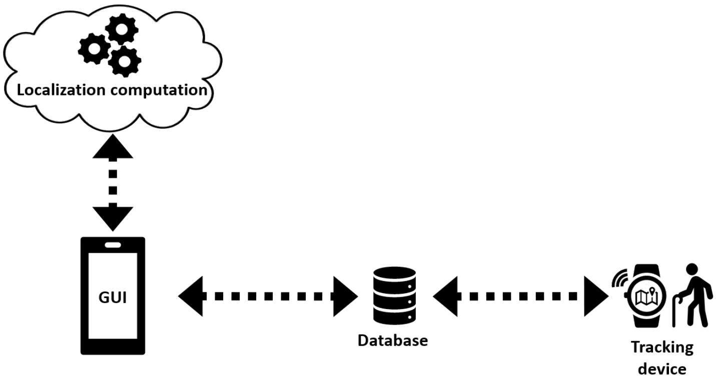


Figure 4.1: System Architecture.

4.1 Hardware

The device architecture shown in Figure 4.2, is composed of two main blocks: (i) the connectivity module, that has the main components and will be the starting point and (ii) a Printed Circuit Board (PCB) that embeds the connectivity module and includes the peripherals (such as interface and battery) and the antennas.

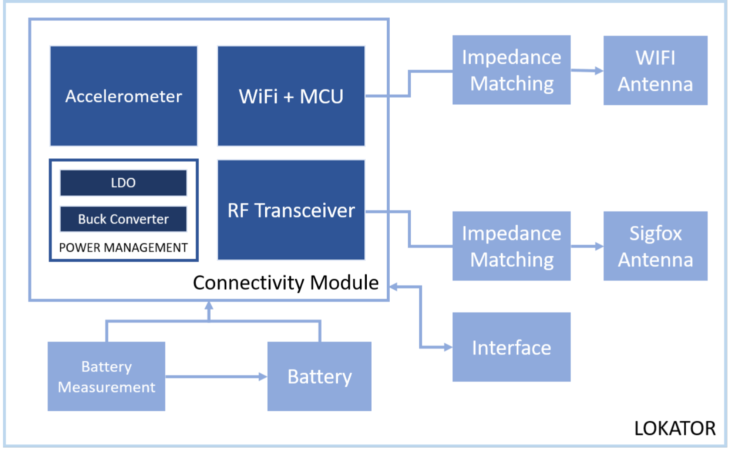


Figure 4.2: Block diagram of the device components. The device itself has been named Lokator.

4.1.1 Connectivity Module

The connectivity module is the hearth of the device and its components are:

- The ESP32, is a system on a chip MCU with embedded Wi-Fi and Bluetooth/BLE connectivity. There are other suitable microcontrollers but this one suits best, the application, considering that there won't be a need to add a Wi-Fi module [40].
- The subGHz transceiver is what enables the communication with the Sigfox network. The S2-LP is an ultra-low power transceiver that works in ISM bands and complies with European Telecommunications Standards Institute (ETSI) regulations [13].
- The accelerometer, in the current version of the firmware is not used, although it can be used as encountered in some of the solutions described in Chapter 3, allowing to extend the battery of the device. The LIS2DE that consumes 6 µA during normal operation [41].
- The power management unit composed of two regulators, a Low-Dropout (LDO) (AP2138) and a buck converter (AP3428). The need for both is, once again, power consumption. In one hand, the LDO can consume less than a buck converter at lighter loads but, is more inefficient at higher loads which makes it a good choice to regulate voltage when the device is in sleep mode. On the other hand, the buck converter is more efficient when the device is awake [42] [43].

The module dimensions are 19 mmx 22 mm, this makes it a really compact sized module with the sufficient IO needed to the application. The module has an Universal Asynchronous Receiver/Transmitter (UART) interface to program the ESP32 and control the internal peripherals such as the transceiver or the accelerometer. The only change that is possible to do regarding the power management is the internal power supply that can be changed between 2.5 V and 3.3 V. The internal power supply will power the other peripherals.

4.1.2 Antennas

The device has two antennas one for Sigfox that communicates at 868 MHz and Wi-Fi that communicates at 2.4 GHz.

There are three important considerations to have when designing or embedding antennas on wearable devices the efficiency of the antenna and the return loss (ratio between transmitted and reflected power).

The Sigfox antenna is the most complicated to embed in a small device because of its operating frequency, 868 MHz, meaning that a monopole should have a quarter of the wavelength, 8.6 cm. It is important to notice that in a monopole ground complements the antenna length so it should also have 8.6 cm. However, ground area is hard to come by in such small devices and reducing it also decreases significantly the operating frequency bandwidth. The best option to comply with this sizes would be to have an external wire antenna that would extend through the bracelet and also extending the ground to the other bracelet. This would increase costs as its a complicated manufacturing process. Having all this into consideration the chosen antenna falls over a wire coiled monopole, which biggest disadvantage is the low design freedom, chip antennas are excluded due to its reduced gain and take a considerable amount of PCB space. For example the chip antenna ILA.02, fabricated by Taoglas, would need 12 mmX10 mm ground clearance in the PCB [44]. Table 4.1, resumes the specifications of the chosen antenna, although it is important to notice that they change with ground size, coupling effect and antenna configuration.

Table 4.1: Sigfox antenna nominal specifications, SW868-TH13 [45].

Frequency Range	[863 MHz,873 MHz]
VSWR	≤ 1.5
Gain	2.15 dBi
Return Loss	14 dB

At this stage the final PCB is already produced and antenna position is also defined, ideally the antenna would be perpendicular or pointing outward relative to the PCB however they are not compatible with a wearable device one would make it too thick and the other would extend the length, the working solution is displayed in Figure 4.3. One of the advantages of this configuration is that the antenna is substantially immune to the dielectric that is beneath the ground plane, meaning that it will radiate properly in the pulse, on the top of a table and even when it is charging.

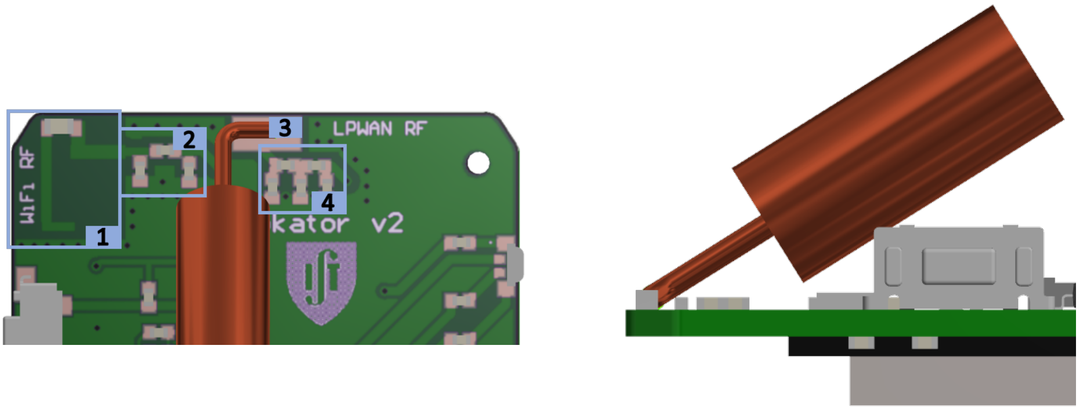


Figure 4.3: PCB antenna area zoom. (1) Wi-Fi antenna. (2) Wi-Fi matching circuit. (3) Sigfox antenna. (4) Sigfox matching circuit.

Since the antenna is not in ideal conditions the load impedance (Z_{Load}) must be tuned to the source impedance ($Z_{Source} = 50\,\Omega$) with a matching circuit, as represented in Figure 4.4. A matching network will maximise the power delivered to the load from the source, by minimising signal reflection. The PCB is ready for a double pi-matching circuit.

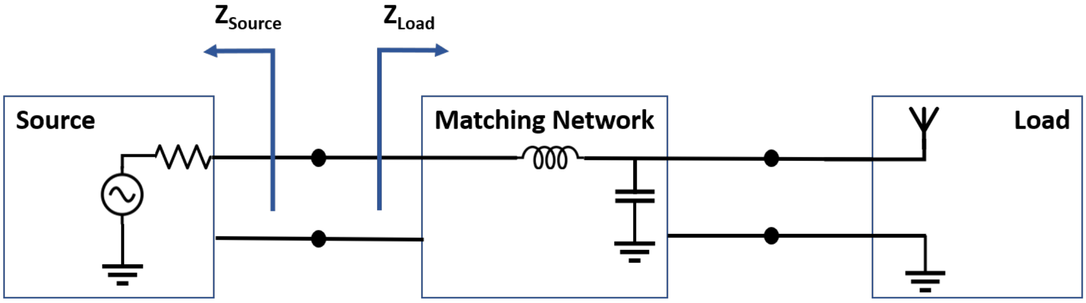


Figure 4.4: Impedance matching.

To calculate the values of the matching network components, Z_{Load} must be measured. In order to make this measurement, it is crucial that the source (Connectivity Module) is detached, no components are between the measurement point and the antenna, the Vector Network Analyser (VNA) must be properly calibrated and, maintaining the measurement precision by minimising the variations between measurements. Additionally, the design of the device is also finalised so that the measurements are done as close as possible to the final environment since everything surrounding an antenna will influence its impedance. The measurement setup is shown in Figure 4.5, the coaxial cable is connected where the Sigfox output of the connectivity module would be soldered. The ”miniVNA Tiny”, from mini Radio Solutions, is used to measure the signal reflection, insertion loss, S parameters, and transmission and return loss.

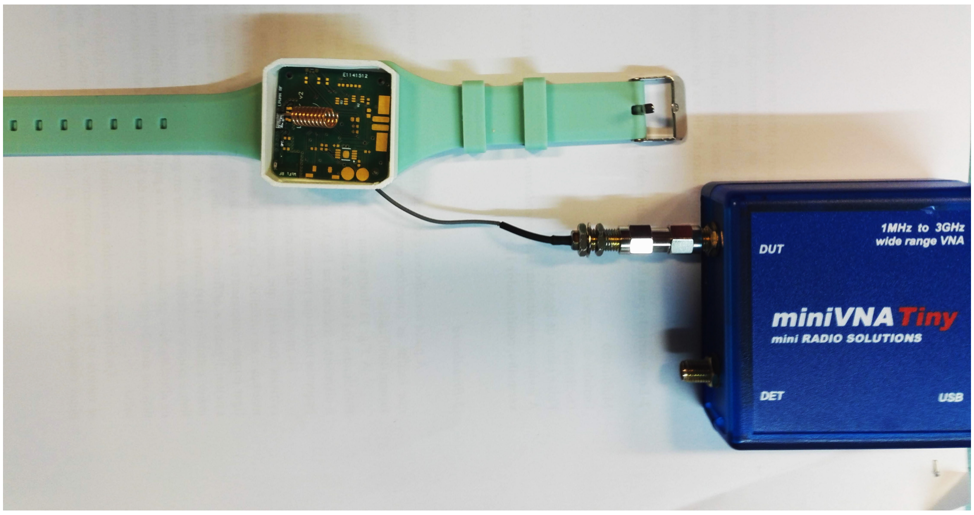


Figure 4.5: VNA measurement setup.

To minimise calculation and fine tuning complexity the matching circuit is a L-network, Figure 4.4, fine tuning is necessary because component values do not match exactly the calculated and because the first estimate of the antenna impedance has a low accuracy. The inductance L and capacitance C is calculated knowing that in a matched circuit,

$$Z_{Source} = Z_{Load} = j\omega L + \cfrac{1}{j\omega C + \cfrac{1}{R_{Load} + X_{Load}}} \tag{4.1}$$

separating the real and imaginary part,

$$\begin{cases} R_{Source} = \dfrac{\dfrac{R_{Load}}{R_{Load}^2 + X_{Load}^2}}{\left(\dfrac{R_{Load}}{R_{Load}^2 + X_{Load}^2}\right)^2 + \left(\dfrac{X_{Load}}{R_{Load}^2 + X_{Load}^2} + \omega C\right)^2} = 50\Omega \\ X_{Source} = j\omega L + \dfrac{j\left(\dfrac{X_{Load}}{R_{Load}^2 + X_{Load}^2} + \omega C\right)}{\left(\dfrac{R_{Load}}{R_{Load}^2 + X_{Load}^2}\right)^2 + \left(\dfrac{X_{Load}}{R_{Load}^2 + X_{Load}^2} + \omega C\right)^2} = 0\Omega \end{cases} \tag{4.2}$$

it is obtained an equation that can be solved in order of L and C. The measured load impedance without matching needed for the calculation is in Table 4.2, ergo the first iteration should have values near L=32.51 nH; C=2.78 pF. The various iterations of Z_{Load} and return loss can be observed in, Table 4.2 for the centre frequency, and in Figure 4.6 a sweep from 1 MHz to 1.5 GHz. It is possible to see that the iterations are converging to a matched circuit. Where the final result is an antenna that radiates well enough for our system to work.

Table 4.2: Sigfox relevant VNA measurements.

	Return Loss [dB]	$R_{Load}[\omega]$	$X_{Load}[\omega]$
Without Matching	-1	14.5	98.2
1st - L=27 nH; C=2.7 pF	-6.6	117.1	-45.6
2nd - L=33 nH; C=2.7 pF	-9	91.8	-30.5
3rd - L=27 nH; C=3 pF	-15	48.1	18

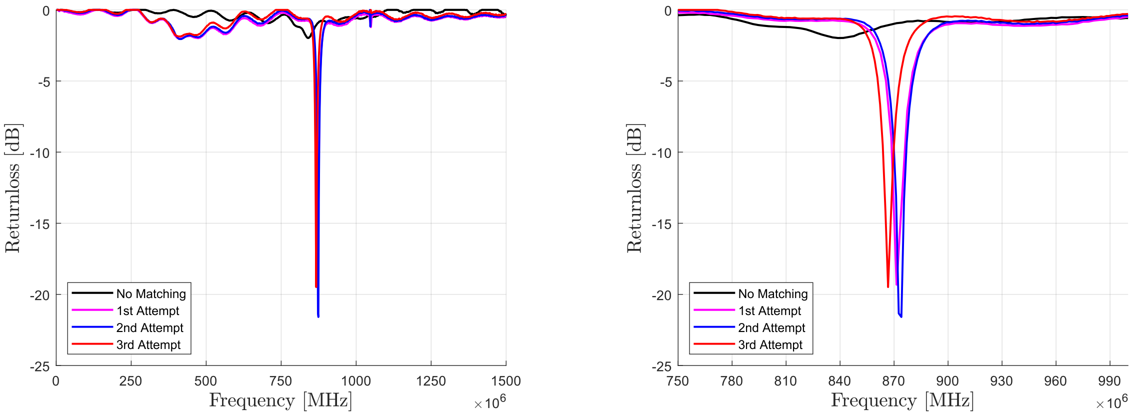


Figure 4.6: Sigfox antenna return loss before and after matching.

Furthermore, the Wi-Fi uses a chip antenna (2450AT42E0100) the relevant specifications are presented in Table 4.3. This has a low efficiency compared to the first, but in close range communications the efficiency is less critical. Although there is an efficiency loss, there is gain with the reduction of the occupied space. The design is ready for a CLC (two capacitors in parallel with an inductor) impedance matching network.

Table 4.3: Wi-Fi antenna specifications [46].

Frequency Range	[2.4 GHz,2.48 GHz]
Average Gain	−2 dBi
Return Loss	9.5 dB

This antenna will likely work without a matching circuit since it has fewer variables factoring in the load impedance. It was designed directly in the PCB strictly following the specifications provided by the chip antenna manufacturer, such as ground clearance and trace dimensions, the result is visible in Figure 4.3. However, the matching will follow the same rules as done with the Sigfox antenna because load impedance is still affected by the transmission line, between the connectivity module and the antenna, and other components such as the battery and plastic enclosure.

The matching circuit is the same as the used with Sigfox an L-network, shown in Figure 4.4. Thus, after measuring Z_{Load} without matching and replacing $R_{Load} = 16.4\,\Omega$ and $X_{Load} = 17.5\,\Omega$ in (4.2) it is obtained L=10.16 nH; C=0.84 pF. The various iterations Z_{Load} and return loss can be observed in, Table 4.4 for the centre frequency, and in Figure 4.6 a sweep from 10 MHz to 3 GHz. It is possible to see that the iterations are converging to a matched circuit and the final result improves an already working antenna.

Table 4.4: Wi-Fi relevant VNA measurements.

	Return Loss [dB]	$R_{Load}[\Omega]$	$X_{Load}[\Omega]$
No Matching	-5.2	16.4	17.5
1st - L=10 nH; C=0.75 pF	-6.1	105.9	61.1
2nd - L=7.5 nH; C=0.75 pF	-11.3	80.4	19.2
3rd - L=7.5 nH; C=1 pF	-2	33.7	109
4th - L=6.8 nH; C=0.75 pF	-22.4	50.7	7.6

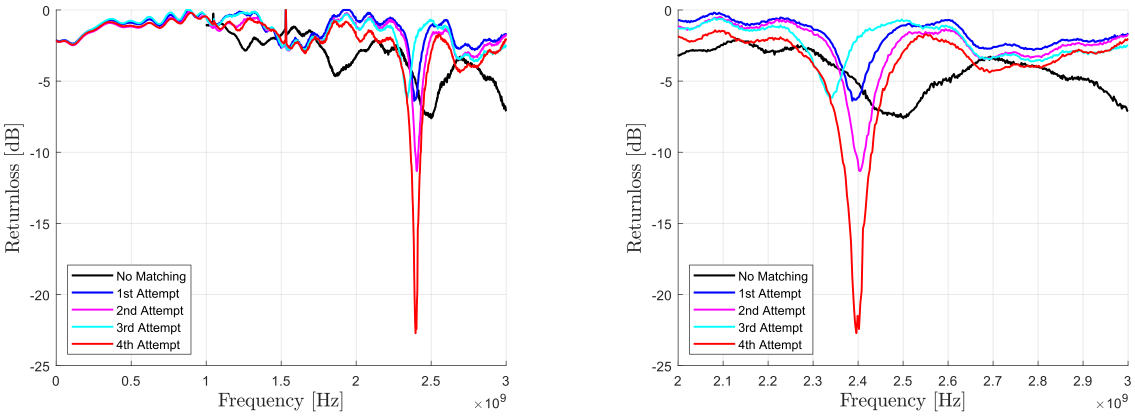


Figure 4.7: Wi-Fi antenna return loss before and after matching iterations.

4.1.3 Interface

The interface is composed of a button and an Red, Green and Blue (RGB) Light Emitting Diode (LED). The button is used to wake up the device and to reset the device to default configuration. It has an external pull-up resistor to avoid using the microcontroller internal unstable pull-up.

The RGB LED is used to notify the user. Table 4.5 shows that the power consumption of the RGB is low.

Table 4.5: RGB LED power consumption [47].

	RGB
Power Consumption (ON)	50 mW
Power Dissipation (OFF)	25 µW

4.1.4 Battery Measurement and Charging Circuit

The battery used in the device is an LP502030, a lithium polymer battery, that has a 250 mA capacity at a nominal voltage of 3.7 V. The dimensions are 20 mm x 30 mm approximately the same size as the connectivity module making it smaller than the PCB. The battery also comes with a protection circuit module that protects it from overcharge voltage, overdischarge voltage, overcurrent and short circuit. The input of the module is connected to the battery and the output is soldered to the PCB power supply input [48].

The battery voltage measurement circuit, Figure 4.8, is a simple voltage divider that is powered down when the input DCDC_EN is low. This circuit allows to have the Q2A transistor in the triode when the circuit is enabled and in the cutoff when is disabled. If Q2A would be in the saturation region the voltage read in the voltage divider would be inaccurate because the current is limited. The cutoff of Q2A is necessary to stop current draw in the voltage divider and current leakage to the ESP32 input when the device is sleeping. Alternating between these regions is possible because of transistor Q3A.

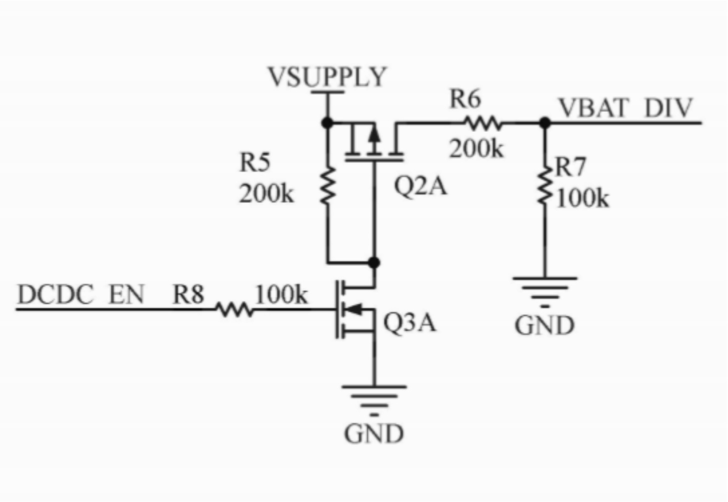


Figure 4.8: Battery measurement circuit.

The battery charger, Figure 4.9, DIO5158 manufactured by DIOO Microcircuits, manages battery charge voltage and current.The components values are given in the datasheet, C16 is an input bypass capacitor, C17 is required as a feedback loop stabiliser, R11 an R12 are pull-up resistors since the CHRG and DONE outputs have an open drain configuration finally R10 sets the charging current and is calculated by,

$$I_{CH} = 1218V/R_{10} \tag{4.3}$$

where the I_{CH} is the charging current in A and it is set to 0.25 A the maximum current charge of the battery, replacing it in the equation it solves to $R_{10} =$ 4.872 Ω. The input supply voltage can be 3.8 V to 6.5 V so a common 5 V charger can be connected to the device. An eventual update in the battery with a higher capacity would only require a change in this resistor.

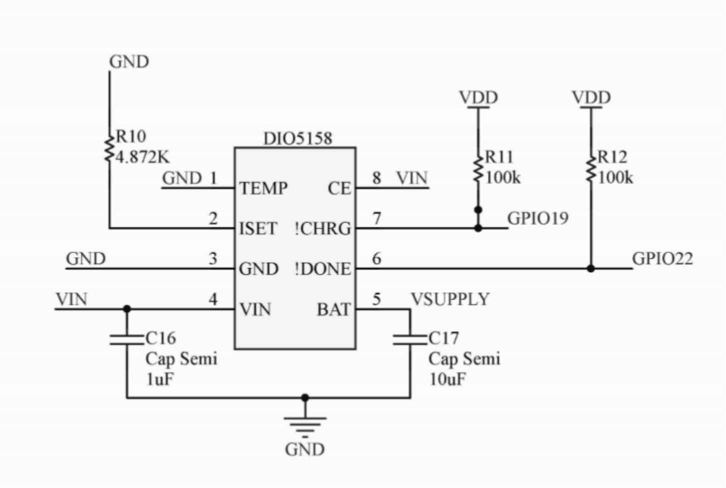
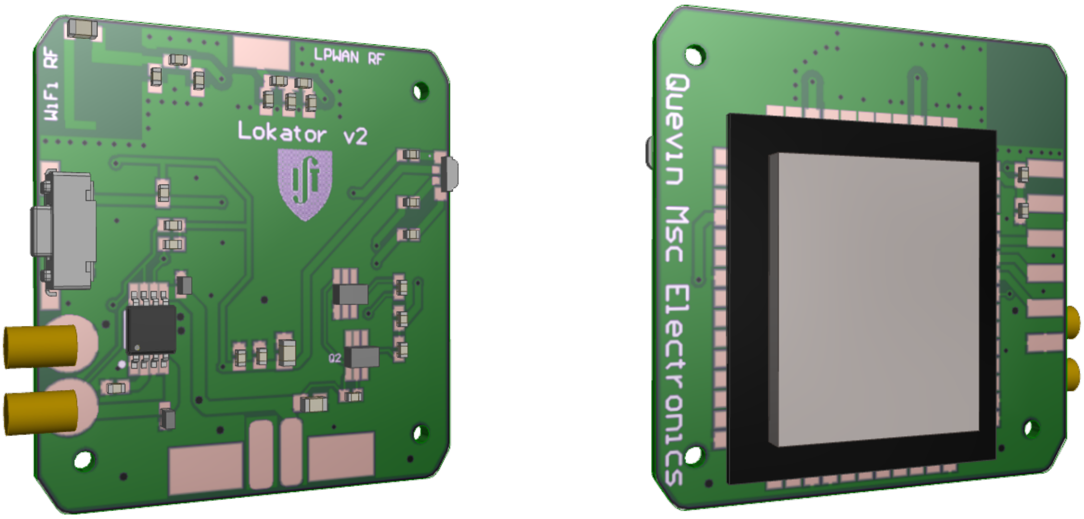


Figure 4.9: Battery charger.

4.1.5 PCB Prototype

The first version of the PCB was essential to test the functionalities of the system and detect flaws in the designing process. Some of the critical design flaws were the battery pins needed to be exposed on the plastics for it to be charged, a problem that was solved by adding the charging circuit directly in the PCB, the button was connected to pin that did not allow interruptions and there was no support to fix the PCB in the plastic enclosure. These and other small problems were solved and minor improvements were done to obtain the prototype displayed in Figure 4.10.



(a) Top Layer.

(b) Bottom Layer.

Figure 4.10: Final PCB Prototype.

Table 4.6, presents the costs of acquiring the needed components to estimate how much the production will cost. On the hardware side there is no estimate on how much would cost to have a company assemble the PCB. Future costs might increase with the enclosure.

Table 4.6: Bill of materials and Hardware cost.

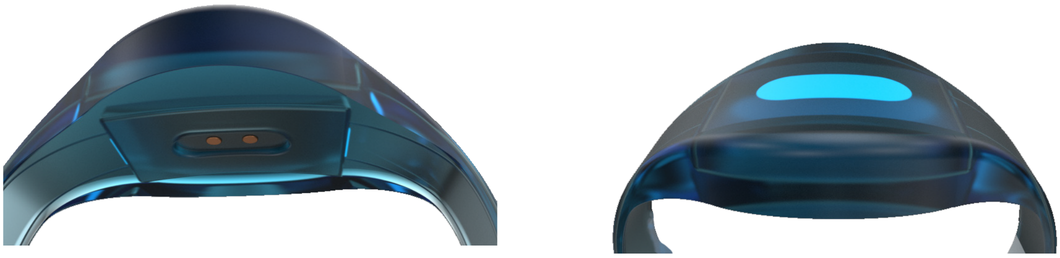
Component	Unitary Price €	
	10 Units	1000 Units
MCU	2.62	2.62
RF-Transceiver	2.17	1.34
Accelerometer	0.978	0.524
Antennas and Matching	1.206	0.661
Power Management and Battery	4.681	2.475
Interface	0.832	0.306
Others	0.875	0.226
PCB Fabrication	1	0.312
Total	14.462	7.464

4.2 Design

To design and help with the creative part of the device, two designers, from Instituto de Sistemas e Robótica (ISR) were involved. They have experience with senior citizens, thanks to other projects within

ISR so their feedback and study has been of important to develop the system. Figures 4.11a to 4.11c shows part of the developed work. The material of the enclosure will be silicone, hypoallergenic. The only port connection will be the two metallic pins to charge the device as seen in Figure 4.11b. Both Figures 4.11a and 4.11c illustrate how the LED would give some kind of alert to the user. The costs of manufacturing this has not been calculated nor researched by the designers.

(a) Device concept.



(b) Charging port.

(c) Led indicator.

Figure 4.11: Outsourced design concept.

The main objective at this point is to demonstrate a proof of concept, in other words demonstrating that the system works as idealised. To achieve this the hardware must be enclosed in something with similar shape of the concept however manufacturing a complex enclosure adds unnecessary costs at an early stage of the product development. As such various 3D models of plastic enclosure were developed and one printed. Figure 4.12 depicts how the chosen design looks with an exploded view to clarify how each component is placed. The costs to manufacture is low since the case is produced with a 3D printer available at ISR and the watch straps attached to the 3D printed box is €5.

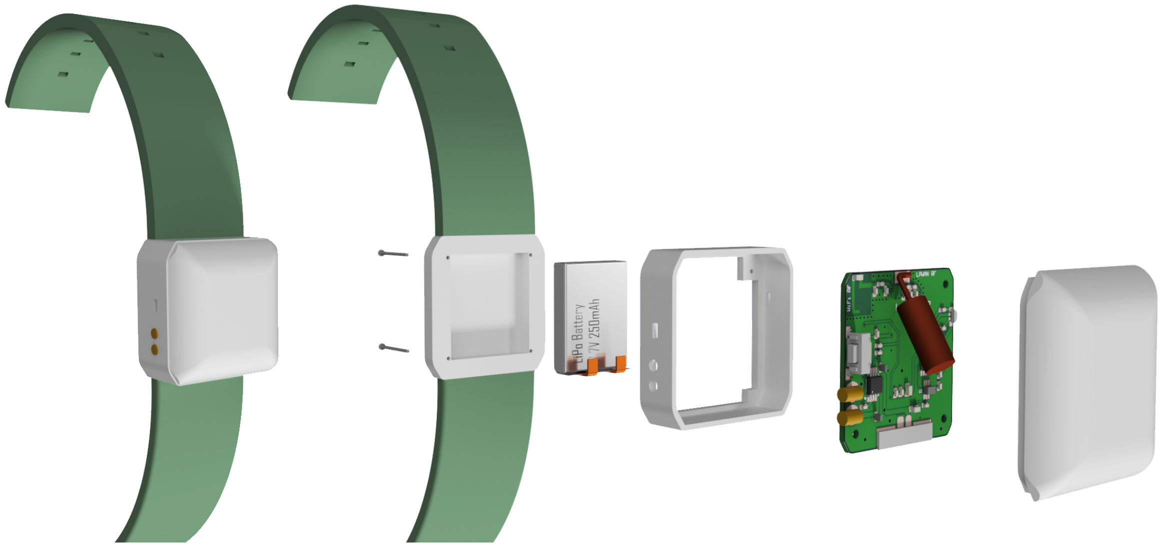


Figure 4.12: Second device concept.

4.3 Firmware

The Firmware of the device is simple as the only function of the device is sending Wi-Fi scan data to a database. The Wi-Fi scan data is composed by the MAC address and the RSSI of each available AP. Additionally, it is established that it can send the data in two ways via Wi-Fi or via Sigfox. Wi-Fi communication is added since it does not have data quantity nor message quantity restrictions.

Figure 4.13, is the first routine the device must do when its woke, it runs independently of the selected mode and it has two sources the button and the timer. The default mode is the tracking mode and can be set with a long button press. Also, this routine is responsible for triggering the low power mode. The low power mode is the selected mode without a timer wake-up the only way to wake-up is by pressing the button.

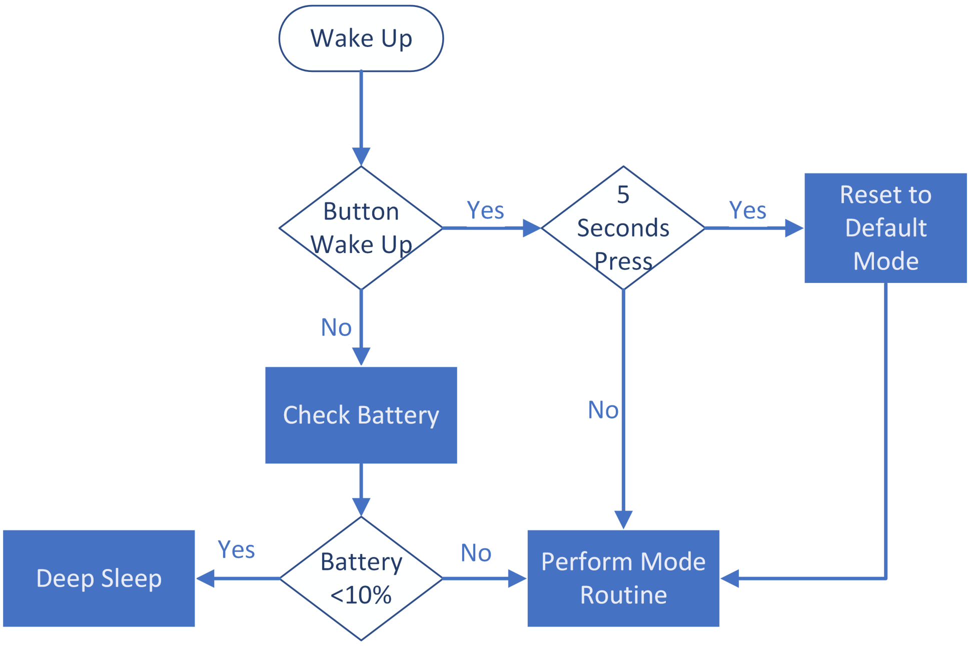


Figure 4.13: Wake-up routine.

When LPWAN mode, Figure 4.14, is active, there is no downlink and no attempt to connect to the network, so to update configurations, the mode must be reset with the long button press, as depicted in Figure 4.13.

As already stated, Sigfox has constrains in the number of messages sent per day, it is necessary to only upload data when the device finds no matching between the previous scan and the current scan. The rule to consider the scan different is when at least 50 % of APs have changed since the last scan.

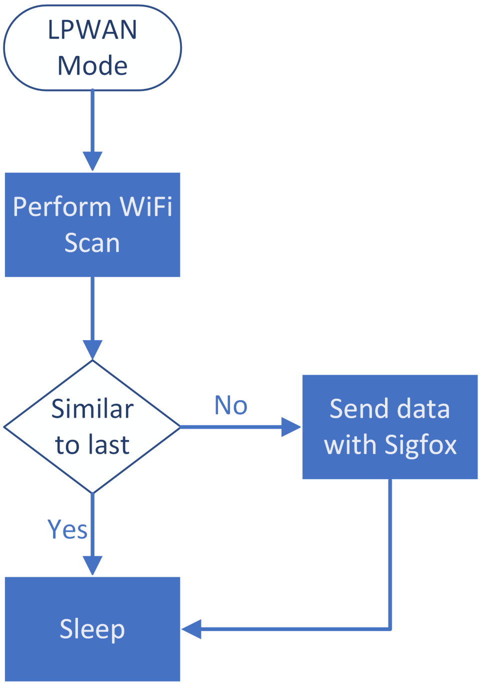


Figure 4.14: LPWAN mode routine.

This concern to evaluate the need to send data grows even more since both chosen localisation methods need, at the least, information from two APs to work and Sigfox has a 12 B size limit in each message consequently two messages, constructed as shown in Figure 4.15, are needed to send the data. Since two messages are mandatory, there is enough space for three APs information.

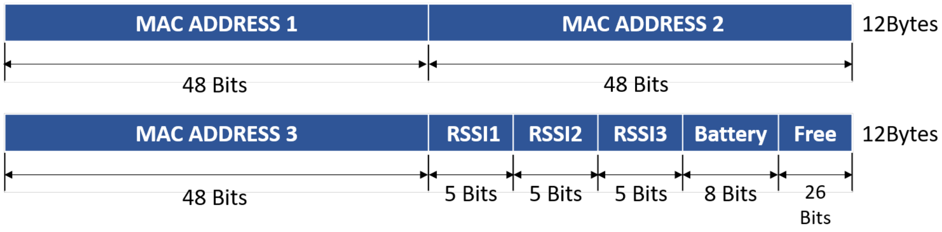


Figure 4.15: Sigfox uplink data.

The next routine, Figure 4.16, is the default mode of the device. This routine differs from the previous because there is an attempt to send the scan data with Wi-Fi this is the preferred method because there is no size or message quantity limit. And once again this mode has downlink communication which allows configurations to change.

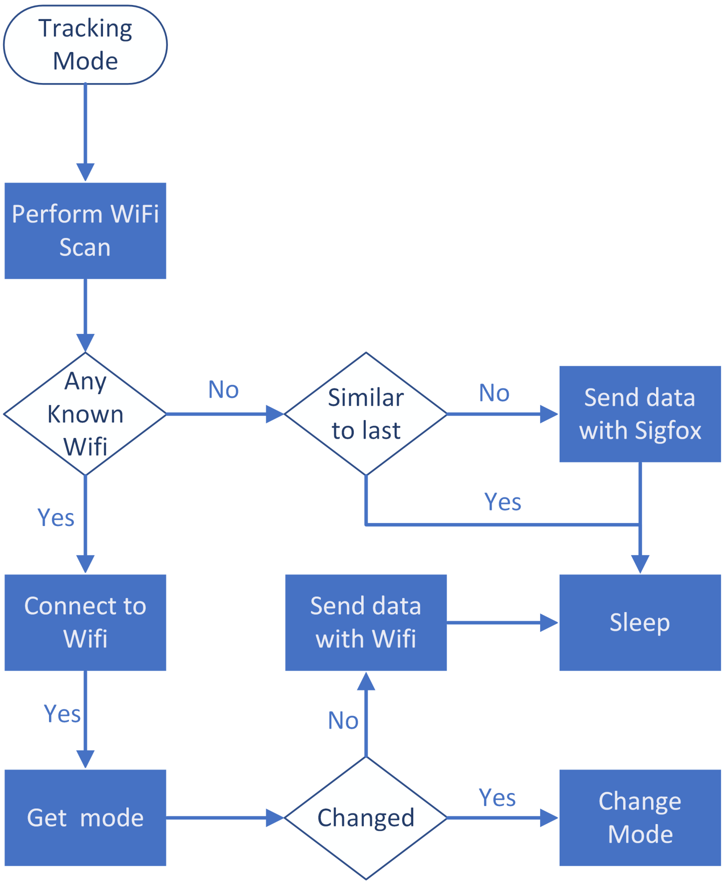


Figure 4.16: Tracking mode routine.

The last mode is specific to the indoor localisation method FIND, mentioned in Subsection 3.1.4, to train the algorithms. The training is simple requiring only the same scan information plus the actual location (e.g. Kitchen or Room) where the device is, this location is fetched from the database. Training is only available with Wi-Fi because it needs more APs and multiple scans to characterise a single room.

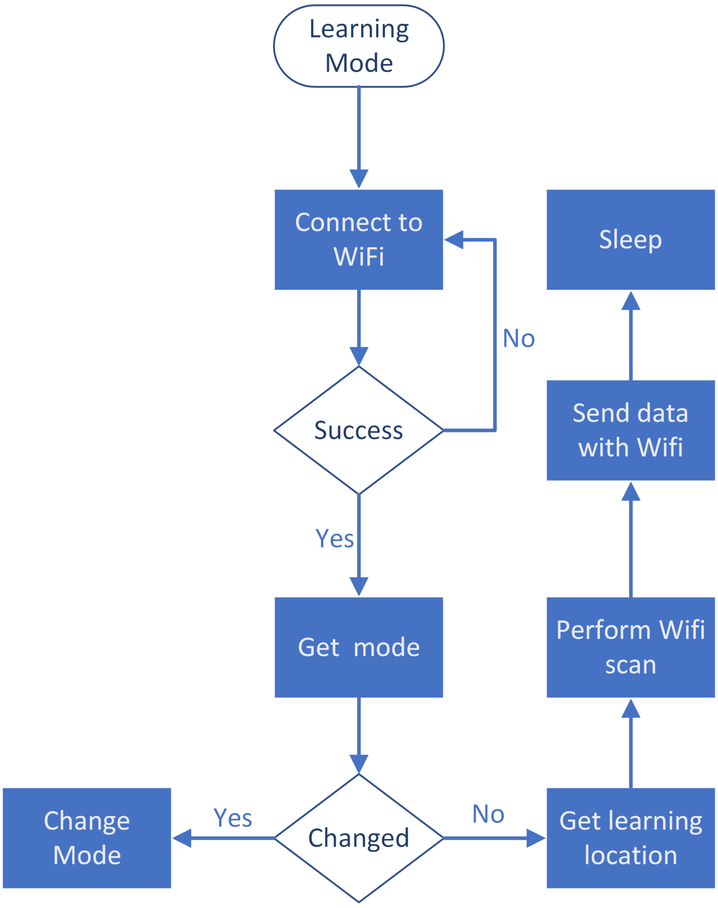


Figure 4.17: Learning mode routine.

Furthermore the RGB LED is used to give notifications to the user, Table 4.7 lists which notifications are available.

Table 4.7: RGB LED modes.

Colour	**Mode**	**Indicates**
Red	Fixed	Low Battery
	Blink	Battery Charging
Green	Fixed	Battery Charged
	Blink	Configurable
Blue	Fixed	Configurable
	Blink	Configurable

Finally default configurations of the system are specified in Table 4.8.

Table 4.8: Device default configurations.

	Default Configuration
Mode	Tracking
Sleep Time	10 minutes
WiFi AP	SSID: Lokator
	Password: IST-Lokator

4.4 Software

Software is what transforms this system and brings everything together. Besides the device that already has its part explained there is the database, GUI and the localisation methods. The database, used to store all the data coming from the device via Sigfox and Wi-Fi, is Firebase a service provided by Google that allows to store data in real-time.

The GUI is the connection between localisation method and the stored data. It is also here that the user can change the configurations (see Table 4.8) of a specific device and store them in the database. The reason why configurations are saved in the database and not immediately uploaded to the device is obviously because it is sleeping most of the time. The caretaker is also notified when the battery is low so that it can proceed to charge the battery.

The localisation methods are both external services that were already introduced in the Chapter 3. The indoor localisation method is FIND which uses Wi-Fi radio maps (fingerprinting) to estimate indoor locations. The outdoor localisation method is Google geolocation service.

Figure 4.18, illustrates how data flows between each block of our system. The data flow is separated in different independent functions of the system.

- Change configuration:
    1. The configuration of the device is changed with the GUI, and stored in the database.
- Get configuration:
    1. The device query's the database if there's any change in the configuration.
    2. If there is any change the information will be uploaded to the device.
- Send location data:
    1. The device posts to the database via Sigfox or Wi-Fi.
- Learning mode:
    1. The application fetches data collected while device is in learning mode.

2. The data is posted to FIND server.

- Tracking mode:

1. The application fetches data collected while device is in tracking/LPWAN mode.
2. The data is posted to the chosen localisation method (Google or FIND). (see examples Figure A.1 and Figure A.3)
3. The estimated location is the response to the posted data. (see examples Figure A.2 and Figure A.4)

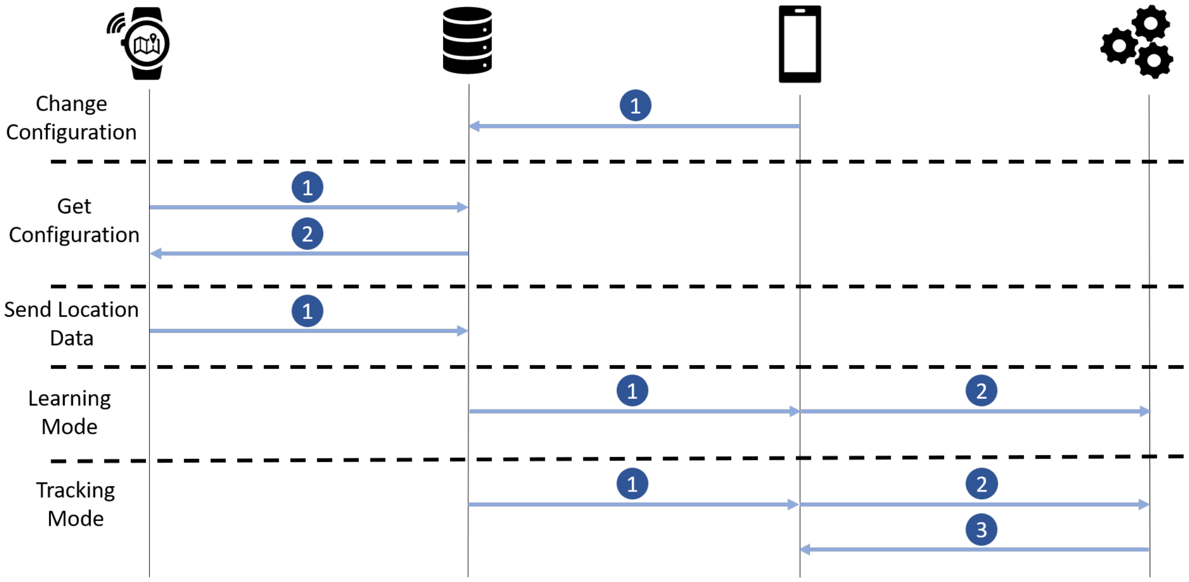
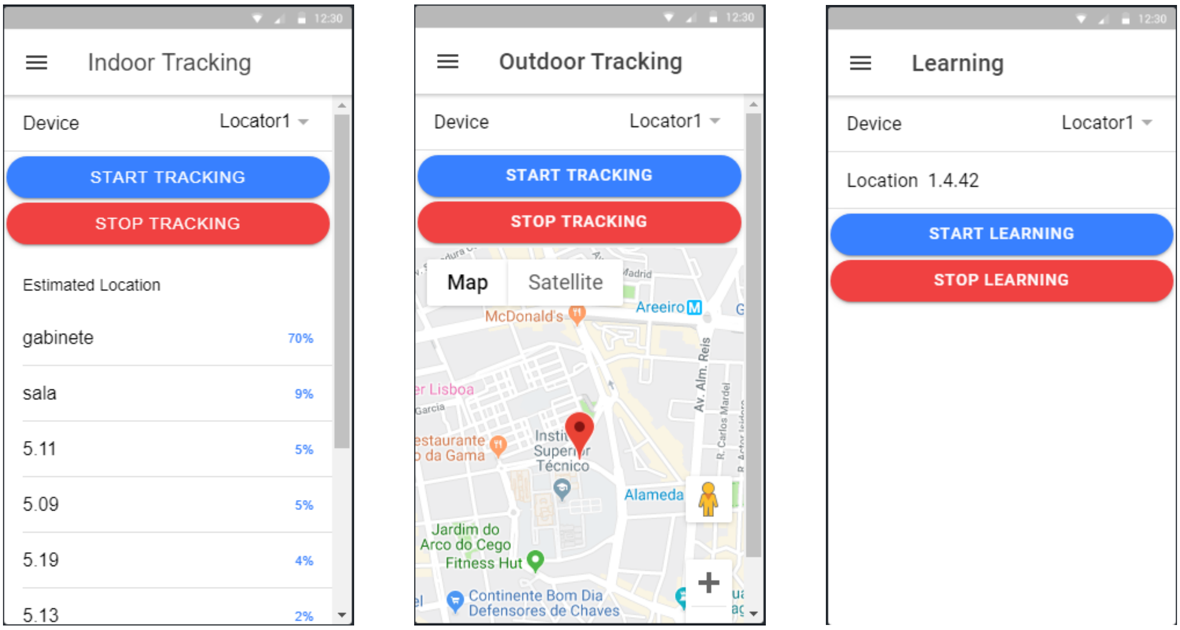


Figure 4.18: Data flow diagram.

4.4.1 Graphical User Interface (GUI)

The GUI, Figure 4.19, is a smartphone application developed with Ionic framework, an open source software development kit used to develop cross platform mobile applications. This framework is preferable over, building native applications, because the app is developed with Typescript and HTML, as it were a website, and then used a wrapper to run it as a native app. Consequently the application is compatible with both iOS and Android, although to compile the app to iOS a license of Xcode, Apple software development environment, is required [49]. Figure 4.19a and Figure 4.19b are both for the tracking mode. The first communicates with FIND exclusively and displays the estimated probability of being in each room. The second communicates with Google geolocation API and using Google Maps API the result is directly presented in a map instead of only presenting it as latitude and longitude (Figure A.4 the response is only coordinates). Figure 4.19c is where the user can put the selected device in learning mode and configure the location to train the FIND engine. Finally the device configurations can be changed in Figure 4.19d.



Device Locator1

Estimated Location

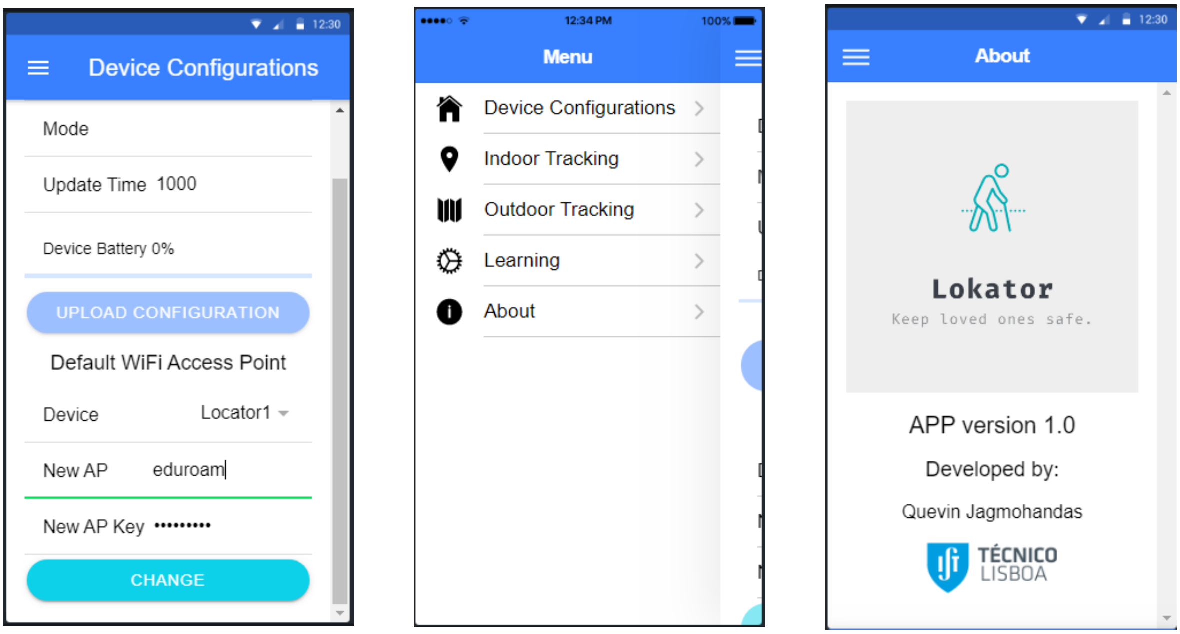
gabinete	70%
sala	9%
5.11	5%
5.09	5%
5.19	4%
5.13	2%

Device Locator1

Device Locator1

Location 1.4.42

(a) Indoor tracking page. **(b)** Outdoor Tracking Page. **(c)** Learning Page.



Mode

Update Time 1000

Device Battery 0%

Default WiFi Access Point

Device Locator1

New AP eduroam

New AP Key •••••••••

APP version 1.0

Developed by:

Quevin Jagmohandas

(d) Configurations page. **(e)** Menu. **(f)** About Page.

Figure 4.19: Smartphone application.

5

Results

Contents

Results

This chapter describes how the developed system was tested to evaluate its performance.

5.1 Localisation Accuracy and Reliability

One of the initially posed problems was Sigfox's ability to maintain a reliable message delivery. To test the coverage and the ability to send messages, the system is tested in the institution and surrounding area and gathered data of how well it performed. None of the 50 messages sent were lost and the signal power of received messages gives the perception of the worst locations to send messages, this data is compiled in Figure 5.1. This result confirms that the Sigfox antenna is working properly and reliably.

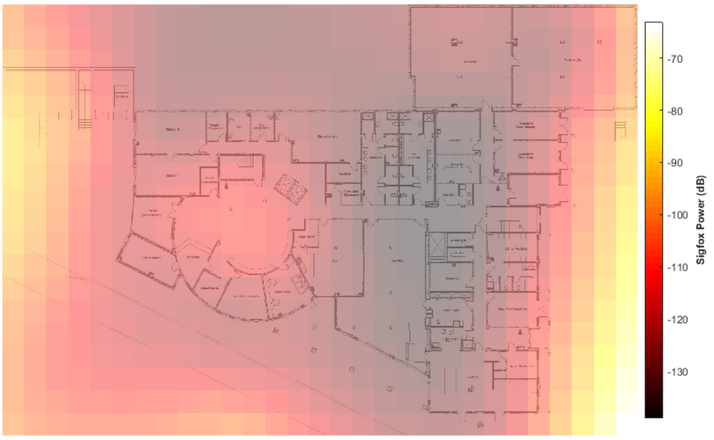


Figure 5.1: Sigfox coverage inside institution.

Wi-Fi coverage in the institution posed a problem since using FIND as a positioning method requires a minimum of APs to construct the radio map which was not met, making the results obtained through this method unreliable. However, as Figure 5.2 indicates, testing Google geolocation API obtained results as intended. The average distance between real and estimated position was approximately 30 meters.

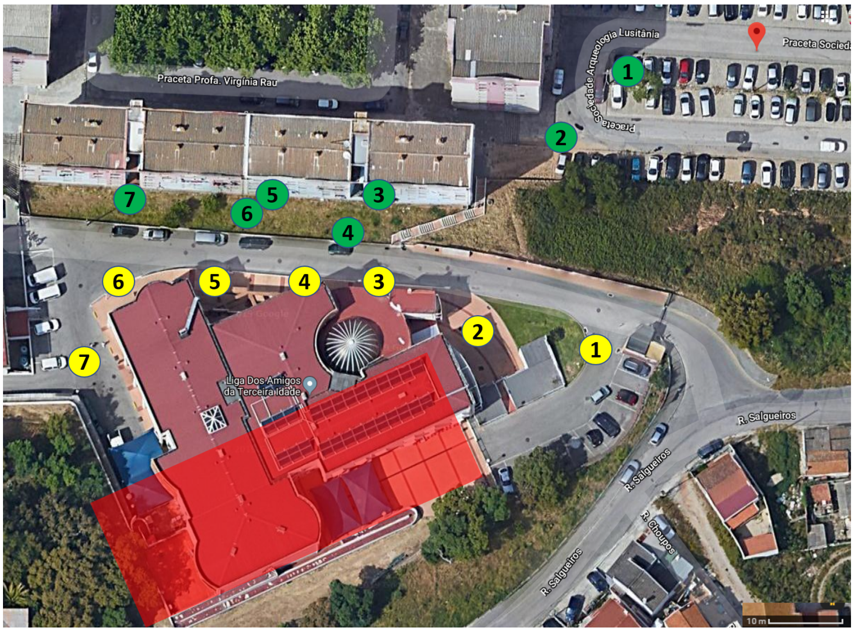


Figure 5.2: Google geolocation API test in LATI. Yellow points real position; Green points Google estimated position; Red area represents area without Wi-Fi coverage.

To prove that FIND is a reliable positioning method for indoor environments the system was tested in Instituto Superior Técnico (IST) campus Alameda more precisely in the North tower. As a disclaimer, of the obtained results, it should be highlighted that the tower has 4 APs, in each floor, which combined with the simplicity of the blueprint make the testing conditions ideal. However the results point to a situation that even if the building was more complex and with less APs that the system could point to the correct location, with less accuracy, within the requirements. The locations where the samples are taken are presented in Figure 5.3 and the results of using FIND after training the engine are shown in Table 5.1 and Table 5.2. The results met the requirements even in other samples the engine consistently estimated correctly the location. The total of probability is not 100% due to the fact that the remaining points have each less than 1% therefore are not significant and as such are not represented in the tables, this includes locations in both floors.

(a) 4th floor.

(b) 5th floor.

Figure 5.3: Samples and Wi-Fi APs locations. (each corridor is roughly 20 m)

Table 5.1: 5th floor positioning results.

		Sample Position							
		1	2	3	4	5	6	7	8
Estimated Location	1	68%	31%	5%	2%			1%	17%
	2	10%	64%	3%					
	3	4%	3%	85%	12%	12%		1%	2%
	4			5%	50%	2 %			
	5				28%	73%	29%	1%	2%
	6					6%	61%	3%	
	7						2%	83%	26%
	8	6%						4%	41%

Table 5.2: 4th floor positioning results

		Sample Position							
		A	B	C	D	E	F	G	H
Estimated Location	A	66%	27%	11%	1%		1%	1%	9%
	B	5%	62%	10%					
	C	7%	4%	71%	11%	1%	1%	1%	3%
	D			7%	69%	3 %		1%	7%
	E				12%	82%	7%	5%	1%
	F		1%			10%	78%	13%	1%
	G	8%	1%				7%	63%	17%
	H	8%			1%			8%	56%

5.2 Power Consumption and Battery

One of the mains requirements of the device is the time it should go without a charge. Thus it is important to choose an adequate battery size and capacity, there is a need to understand how much power the device consumes. To acquire the measurements, a instrument was setup, as shown in Figure 5.4. The current is measured with a high-side shunt resistor placed in series between the supply voltage and the load (Lokator). Since the resistor is very small (0.25 Ω) and the consumed currents can be as low as 5 mA, in active mode, the voltage drop across the resistor needs to be amplified to usable levels. To this end, it is used the amplifier AD8211. A Rigol DP832 power supply was used to power both the amplifier(5 V) and the load(3.5 V). The acquisition was done with a Rigol DS1054Z oscilloscope triggered by a General Purpose Input Output (GPIO) of Lokator. The data is sent to a computer, through Universal Serial Bus (USB), with NIVisa drivers, the PyVisa library and a Python application. The raw data (current drawn at each instant, sampling frequency, power supply voltage) is then exported to an excel.

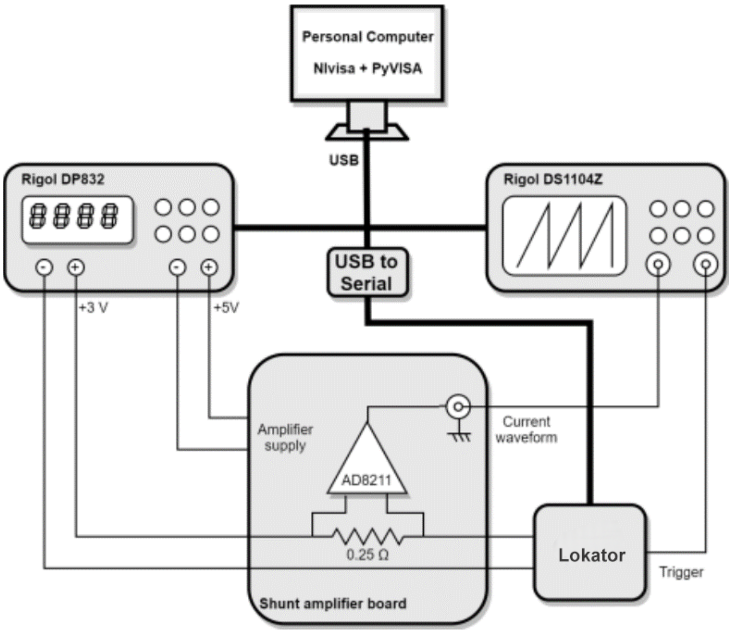


Figure 5.4: Instrument setup for power consumption measurement [50].

5.2.1 Tasks power consumption

The main tasks are Wi-Fi APs scans, Sigfox uplink messages and Wi-Fi uplink and downlink messages. Computation time and its consequent power consumption are almost nonexistent, from the moment the device wakes up to the moment it will go back to sleep, any computation that takes place is accounted for in these tasks. As already stated before, the only function of the device is to upload sensor data and there is no information processing taking place. The acquisition of the measurements is performed independently and the results are presented from Figure 5.5 to Figure 5.7.

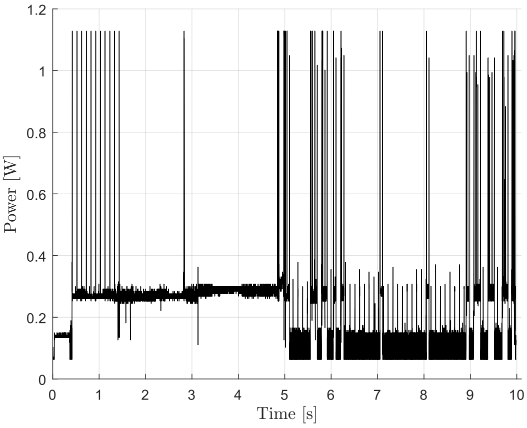


Figure 5.5: Wifi scan uplink plus downlink of configurations.

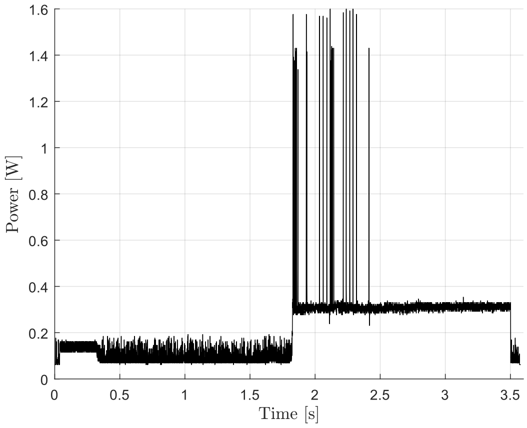


Figure 5.6: Power consumption, while performing Wi-Fi APs scan.

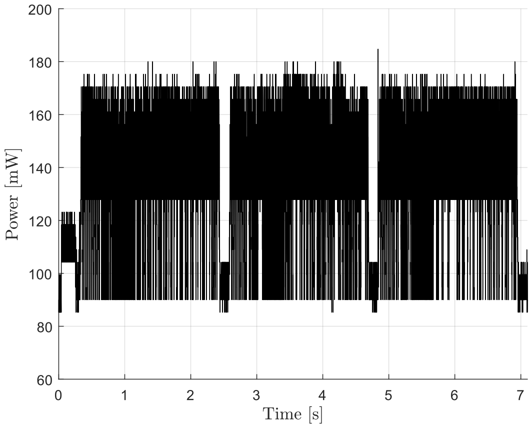


Figure 5.7: Power consumption, while transmitting a Sigfox uplink message.

With this data it is possible to create three power consumption profiles. The first is a Wi-Fi AP survey which leads the device to infer that the location has not changed, going back to sleep mode. The second is a Wi-Fi AP survey, followed by a Sigfox uplink message with the survey data, since the device infers that the current location has changed. The third power profile is the most recurrent if Wi-Fi is available where the device updates configurations and uploads via Wi-Fi.

5.2.2 Battery characterisation

To characterise how the lifetime of the battery changes with different amounts of sourced power to the load a power function was fitted from data of the datasheet. The chosen battery's datasheet provides the constant current discharge curve for five different rates [48]. When describing batteries, the discharge current is often expressed in C-rate. A C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity. A 1C rate means that the discharge current will discharge the entire battery in 1 hour. In Figure 5.8 are represented the five points extracted from the curves. Each point is the time it took the battery to completely discharge at the different rates (0.02C, 0.2C, 0.5C, 1C, 2C). A power function curve was fitted to the data resulting in,

$$BL(p)[h] = 0.9031 \times p^{-1.018} \tag{5.1}$$

where BL is the battery life in hours and p is the power drawn in W.

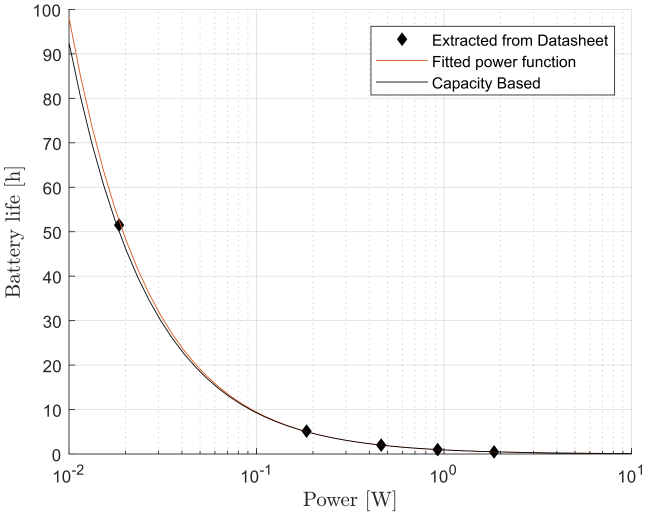


Figure 5.8: Battery lifetime change, with the sourced power.

The battery drop, BD,

$$BD[\%] = \sum_{i=1}^{i=N} \frac{100 \times \frac{\Delta t}{3600}}{BL(p(i))} \tag{5.2}$$

where $p(i)$ is the power consumed at the instant at which the sample is taken, Δt is the the sampling period expressed in seconds(s) and N is the number of samples took during the power profile.

Now it is possible to estimate how much battery drop each task causes. The results are summarised in Table 5.3. The ”Estimate Count” refers to the number of times each task can be done with a full battery.

Table 5.3: Model results and battery leakage.

Task	Battery Drop [%]	Estimate Count
Wifi Scan	0.021358017	4682
Sigfox Uplink Message	0.026455828	3780
Scan + Sigfox Uplink	0.047813845	2091
Scan + 2 Sigfox Uplink Messages	0,069171862	1446
Scan + Wifi (DownLink and Uplink)	0.061966	1614
Daily Leakage (assuming 15 µA current leakage)	0.144	694

Finally, based only on the described tasks it is possible to estimate how much time the battery can last until the device is charged again. Two scenarios are described:

- Worst case scenario: Where the device sends the maximum amount of messages. In this scenario the device wakes up every 10 minutes to make the Wi-Fi survey and sends the data.
- Estimated Normal use scenario: The device only sends uplink messages when it assumes its position hasn't changed, waking up every 10 minutes to verify it. It's assumed that the time it only does Wi-Fi surveys is 8 hours

Table 5.4, presents the battery life estimated in tracking and LPWAN mode. In tracking mode all of the messages were sent with Wi-Fi in a real scenario there it is possible that at some point of the day the user will be in an area that is not covered by a known Wi-Fi. The consequence of this will be a higher consumption since the required two messages consume more than a Wi-Fi uplink.

Table 5.4: Estimated battery life in different modes.

	LPWAN Mode	Tracking Mode
Worst Case Scenario	10 days	11 days
Estimated Scenario	14 days	16 days

Certainly these estimates will vary widely depending on the behaviour of each user. Only after a wide test it will be possible to deliver more accurate estimates. The unexpected need of sending 2 messages to make the tracking methods work have affected significantly the power consumption, this will also need to be improved.

6

Conclusions

Conclusions

Developing an indoor and outdoor localisation wearable device is the most suitable option to ensure that elderly people with dementia can be found in case of emergency. The challenges arise when developing a device that must be small and contain technologies to track persons in both indoor and outdoor environment while at the same time having low power consumption. When designing such system a trade off analysis between the different technologies must be considered to make sure that requirements such as positioning accuracy, power consumption, cost and size are met avoiding compromises.

This thesis designed such system and demonstrated a proof of concept. The system was designed in such way that the device has only one function and that is to transmit sensor data leaving information processing and tracking capabilities to a server and a GUI. The chosen technologies were Sigfox to transmit data and Wi-Fi sensor data to track the device. Both of them are critical and as such a good antenna is designed to both making sure that Sigfox is capable to send messages without loss and Wi-Fi achieves a good coverage. This is achieved by choosing an antenna adequate to small devices and making sure the antenna path has its impedance matched. The device also has an LED for notifications and a button to send an emergency message. Finally, the device must have a functional and pleasant enclosure so a 3D piece was designed to house the hardware. The second part of the developed system is where the sensor data from the device is transformed in the localisation information. This system uses Google geolocation API to locate in outdoor environment and FIND to locate in indoor environment. Before using FIND each location must be previously mapped with Wi-Fi fingerprint data. The smartphone application is what agglomerates these services and uses them to display the estimated last known location in a map, of the selected device, and allows to change its configurations everything is simple and intuitive to the user. Ultimately what the development of this system has proven is that the concept works as imagined and it has real potential as a tracking device for elderly people. However, due to the lack of Wi-Fi coverage in the institution the system is not capable of pinpointing the location indoors. In the outdoor environment using the Google geolocation API the system can determinate if the user is outside and the relative direction being taken. Another important requirement is the battery lifetime which should not need to be daily charged and this is possible even if the usage varies. The estimation point to at least 10 days of usage without charging.

For future work rough edges of this development should be perfected such as producing a more refined and waterproof enclosure as this would allow further tests with patients. A third version of the hardware must include any changes needed to correct the flaws detected in real use and add a secondary functionality such as a low power display to show time or notifications to the senior citizen. In the software side improvements in indoor positioning are possible with an additional cost of Bluetooth beacons. Finally, a reassessment of the LPWAN should be done since network providers in Portugal are on the verge of releasing NB-IoT.

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Appendix A- Data exchange messages

Figure A.1 is a example of a message sent to the FIND server with sensor data. The device that is posting to the server needs to be identified in the server and that is done in device name field (”d”). Each of the devices are associated with a family (”f”) each family can characterise a different indoor location (e.g. IST campi Alameda and Taguspark). The current timestamp can be specified as the Epoch time in milliseconds at UTC (”t”), instead of using the ESP32 time it is used the database timestamp. The location(”l”) is optional. If it is specified it designates that the sensor data is going to be used for learning. If it is not specified it designates that the sensor data will be used for only tracking. The GPS coordinates are optional. If submitted, they will be saved in a database with the location (if provided) and the sensor data. The sensor data (”s”) is where the keys (Wi-Fi, Bluetooth) are the type of the data. It is possible to insert any type of data, in this thesis, only Wi-Fi data is used other possibilities may consist in gyroscope or Bluetooth sensor data. These types of data are keys to a map of all the devices and their signals associated with that signal type.

Figure A.2, is the message received from the server FIND after performing a ”GET /api/v1/location /FAMILY/DEVICE” where FAMILY is the mapped location and DEVICE the device which last location is needed. The analysis returns an array with the location plus the probability of being at mentioned location. The server also gives the results of applying different algorithms to the data. The algorithms are truncated for brevity.

Using the Google geolocation API is significantly simpler, Figure A.3 is the request with each scanned AP MAC address plus the RSSI. An immediate response with the geographical coordinates is returned as depicted in Figure A.4.

```
{
   "d":"DEVICE",
   "f":"FAMILY",
   "t":1520424248897,
   "l":"LOCATION",
   "s":{
      "bluetooth":{
         "20:25:64:b7:91:42":-72,
         "20:25:64:b8:06:38":-81,
      },
      "wifi":{
         "20:25:64:b7:91:40":-73,
         "70:4d:7b:11:3a:c8":-81,
         "88:d7:f6:a7:2a:4c":-39,
         "8c:0f:6f:e7:2b:78":-42,
         "8c:0f:6f:e7:2b:80":-43,
         "92:0f:6f:e7:2b:80":-43,
         "96:0f:6f:e7:2b:78":-39,
         "9e:0f:6f:e7:2b:80":-43,
         "ac:9e:17:7f:38:a4":-55,
         "dc:fe:07:79:aa:c0":-90,
         "dc:fe:07:79:aa:c3":-89
      }
   },
   "gps":{
       "lat":12.1,
       "lon":10.1,
       "alt":54
   }
}
```

Figure A.1: POST, in JSON format, with Wi-Fi scan data sent from the database to FIND.

```
{
    "analysis": {
        "guesses": [
            {
                "location": "living room",
                "probability": 0.7555629615587942
            },
            {
                "location": "kitchen",
                "probability": 0.23040164675357372
            }
        ],
        "location_names": {
            "0": "guest room",
            "1": "kitchen",
            "2": "living room",
            "3": "bathroom",
        },
        "predictions": [
            {
                "locations": [
                    "1",
                    "2",
                    "0",
                    "3",
                ],
                "name": "Nearest Neighbours",
                "probabilities": [
                    0.67,
                    0.33
                ]
            },
            {
                "locations": [
                    "2",
                    "1",
                    "3",
                    "0"
                ],
                "name": "Extended Naive Bayes2",
                "probabilities": [
                    1
                ]
            }
        ]
    }
}

```

Figure A.2: Response, in JSON format, with last location data from FIND.

```json
{
  "considerIp": "false",
  "wifiAccessPoints": [
    {
        "macAddress": "00:25:9c:cf:1c:ac",
        "signalStrength": -43,
    },
    {
        "macAddress": "00:25:9c:cf:1c:ad",
        "signalStrength": -55,
    }
  ]
}

```

Figure A.3: Request, in JSON format, with Wi-Fi scan data to Google geolocation service.

```json
{
  "location": {
    "lat": 51.0,
    "lng": -0.1
  },
  "accuracy": 1200.4
}

```

Figure A.4: Response, in JSON format, received from Google geolocation service with geographical coordinates.