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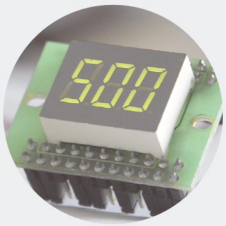

# Embedded Wireless System within Urban Premises

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POLITÉCNICO
DO PORTO

# EMBEDDED WIRELESS SYSTEM WITHIN URBAN PREMISES

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# *Resumo*

O projeto apresentado neste documento consiste no desenvolvimento de um sistema sem fios de controlo de acessos que deverá ser aplicado em instalações urbanas, tais como arranha céus ou casas ajardinadas. Existirá uma sala de controlo principal que deverá conseguir comunicar com estas propriedades que podem estar a uma distância considerável. O problema em questão consiste no desenvolvimento de um sistema de monotorização sem fios dadas as limitações arquitetónicas e altos custos de uma implementação com cablagem. Esta solução deve permitir comunicações de longo alcance, a inserção de novos nós de forma simples e um esquema modular que permita a inserção de novas funcionalidades de forma prática.

Para o desenvolvimento e implementação desta plataforma foram inicialmente estudadas diversas tecnologias rádio tais como Bluetooth, Z-Wave, Sigfox, LoRa, Wi-Fi e Narrowband-IoT, sendo feita depois uma comparação entre estas para escolher a mais adequada ao projeto.

A tecnologia escolhida para o desenvolvimento do projeto foi a LoRa, uma vez que possui bastante suporte e informação, além de possuir as características necessárias e desejadas para a sua implementação no presente sistema. É entre todas as tecnologias analisadas a que permite um maior alcance, acompanhada de uma maior eficiência energética.

As aplicações são o funcionamento como *gateway*, acionamento de relés, deteção de fuga de água e deteção de fumo que neste projeto foi trabalhado como sensor de humidade e temperatura. Relativamente ao software desenvolvido, este foi também baseado neste conceito de expandir e modificar facilmente o sistema, está dividido por funções permitindo uma melhor gestão do seu funcionamento.

Foram realizados testes através de *breadboards* a cada um dos pontos onde o sistema pode ser aplicado e foram realizados também testes de alcance de forma a garantir e confirmar que a tecnologia escolhida oferecia a resposta para o problema em questão. Após definidas as aplicações necessárias para o desenvolvimento do projeto, foram desenvolvidas PCBs, utilizando sempre um núcleo central, sendo assim possível modificar facilmente o tipo de aplicação e expandir o projeto para outras áreas.

## *Palavras-Chave*

Automação residencial, Controlo de Acessos, Propriedades multifamiliares, LoRa.

# *Abstract*

The project presented in this document consists of the development of a wireless access control system that should be applied in urban facilities, such as garden-style apartments and high-rises. There will be a main control room that should be able to communicate with these properties which may be at a considerable distance. The problem in question is the development of a wireless monitoring system given the architectural limitations and high costs of a cabling implementation. This solution should allow long-range communications, the insertion of new nodes in an easy way and a modular scheme that allows the insertion of new features in a practical way. For the development and implementation of this system, several radio technologies were initially studied, such as Bluetooth, Z-Wave, Sigfox, LoRa, Wi-Fi and Narrowband-IoT, and then a comparison was made between them to choose the most appropriate to the project.

The technology chosen for the development of the project was LoRa, since it has a lot of support and information besides having the necessary and desire characteristics for its implementation in the present system. It is among all the technologies analysed, the one that allows a greater reach, accompanied by greater energy efficiency.

The applications are the operation as gateway, multiple relays trigger, water leakage and smoke detector that in this project was worked as a humidity and temperature sensor. Regarding the software developed, this was also based on this concept of easily expanding and modifying the system, it is divided by functions allowing a better management of its operation.

Tests were carried out by using breadboards for each of the points where the system can be applied and reach tests were also carried out to ensure and confirm that the chosen technology offered the answer to the problem in question. After defined the applications in this project, PCBs were developed, always using a central core, so it can be easily modified to the type of application and expand the project to other areas.

# *Keywords*

Home Automation, Access Control, Multi-Family Properties, LoRa.

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## *Acronyms*

| | | |
|---|---|---|
| AP | – | Access Point |
| BLE | – | Bluetooth Low Energy |
| BPSK | – | Binary Phase-Shift Keying |
| BW | – | Bandwidth |
| CBRS | – | Citizens Broadband Radio Service |
| CDMA | – | Code Division Multiple Access |
| CF | – | Carrier Frequency |
| CR | – | Change Request |
| CSS | – | Chirp Spread Spectrum |
| DCF | – | Distributed Coordination Function |
| DER | – | Data Extraction Rate |
| FOTA | – | Firmware Over-the Air |
| GPRS | – | General Packet Radio Service |
| GSM | – | Global System for Mobile Communications |
| HART | – | Highway Addressable Remote Transducer |
| IoT | – | Internet of Things |
| IP | – | Internet Protocol |
| ISM | – | Industrial, Scientific, and Medical |

| | | |
|---|---|---|
| LBT | – | Listen-Before-Talk |
| LoRa | – | Long Range |
| LoRaWAN | – | Long Range Wide-Area Network |
| LPWAN | – | Low Power Wide Area Network |
| LTE | – | Long term Evolution |
| MAC | – | Media Access Layer |
| MTC | – | Machine Type Communications |
| NB | – | Narrowband |
| OFDMA | – | Orthogonal Frequency-Division Multiple Access |
| PCB | – | Printed Circuit Board |
| PHY | – | Physical Layer |
| PPR | – | Packet reception rate |
| RF | – | Radio Frequency |
| RSSI | – | Received Signal Strength Indication |
| SC-FDMA | – | Single Carrier - Frequency-Division Multiple Access |
| SF | – | Spreading Factor |
| SHF | – | Super High frequency |
| SINR | – | Signal-to-Noise-and-Interference Ratio |
| TP | – | Transmission Power |
| UHF | – | Ultra-High Frequency |

UMTS – Universal Mobile Telecommunications System

VHF – Very High frequency

WLAN – Wireless Local Area Network

# 1. INTRODUCTION

In this chapter, chapter 1, is made a brief contextualization, a definition of the problems and requirements, main objectives of the project, the contributions, and what was the timing of the dissertation. It is, in the last section, referring to how this document is structured.

## 1.1. CONTEXTUALIZATION

Mosano is a company based in Oporto that provides software development services to its clients with the aim of growing their business.

Mosano has a client that is located in the United States of America who intends to do the monitoring of access control of multifamily properties, that in addition to its software development needs specific hardware development, the opportunity of the realization of this dissertation presented itself.

The client intends to apply the system developed in various types of multifamily properties, such as garden-style apartments and high-rises, these places have their receivers, called access points located far away from the transmitter that will control them, located in the main control room and a wired solution is not viable due to architectural limitations and the high cost of installation.

The access control system requires power to reach each access point, therefore, a wireless solution needs to be explored with the ability to penetrate and reach farther distances than a standard wireless network like wi-fi, this will allow to secure the communication between the main control room and the access points.

Internet of Things (IoT) applications involve sensors transmitting minimal data from remote locations where a fundamental requirement is low power consumption, most applications are battery-operated, so long battery life is a must because sometimes the access for battery replacement is difficult.

Another requirement is long-range, most IoT applications cover a short-range from 10 to 100 meters, however, many others need to extend that range from 100 meters to many kilometres, in this case low data rates like less than 1 Mbps are typical. The distance travelled by a radio wave of a given power, antenna gain, and receiver sensitivity directly relates to the operating frequency. The physics of radio indicates that the range is inversely related to frequency, in other words, lower-frequency signals naturally travel farther than higher-frequency signals, however, the lower the frequency the lower the data rate it can support.

Most of the basic short-range technologies operate in the 2.4 GHz band or 5 GHz, dropping the operating frequency below 1 GHz will significantly extend the useful range, another benefit of lower-frequency signals is that they penetrate buildings and other obstacles better than higher frequencies.

Due to the disperse requirements of all potential use cases, multiple IoT connectivity technologies have been developed in the IoT domain for the last 20 years, previously known as M2M, a brief summary of these technologies is listed below (Figure 1) [1]:

- Short Range: ZigBee, Bluetooth/BLE, Z-Wave, IEEE 802.11ad (Wi-Gig).
- Medium Range: Wi-Fi, IEEE 802.11ah (Wi-Fi HaLow), IEEE 802.11p (vehicular transmission systems).
- Long Range Low-Power Wide Area Network (LPWAN): LoRa, Sigfox, Wi Sun, Ingenu, DASH-7, Weightless.

- Long Range Cellular: 2G-GSM / GPRS / IS 95 (CDMA 2G), 3G UMTS / CDMA, Long Term Evolution (LTE), NB-IoT, LTE-M (Cat M1), CBRS, Multi-Fire, 5G.

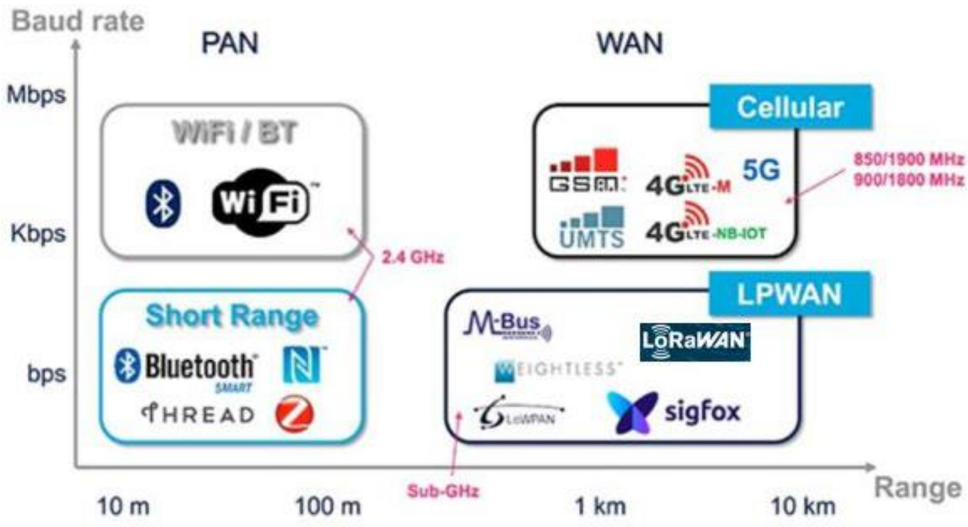



**Figure 1 Overview of the different technologies [1]**

## 1.2. REQUIREMENTS

There is the need to research and develop a wireless transmission system that:

- Can reach longer distances than wi-fi.
- Can have its range increased by adding more nodes within like a mesh network.
- Can interface with the main system through a Serial Port.
- Can have different appliances without changing the electric schema design in between those.

## 1.3. OBJECTIVES

The overall purpose of this dissertation is the integration of a wireless system into multi-family properties that does the monitoring of the communication between nodes for access control. To achieve this goal, the work was divided into multiple tasks, such as:

- Research options of radio technologies and protocols that allows the system to acknowledge packet delivery, dropped packets, auto-discovery of bound network nodes and have a network binding procedure.
- Research of possible problems that these radio technologies can find over time, in terms of distance, used antennas and electromagnetic and radio interference.

- Development of software that handles bi-directional packet routing, includes a serial interface to receive and send packets within the network, allows handling of different types of sensors, and allows state management of output components such as relays.
- PCB design and prototyping of some possible purposes like:
  - Gateway board – bridges other communication means with the network.
  - Multiple-Relay board – receives commands to turn on and off one or more relays.
  - Water Leak Detector board – broadcasts alerts for when it detects leaks.
  - Smoke Detector board – broadcasts alerts for when it detects smoke.

Based on the requirements and these tasks it is possible to elaborate the overall architecture of the system, as can be seen in Figure 2, the main control room is centered on the Figure being what makes the management of packets received and sent from the other access points.

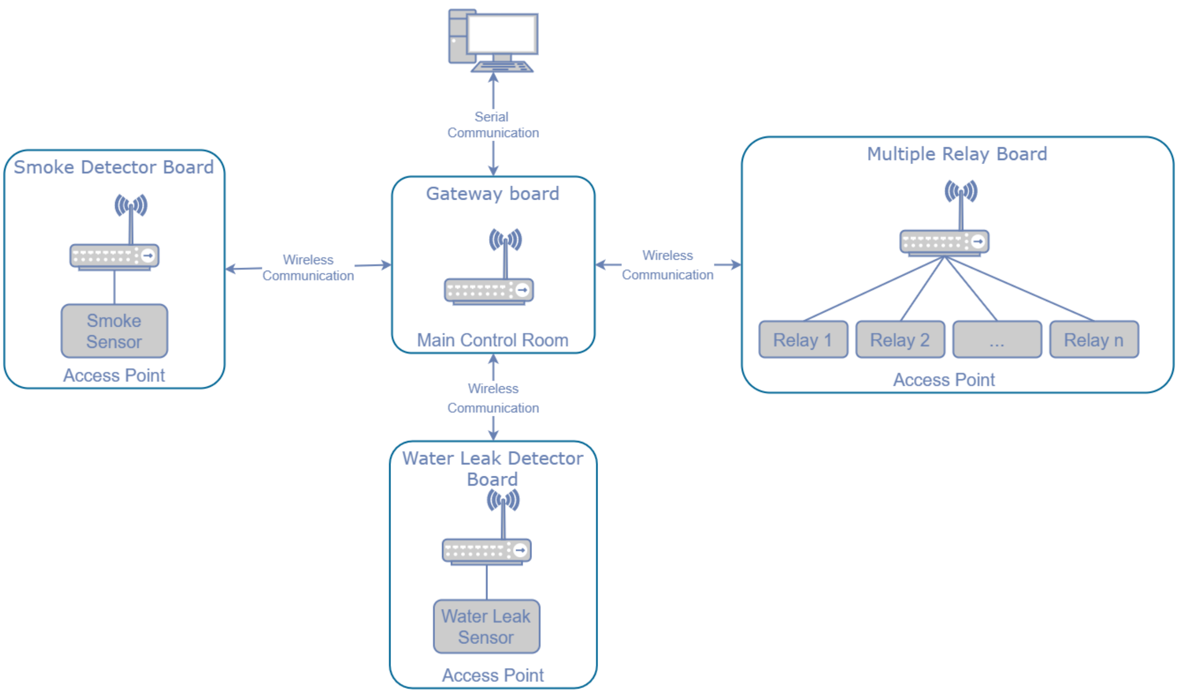



**Figure 2 Overall Architecture of the system**

## 1.4. CONTRIBUTIONS

In this dissertation several long-range radio technologies were studied that can be used in IoT applications in several areas, although only one technology has been addressed it has been seen that there are several other options that may or may not be viable depending on the context in which they are applied.

The developed project has the basic features for access control in buildings, the software developed was carried out in such a way that it can be used easily in other similar applications adapting its use, and the hardware in modules allows its expansion to other functionalities by adding other input or output devices, thus being possible to expand the system.

As mentioned before the project is divided into four boards, the Gateway, the relays, the water leakage sensor and the smoke detector, the latter was developed as a temperature and humidity sensor as a form of proof of concept due to the ease of application, but its functionality remains unchanged, allowing the detection of a possible fire in the premises.

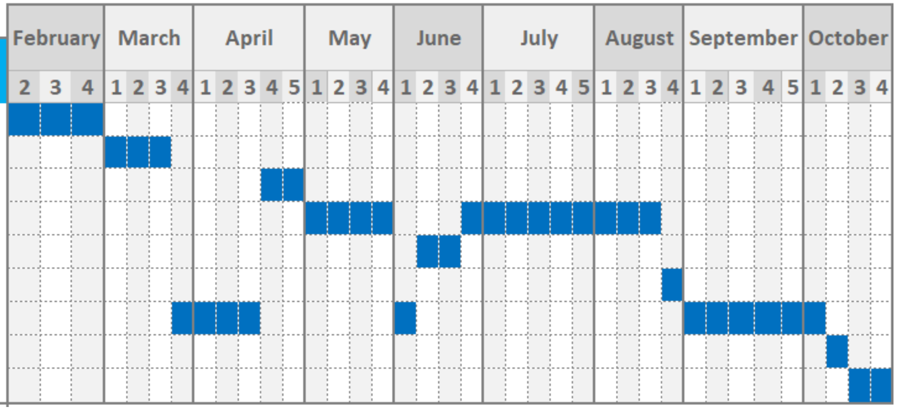
## 1.5. SCHEDULING

This dissertation started at February 10$^{th}$ and was delivered on October 31$^{st}$, what resulted in approximately 8 months of work where the task execution plan is presented in the Table 1 on a Gantt format.

The project started with the research of radio technologies and protocols, followed by a comparison and the subsequent research of problems that the technologies of interest could encounter over time. After choosing the technology, were acquired modules for testing and development of the whole system. This boards were initially tested, to be possible to carry out the software essential for the operation of the system. In the next phase, the printed circuit boards were developed and designed, and then tests were made of the final operation of the system.

**Table 1 Project Scheduling**

| TASK NAME | START DATE | END DATE | DURATION (Hours) |
|---|---|---|---|
| Research of radio technologies and protocols | 02/10/20 | 02/28/20 | 120 |
| Research of possibles problems radio technologies | 03/02/20 | 03/20/20 | 120 |
| Tests to the TTGO modules | 04/20/20 | 05/01/20 | 80 |
| Software Development | 05/04/20 | 08/21/20 | 360 |
| Development of the PCBs | 06/08/20 | 06/19/20 | 80 |
| Tests to the system | 08/24/20 | 08/28/20 | 40 |
| Writing of the final report | 03/23/20 | 10/09/20 | 440 |
| Make the Presentation | 09/30/20 | 10/02/20 | 40 |
| Document Revision and Changes | 10/05/20 | 10/23/20 | 80 |



## 1.6. DISSERTATION OUTLINE

This dissertation is divided into 8 chapters, that describe the entire development of the project. In this chapter, a brief introduction is made, as well as a contextualization, a description of the problem and the project requisites, defined the main objectives and presented a summary of what was accomplished for the entire project. To reach these results, a schedule was also presented in this chapter. In Chapter 2, a study is done on some types of radio technologies that exist referring to their main characteristics and mode of operation, after this study an analysis is made to realize what technologies are best to adapt to the current project. Conclusions are finally made in this chapter, regarding all the study done, where the choice of the technology to be applied in the system arises and what is the reason for that choice.

In chapter 3, are mentioned the problems that the selected radio technology encounter in the long term, such performance and reliability, interference with other networks and the network itself. Some solutions are presented to work around these problems.

In chapter 4, the initial tests carried out on the modules used to understand their operation are described.

It is in chapter 5 that a description of the hardware developed to be applied to the system is made followed by the description of the software in chapter 6, that was used for each application.

In chapter 7 a summary of the implementation of the system is made considering the results obtained.

Finally, in chapter 8 a conclusion is made of the entire project.

This dissertation also has 1 annex that contain some additional information relevant for the project.

# 2. ANALYSIS OF RADIO TECHNOLOGIES

In this chapter a study is made on some types of radio technologies that exist referring to their main characteristics and mode of operation, after this study is done, it is possible to realize what technologies best adapt to the project in question.

In terms of the radio technologies characteristics there are several aspects that characterize the signal.

The physical (PHY) layer of a wireless technology defines the modulation scheme and other techniques it uses to send data over a specific radio frequency (RF) band, this includes the number of channels available, how effectively those channels are utilized, the use of error correction, the guards in place to counter interference, and much more.

Receiver sensitivity is the measure of the minimum signal strength a receiver can interpret, in other words, it’s the lowest power level at which the receiver can detect a radio signal, maintain a connection, and still demodulate data.

Choosing a transmit power level involves range and power consumption, the higher the transmit power, the more likely the signal can be received at longer distances and the longer the effective range, on the other hand, increasing the transmit power increases the power consumption of the device.

Path loss is the reduction in signal strength that occurs as a radio wave propagates through the air. Path loss, or path attenuation, occurs naturally over distance and is impacted by the environment in which the signal is being transmitted. Obstacles between the transmitter and the receiver can deteriorate the signal. Attenuators can be anything from humidity and precipitation to walls, windows, and other obstacles made of glass, wood, metal, or concrete, including metal towers or panels that reflect and disperse radio waves.

The following sections of this chapter specify different radio technologies addressing the characteristics mentioned, the technologies that are described are Bluetooth, Z-Wave, Sigfox, LoRa, Wi-Fi and Narrowband IoT.

## 2.1. Bluetooth

Bluetooth radio technology can be divided into two categories, the Bluetooth Classic and the Bluetooth Low Energy (BLE).

The Bluetooth Classic is designed for low power operation and leverages a robust Adaptive Frequency Hopping approach, transmitting data over 79 channels. The Bluetooth radio includes multiple physical layer (PHY) options that support data rates from 1 Mbps to 3 Mbps, and supports multiple power levels, from 1mW to 100 mW, multiple security options, and point-to-point network topology.

The BLE radio is designed for very low power operation, to enable consistent operation in the 2.4 GHz frequency band, it leverages a robust frequency-hopping spread spectrum approach that transmits data over 40 channels. The BLE radio provides developers a tremendous amount of flexibility, including multiple PHY options that support data rates from 125 Kbps to 2 Mbps, multiple power levels, from 1mW to 100 mW, as well as multiple security options up to government grade. BLE also supports multiple network topologies, including point-to-point, broadcast, and mesh networking [2].

### 2.1.1. Bluetooth Range

Unlike other wireless technologies, Bluetooth is designed to support a wide variety of achievable ranges between two devices, providing developers tremendous flexibility to create wireless solutions that best meet the needs of their target use case. Several key factors influence the effective range of a reliable Bluetooth connection, including the following [3]:

- Radio Spectrum – Bluetooth uses the 2.4 GHz ISM spectrum band (2400 to 2483.5 MHz), which enables a good balance between range and throughput. In addition, the 2.4 GHz band is available worldwide, making it a true standard for low-power wireless connectivity.
- PHY – Bluetooth provides multiple PHY options, each with different characteristics that determine effective range and data rates.
- Receiver Sensitivity – Bluetooth specifies that devices must be able to achieve a minimum receiver sensitivity of -70 dBm to -82 dBm, depending on the PHY used. However, Bluetooth implementations typically achieve much higher receiver sensitivity levels.
- Transmit Power –Bluetooth supports transmit powers from -20 dBm (0.01 mW) to +20 dBm (100 mW).
- Antenna Gain – Bluetooth designers can choose to implement a variety of antenna options; devices typically achieve an antenna gain in the range of –10 dBi to +10 dBi.

## 2.2. Z-Wave

Z-Wave is a low powered radio frequency technology that operates at Industrial, Scientific and Medical (ISM) band, it is designed specifically for control and status apps, supports data rates of up to 100 kbps, with AES128 encryption, IPV6, and multi-channel operation [4]. Z-Wave is a highly scalable technology, it can control from one device up to 232 devices in just one smart home network [5]. There are two kinds of devices, controllers and slaves, slaves receive and execute the command from the controller and do not have a routing table. There may be more than one central controller that finds the dominant and secure path, but there is always just one controller that carries the reliable information about the network topology. Each controller contains a routing table that represents the full topology information of the smart home and allows to find the efficient paths and connect with the destination node, the packets are transmitted to the destination by hopping through other nodes. Hopping is the number of times a message can be repeated before being dropped, in the Z-Wave network, the message can hope up to 4 times [6] [7].

Since paths are automatically established, the bad routes are automatically removed, in addition to routing, one of the Z-Wave terminologies is Beaming, meaning the battery-powered nodes have a battery saver characteristic. The battery appliances work by making the radio turns off to conserve battery for 1.5 seconds and then wakes up for 1.5 seconds. If the beam discovers the battery appliance fully awake, checks into the network with a broadcast to all the neighbour nodes, when the devices receive this broadcast, they reply with a confirmation and beams send the command to the correspondent slave. If the device does not hear the beam command, it falls back to sleep and 1.5 seconds later start the cycle over. This protocol architecture contains four layers: the application layer, the routing layer, the Media Access Layer (MAC), and the transfer layer [6]. Figure 3 shows the Z-Wave data in the different layers.

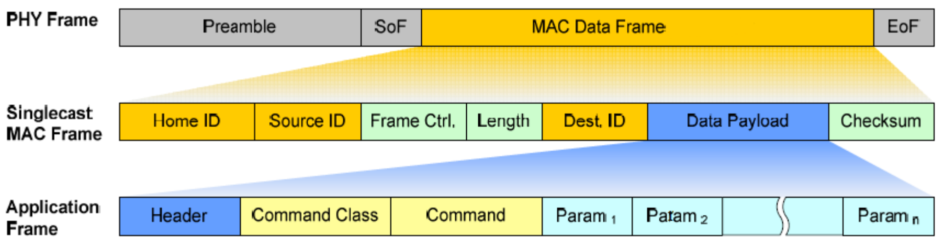



**Figure 3 Z-Wave data in the different layers [6]**

## 2.2.1. Z-WAVE RANGE

While Z-Wave has a range of 100 meters in the open air, building materials reduce that range, it is recommended to have a Z-Wave device roughly every 9 meters or even closer for maximum efficiency. The more line-powered devices in a Z-Wave network, the better, as they also act as repeaters to extend the Z-Wave signal. Z-Wave's mesh networking allows a Z-Wave signal to "hop" through other Z-Wave products to reach the destination device to be controlled. If there is a wall interfering with this signal, it is needed a Z-Wave repeater or other line-powered devices to work around the wall so the signal can continue to its destination. The maximum range with 4 hops is roughly 200 meters [5].

## 2.3. SIGFOX

Sigfox deploys its proprietary base stations equipped with cognitive software-defined radios and connect them to the backend servers using an Internet Protocol (IP) based network. The end devices are connected to these base stations using Binary Phase-Shift Keying (BPSK) modulation in an ultra-narrow band (100 Hz) sub-GHZ ISM band carrier. By employing the ultra-narrow band, Sigfox uses the frequency bandwidth (BW) efficiently and experiences very low noise levels, leading to very low power consumption, high receiver sensitivity, and low-cost antenna design at the expense of maximum throughput of only 100 bps to 600 bps.

Sigfox initially supported only uplink communication, but later evolved to bidirectional technology with a significant link asymmetry. The downlink communication, i.e., data from the base stations to the end devices can only occur following an uplink communication [8]. The number of messages over the uplink is limited to 140 messages per day, with a maximum payload length for each uplink message of 12 bytes. For downlink messages the size of the payload is a static value of 8 bytes. The number of messages over the downlink is limited to 4 messages per device per day, which means that the acknowledgment of every uplink message is not supported [9]. Without the adequate support of acknowledgments, the uplink communication reliability is ensured using time and frequency diversity as well as transmission duplication. Each end-device message is transmitted multiple times, by default, three times, over different frequency channels. For this purpose, in Europe for example, the band between 868.180 MHz and 868.220 MHz is divided into 400 orthogonal 100 Hz channels among them 40 channels are reserved and not used. As the base stations can receive messages simultaneously over all channels, the end device can randomly choose a frequency channel to transmit their messages, this simplifies the end device design and reduces its cost [8].

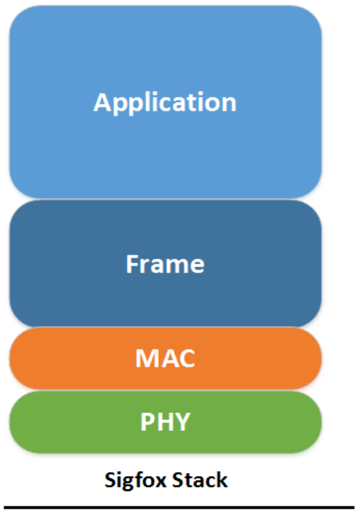



**Figure 4 Sigfox Stack [10]**

### 2.3.1. Sigfox Range

Sigfox claims that each Access Point (AP) can handle up to a million end-devices, with a coverage area of 30–50 km in rural areas and 3–10 km in urban areas [11].

## 2.4. LoRa

LoRa, which stands for “Long Range”, is a long-range wireless communications system, promoted by the LoRa Alliance, this system aims at being usable in long-lived battery-powered devices, where energy consumption is of extreme importance.

LoRa can commonly refer to two distinct layers, a physical layer using the Chirp Spread Spectrum (CSS) radio modulation technique and a MAC layer protocol, although the LoRa communications system also implies a specific access network architecture.

The LoRa physical layer, developed by Semtech, allows for long-range, low-power, and low-throughput communications, the payload of each transmission can range from 2–255 octets and the data rate can reach up to 50 kbps when channel aggregation is employed.

LoRaWAN provides a medium access control mechanism, enabling many end-devices to communicate with a gateway using the LoRa modulation, while the LoRa modulation is proprietary, the LoRaWAN is an open standard being developed by the LoRa Alliance [12].

There are three classes of LoRa end-devices, which differ only with regards to the downlink scheduling [13]:

- Class A, bi-directional: Class A end-devices can schedule an uplink transmission based on their own needs, with a small jitter (random variation before transmission). This class of devices allows bi-directional communications, whereby each uplink transmission is followed by two short downlinks receive windows. Downlink transmission from the server at any other time must wait until the next uplink transmission occurs. Class A devices have the lowest power consumption, but also offer less flexibility on downlink transmissions.
- Class B, bi-directional with scheduled receive slots: Class B end-devices open extra receive windows at scheduled times, apart from the random time slots during which data can be received that the type A device allows for. A synchronized beacon from the gateway is thus required, so that the network server can know when the end-device is listening.
- Class C, bi-directional with maximal receive slots: Class C end-devices have almost continuous receive windows, the only time when a class C device cannot receive information is when it sends it. They thus have maximum power consumption.

According to the LoRa standard, each module must implement the class A communication mechanism, while the specific functions of the other categories are optional.

### 2.4.1. LoRaWAN

LoRaWAN (Low-Power Wide-Area Network) is an open protocol stack proposed by LoRa Alliance and employed for public LoRa networks deployed by network operators [12]. LoRaWAN proposes the compromise of lowering the data rate at the expense of longer communication ranges, thus, the standard is suitable for applications where a reduced amount of data is transferred, and the information collected from the sensors does not change rapidly over time [14].

It defines network topology and MAC on top of the LoRa PHY layer. The three main components of the LoRaWAN network are LoRa end-devices, gateways and a network server [11] [12].

The end-devices are the low-power consumption sensors that communicate with gateways using LoRa, the gateway is the intermediate device that forward packets coming from end-devices to a network server over an IP backhaul interface with higher throughput, typically Ethernet or 3G, consequently, gateways are only protocol converters, with the network server being responsible for decoding the packets sent by the devices and generating the packets that should be sent back to the devices [11]. There can be multiple gateways in a LoRa deployment, and the same data packet can be received and forwarded by more than one gateway. The network server is responsible for de-duplicating and decoding the packets sent by the devices and generating the packets that should be sent back to the devices.

The wireless communication takes advantage of the long-range characteristics of the LoRa physical layer, allowing a single-hop link between the end-device and one or many gateways. All nodes are capable of bi-directional communication, and there is support for multicast addressing groups to make efficient use of spectrum during tasks such as Firmware Over-The-Air (FOTA) upgrades or other mass distribution messages [13]. There is no initial gateway search procedure at the end-nodes, and each node is not associated with a specific gateway. A packet from a node is delivered to the network server through multiple gateways, the network server decodes duplicate packets transmitted from the multiple gateways and chooses the best reliable packet. If necessary, the network server sends back an acknowledgment to the end-node through the corresponding gateway. LoRaWAN uplink achieves diversity gain and hands over for mobile end-nodes implicitly.

The working scenario of LoRaWAN assumes the preliminary condition that there are enough well-planned gateways such that each node can reach one or multiple gateways in a single hop of LoRa communication, in the LoRaWAN topology, direct communication is not supported between the LoRa nodes. Any node-to-node communication must be through the network server via two-gateway transmission.

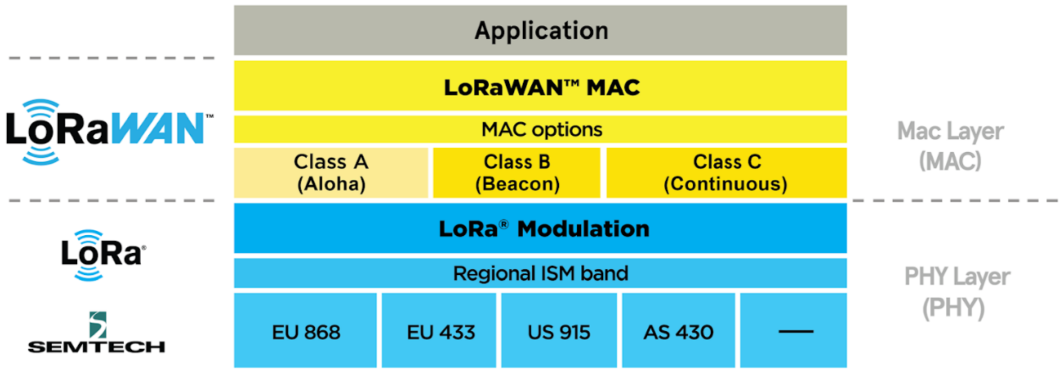



**Figure 5 LoRa Stack [1]**

### 2.4.2. LoRa Range

The advantage of LoRa, according to its developers, is in the technology's long-range capability. A single gateway or base station can cover entire cities or hundreds of square kilometres. Range highly depends on the environment or obstructions in each location, but typically in rural areas, it is possible to achieve 20 km and in urban areas 5 km. With a minimal amount of infrastructure, entire countries can easily be covered [13].

## 2.5. Wi-Fi

Wi-Fi is a family of radio technologies commonly used for wireless local area networking (WLAN) of devices. It is based on the IEEE 802.11 family of standards and is designed to seamlessly interwork with the wired protocol Ethernet. Wi-Fi most commonly uses the 2.4 GHz Ultra High Frequency (UHF) and the 5 GHz Super High Frequency (SHF) and ISM radio bands. At close range, some versions of Wi-Fi, running on suitable hardware, can achieve speeds of over 1 Gbps [1]. The different versions of Wi-Fi are specified by various IEEE 802.11 protocol standards, with the different radio technologies determining the ranges, radio bands, and speeds that may be achieved [1].

The access methods to the 802.11 standards do not implement any traffic prioritization mechanism, all stations and all traffic are subject to the same transmission rules, regardless of whether the physical topology of the wireless local area network is infrastructure or ad hoc. When a wireless LAN is operating with Distributed Coordination Function (DCF), the right to initiate a transmission is given to the station that has the shortest back off time. As this back off time is established based on the values of the containment window that are established by the 802.11 standards, there is no prioritization of the station that will have the transmission right.

Another factor is that, regardless of the type of traffic to be transmitted, voice, video or data, the method, and values involved to obtain the back off time value and, consequently, access to the medium, are the same. This means that a station that has voice traffic to transmit and another station that has data traffic, will have the same opportunities, that is, the transmission occurs in the best effort method.

### 2.5.1. Wi-Fi Range

Compatible devices can connect to each other over Wi-Fi through a wireless AP as well as to connected Ethernet devices and may use it to access the Internet. Such an AP (or Hotspot) has a range about 20 meters indoors and a greater range outdoors. Hotspot coverage can be as small as a single room with walls that block radio waves, or as large as many square kilometres achieved by using multiple overlapping APs.

### 2.5.2. 802.11ah (HaLow)

Most Wi-Fi standards operate at either 2.4 GHz or 5 GHz, and with this relatively high data rate comes lower sensitivity. To increase the relatively short range of Wi-Fi, specifically for IoT sensors that do not require high data rates, 802.11ah was introduced in 2016. 802.11ah commonly named as HaLow work at the ISM band so it is meant for long-range data transmission. HaLow also theoretically addresses low power consumption, uses target wake time to reduce the amount of energy a device needs to stay connected to the network, it does this by having devices wake up for very short times at defined intervals to accept messages. It’s ideal for short data that doesn’t consume a good deal of power and needs to travel long distances like smart building applications, smart lighting, smart HVAC, and smart security systems, it would also work for smart city applications, like parking garages and parking meters [15].

802.11ah standard had to adopt some physical and MAC layer modifications, in order to be able to deal with technical challenges associated with IoT: longer range, power saving method and increased number of station per access point [16].

- Physical Layer – IEEE 802.11ah is OFDM-based technology, which inherits the baseline physical layer design from 802.11ac/n. Since using the sub 1 GHz frequency bands, 802.11ah obtained narrower band accommodation by down-clocking ten times the IEEE 802.11ac channel bandwidths, achieving the increase of signal to noise ratio (SNR) at receiver. 802.11ah supports 1 MHz, 2 MHz, 4 MHz, 8 MHz and 16 MHz channel bandwidths, the number of sub-carriers for 1 MHz channel is 26 per OFDM symbol (2 pilot tones and 24 data sub-carriers) and for higher channel bandwidths the number of data and pilot tones (fixed, travelled) increases up to 484 tones for 16MHz bandwidth.

  Besides the utilization of sub-GHz frequency spectrum, extended range in 802.11ah is also enabled by introducing a new modulation and coding scheme (MCS) for the 1MHz channel. MCS, denoted as MCS10 is a scheme which implies 2x repetition coding, BPSK modulation and 1/2 coding rate.

  The supported values of physical parameters of 802.11ah are a very scalable standard, which can provide wide range of possible data rates and communication ranges, by using the different combinations of parameters. Minimum receiver sensitivity in 802.11ah is going from -98dBm for BPSK to -72dBm for 256QAM.

- MAC layer – 802.11ah MAC layer design features are enhanced compared with the existing 802.11 MAC, including improvements related with the support of new physical layer parameters, large number of stations, power saving, medium access mechanisms and throughput enhancements. It is expected from IEEE 802.11ah MAC to provide mechanisms that enable the coexistence with other systems in the same license exempt radio band. Power saving improvements are accomplished by means of reduced transmitter (Tx) and receiver (Rx) active time and increased standby time of the stations. Reducing Tx/Rx active time is managed by defining a null data packet (NDP) carrying MAC (CMAC) frame format without data field and defining the new Short MAC header, reduced to 12 bytes. Short management frames, mechanisms for supporting energy limited stations and Bidirectional TXOP (BDT) can also reduce active Tx/Rx time.

  Medium access improving mechanisms assume reduced contention and channel access time with pseudo-scheduling and grouping stations using Restricted Access Window

(RAW), Slotted medium access with sync frame and Bidirectional Transmission Opportunity (TXOP; BDT) for quick data transaction.

Support for large number of stations, up to 8000 stations, in 802.11ah is achieved by involving new hierarchical TIM structure and efficient encoding. The basic access to the medium in IEEE 802.11ah is the CSMA/CA scheme.

HaLow supports WPA3 (Wi-Fi Protected Access) security, the next generation security in Wi-Fi and the highest security level in wireless connectivity. WPA3 adds new features to simplify Wi-Fi security, enable more robust authentication, deliver increased cryptographic strength for highly sensitive data markets, and maintain resiliency of mission critical networks. All WPA3 networks, use the latest security methods, disallow outdated legacy protocols, and require use of Protected Management Frames (PMF).

Since Wi-Fi networks differ in usage purpose and security needs, WPA3 includes additional capabilities specifically for personal and enterprise networks. Users of WPA3-Personal receive increased protections from password guessing attempts, while WPA3-Enterprise users can now take advantage of higher-grade security protocols for sensitive data networks [17].

### 2.5.3. 802.11AF (WHITE-FI)

802.11af known as White-Fi utilizes unused television spectrum frequencies (i.e. "white spaces") in UHF and Very High Frequency (VHF) to transmit information. Because these frequencies are between 54 MHz and 698 MHz in USA and 470 to 790 MHz in Europe, the White-Fi can be used for low power, wide-area range, like HaLow described above.

802.11af was released in 2014, but never really took off for several reasons, first, there are many complexities around geolocation, in one place in the world it may be allowed to use a certain UHF channel because it's available in that area but on another one if the same channel is used, a broadcaster there may already own the license. Additionally, radio front ends must be specifically designed and filtered to work across hundreds of MHz of UHF spectrum. This means there is never going to be possible to buy equipment that can access all these channels without paying very high amounts of money.

Because White-Fi can utilize several unused TV channels at once, it works well for very long range devices, potentially up to several kilometres, with high data rates but the downfalls of this technology are that it requires expensive, band-specific hardware and the "White space" channels are not available everywhere, particularly in big cities [15].

## 2.6. NARROWBAND IOT

Narrowband-IoT (NB-IoT) is a radio technology that can coexist with Global System for Mobile Communications (GSM) and LTE under licensed frequency bands (e.g., 700 MHz, 800 MHz, and 900 MHz). NB-IoT occupies a frequency bandwidth of 200 kHz, which corresponds to one resource block in GSM and LTE transmission, both protocols use Orthogonal Frequency-Division Multiple Access (OFDMA) in the downlink and Sigle Carrier - Frequency-Division Multiple Access (SC-FDMA) in the uplink [8].

The 200 kHz spectrum is divided into channels as narrow as 3.75 kHz to support a combination of extreme coverage and high uplink capacity requirements, considering the narrow spectrum deployment [18].

With this frequency band selection, the following operation modes are possible, as shown in Figure 6 [8]:

- Stand-alone operation – a possible scenario is the utilization of GSM frequencies bands currently used.
- Guard-band operation – utilizing the unused resource blocks within an LTE carrier's guard band.
- In-band operation – utilizing resource blocks within an LTE carrier.

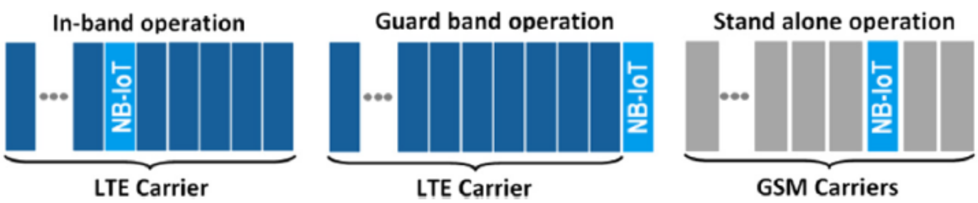



**Figure 6 Operation modes of NB-IoT [8]**

NB-IoT is optimized for machine type data traffic. It is designed to be kept as simple as possible with the goal to minimize device costs and the objective of achieving energy efficiency through the minimization of battery consumption. In addition, one major design objective of the NB-IoT is also to adapt it to work in difficult (harsh) radio conditions. This is mainly because the NB-IoT designs normally target the applications involving Machine Type Communications (MTC) devices and most often, the MTC devices' operational area is of harsh radio conditions.

This results in significantly reducing the time required to develop the NB-IoT's full specifications but also comes with an associated cost in terms of non-appropriateness of some of the LTE systems' components to specific type of IoT applications namely the critical IoT applications such as remote health-care, traffic safety and control, smart grid or remote manufacturing [19].

### 2.6.1. NB-IoT Range

NB-IoT can cover in rural areas up to 10 km and in urban areas up to 1 km [8], the deployment of NB-IoT is limited to LTE base stations, thus, it is not suitable for rural or suburban regions that do not benefit from LTE coverage.

## 2.7. Radio Technologies Analysis

It is important to refer that Wi-Fi tests were performed after this analysis in the location and was seen that it did not have enough range between two points in the high-rise that have an elevator in the inside, being that it is intended to use a long-range network in order not to be needed repeaters or other devices between points, wi-fi is not a viable alternative to the project.

Taking this into account, the other radio technologies considered have been compared on cost, power consumption, frequency, range, and data rate, as can be seen in Table 2.

**Table 2** **Analysis of the radio technologies**

| | Cost [24] | Power Consumption [24] | Frequency | Range | Data Rate Transmission |
|---|---|---|---|---|---|
| Bluetooth | | | 2.4 GHz | Classic Open air: 50 - 80 m Buildings: 5 - 10 m BLE: 400 m | Classic: 1 Mbps - 3 Mbps BLE: 125 kbps - 2 Mbps |
| Z-Wave | | | 433 / 868 / 915 MHz (ISM) | Open air: 100 m Buildings: 9 m | 100 kbps |
| Sigfox | Medium | Low | 433 / 868 / 915 MHz (ISM) | Rural areas: 30 - 50 km Urban areas: 3 - 10 km | 100 – 600 bps [11] |
| NB-IoT | High | Medium | 700 / 800 / 900 MHz (LTE frequency) | Rural areas: 10 km Urban areas: 1 km [8] | 200 kbps [8] |
| LoRa | Low | Low | 433 / 868 / 915 MHz (ISM) | Rural areas: 20 km Urban areas: 5 km [8] | Europe: 250bps - 50 kbps North America: 980bps - 21.9kbps |
| Wi-Fi | | | 2.4 GHz / 5 GHz | Open air: 90 m Buildings: 45 m | 2.4 GHz: 450 Mbps - 600 Mbps 5 GHz: Up to 1300 Mbps |
| White-Fi | | Low | TV bands 470 – 790 MHz (Europe) | Up to 100 m | 35.6 Mbps |

| | | | | | |
|---|---|---|---|---|---|
| | | | 54 9 – 698 MHz (USA) | | |
| HaLow | | Medium | 433 / 868 / 915 MHz (ISM) | 1 km [21] | 150 kbps to 40 Mbps [21] |

Through the Table 2 and the analysis made it is possible to conclude that in terms of range, which is an important specification to consider, Bluetooth, both classic and Low Energy, is at the start excluded due to the range being the smallest, as well as Z-wave technology. Sigfox technology is the one that allows a wider range, followed by LoRa, NB-IoT and HaLow.

Despite of the fact that Sigfox have a longer range, it is not an open use technology and it has a message limit that can be sent per day both uplink and downlink being that downlink are 4 messages per day so it was not possible to make acknowledgment of all communications, in addition to a low data rate compared to the others technologies, it will also be removed as a viable option, just like NB-IoT that uses LTE frequencies band which means it's limited to LTE base stations and in addition, it has some disadvantages in terms of components not appropriate for specific IoT.

At this point the two radio technologies in study are LoRa and HaLow, although HaLow is an option there is still little support and information regarding this being a relatively recent technology, and one of the requirements is to have support available. The technology that meets the most requirements is LoRa, this technology will be thus tested and used throughout the project.

# 3. LoRa Problems and Restrictions

This chapter describes the main problems and restrictions of the LoRa network, addressing its performance and reliability, and analyzing their behavior regarding cross-technology interference and inter-network interference.

The core of LoRa technology is the Chirp Spread Spectrum (CSS) modulation in which the carrier signal of LoRa consists of signals whose frequency increases or decreases over time, chirps. LoRa’s chirps allow the signal to travel long distances and to be demodulated even when its power can be up to 20 dB lower than the noise floor. LoRa radios allow carrier detection via a CAD mode, a special reception state consuming half of the energy compared to the normal reception mode, however, the signals produced by different LoRa networks operating on different settings could create interference leading to false detections [22].

LoRa’s communication performance can be fine-tuned by varying the selection of several PHY settings, including bandwidth, spreading factor, coding rate, transmission power, and carrier frequency, as summarized in Table 3. The impact of each PHY parameter on data rate, receiver sensitivity (including resilience to interference), transmission range, and energy-efficiency is explained below [23].

**Table 3 Summary of LoRa's configurable settings**

| Setting | Bandwidth | Spreading Factor | Coding Rate | Transmission Power |
|---|---|---|---|---|
| Values | 125 to 500 kHz | 6 to 12 | 4/5 to 4/8 | -4 to 20 dBm |

Bandwidth (BW) – Varying the range of frequencies (bandwidth) over which LoRa chirp spread allows for trading radio airtime against radio sensitivity, thus energy efficiency against communication range and robustness. The higher is the bandwidth, the shorter is the airtime and the lower is the sensitivity but that allows a higher data rate. A lower bandwidth also requires a more accurate crystal to minimize problems related to the clock drift.

Spreading Factor (SF) – To transmit information, LoRa "spreads" each symbol over several chips (spreading factor) to increase the receiver's sensitivity even more. LoRa's spreading factor SF can be selected between 6 and 12, resulting in a spreading rate ranging from 26 to 212 chips/symbols. Higher spreading factor increases the signal-to-noise ratio and, therefore, radio sensitivity, increasing the communication range at the cost of longer packets and hence a higher energy expenditure. In LoRa, packets transmitted with different spreading factors are orthogonal with each other and do not cause collisions if transmitted concurrently.

Coding Rate (CR) – To increase the resilience to corrupted bits, LoRa supports forward error correction techniques with a variable number CR of redundant bits, ranging from 1 to 4.

The more interference bursts are expected, the higher the coding rate that should be used to maximize the probability of successful packet reception, resulting in longer packets and higher energy consumption. LoRa radios with different coding rates can still communicate, since the packet header can include the code rate used for the payload.

Transmission Power (TP) – As most wireless radios, LoRa transceivers also allow for adjusting the transmission power, drastically changing the energy required to transmit a packet. By switching the transmission power, for example, from -4 to +20 dBm, the power consumption increases from 66mW to 396mW when using the RFM95 transceiver [24]. For transmission powers higher than +17 dBm, hardware limitations and legal regulations limit the radio duty cycle to a maximum of 1%.

## 3.1. PERFORMANCE AND RELIABILITY

The study of the reliability of LoRa is based on [25] held in the Institute of Technical Informatics, in Austria, to carry out the experiments three senders have been placed at three given locations(S) and three receivers at different distances (1, 2, 3) for three scenarios: indoor with obstacles (i), outdoor with direct line of sight (o), and underground covered by a metal manhole (u). Each transmitter sends a packet with a 5-byte payload every 3 seconds at a transmission power of +20 dBm, emulating a timely report of a typical IoT sensor for urban monitoring. Every six minutes, transmitter and receivers reboot and switch to a different setting according to a set of hard-coded combinations where the SF, CR, BW, and data rate were varied. For each of the three scenarios (indoor, outdoor, and underground), each setting configuration was tested sequentially every six minutes for a duration of 24 h, consequently resulting in a total of 1600 packets exchanged per setting.


**Figure 7 Deployment map for the experiments indoor (i), outdoor (o), and underground (u). The sender node for each scenario is indicated with iS, oS, and uS, respectively.**

**Table 4 LoRa settings used in the experiments**

| Setting ID | SF | CR | BW (kHz) | BR (kb/s) |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| **1** | 7 | 4/5 | 500 | 21.87 |
| **2** | 7 | 4/8 | 500 | 13.62 |
| **3** | 7 | 4/5 | 250 | 10.93 |
| **4** | 9 | 4/5 | 500 | 7.03 |
| **5** | 7 | 4/8 | 250 | 6.83 |
| **6** | 7 | 4/5 | 125 | 5.47 |
| **7** | 9 | 4/8 | 500 | 4.39 |
| **8** | 9 | 4/5 | 250 | 3.51 |
| **9** | 7 | 4/8 | 125 | 3.41 |
| **10** | 9 | 4/8 | 125 | 2.2 |
| **11** | 9 | 4/5 | 125 | 1.76 |
| **12** | 12 | 4/5 | 500 | 1.16 |
| **13** | 9 | 4/8 | 125 | 1.09 |
| **14** | 12 | 4/8 | 500 | 0.72 |
| **15** | 12 | 4/5 | 250 | 0.58 |
| **16** | 12 | 4/8 | 250 | 0.37 |
| **17** | 12 | 4/5 | 125 | 0.30 |
| **18** | 12 | 4/8 | 125 | 0.18 |

The experiments were conducted using a custom-built platform equipped with an ATMega1284P microcontroller, and a HopeRF RFM95 LoRa transceiver operating at 868 MHz. For persistent storage, an SD card logs each received packet together with its sequence number, as well as the timestamp provided by a real-time clock. The presence of cyclic redundancy check (CRC) errors in the received packets in the traces were also saved. This hardware setup was used in the experiments both for senders and receivers.

For each 6 minutes experiment, the packet reception ratio (prr) and the receiver sensitivity were computed. The correlation of the computed prr with the employed PHY settings was then checked, as well as received signal strength values.

Figure 8 shows the packet reception ratio i.e., the percentage of packets sent that were correctly received, indoor, outdoor and underground for a number of different radio settings, this Figure plots all 6-min experiments grouped by setting ID. Horizontal red lines represent the median, while blue boxes represent the 25th and 75th percentiles.

The remaining results are enclosed by vertical dashed black lines while statistical outliers are represented by red crosses. Note that these results were previously presented in [25].

The results show that LoRa setting ID 11 (i.e., BW = 125, SF = 9, and CR = 4/5) achieves a packet reception ratio above 95% regardless of the scenario and distance between nodes. Nevertheless, setting ID 2 also performs remarkably well: although it sustains a lower prr, it sends packets using a bitrate (BR) that is almost eight times faster than the one used by setting ID 11. This observation will be the starting point for the analysis to answer the question of whether it is worth selecting PHY settings that reduce the data rate to maximize the link quality.

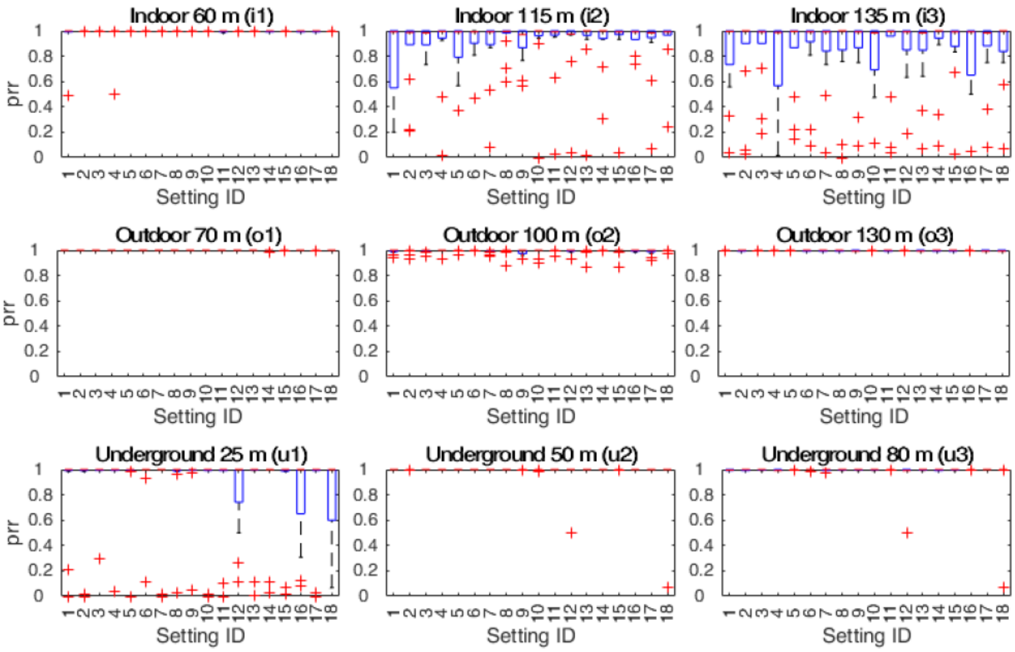



**Figure 8 Packet reception ratio**

Figure 8, also show the distribution of the experiment results rather than just the median and mean values. This allows to make three observations. First while the median prr is close to 1 for most settings, the quartiles and minima are not. Second, due to the lower multi-path and fading effects outdoor and underground, LoRa communications are more reliable in these scenarios rather than indoors, with packet reception ratios above 97% for almost all setting IDs. Third, the range of the LoRa radios is consistent throughout the different settings: even though the reception rate changes, all settings can deliver packets in similar conditions.

It was then explored which environmental factors affect the reliability of LoRa. Towards this goal, were used the traces collected in the previous experiments and focus on the correlation between the packet reception rate (prr), setting ID (set), temperature (temp), humidity (hum), spreading factor (SF), coding rate (CR), bandwidth (BW), receiver sensitivity (sens), receiver signal strength (rss), and hour of the day (hour). In particular, was traced the Pearson correlation of each pair of parameters for different experimental scenarios in Figure 9: a value close to 1 (black) means that the two parameters are linearly correlated, while a value of 0 (white) implies that the two parameters are independent.

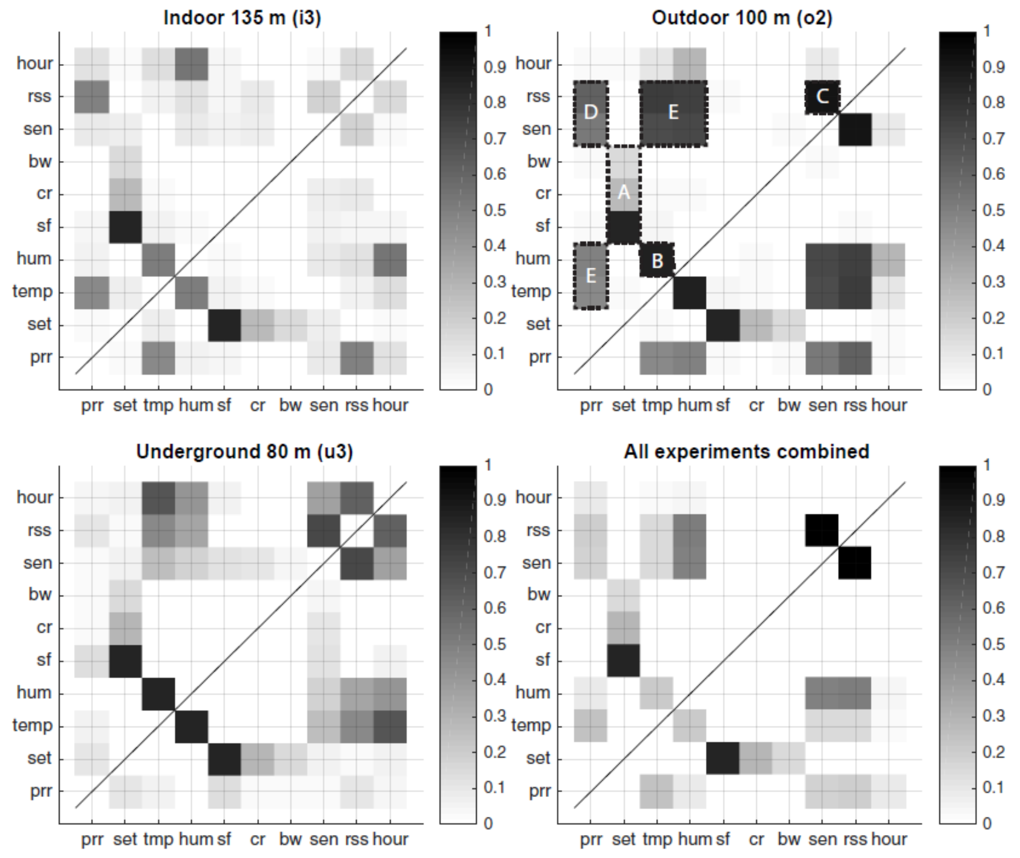



**Figure 9 Correlation matrix for different LoRa settings indoor, outdoor, and underground. The plot on the bottom right combines all nine of the settings from Figure 8.**

Figure 9 shows that, in all three scenarios (indoor, outdoor, and underground), there are some obvious correlations. First (A), the setting ID depends on the bandwidth, coding rate (CR), and spreading factor (SF). This is to be expected, because the setting ID unequivocally describes a combination of these three PHY parameters. Second (B), temperature (temp) is highly correlated with humidity (hum) and both are correlated with the time of the day (hour). This is also an expected correlation, as these environmental factors are highly dependent on the sun exposure. Third (C), the radio sensitivity (sen) is correlated to the received signal strength (rss) since the former is defined as the minimum of the latter. Furthermore, one can also note in Figure 9 that the received signal strength (rss) is correlated with the packet reception ratio (prr) (D), as the LoRa radio is able to successfully decode packets that are above a certain signal-to-noise ratio.

Figure 9 also shows that temperature is tightly correlated with the received signal strength (rss) and the packet reception ratio (prr). This seem to hint that temperature variations may affect the operation of the employed LoRa radio in a similar way as observed on some IEEE 802.15.4 transceivers. When analysing the figure in detail, one can actually observe a correlation cluster (E) between temperature, humidity, time of the day, packet reception ratio, and received signal strength: the strength of these correlations varies depending on the scenario and is stronger outdoors.

The experimental campaign presented above has shown that it is possible to improve the reliability of LoRa by carefully choosing the PHY settings, i.e., some of the settings allow for sustaining a higher prr. Then, were analysed the costs of such improvement in terms of energy efficiency and analysed in detail the trade-off between packet delivery rate and setting's bandwidth, providing an answer to the question if is it more efficient to use resilient and slow settings or to use faster (but more fragile) configurations together with a re-transmission mechanism.

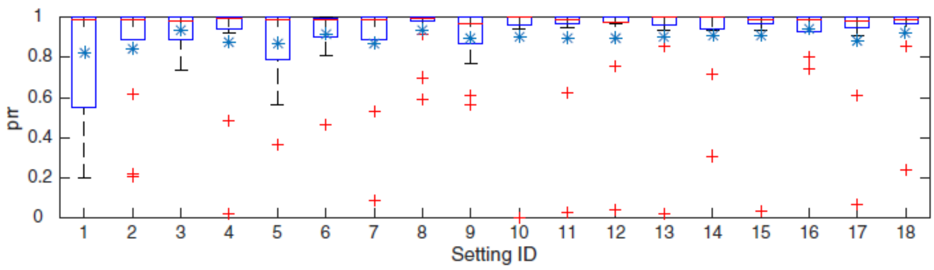
To answer this question, the focus was on the most challenging scenario in the experimental campaign, the indoor, no line of sight, and with a distance between two devices of 115 m. Figure 10a shows the distribution of packet reception ratios as a function of setting ID. Averages are represented by '*', while median, quartiles, and extreme values are enclosed by a blue box and two black bars (outliers are indicated with crosses). PHY settings are ordered by decreasing bitrate, from faster and more lightweight settings on the left, to slower settings increasing the transceiver's on-time on the right. As it is possible to see, using the fastest setting (setting ID 1 and 2), the average prr is 80% with a worst-case scenario where prr is as low as 20%. As expected, by selecting a PHY configuration that reduces the bitrate i.e., by decreasing the bandwidth and increasing the bit redundancy, the packet reception ratio improves, as well as its distribution.

Nevertheless, one can argue that it is more energy-efficient to re-transmit a packet using the faster settings available rather than employing PHY settings that reduce the bitrate. To prove this point, the expected number of re-transmissions (ETX) was estimated as shown in equation (1) and compare them against each setting's original bitrate (BR). It is possible to see in Figure 10b, the expected number of re-transmissions (squares) does not directly depend on the settings' bit-rate (triangles), suggesting that not all settings are worth their overhead. To give an indication on how efficiently LoRa settings trade communication efficiency against reliability, the effective bitrate (EBR) was estimated as in equation (2) and show both mean and distribution in Figure 5c.

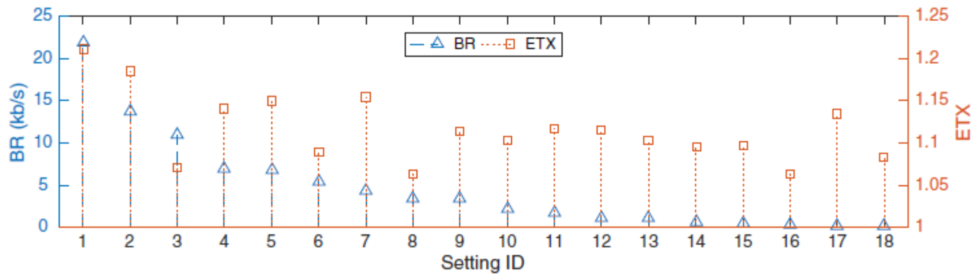
$$ETX = \frac{1}{prr} . \tag{1}$$

$$EBR = \frac{BR}{ETX} = BR * prr . \tag{2}$$

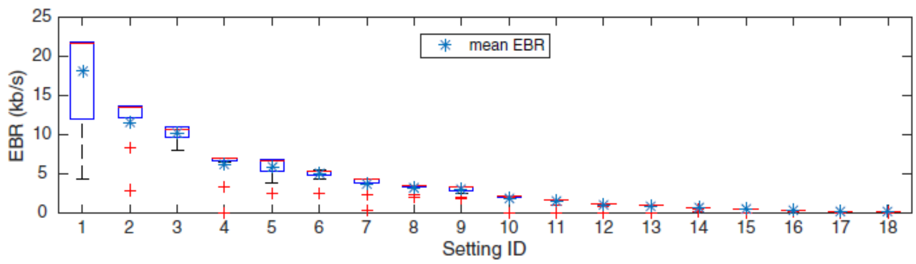
The EBR shows the expected bitrate of each setting in the case packets are re-transmitted back-to-back until one is successfully received. As showed in Figure 10c, the mean EBR is by far the highest when the fastest LoRa setting is used (setting ID 1). Setting ID 2, on the other hand, is more consistent, showing a lower variance and the highest minimum (crosses represent outliers).




(a) Packet reception rate (prr) for different LoRa setting. The higher de ppr, the better




(b) Bitrate (BR) versus expected number of retransmissions (ETX) computed as 1/prr




(c) Expected bitrate computed as BR/ETX

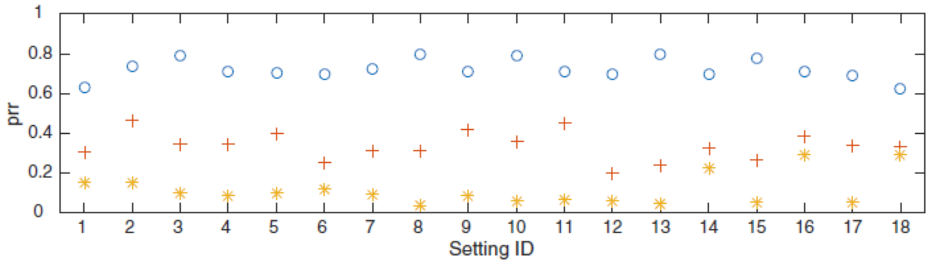
**Figure 10 LoRa performance as a function of PHY settings in an indoor scenario without line of sight at 115 m**

Even though these results can heavily depend on the surrounding environment, it was possible to argue that, in order to maximize the effective bitrate, one should opt for a re-transmission mechanism and use the settings with sufficient prr (e.g., >0.2) and the highest bitrate possible.

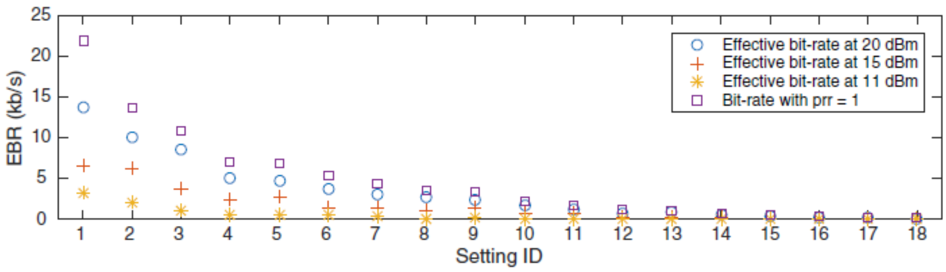
The energy efficiency of different PHY settings was evaluated by repeating the indoor experiments without line of sight at a distance of 115 m, this time, was slightly varied the experimental setup as follows: the two nodes were positioned at the edge of transmission range and send each packet with a different power level, sequentially selected from the set {+20, +17, +15, +11, +7, +5} dBm. First was checked if using the fastest PHY setting leads to the highest energy efficiency both in challenging and non-challenging conditions (the lower the transmission power, the more challenging the communication). Then was computed the most energy-efficient setting by computing the effective energy consumed to send a kilobit of data EKB.

Figure 11a shows the packet reception rate when using three different power levels: +20, +15, and +11 dBm. As expected, changing the transmission power drastically affects the prr, since the nodes are intentionally placed on the edge of the communication range. In agreement with the results presented previously, Figure 11b shows that the fastest settings are the ones with highest effective bit-rate EBR—independently of the employed transmission power. As lower transmission powers imply lower energy expenditures, was still needed to answer which transmission power configuration results in the highest energy efficiency.

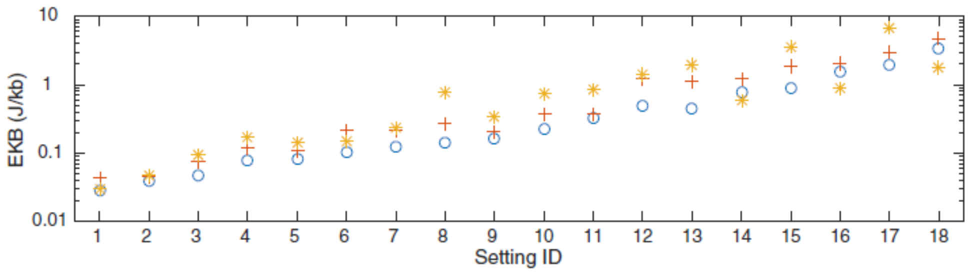
Figure 11c shows the energy required by each PHY setting to transmit a kilobit of data (EKB), including the cost of the re-transmissions. As we can see, the most efficient transmission power configuration (i.e., leading to the lowest EKB) is the highest, i.e., +20 dBm. Therefore, our experimental results suggest that, together with the fastest setting, the highest transmission power should be preferred: this combination provides the highest bitrate EBR and the lowest energy consumption EKB. It is worth highlighting that, in less challenging scenarios in which several transmission powers achieve a prr = 1, the lowest one should be used, as the higher transmission powers may increase the energy consumption without any additional benefit.




(a) Packet reception rate (prr) for different LoRa settings. The higher the prr the better




(b) Expected bitrate computed as BR/ETX




(c) Expected energy per kilobit (EKB). The lower EKB, the more energy efficient is LoRa

**Figure 11 LoRa performance for different settings and transmission powers**

## 3.2. INTER-NETWORK INTERFERENCE

The [22] study made experiments to characterise the behaviour of LoRa when it comes to inter-network interference, to do that the LoRaSim simulation tool was used, this tool allows the definition of communication settings such as Transmission Power (TP), Spreading Factor (SF) and Bandwidth (BW), allows the verification of the capture effect behaviour of LoRa transmissions depending on transmission timings and power and have the ability to simulate directional transmissions. The correct representation of these effects is important as they determine if interfering transmissions can be decoded by a receiver.

The communication characteristics of a LoRa node are defined by the transmission parameters, Carrier Frequency (CF), SF, BW and Change Request (CR). Furthermore, a node's transmission behaviour is described by the average packet transmission rate and the size of the packet payload. LoRaSim emulates LoRa gateways chips that can receive up to eight concurrent signals if they use different SF.

A transmission is successfully received if the received signal power lies above the sensitivity threshold of the receiver. The received signal power depends on the transmit power and all gains and losses along the communication path. On the transmitter side, range can only be changed by changing the transmit power. The range can also be influenced using a directional antenna. On the receiver side, the range is limited by the sensitivity threshold, which is influenced by the LoRa parameters SF and BW, the measured sensitivity on this project was used from calibration experiments based on the Semtech SX1272 LoRa transceiver [22].

When two LoRa transmissions overlap at the receiver, there are several conditions which determine whether the receiver can decode one or two packets, or nothing at all. These conditions are CF, SF, power, and timing. LoRa exhibits the capture effect, this effect occurs when two signals are present at the receiver and the weaker signal is suppressed by the stronger signal, the difference in received signal strength can be relatively small, it's possible to increase the signal strength using a directional antenna [22].

For directional antennas, the transmissions were modelled according to the SPIDA antenna, an electronically switchable directional antenna designed for low-power wireless sensor networks. SPIDA has six parasitic elements that can be individually grounded or isolated via a software control at negligible energy cost, if all the parasitic elements except one are grounded, the direction of the maximum antenna gain is towards the isolated element. In the experiments the direction of maximum gain points towards the receiving gateway. As a result, the received signal power of transmissions at the intended receiver increases, while it might increase or decrease at other receivers depending on their location, this was based on previous measurements with SPIDA.

To evaluate the inter-network interference, all experiments use the same node configuration set that corresponds to the most robust LoRa transmitter settings, these transmissions have the longest possible airtime: 1712.13 ms.

In the current experiment, N nodes were randomly placed to create networks within a circle of radius R around a gateway. The distance between nodes and gateways is such that all nodes can reach the gateway with the given transmitter settings. If no interference occurs, the transmissions of the nodes reach the gateway without loss, the radius used is 99 m which represents a realistic range for built-up environments. In this experiment were deployed a variable number of interfering networks around the network of interest, called the interfered network. Interfering networks are positioned in the same way as the main network. Figure 12 shows an example configuration, the network of interest is the black network located in the centre, the other 4 networks are interfering systems. In all experiments, it is assumed that in the main network and the interfering networks each node sends a 20-byte packet every 16.7 min representing a realistic application[25]. The interfered network's transmissions to the gateways might interfere with packets from other networks or with packets from the network itself depending on the position of the gateways.

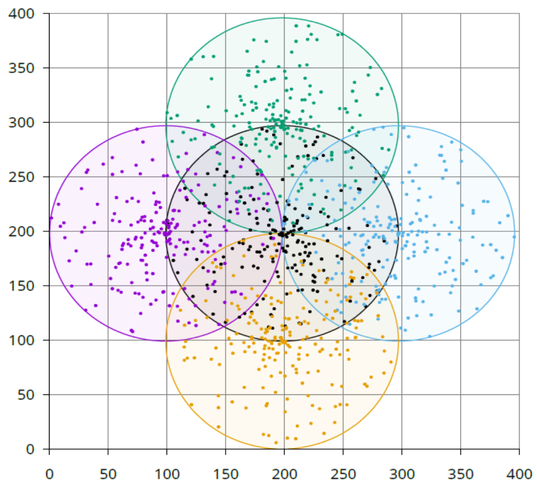



**Figure 12 Example configuration used in the simulations [22]**

The aim of the study was to evaluate the performance of this network in the form of Data Extraction Rate (DER). In the first experiment, it was assumed that each network has N = 200 nodes, it was varied the distance between the gateways of the interfering networks to the one of the interfered network, the purpose of this first experiment is to show how inter-network interference impacts on DER, the results are shown in Figure 13. When all base stations are placed at the same location, the interference is the highest since the transmissions of all nodes in the interfering network can interfere with the transmissions of the interfered network. With an increasing distance, fewer nodes of the interfering networks interfere with the transmissions of the interfered network which leads to a higher DER. When the distance between the base stations is 200 m, no interference between the base stations is possible. DER is here around 0.8 which is the maximum achievable performance due to interference from within the own network [26].

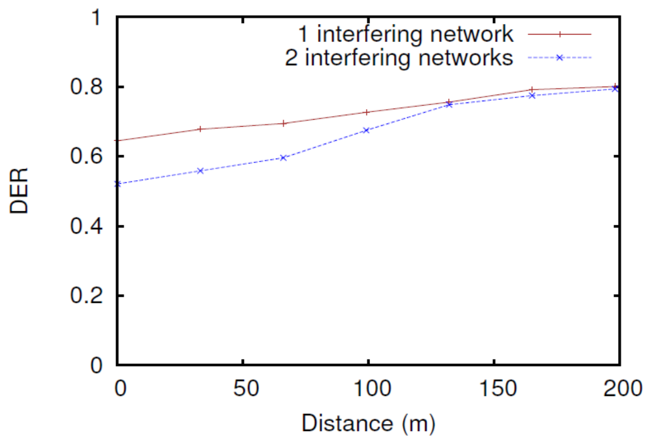



**Figure 13 First experiment [22]**

In the second experiment, it was the number of nodes per network and the number of interfering networks that was varied. The distance between the gateways in this second experiment is 99 m which is also the network radius. Figure 14 depicts the results of the second experiment, as expected when the number of interfering networks increases, DER decreases significantly, when the number of nodes is high. For example, with 500 nodes per network, the DER of the interfered network decreases from 0.6 without interference to about 0.3 when there is interference from four networks.

The experiments shows that the deployment of noncooperating LoRa networks in the same space has a significant impact on network performance, therefore, it is desirable to address and mitigate this issue [26].

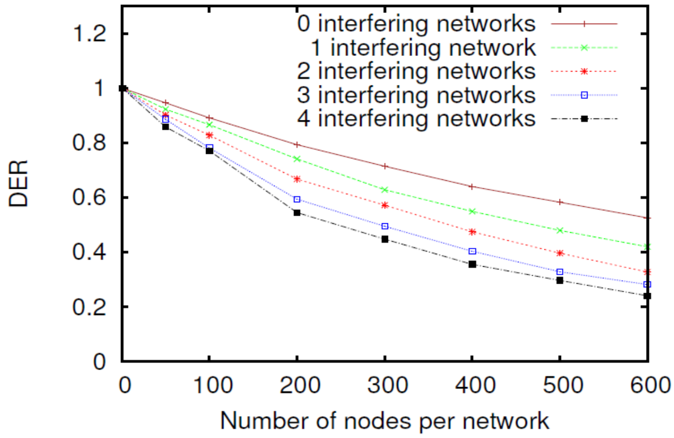



**Figure 14 Second experiment [26]**

Experiments have also been made regarding directional antennas, in this case it is evaluated if extend directional antennas can improve the DER of an interfered LoRa network, it is expectable that this is possible as the directional antennas can radiate more energy towards the intended gateway, thereby increasing the signal strength at the gateway. Directional antennas also reduce the interference of other gateways which is likely to increase the overall performance of all networks. The experimental setup is similar to the previous ones but the nodes in the network of interest (the centre network in Figure 12) are equipped with directional antennas.

Figure 15 illustrates the results, the figure shows that, as expected, directional transmissions improve DER, when the number of nodes is high. The signal strength of the nodes of the interfered network increases, consequently, it is more likely that due to the capture effect these transmissions succeed even when there are collisions. For most of the setups, DER increases by about 0.04 when the nodes are equipped, in the interfered network, with directional antennas. Using even better directional antennas, the DER increases by another 0.04 [26].

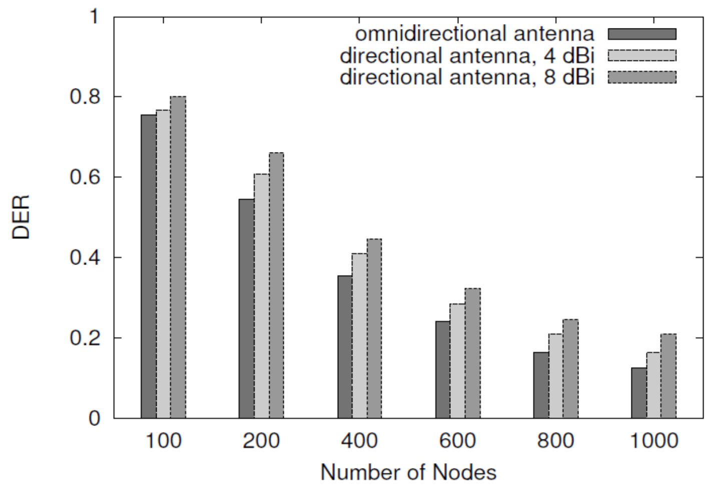



**Figure 15 Comparison with omnidirectional antenna, directional antenna, and better directional antenna [26]**

In the next part of the experiments, it was evaluated whether the increased number of gateways influences the interference settings. The gateway in the centre of the setup shown in Figure 12 was replaced by two and then by three gateways.

For the two gateways scenario, the original base station was moved a certain distance to the right leaving its vertical position as it is and add an additional base station to the left of the original location at the same distance as the right one. When replacing the original base station with three gateways, one base station was moved upwards by a certain distance and the other two 45º down and to the left and right respectively, so that the distance is also the same from the original location of the gateway. The placement of the sensor nodes is unchanged, i.e., they are placed within the radius around the original location of the gateway. Packet transmission is counted as successful if either one of the gateways receives it, being that all four interfering networks are active.

Figure 16 shows the results when the original gateway is replaced by two others, the figure shows that with 0 m the DER is quite low. There is no improvement compared to the results with the omnidirectional antennas in Figure 15, placing two base stations at the same place does not change anything as they will receive the same packets. For larger distances like 97 m, the DER is even lower since some nodes might not even reach the gateway. The best distances are between 33 m and 67 m for all setups [26].

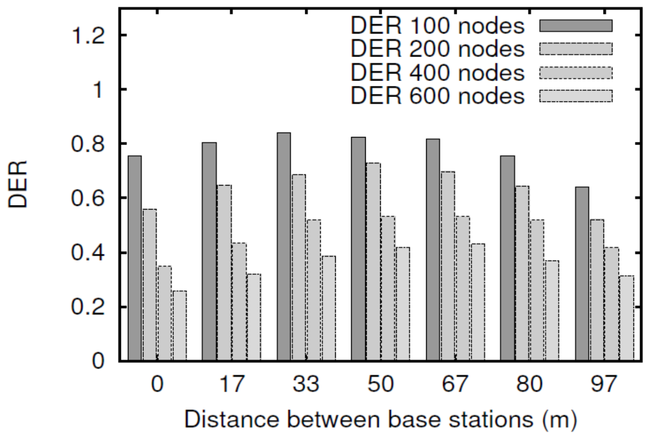



**Figure 16 Impact of distance between two base stations on DER for different number of nodes [26]**

Figure 17 depicts the results when the original gateway is replaced with three base stations. In general, while the trends are like those in Figure 16, the DER is higher than with two gateways. In particular, the results with larger distances (97 m) are much better. The reason is the distribution of the gateway that ensures that all nodes are in reach of a base station which was not the case for two of them. Also, the overall results are higher since the chance that a transmission finds a gateway where the capture effect comes into play increases [26].

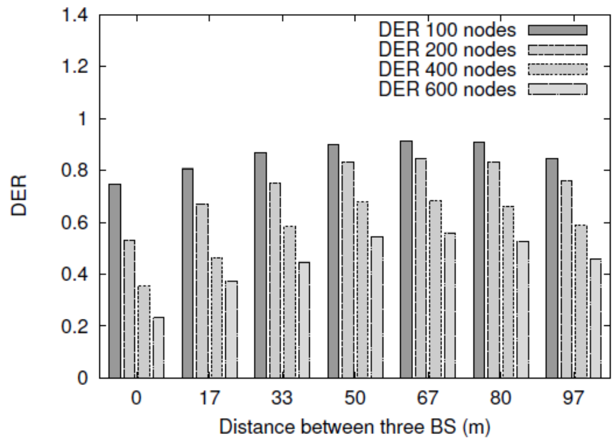



**Figure 17 Impact of distance between three base stations on DER for different number of nodes [26]**

Using the experimental results, it is now possible to answer the question if it is better to equip sensor nodes with directional antennas or to deploy additional gateways to achieve a high DER under interference. The result in Figure 18 shows that to achieve a higher DER under interference, deploying multiple gateways is more efficient than using directional antennas [26].

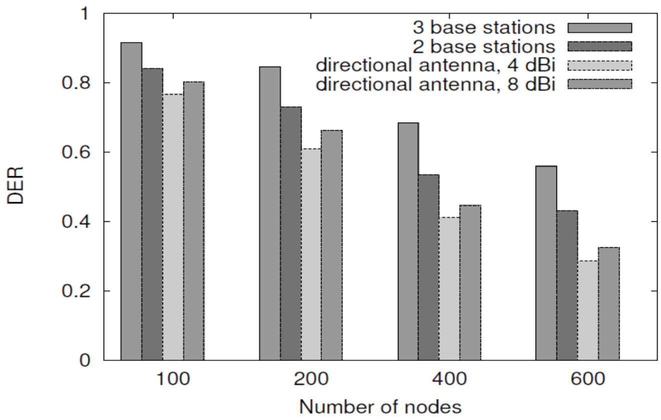



**Figure 18 Summary of results [26]**

Moreover, with multiple gateways, LoRa can achieve a DER that is higher than for one gateway without inter-network interference, even when there is no inter-network interference, the transmissions of the nodes from the own network can cause collisions. Combining both methods, additional gateways and directional antennas is theoretically possible but seems an impractical choice [26].

## 3.3. CROSS-TECHNOLOGY INTERFERENCE

The purpose of the study [27] was the analysis of the signals in the 868 MHz band of the ISM band, this band is composed of many smaller sub-bands, which accommodate various applications and thus traffic patterns. In order to capture as many of these different patterns as possible, even at low received power levels, a radio network analyser scanner was applied, the scanner was set to measure from 863 MHz to 870 MHz using 7 kHz bins and 200 ms of sampling time. The total measurement time per location was two hours to capture at least two periods of the duty cycle, which is specified over one hour. The scanner comes with a calibrated, omni-directional antenna and has a sensitivity of approximately -115 dB in the 870MHz – 863 MHz = 7 MHz bandwidth. Finally, a van was used to supply the scanner and the laptop recording the measurements, while the antenna was mounted on the van's roof [27].

The measurements were performed at five distinct locations within Aalborg, Denmark, during normal working hours in weekdays. The locations are illustrated in Figure 19, the three downtown measurements were made in a shopping area with shopping streets and 3-5 store-apartment buildings, a business park with office buildings and 3-5 store-apartment buildings and a hospital complex with multiple, large hospital buildings and some single family houses. The industrial area consists of industrial production facilities and office buildings, while the residential area is a suburb of Aalborg with single-family houses. All measurements were performed while parked in a parking lot or at the roadside that is at street level [27].

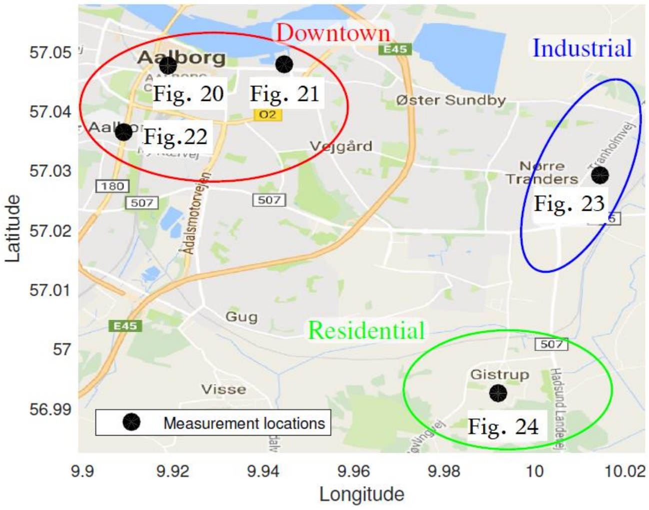



**Figure 19 The five measurement locations within Aalborg municipality [27]**

Besides examining the overall signal activity and power levels in the 868 MHz ISM band at each location, the measurements are post-processed sample by sample, the goal is to determine the probability of samples (200 ms x 7 kHz) being above a -105 dBm threshold, which is 10 dB above the scanner's sensitivity. Such high-power samples will affect the LoRa and Sigfox systems' performance because the SINR is degraded. Although Sigfox technology is not approached in this chapter, the study was done for both technologies and so it is referred in some points of this section. The LoRa technology applies spread spectrum modulation to spread the interference across the receive bandwidth, while Sigfox utilizes frequency hopping by transmitting the same packet on three separate channels. Independently of the interference mitigation mechanism it is interesting to determine the probability of high-power samples in the measurements, and this result is provided after the main measurement results [27].

Figure 20 shows the measurement result from the shopping area in downtown Aalborg. The result is examined sub band by sub band and marked with a dashed red line at the lower frequency bound and a dashed green line at the upper frequency bound. The two channels, which are of interest to LoRa and Sigfox are marked with black lines. The first observation is the activity in the audio band of 863-865 MHz. This band is not duty cycle restricted and thus nearly continuous activity is observed. The next band with high activity is the mandatory LoRa and Sigfox 868.0-868.6 MHz band. The measurement show two almost continuous signals centred at 868.25 MHz and 868.4 MHz, with -97 dBm and -93 dBm power levels, respectively, since the band is restricted to a 1% duty cycle or use of Listen-Before-Talk (LBT) with a maximum continuous transmission time of 1 s and accumulated time of 100 s in one hour, there are either some devices which are violating the regulations or a large number of devices each are transmitting frequently, the signals may be originate home automation systems. In addition to the two main signals there is also quite high activity levels in the rest of the 868.0-868.6 MHz band and therefore LoRa and Sigfox will experience significant interference in this area of the city. The final band with activity in the shopping area is the 868.7-869.2 MHz band that despite its 0.1% duty cycle restriction shows an almost continuous transmission with signals stronger than −70 dBm. From a LoRa and Sigfox perspective the potential downlink band 869.4-869.65 MHz seems not to be utilized in this area [27].

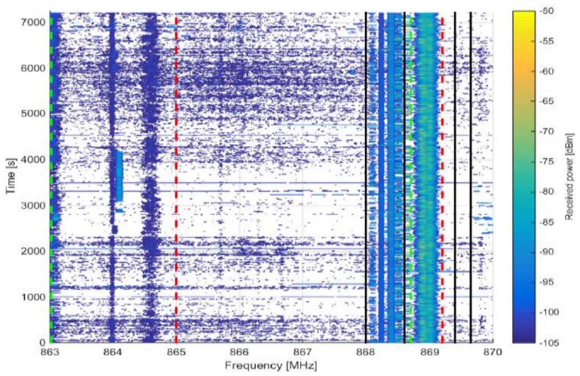



**Figure 20 Measurement in the shopping area [27]**

The next measurement result, illustrated in Figure 21, from downtown Aalborg was performed in the business park. Like the previous observation there is activity in the non-duty cycled audio band below 865 MHz. The 868.0-868.6 band is again shown to be highly occupied with power levels above -75 dBm. Like the previous measurement the 868.7-

869.2 MHz band is occupied, probably by the same source, and in addition the band 869.4-869.65 MHz contains a strong continuous signal of approximately -80 dBm which may prevent efficient LoRa and Sigfox downlink operation. The signal may originate from updates or industrial data links in the offices. It is notable that the general noise level in the entire 868 MHz ISM band in this location is above -105 dBm during most of the measurement time [27].

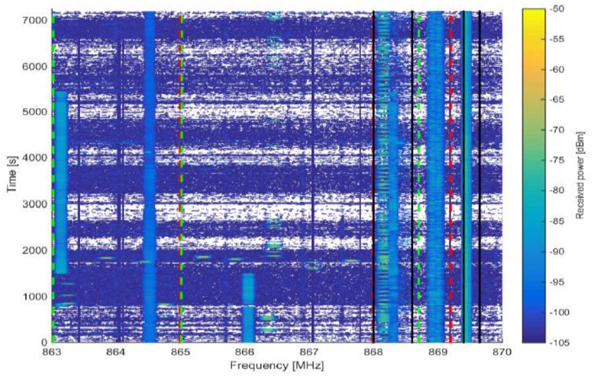



**Figure 21 Measurements in the business park [27]**

The final measurement in downtown Aalborg was performed in the hospital complex. The results are illustrated in Figure 22 and activity in the audio band is again noted, especially in the narrow 864.8-865 MHz band. The hospital is known to utilize RFID for tracking of medical equipment, beds, and other objects that are moved within the complex, and this is also evident from the measurement, which shows high activity in the four interrogator sub bands of the 865-868 MHz RFID band. The 868.0-868.6 MHz band is much less occupied as compared to the other downtown measurement locations, and the transmitting devices seem to respect the duty cycle restrictions. Like the previous locations, activity is observed in the 868.7-869.2 MHz band, and the strong signal is expected to be from the same source. This may also be the case for the weak signal in the 869.4-869.65 MHz band [27].

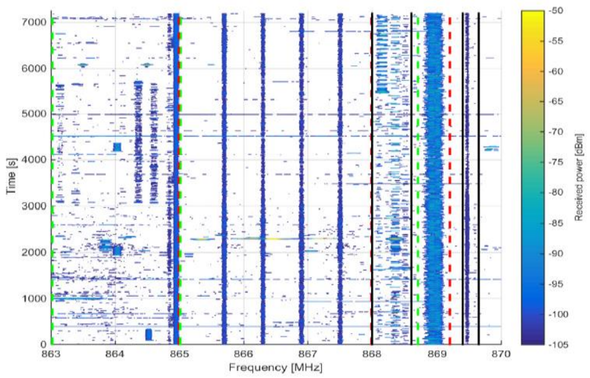



**Figure 22 Measurements in the Hospital complex [27]**

The next measurement was performed in the industrial area east of downtown Aalborg as indicated in Figure 19. The results are shown in the Figure 23, the industry applies RFID for tracking of goods and equipment, and, as expected, activity is observed at the four interrogator carriers of the RFID band 865-868 MHz. The 868.0-868.6 MHz band has periodic activity on three specific carriers; 868.2 MHz, 868.35 MHz, and 868.5 MHz, but the power levels rarely exceed -100 dBm, one signal source may be the industrial Wireless Highway Addressable Remote Transducer (HART) technology using IEEE 802.15.4 combined with the low periodicity, LoRa and Sigfox should be able to operate in this area with a limited number of collisions. Again a very strong and almost continuous signal is observed in the 868.7-869.2 MHz band and if it is the same source it may be located somewhere between the industrial area and the business park, because the latter measurement also showed high received power. It is notable that the potential downlink LoRa and Sigfox band 869.4-869.65 MHz is virtually empty [27].

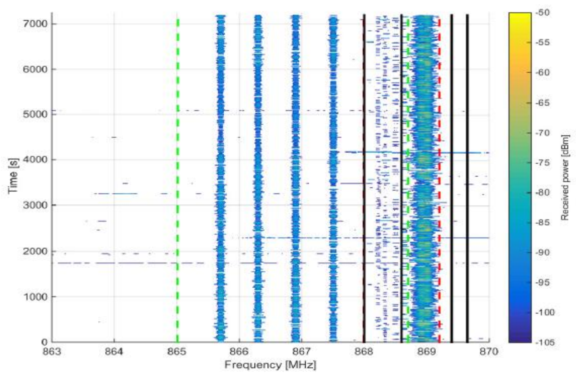



**Figure 23 Measurement in the industrial area [27]**

The final measurement was performed in the residential area. In the first 1300 seconds of the measurement a signal exceeding -70 dBm is observed in the audio band 864.8-865 MHz, and this could be an alarm placed in a baby carriage outside a house. It is interesting to note that there is quite a lot of activity in the 868.0 - 868.6 MHz band in this area, and it may be due to IEEE 802.15.4 home automation technologies. However, the low power and periodicity should not be a significant issue for LoRa and Sigfox operations and in addition the downlink band 869.4-869.65 MHz is not occupied, the results are shown in the Figure 24. The residential area is the first measurement location where activity in the 869.7-870.0 MHz band is observed, but it is highly sporadic. The two-hour measurements at each of the five locations have shown that the bands of interest for LoRa and Sigfox have very different levels of activity [27].

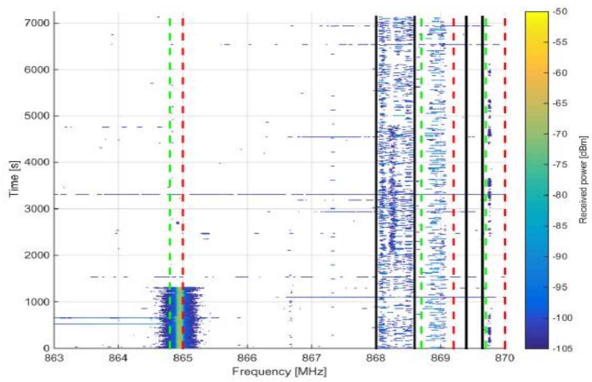



**Figure 24 Measurements in the residential area [27]**

In conclusion the shopping area and business park measurement locations in downtown Aalborg, illustrated in Figure 20 and Figure 21, were observed to have almost continuous, high power signals in the 868.0-868.6 MHz band and this is reflected in interference probabilities with values between 22-34%. In addition, the potential downlink band 869.4-869.65 MHz also has an interference probability of almost 60% in the business park. The hospital complex, industrial area and residential area all reported periodic activity in the 868.0-868.6 MHz band, but the probabilities are in the order 1 – 3 % [27].

# 4. Initial Tests

In order to understand the behavior of the LoRa technology, several tests were carried out with development modules equipped with LoRa chips, these modules were applied in various environments and situations in order to simulate the behavior that the system will have in the final project. With these tests it was possible to observe the behavior of the modules in relation to several factors, such as the range in various environments, the signal strength and what type of configurations would work best.

The modules used are from TTGO with an ESP32 microcontroller, these modules have integrated several technologies, such as LoRa, having the SX1276 chip, wi-fi and Bluetooth, both the classic and the Low Energy, also have an OLED display very useful to show important information. These modules have an antenna integrated into the printed circuit board (PCB) for wi-fi and another with IPEX connection intended for radio operation by LoRa.

The following sections describe all the tests performed and what results were obtained in these tests.

## 4.1. RANGE TEST BETWEEN TWO NODES

For the range tests were made two programs, one for the transmitter and one for the receiver, the transmitter program allows the selection of the frequency to be used that has to be equal in both modules, allowing the definition of the Spreading Factor and the Transmission Power.

The higher the value of the Spreading Factor, the more the receiver sensitivity becomes negative, so the receiver becomes more sensitive, for a greater distance between nodes. The spreading factor must be higher to obtain a lower sensitivity value and thus be able to demodulate the signal. The Transmission Power have to have a value that follows the ERC Recommendations, according to these recommendations, for the frequency used in Portugal, from 865 to 868 MHz, the Effective Radiated Power (ERP) must have a value of 25 mW which corresponds to approximately 14 dB and the Spectrum Access and migration requirements has to be ≤ 1 % duty cycle or Listen Before Talk and Automatic Frequency (LBT + AFA), this information can be found in Annex A [28]. The ERP is calculated by assuming an antenna of 2.1 dBi, then the maximum transmission power would be 14 dB, but the modules that were used have a 3dBi antenna, therefore the calculations of the transmission power have to take into account this difference presented in the equation (3) which results in, according to the equation (4), a maximum Transmission Power of 13.1 dB [29].

$$3 - 2.1 = 0.9\,. \tag{3}$$

$$14 - 0.9 = 13.1\,. \tag{4}$$

The transmitter node sends the LoRa packets by starting them and setting the message to be sent, in this case it is a String and the value of an incremented counter of a unit in each sent packet , the message is sent every 5 seconds. On the receiver side is also set the frequency and it is checked if there are LoRa packets to be received, the message is then displayed on the Serial Monitor and the module's OLED LCD. The receiver also checks the Received Signal Strength Indication (RSSI) value and presents it in the same devices mentioned above.

### 4.1.1. TEST ENVIRONMENTS

The tests were performed in one house, keeping one of the modules, the transmitter, always in the same place at one end of the house and moving the other module, the receiver, to several locations. First, the behavior at each end of the house was analyzed, at approximately 12 meters, experimenting in several environments:

- In open air.
- Inside the microwave.
- On top of the microwave while it was in operation.
- Inside a wooden cabinet.

Then the receiver was moved further, to approximately 20 meters. After this, the behavior of these modules became clear and other experiments were carried out. Keeping the transmitter module always in the same place, the receiver module was moved to greater distances in two environments, an environment of mostly houses and a grove environment.

After these tests, others were realized in a much wider and open area to understand the operation if both modules have a line of sight as far as possible.

### 4.1.2. RESULTS

The results regarding the tests performed at the house are presented in Table 5, it's possible to see that inside the perimeter of the house the communication don't have any issues since all packets have been received and the RSSI presents reasonable values despite the fluctuations it presented from very low values, the values fluctuated between -20 dBm and -113 dBm. However, when moving the module to higher distances it is necessary to consider several parameters such as the orientation of the antennas of both receiver and transmitter modules, the Transmission Power and Spreading Factor, previously mentioned, in this case, in the area with houses, the communication between the modules was possible, up to the 94 meters where it would stop receiving messages, reaching 75 meters, there began to be losses of messages, as the distance increased the value of the RSSI decreased up to -180 dBm, advancing to the tree area, it was possible to communicate between the modules up to 91 meters , where it stopped receiving packets, also here the value of RSSI decreases up to -180 dBm.

Table 5 **Results at the house**

<table>
<tr><th colspan="2">Indoor - House</th><th>Results</th></tr>
<tr><td rowspan="4">Other end of the house (12 meters)</td><td>Open air</td><td rowspan="5">Received all the packets<br>RSSI at 915 MHz: from -20 to -113 dBm</td></tr>
<tr><td>Inside the microwave</td></tr>
<tr><td>On top of the microwave while it is running</td></tr>
<tr><td>Inside a wooden cabinet</td></tr>
<tr><td colspan="2">To the garden at the other end (20 meters)</td></tr>
<tr><th colspan="2">Outdoor – House</th><th>Results</th></tr>
<tr><td colspan="2">Area with houses</td><td>Up to 75 meters – starts to lose some packets<br>Up to 94 meters – stops receiving packets<br>RSSI at 915 MHz: decreases to approximately -180 dBm</td></tr>
<tr><td colspan="2">Area with trees</td><td>Up to 91 meters – stops receiving packets<br>RSSI at 915 MHz: decreases to approximately -180 dBm</td></tr>
</table>

The results of the tests performed in the open area are presented in the Table 6, as it is possible to see, in this environment the distance reached was higher than the tests previously performed where there were many obstacles, it was possible to reach up to 400 meters and the RSSI reached better values stopping at approximately -120 dBm.

Table 6 **Results at the open area**

| Outdoor | Results |
|---|---|
| | **TTGO ESP32 Sx1276** |
| Open area with line of sight | Up to 280 meters – Starts to lose some packets<br>Up to 400 meters - stops receiving packets<br>RSSI at 915 MHz: from -30 to -120 dBm |

# 5. DESIGN OF THE HARDWARE BOARDS

As stated earlier in section 4 in relation to the tests performed, the modules used are from TTGO with an ESP32 microcontroller, a LoRa chip, wi-fi and Bluetooth. These modules, that can be seen in Figure 25, have an antenna integrated into the PCB for wi-fi and another with IPEX connection intended for radio operation by LoRa.

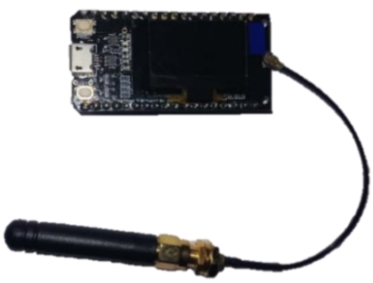


**Figure 25 TTGO ESP32 module**

All development and testing was carried out with these modules, but it was thought that, for a future implementation of the system, specific boards should be developed for each functionality where the core is the same but then has the peripherals and sensors corresponding to each application that one wishes to implement, Figure 26 shows a general diagram of the entire system where the main components are represented. Thus, four printed circuit boards were made for operation as gateway board, relay trigger board, water leakage sensor board and temperature and humidity sensor board.

In this chapter a description of the work done in terms of hardware for the development of these boards is made, referring to the main components used.

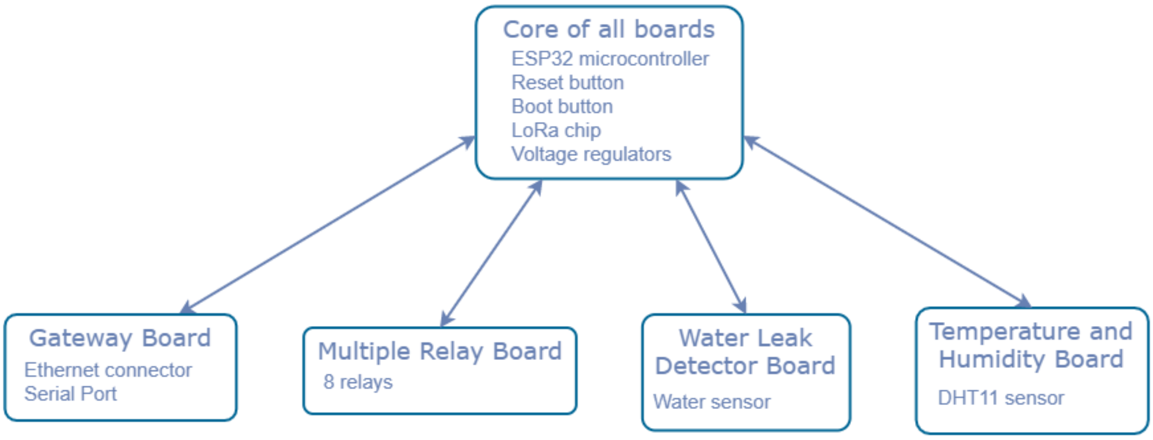



**Figure 26 Description of the operation of each board**

## 5.1. CORE OF THE BOARDS

In the Figure 27 it is possible to see the core that has the ESP32 microcontroller where the respective connections will be made depending on the required application, this microcontroller as can be seen in Figure 28a is surface mounted device (SMD) and already has the built-in wi-fi antenna as well as the Bluetooth. There are also two buttons, one for reset and one for boot, these buttons have the same function as those of the TTGO module, one resets the chip, and the boot is used for download programs to the microcontroller or flash firmware on it. There is also a RF95 transceiver module that has all the connections and components necessary for the operation of the LoRa chip incorporated in it, this module is connected via SPI protocol and the use of this module aims to simplify the printed circuit board, it also allows the SMD connection as can be seen in Figure 28b.

In addition, there is a connector for a 12V power supply with an ON-OFF switch, and two voltage regulators with 5 V and 3.3 V outputs, which are the voltages required for the devices used.

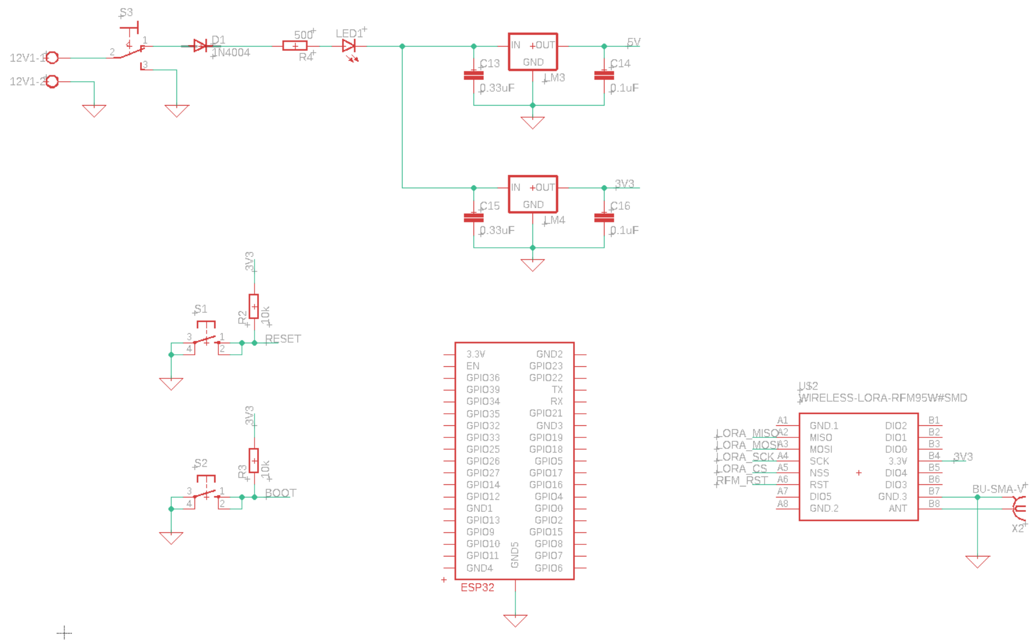



**Figure 27 Components and connections of the core of the all the PCBs**

a) b)

**Figure 28 ESP32 microcontroller with wi-fi and Bluetooth [30] (a) and RFM95 module [31] (b)**

## 5.2. GATEWAY BOARD

Regarding the operation as a gateway, to the set of components of the core was added the USR-ES1 W5500 module to enable ethernet connection, this module is represented in Figure 30a, as can be seen it has a through hole technology (THT). A serial port connection is also possible with a serial connector (Figure 30b) and the MAX232 integrated circuit

(Figure 30c) which is a level converter that transforms the signals of a serial port into signals suitable for use in microprocessors , in Figure 29 it is possible to see these components and the necessary connections in the ESP32 microcontroller.

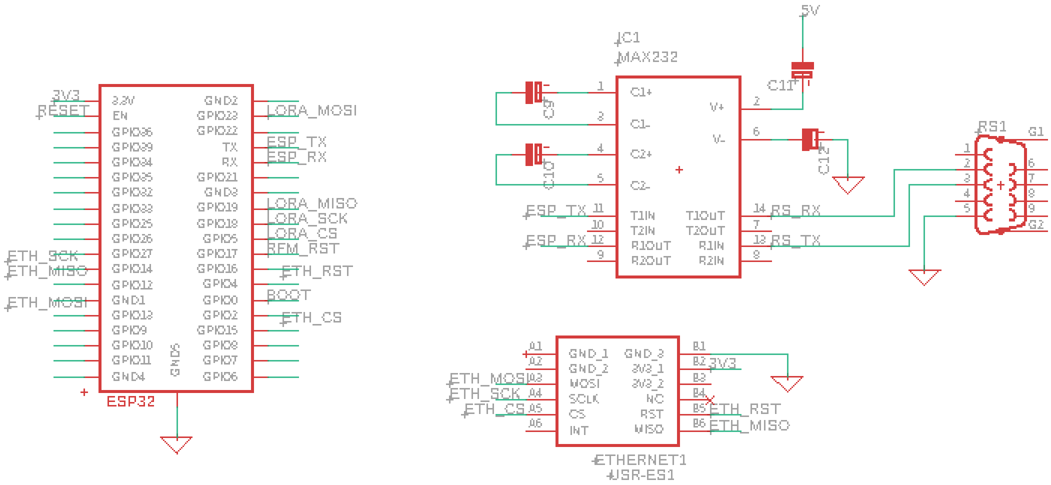



**Figure 29 Components and connections related to the gateway board**

a) b) c)

**Figure 30 USR-ES1 W5500 module [32] (a), Serial Port Connector [33] (b) and MAX232 integrated circuit [34] (c)**

## 5.3. RELAY TRIGGER BOARD

With regard to the relay trigger board, 8 relays of 5V (Figure 32) have been added to the main core, as can be seen in Figure 31, the circuit of these relays includes a BC548 transistor that have a low base emitter voltage which can be triggered with only 3.3V, the resistor of

1K is used as a base current limiter resistor [35], the microcontroller connections have also been modified according to the new operation for the connection of each relay.

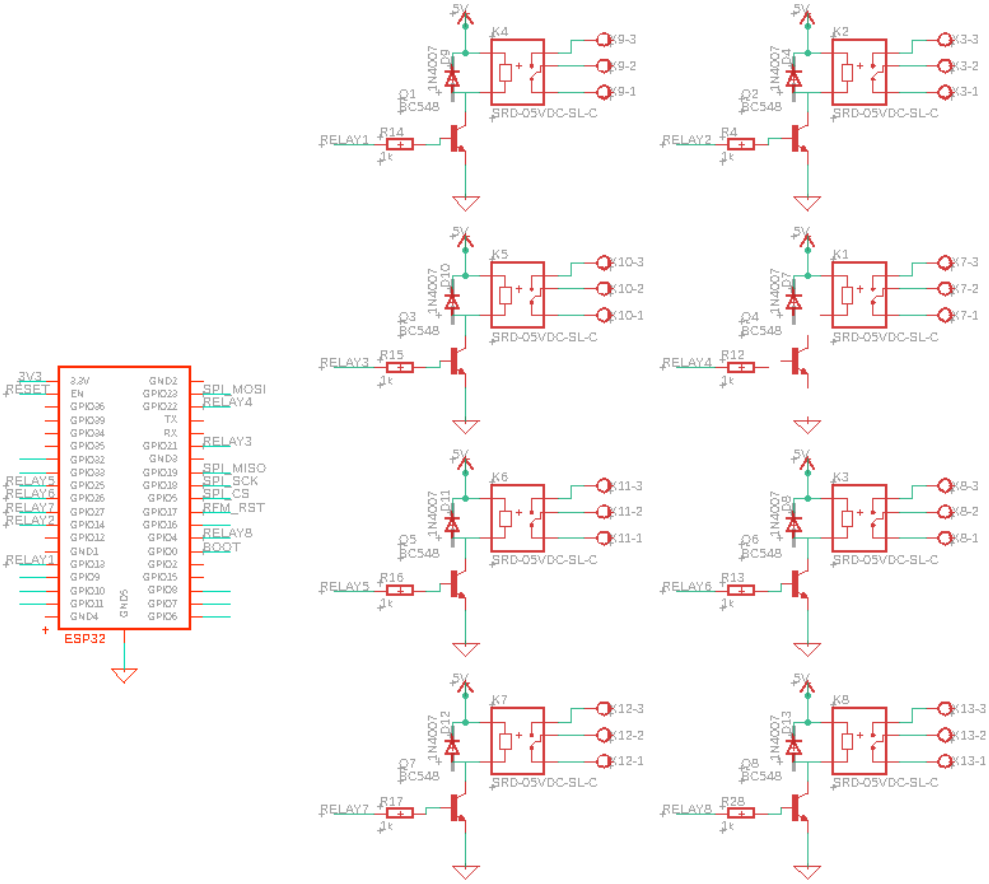



**Figure 31 Components and connections relater to the relay trigger board**

**Figure 32 5V Relay [36]**

## 5.4. WATER LEAK SENSOR BOARD

Next, for the water leak sensor board, only a connector was added to connect the sensor that only needs the power and the signal pin of the microcontroller, this sensor creates a short circuit when there is a conductive material, like water, between the pins, the connections can be seen in Figure 33.

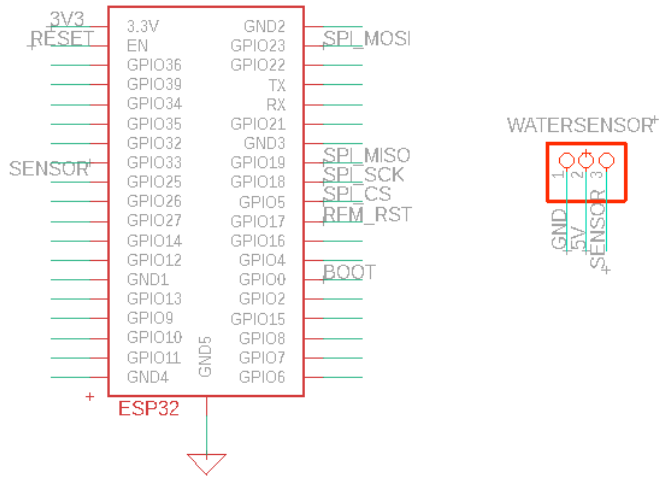



**Figure 33 Components and connections related to the water leakage sensor board**

## 5.5. Temperature and Humidity Sensor Board

Finally, with regard to the temperature and humidity sensor, the DHT11 sensor (Figure 35) was used that is connected directly to the printed circuit board, as previously mentioned, Figure 34 shows the connections of the sensor and the ESP32 microcontroller.

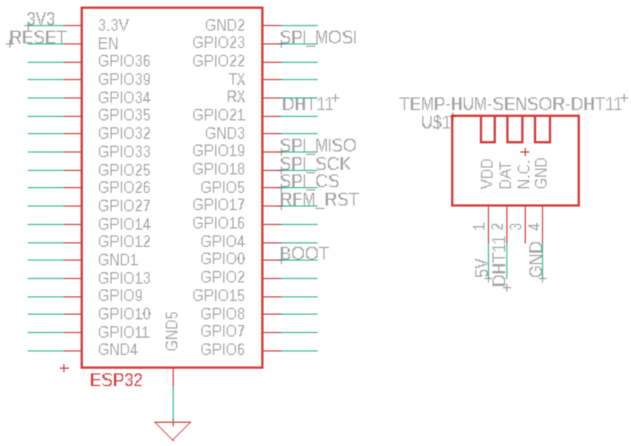



**Figure 34 Components and connections related to the temperature and humidity sensor board.**

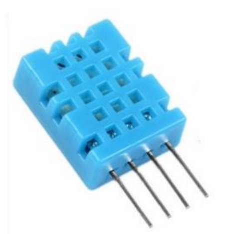


**Figure 35 DHT11 sensor [37]**

# 6. Development of the Software

The development of the software was carried out in C++ language using the ArduinoIDE Platform, the focus of this project was the development of a radio system with long range, several libraries were used to facilitate the writing and understanding of the code.

This code is divided into two parts, the star topology system and the retransmission system. On the first part, codes have been made for each desired feature to test each one of them, then added one by one to a single global code. This code allows the selection of the operating mode, between a relay trigger, a gateway, a water sensor, or a temperature sensor. The second part, regarding the retransmission method, has two programs, one referring to a node that may have internet access, Bluetooth, or other type of communication, to which it is possible to call gateway, and another for the remaining nodes that only work through LoRa. This second part of the project is the starting point for a future development of a mesh system where the path and retransmission will be dynamic and well defined.

## 6.1. STAR NETWORK TOPOLOGY SYSTEM

In this functionality several files have been created that work together with the main code in order to divide the code according to each task that will be performed. There are files used by several others such as the LoRa and OLED files, these two files can be used both when the operation is set as gateway and when it is relay trigger. Others are used only when the operating mode is for the gateway such as Bluetooth, Serial, and Wi-Fi.

Figure 36 shows a diagram of the system architecture, where the central block is the gateway that makes the management of messages. This device can receive messages from a smartphone via Bluetooth, can receive messages through a web page over Wi-Fi, ethernet, or through a serial port, can also over LoRa receive messages from various sensors, such as temperature or water leakage. Being able, according to the received messages, to send through LoRa, messages to the relay trigger board and even to the web page.

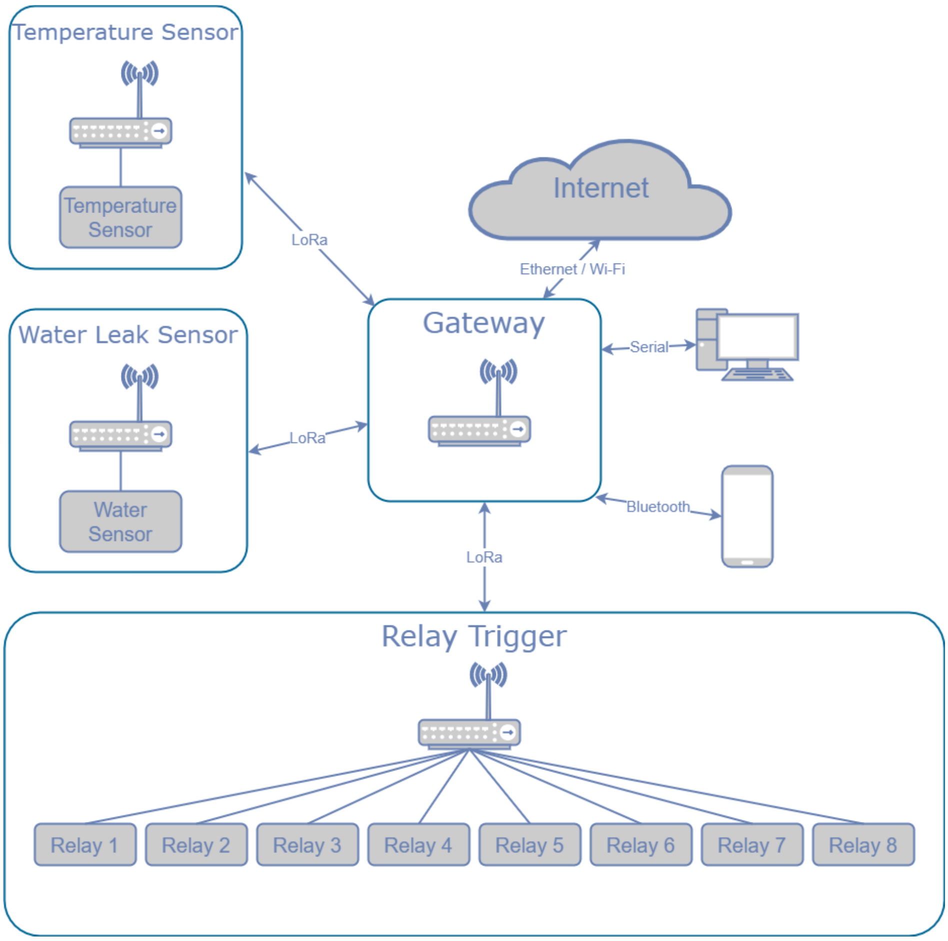



**Figure 36 Architecture diagram of the star topology system**

The operation of the program is divided into the following sections, where in each one it is possible to see the flowchart referencing that part of the code.

### 6.1.1. BOOT

The "boot.ino" section has two functions, the initial one, named “Start”, as it is possible to see in the flowchart in Figure 37, is the one that do the initial configurations and checks which type of node is being used from two pins with jumpers that allows to make this selection, 0 shows the available selection options, for each reading is called the respective function that will execute the remaining code for the chosen type.

**Table 7 Selection options for each node**

| Mode Select 1 | Mode Select 2 | Node Type |
|---|---|---|
| 1 | 1 | Relay Trigger Board |
| 1 | 0 | Water Sensor Board |
| 0 | 1 | Temperature Sensor Board |
| 0 | 0 | Gateway Board |

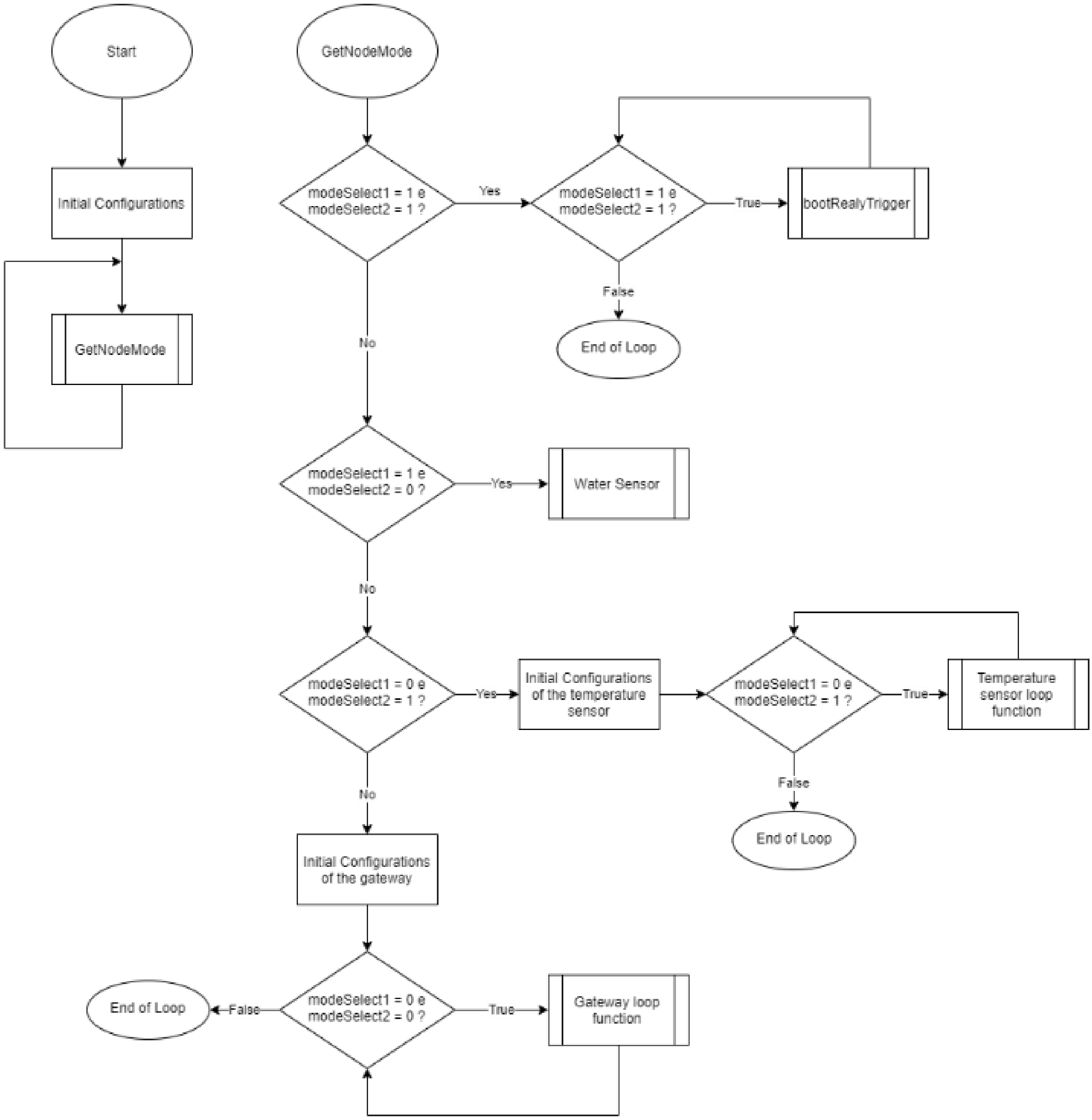



**Figure 37 Flowchart for the initial function and the node type choice function**

It is also in this segment of code that the data referring to the relays are treated and functions are called that will act on them in order to open or close them according to the indication given to perform access control, it is possible to see this reading in Figure 38.

After the reception function there is a function to check if it is to know what the neighbours are, sending the message with the respective address or, otherwise, the initial settings of the relays are made and is performed the relays trigger depending on the message received, open or closed, or, in case of receiving a duration, acts on the relay only during that time.

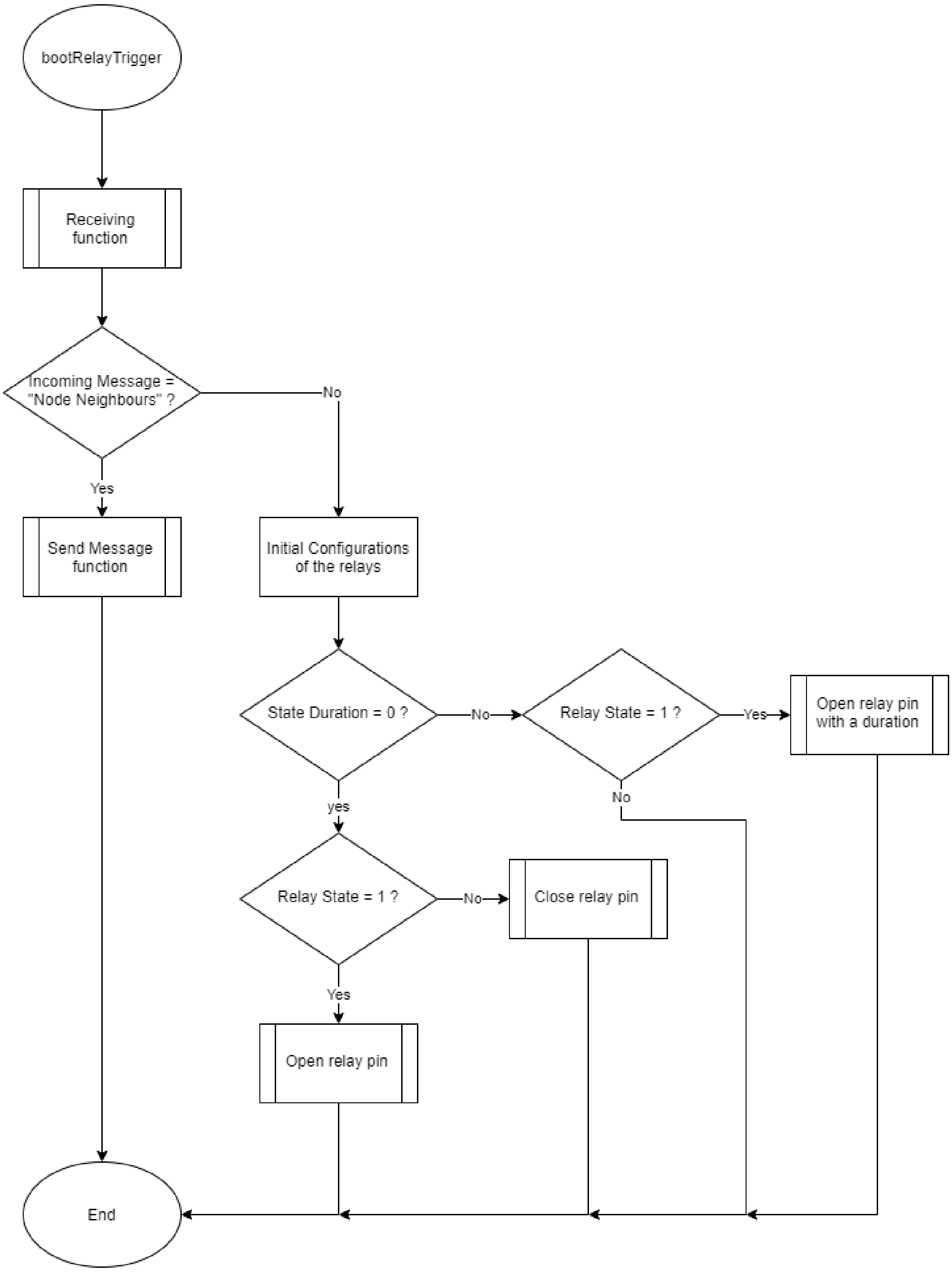



**Figure 38 Flowchart for the Relay Trigger function**

## 6.1.2. GATEWAY

The code referring to the gateway makes the initialization of two buttons, the definition of variables referring to the state of these two buttons and two LEDs, initializes the functions referring to Wi-Fi, LoRa, Bluetooth and serial port, then performs the main function where it reads the buttons. These buttons each changes the state of a variable referring to a led (toggle) and saves this information in a string that will be sent later via LoRa.

After that, it performs the functions for what it desirable to apply, such as linking to the webpage, Bluetooth application and/or serial communication. All these functions create a string with the desired information to be sent through LoRa. After performing the functions related to each application, finally send the desired recipient of the message through the function created for LoRa communication, also presenting the message sent on the LCD of the TTGO module, it is possible to analyze this operation in Figure 39 through the flowchart presented and the following sub-sections, the main features of each part of the code are presented.

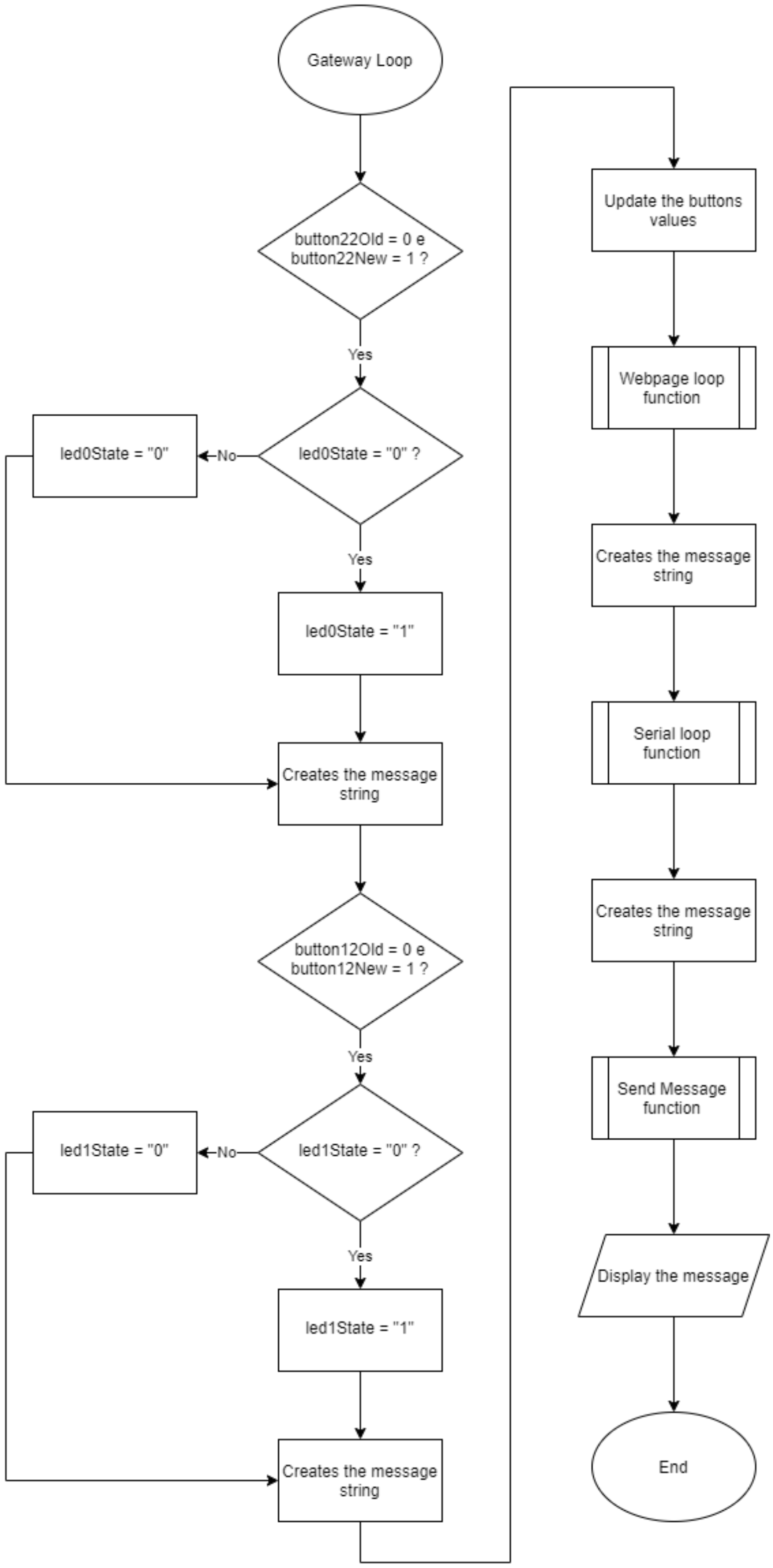



**Figure 39 Flowchart for the Gateway Loop function**

### 6.1.3. RELAY

For the control of the relays, the address of the module in question is defined through the program, and all control pins are initialized, then the functions are set to receive the status of a pin, act on one of the pins changing its state to open and to close the contacts permanently or for a certain period of time indicated in the LoRa message that is received.

### 6.1.4. LORA

In this part is done all the management of messages related to this technology, initially are defined the pins to be used, the frequency of operation, and initialized the necessary auxiliary variables, then the functions where the configuration of the modules is made and the definition of the spreading factor and transmission power, here are created the functions of sending messages, receiving and processing data, and discovering neighboring nodes. The function of sending messages is called by several others when it is wanted to send via LoRa some packet with information, the reception function manage the received message by differentiating its contents into different variables that can now be used to, for example, act on one of the pins of the relays.

### 6.1.5. BLUETOOTH

Because it is possible to connect Bluetooth devices to the boards, it is also possible to read the temperature and humidity values and display them on a smartphone and control accesses via smartphone, the application developed can turn on and off an LED, as proof of concept this LED can be replaced by a relay that will control a door that is the application of interest for this project. All boards used in this project have Bluetooth, but only the Gateway can connect and use this feature.

The mobile application was made in the MIT App Inventor, in the Figure 40 it is possible to see the part were the humidity and temperature values are displayed and the Figure 41 shows how the LED is turned ON/OFF.

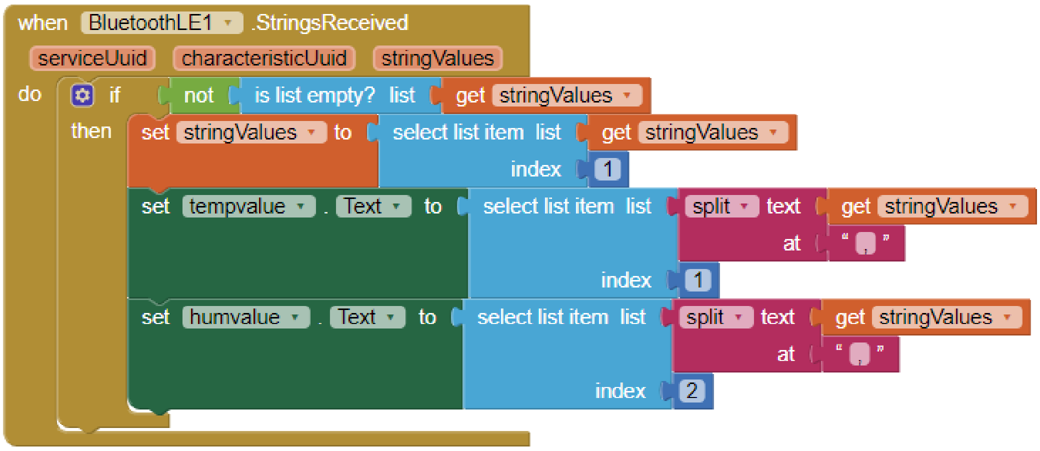



**Figure 40 Block that makes the receipt of the temperature and humidity values**

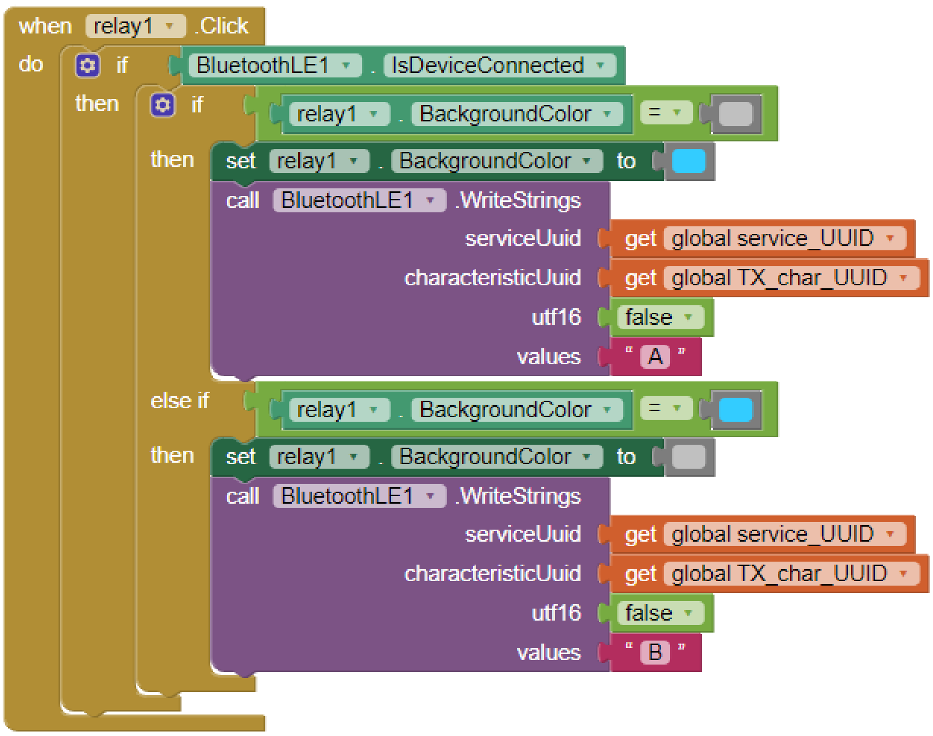



**Figure 41 Block that makes the activation/deactivation of the LED**

### 6.1.6. Wi-Fi

The Wi-Fi function allows the introduction of the SSID and password into the network to be used and makes its internet connection through the module present on the TTGO module, this connection allows the gateway to have internet access in order to send and receive data via this way.

### 6.1.7. WEBPAGE

The webpage works similarly to Bluetooth, allowing the control of seven LEDs that are once again simulating the operation of the relays, their state is changed from the webpage that is related to the gateway module, which makes the subsequent sending of the message to the relays trigger board, all the boards used in this project allow the connection by Wi-Fi but only the Gateway performs this action, it is also possible this operation via ethernet.

### 6.1.8. SERIAL

The communication series part reads the messages received by the serial port, this application is a requirement of the client in order to increase the possibilities of connecting the gateway board, used in this case in the main control room.

## 6.2. SYSTEM WITH BROADCAST MESSAGES THAT MULTIPLIES THE EMISSION AND RECEPTION

For this functionality the system sends broadcast messages that are multiplicated until it reaches the correct destination, Figure 42 shows a diagram of the system architecture, where the gateway works similarly to the previous topology, receives messages from a smartphone via Bluetooth, can receive messages through a web page over Wi-Fi, ethernet, or through a serial port, can also over LoRa receive messages from various sensors, such as temperature or water leakage, after this sends these messages by LoRa to the modules that are within the reach, these are the ones who read the message received in order to realize if it is for itself or to relay the message until it reaches the module with the correct address. The communication part via Bluetooth, Wi-Fi, ethernet or serial port has not been implemented, but the code was designed for this.

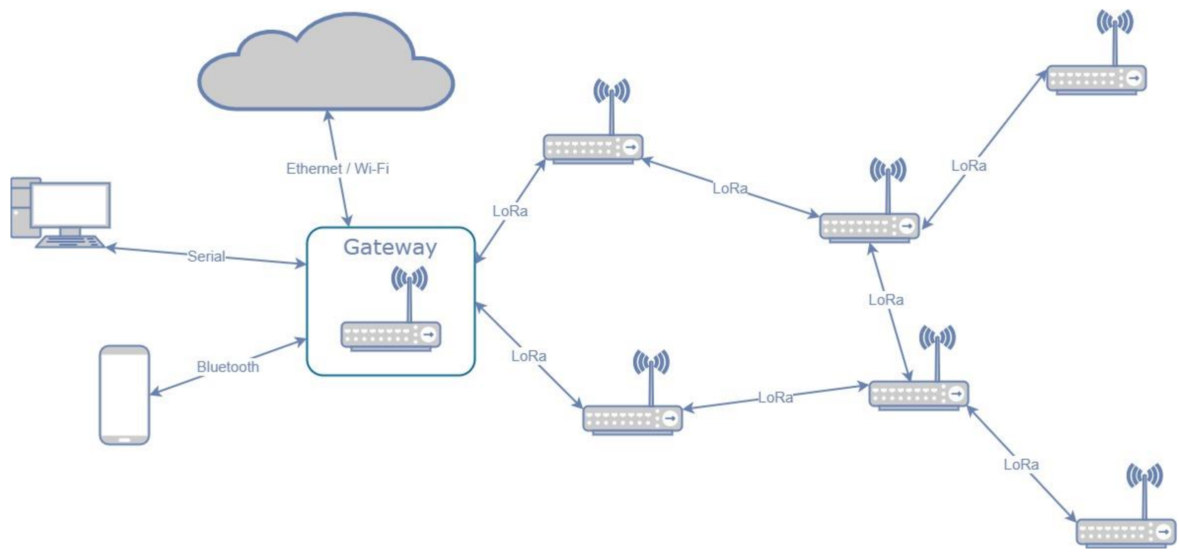



**Figure 42 Architecture diagram of the broadcast system**

The most relevant part of the code is the function of receiving messages via LoRa, this function makes the message reception, its division by several variables in order to distinguish each information and then checks whether the message went to a new neighboring address and in this case adds it to the neighbor vector or if it is for itself, in this case printing on the LCD the information.

# 7. System Implementation

All the system was implemented using breadboards, since the final product has not been made for permanent installation in multifamily properties. It is possible to divide this implementation into two parts, the first is the star topology where there is a central node that does all the management, and the second one is the one where only one node is a gateway that communicate with other nodes and has a retransmission system. This chapter describes how the system was implemented presenting some practical results.

## 7.1. Star Topology System

This mode of operation has always been tested with the boards side by side, and there is no record of their behavior if the distance between them increased, the code described in section 6.1 was applied to the modules and the results described below.

Starting with the gateway and its features, in Figure 43 it is possible to see the result of the webpage where 7 relays can be controlled and the current state of each pin is indicated. Figure 44 shows the presentation in serial monitor of when the state of a pin changes on the webpage, showing that the connection was made to a new client and, in this case, GPIO 0 was placed in the low state, it is then disconnected with the client.

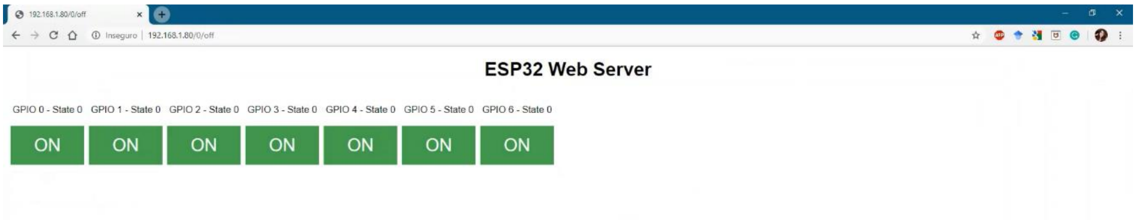



**Figure 43 Webpage Example**


**Figure 44 Serial Monitor showing the change on the webpage**

Regarding the Bluetooth connection with a smartphone, this application can be seen in Figure 45, where the humidity and temperature values are shown and it is possible to control 8 relays in a similar way to what happens on the website.

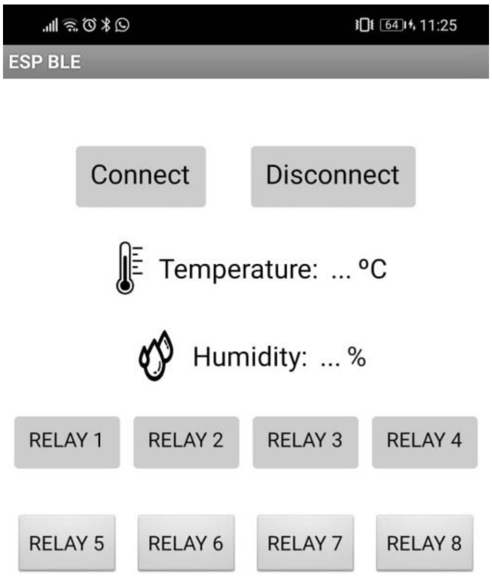
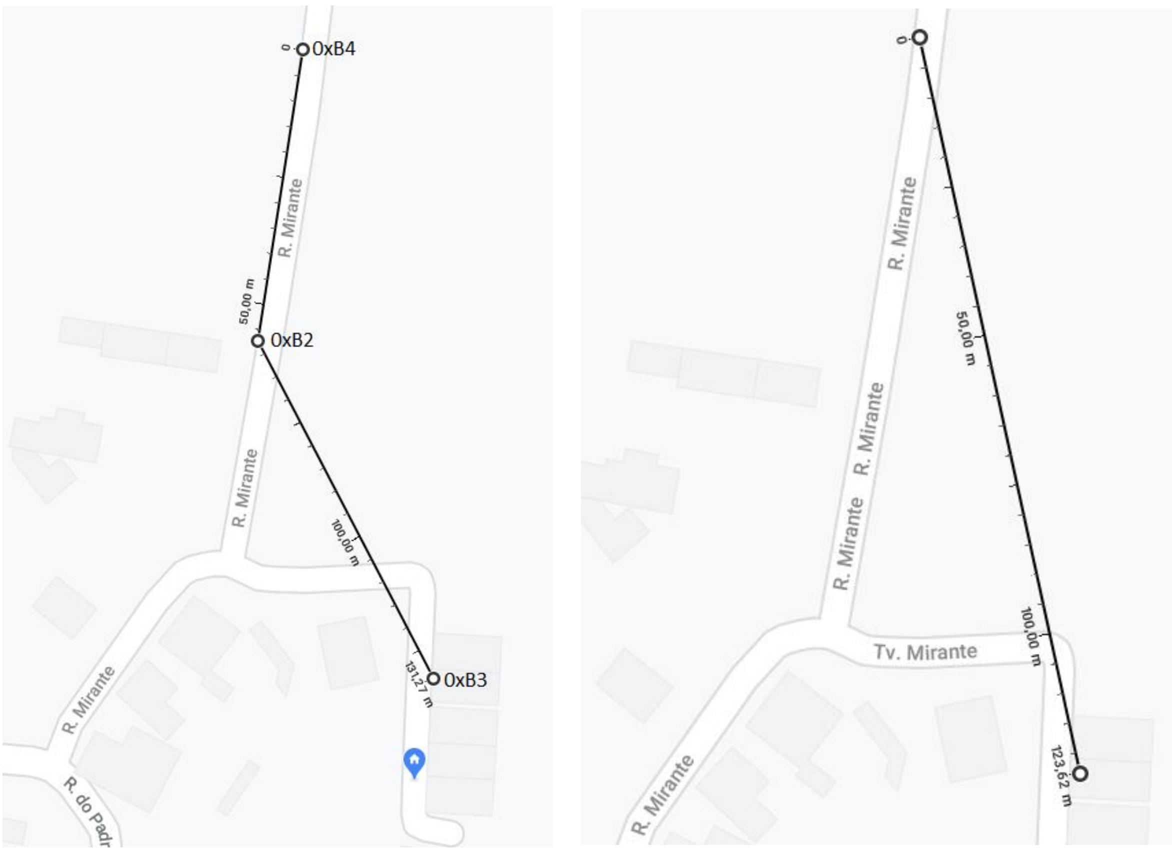



**Figure 45 Bluetooth App**

## 7.2. System with Broadcast Messages that Multiplies the Emission and Reception

The developed system works with several nodes and was tested with 3 modules and with 4 modules, in the first case, a module was left indoors, with the address 0xB3, which sends a message to the module that is further away, address 0xB4, these boards are out of reach of each other, and there is a board in the middle, address 0xB2, which makes the passage of the message so that it is received correctly by the right recipient , this distribution can be seen in Figure 46a. The environment where this system was applied is mostly trees, which resulted in a lower than expected range, module 0xB3 and module 0xB2 are at a distance of approximately 68 meters while module 0xB2 and 0xB4 are at a distance of 63 meters, resulting in a total distance of approximately 131 meters (Figure 46a) , the distance between the two straight ends is approximately 124 meters as can be seen in Figure 46b.




a) b)

**Figure 46 Three Nodes distribution (a) and Distance between the farthest nodes (b)**

Regarding the operation of this system, several messages were sent, with an interval between 2 to 4 seconds, both the 0xB2 module and 0xB4 sent broadcast messages, while the 0xB3 module only sent the desired message to a single recipient, it was possible to conclude that it is quite reliable, and all packets sent were received with less than one second of latency , sometimes there could be some delay in receiving due to broadcast messages but without these the sending was immediate. This receive and send control was performed through a message counter that incremented a unit whenever each module receives a message, this counter can be seen in Figure 47 called "MessageID", can also be seen the source address "Received from" and destination "Sent to". As it is possible to see, the 0xB2 address module is only transmitting the message because it is not directly for it, the RSSI has rounded the -114 dBm and the SNR 2.75.

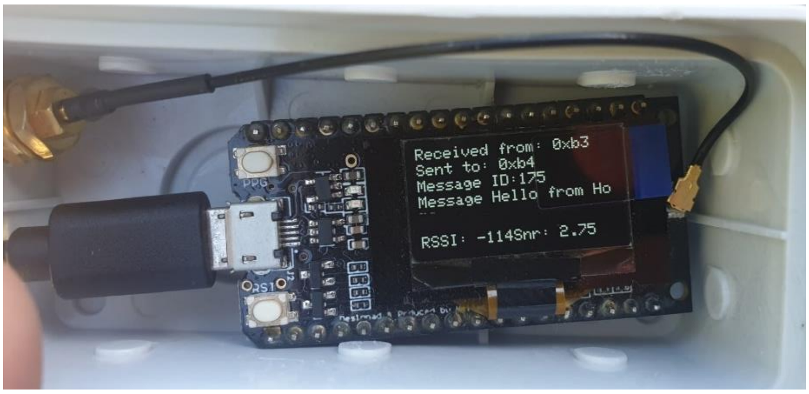



**Figure 47 Example of the text displayed on each module, in this case is the 0xB2 module**

To this system of 3 modules, was added one more point, in order to facilitate the tests, the address of the module further away remains the 0xB4, and the added point has as address 0xB6, the objective and the test environment are the same as the previous, the address 0xB3 wants to send a message to the 0xB4, but these modules are not within direct range of each other. The 0xB3 module and the 0xB2 module are at a distance of approximately 70 meters, the 0xB2 and 0xB6 are 45 meters away, while module 0xB6 and 0xB4 are at a distance of 42 meters, as can be seen in Figure 48a, completing a distance of 157 meters. The distance between the two ends in a straight line is approximately 153 meters, as shown in Figure 48b.


a) b)

**Figure 48 Four Nodes distribution (a) and distance between the farthest nodes (b)**

Regarding the operation of this system, which remains unchanged from the previous one, it was possible to conclude that it is quite reliable and has a similar behavior, the only difference being the number of devices and the distance that can be traveled, the RSSI was of aproximately -116 dBm and the SNR 1.75.

# 8. CONCLUSIONS AND FUTURE WORK

Through the work developed it was possible to draw several conclusions, so in this last section a summary of the main conclusions, consequences, relevance of the work carried out and future developments are made.

The project presented in this document consisted of the development of a wireless access control system that should be applied in urban facilities, for this it was studied several radio technologies, and then it was necessary to make a comparison between them to choose the most appropriate to the project, this allowed an increase in the capacity of research and synthesis due to the vast amount of information taken.

The technology chosen for the development of the project was LoRa, which has a lot of support and information besides having characteristics that allow its implementation in this system, it is among all that allows a greater range, accompanied by low cost and power values. To verify if this technology was suitable for the project, it was necessary to perform tests which allowed a better understanding of how radio technologies work and which tests are the most appropriate.

The biggest difficulty in this project was the development of the software, which was the great central point besides the hardware developed, due to being using a new technology it was necessary to understand its operation and understand how it could be applied in a system with several buildings.

This leads to an analysis of future developments, this system could be modified to function as a mesh network where there would be no hierarchies between the nodes and each sent and received the messages doing node-to-node retransmission to the final recipient defined by the initial transmitter, so the increase or reduction of the whole system did not have much influence on its operation because the routes would be automatically calculated for the new reality.

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# Annex A. ERC Recommendations



| Frequency Band | | Power / Magnetic Field | Spectrum access and mitigation requirements | Modulation / maximum occupied bandwidth | ECC/ERC Deliverable | Notes |
|---|---|---|---|---|---|---|
| **f3** | 169.4875-169.5875 MHz | 10 mW e.r.p. | ≤ 0.001% duty cycle except for 00:00 h to 06:00 h local time where the duty cycle limit is ≤ 0.1% | Not specified | ECC/DEC/(05)02 | The frequency band is also identified in Annex 10 |
| **f4** | 169.5875-169.8125 MHz | 10 mW e.r.p. | ≤ 0.1% duty cycle | Not specified | ECC/DEC/(05)02 | |
| **g1** | 433.05-434.79 MHz | 10 mW e.r.p. | ≤ 10% duty cycle | Not specified | | |
| **g2** | 433.05-434.79 MHz | 1 mW e.r.p. Power density: -13 dBm/10 kHz | No requirement (note 3) | Not specified | | Power density limited to -13 dBm/10 kHz for wideband modulation with a bandwidth greater than 250 kHz |
| **g3** | 434.04-434.79 MHz | 10 mW e.r.p. | No requirement (note 3) | ≤ 25 kHz | | |
| **h0** | 862-863 MHz | 25 mW e.r.p. | ≤ 0.1% duty cycle | ≤ 350 kHz | | |
| **h1.0** | 863-870 MHz (note 2) | 25 mW e.r.p. | ≤ 0.1% duty cycle (note 1) | ≤ 100 kHz for 47 or more hop channels | | FHSS. Parts of the frequency band are also identified in Annexes 2, 3, 10 and 11 |
| **h1.1** | 865-868 MHz | 25 mW e.r.p. | ≤ 1% duty cycle (note 1) | ≤ 50 kHz for 58 or more hop channels | | FHSS. The frequency band is also identified in Annexes 2, 3 and 11 |
| **h1.2** | 863-870 MHz (note 2) | 25 mW e.r.p. -4.5 dBm/100 kHz | ≤ 0.1% duty cycle or LBT+AFA | Not specified | | Non-FHSS. Parts of the frequency band are also identified in Annexes 2, 3, 10 and 11 |
| **h1.3** | 863-865 MHz | 25 mW e.r.p. | ≤ 0.1% duty cycle or LBT+AFA | Not specified | | The frequency band is also identified in Annexes 3 and 10 |
| **h1.4** | 865-868 MHz | 25 mW e.r.p. | ≤ 1% duty cycle or LBT +AFA | Not specified | | The frequency band is also identified in Annexes 2, 3 and 11 |
| **h1.5** | 868-868.6 MHz | 25 mW e.r.p. | ≤ 1% duty cycle or LBT +AFA | Not specified | | |
| **h1.6** | 868.7-869.2 MHz | 25 mW e.r.p. | ≤ 0.1% duty cycle or LBT+AFA | Not specified | | |
| **h1.7** | 869.4-869.65 MHz | 500 mW e.r.p. | ≤ 10% duty cycle or LBT+AFA | Not specified | | |
| **h1.8** | 869.7-870 MHz | 5 mW e.r.p. | No requirement (note 3) | Not specified | | |
| **h1.9** | 869.7-870 MHz | 25 mW e.r.p. | ≤ 1% duty cycle or LBT +AFA | Not specified | | |