Universidade de Aveiro Departamento de Electrónica, Telecomunicações e Informática,
2017

Orlando Resende Oliveira

Produção de Satélites de Baixo Custo

Low Cost Satellite Production

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requesitos necessários à obtenção do grau de Mestre em Engenharia Eletrónica e Telecomunicações, realizada sob a orientação científica do Professor Doutor Nuno Miguel Gonçalves Borges de Carvalho, Professor Catedrático do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro

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agradecimentos / acknowledgements

Aos meus pais e irmão, por serem a minha maior fonte de força, exemplo de esforço e dedicação, o meu muito obrigado.
A ti Catarina, pelo apoio incondicional, palavras de força, ânimo e exemplo de preserverança eesenciais para concluir mais esta etapa, muito obrigado.
Aos meus amigos, por tornarem todo este percurso imprevisível e inesperado, mas ao mesmo tempo fantástico e inesquecível, muito obrigado.
À EVOLEO Technologies, especialmente ao Ricardo Gonçalves, por todo o acompanhamento e conhecimento passado, fundamental para que este trabalho fosse realizado, muito obrigado.
Ao meu orientador, Professor Doutor Nuno Miguel Gonçalves Borges de Carvalho, por toda a orientação e auxílio prestado, muito obrigado.

Palavras-Chave Internet do Espaço, Internet das Coisas, LoRa, Satélite, Antenas, Baixo–custo, Baixo–consumo

Resumo A necessidade por uma conectividade contínua, seja por motivos pessoais ou profissionais, está a levar ao congestionamento global das redes terrestres. O espaço e os seus respetivos satélites, são agora, mais do que nunca, uma solução à qual recorrer e as grandes empresas já começaram a re–fazer esse link, chamando-lhe Internet do Espaço. Esta dissertação surge com o propósito de desenvolver um micro satélite de muito baixo custo para uma aplicação de Internet das Coisas, utilizando tecnologia LoRa. O objetivo principal deste trabalho é provar o conceito de que uma nova era de "toaster-size satellites" é agora possível. Esta temática requer conhecimento teórico de conceitos como antenas, tecnologia LoRa e LoRaWAN, assim como eletrónica. Um pequeno prótotipo deste micro satélite foi construído com base em tecnologia LoRaWAN, com a implementação de uma gateway LoRaWAN e o desenho de um nó com muito baixo consumo. De todos os aspetos relacionados com a Internet do Espaço, este trabalho visa o seu foco em antenas e na performance do sistema total.

Key-Words Internet of Space, Internet of Things, LoRa, Satellite, Antennas, Low–cost, Low–power

Abstract The need for continuous connectivity, either for personal or professional purposes, is building a path to a global congestion of terrestrial networks. The space and its satellites are now, more than ever, a solution to go to and big companies have already started to reshape this link, calling it Internet of Space. This dissertation arises with the purpose of developing a super low-cost micro satellite for an Internet of Things network, using LoRa technology. The main goal of this work is to prove the concept that a new era of "toaster-size satellites" is now possible. This thematic requires theoretical knowledge of concepts like antennas, LoRa and LoRaWAN technologies, as well as electronics. A small prototype of this micro satellite network was built based on LoRaWAN technology, with the implementation of a LoRaWAN gateway, and the design of a super low-power end device. Besides all the possible aspects related to IoS, this work aims to focus on the antennas, and on the performance of the assembled system.

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List of Acronyms

ADR Adaptive Data Rate

ADC Analog Digital Converter

BW Bandwidth

BLE Bluetooth Low Energy

CSS Chirp Spread Spectrum

DSSS Direct Sequence Spread Spectrum

ED End-Device

FHSS Frequency Hopping Spread Spectrum

FFD Full Function Device

GW Gateway

GFSK Gaussian Frequency Shift Keying

HAP High Altitude Platform

ISM Industrial, Scientific and Medical

IDE Integrated Development Environment

IoS Internet of Space

IoT Internet of Things

LEO Low Earth Orbit

LoRa Long Range

LoRaWAN Long Range Wide Area Network

LPWAN Low-Power Wide Area Network

LTNs Low Throughput Networks

PCB Printed Circuit Board

RSSI Received Signal Strength Indicator

RFD Reduced Function Device

SPI Serial Peripheral Interface

SNR Signal-to-Noise Ratio

SF Spreading Factor

TTN The Things Network

UNB Ultra Narrow Band

WSN Wireless Sensor Networks

Chapter 1

Introduction

Over the past few years, Internet of Things has become more and more a common and important term in the wireless telecommunications scenario. The basic idea consists on the possibility of having a large variety of different objects, such as mobile phones, tablets, sensors and actuators, but also all kind of wearables and everyday physical objects that have become "smart" and can now communicate with each other and with the internet.

According to [1] around two billion people worldwide, use the internet for the simplest things as sending e-mails, browsing the web or update status on social networks, however, as said in the previous paragraph, the internet is becoming a global platform for machines and smart objects to communicate, coordinate and dialogue, creating that way a bridge to the future, enabling new ways of working, new ways of interacting and essentially, new ways of living.

Modern wars have been a great contributor for scientific breakthroughs and large technological development, however, nowadays the industry plays a leading role in what concerns research and development of new tools to achieve better processes and better-quality products to the final client, not forgetting higher profit margins. In this context the term Industry 4.0 emerge.

Industry 4.0 is the first ever industrial revolution that is predicted a priori, as said in [2], once it was created by an association of representatives from politics, business and academia, who expect that this idea can deliver great improvements in the industrial processes, enabled by the communication between people, machines and resources. Obviously, this leads to the manufacturing of smart products which individually know what its characteristics are, the current state, the final state and the production processes needed to get there.

With the increasing numbers of devices connected to the internet, the amount of data packages that are sent at every second is constantly growing, leading to an understandable closing: the congestion of networks [3].

The general challenge addressed to this work aims to achieve a solution to fight the network congestion that is coming by finding innovative ways for "smart things" to communicate that are based on small, low-power, low-cost satellites, taking the IoT to the IoS –The Internet of Space.

The satellite industry is always associated with relatively low-data rate communications and extremely high costs. These excessive costs are related to the specific materials that should be used to withstand harsh weather conditions felt on space, but also highly because of deployment costs. However, the satellite technology has evolved in such a way that dozens of "Toaster-sized" micro-satellites can be launched at a time, greatly reducing the deployment costs.

Besides the smaller appearance, micro-satellites can have better performances in comparison with older and bigger ones, because they orbit at LEO, Low Earth Orbit. The fact that those satellites are orbiting the earth at much lower altitude, the network latency is significantly reduced, the terrestrial devices can be simpler and less expensive and continue to have the ability to communicate with the satellite. While everything seems to be advantages, some technical challenges appear to difficult things, issues as tracking, synchronization and handoff are important to overcome in order to keep those networks working.

The idea of having satellite systems that are much smaller, cheaper and simpler, but also have better performances, exponentially increase the potential of IoT to become more and more global, by giving it even more applications, accessible all around the world, even on remote places.

To provide an overview of all the work that has already been made on behalf of the theme of IoS, the second chapter of this work exhibit the state of art, contemplating some of the projects that are already deployed and their functionalities.

1.1 High Altitude Platforms

Internet of Space does not only depend on satellites, other infrastructures normally placed at stratosphere play an important role for the diffusion of IoS, the so called High Altitude Platforms (HAPs), are going to be explained along this subsection.

High Altitude Platforms (HAPs) consists on the utilization of Manned or Unmanned airships or aircrafts, which operate at 17km to 21km of altitude [4] with the main purpose of working as a telecommunication platform for several applications. There are some locations where the construction of a telecommunications infrastructure are simply unaffordable such as remote and oceanic regions. The fact that HAPs can stay almost stationary at the upper atmosphere makes them a very attractive device to be utilized to provide all kind of telecommunications services [5].

The chosen working altitude has to do with the fact that the typical wind speed is low at those heights, depending on location, as shown in Fig. 1.1, and of course because it as to be above of aviation airline. Moreover, at those altitudes the signal delay is much lower when compared with the signal delay a satellite would have.

Other aspect that is crucial for the continuous development of HAPs is the fact that they can land for maintenance, refuelling or upgrade, being sent to the stratosphere again.

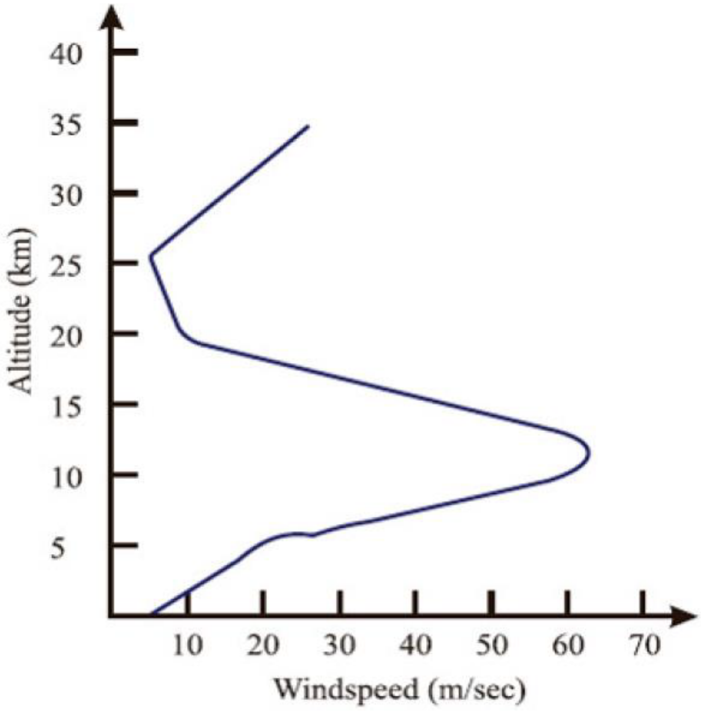


Figure 1.1: Wind speed in the stratosphere, image from [5].

When it comes to categorize HAPs, there are three main groups. The categories are made depending on characteristics like the way they are managed and maintained, also their platform structure and if they are manned or not is very important.

Table 1.1 shows a comparison summary of the three types of HAPs.

	Airships (Unmanned)	**Solar-powered unmanned aircraft**	**Manned aircraft**
Size	Length 150 ∼ 200 m	Wingspan 35 ∼ 70 m	Length 30 m
Total weight	? 30 ton	? 1 ton	? 2.5 ton
Power source	Solar cells (+fuel cells)	Solar cells (+ fuel cells)	Fossil fuel
Flight duration	Up to 5 years	Unspecified (? 6 month)	4 - 8 hours
Position keeping (Radius)	Within 1km cube	1 - 3 km	? 4 km
Mission payload	1000 ∼ 2000 kg	50 ∼ 300 kg	Up to 2000 kg
Power for mission	? 10 kW	? 3 kW	? 40 kW
Example	Japan, Korea, China, ATG,	Helios, Pathfinder Plus	Hallo, M55

Table 1.1: HAPs comparison, table from [5].

1.1.1 Applications

Due to its high versatility, HAPs have a wide range of applications that goes from telecommunications, to agriculture fields monitoring, traffic monitoring and control, weather services, earth observation, remote sensing and, one of the most important nowadays, emergency response. Some of those applications are explained in the next paragraphs.

- **Emergency response**:

  The easy and rapid deployment of HAPs can make a huge difference in disaster regions. Both in natural or human-induced disasters, having a HAP working as an airborne base station, which covers a wide area, can restore almost immediately the communications (cellular or internet services) being also immune to other disasters that can occur like floods and earthquakes.

- **Telecommunications**:

  Telecommunications are one of the most important applications for HAPs because they can provide all kinds of services such as fixed, broadband wireless applications for integration with 3G/4G mobile systems, also multicast/broadcast services can be provided.

- **Military communications**:

  Like in an emergency response case the fact that they can be rapidly deployed can benefit military communications as this can act like nodes within existing military wireless networks or as surrogate satellites. They can also contribute in battle fields with sensor surveillance and ground targets acquisition.

1.1.2 Benefits

As seen previously, HAPs have lots of applications due to their versatility, as so, they also have lots of benefits like the ones listed next:

- **Low cost**:

  Satellite and HAP communications are look alike, however, the cost that one and other have are extremely different. With that said, the implementation of a small cluster of HAPs is typically not so expensive than the launch of a geostationary satellite, a constellation of low earth orbit satellites and it is even less expensive than the implementation of a terrestrial network with several base stations.

- **Large area coverage**:

  Compared with terrestrial systems, it has a large coverage area and experience small rain attenuation when talking about the same distance. Compared with satellites, it covers a small area, however, it can be seen as an advantage depending on the application, for instance, monitoring a field it's easier when the area is smaller.

- **Rapid deployment**:

  A satellite project can take 4 or more years since the initial procurement until the day they are launched and start their mission. On the other side, with prepared HAPs, one is capable of launching within a matter of days or even hours. That's why their rapid deployment fit so well in disaster situations and military missions.

- **Easy upgrading**:

  Although some HAPs can have flight missions for 5 years, they can easily be brought down. That is a huge advantage for this kind of technology because not only the platform but also the payload can be upgraded and restored in case of problems, keeping them alive and doing more than one mission, that can be completely different from the previous.

Table 1.2 extracted from [6], pretends to establish a comparison between terrestrial system, HAPs and satellite systems.

	Terrestrial	**HAP**	**GEO Satellite**
Station coverage (typical diameter)	<1 km	Up to 200 km	Up to global
Cell size (diameter)	0.1 - 1 km	1 - 10 km	400 km minimum
Total service area Maximum transmission rate per user	Spot service 155Mbit/s ATM	National/regional 25-155Mbit/s ATM	quasi-global 155Mbit/s ATM
System deploymet	several base stations before use	flexible	flexible,but long lead time
Estimated cost of infrastructure	varies	$50million upwards	>$200million
In-service date	2000	2004-2008?	1998

Table 1.2: Comparison between terrestrial, HAPs and satellite systems, table from [6].

1.1.3 HAPs VS Satellite

Despite all the benefits that HAPs can bring to the telecommunication's world, satellites are still very important, so, instead of a fight between the two different technologies, this section is about the advantages of using HAPs as a substitute and as a complement to satellites.

To better understand how HAPs can substitute satellites, it is important to know that transmission via satellites has two big limitations. The first one is related to the channel nature, the congestion of the frequency spectrum is forcing the use of higher frequencies in the K (20-30GHz), V (45-75GHz) and even on W (75-95GHz) band. The transmission at those high frequencies suffers from heavy attenuation due to the rain and atmosphere. Logically, the signal is degraded and packed with errors. The other main limitation is due to the distance. Geostationary satellites operate at high altitudes which implies signal degradation with the distance, the need of great diameter dish antennas and high round trip delay [7].

The simple fact of being closer to the ground, makes HAPs have a much better channel conditions than satellites, a line of sight condition available in almost all the coverage area.

On the other side, HAPs and satellites can work together to obtain better communication systems so, there are many advantages in using them as complement to satellite systems.

While satellites can be used to reach more remote sites, HAPs can be used to reach more local sites.

If there were an agreement between neighbouring countries that have adjacent coverage areas, those can be interconnected through this kind of platforms. For last it is even possible to use HAPs to down-convert signals from satellites, so highly-shadowed areas can be better reached.

Fig. 1.2 shows a collaborating network between satellites and HAPs [8].

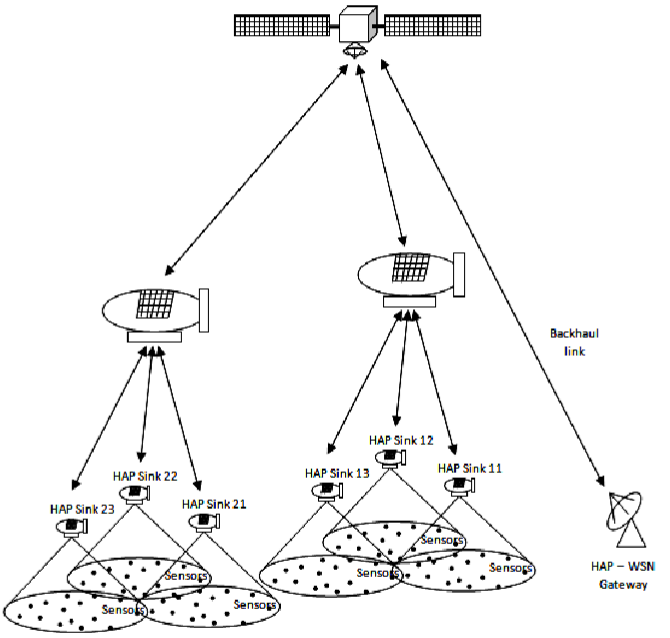


Figure 1.2: Satellite/HAP network, image from [8].

1.2 Communication types on the IoT Universe

As explained in the previous sections, there are plenty of infrastructures already built and some others adapting to the IoT and IoS era. Besides the existent physical support, IoT demands for secure and robust communication protocols, that can help the technology reach even more people.

This section aims to provide an overview and some knowledge about the wide universe of communication protocols that exists regarding IoT and IoS.

1.2.1 ZigBee

As said in [9], "ZigBee is an IEEE 802.15.4 standard for data communications with business and consumer devices". Operating on top of the MAC and Physical layers of IEEE 802.15.4 wireless standard, ZigBee can provide network, security and application support services.

ZigBee works on ISM frequency bands, being 2.4Ghz the most common one.

One of the main characteristics of this technology is the will to have the maximum number of low-consumption devices powered by life lasting batteries, allied to a suite of technologies that can enable scalable and self-organizing networks with different data traffic patterns.

The low-cost associated to this technology allows it to be easily spread for monitoring and control applications, creating mesh networks, providing high reliability and larger range.

ZigBee is one of the best technologies when talking about Wireless Sensor Networks (WSN), not only because of reduced costs and power consumption, but also because of its capabilities to enhance data rate and large distance coverage, being able to support around 150 devices on a single network [10].

ZigBee supports a large variety of networks, but the most commonly used is the mesh topology not only because it gives the ability to any source to communicate with any device, but also because it makes easier to add or remove devices, eliminates dead zones and enhances range.

Fig. 1.3, illustrates a ZigBee mesh topology.

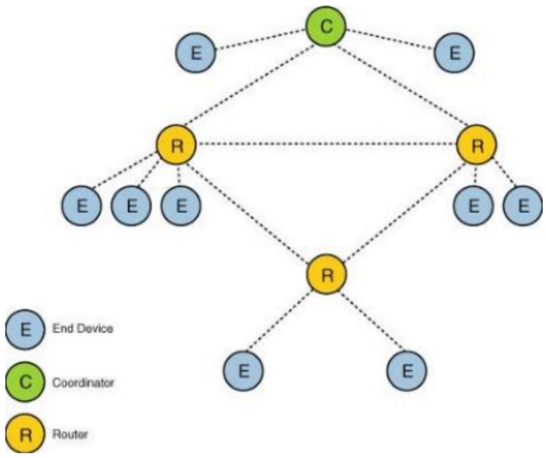


Figure 1.3: ZigBee mesh topology, image from [10]

ZigBee networks are composed by three main devices:

- **Application devices**: responsible for data acquisition and consequent dispatch to the network co-ordinator.
- **Logical devices**: co-ordinator, router and end devices.
  1. Co-ordinator: network manager, responsible for network security and can be the bridge to other networks;
  2. Router: responsible for the links router–coordinator and router–end device;
  3. End devices: responsible for collecting all the network information.
- **Physical device**: it can be a Full Function Device (FFD) or a Reduced Function Device (RDF). A FFD is capable of being any type of the three logical devices while an RFD can basically be a sensor or an end device.

  Like in an emergency response case the fact that they can be rapidly deployed can benefit military communications as this can act like nodes within existing military wireless networks or as surrogate satellites. They can also contribute in battle fields with sensor surveillance and ground targets acquisition.

Relatively to applications, ZigBee is used in home WSNs but it is also very common in "smart" industries, contributing widely to the *Industry 4.0*.

1.2.2 Ant

Ant is a proprietary technology developed by a Canadian company called Dynastream Innovations Inc. This technology works on the same 2.4Ghz ISM band but, it is designed to short-range WSN and represents an ultra-low-power technology. Regardless of its capabilities to adapt to every application used with ZigBee, the actual applications are more related to the implementation of fitness personal-area networks and health monitoring [11].

The ANT protocol uses a time-division-multiplex technique which permits the use of a single 1Mhz channel for multiple nodes, the ones that can be used as master or slave and as simple repeater.

This technology supports data rate of 1MBP/s, but the actual throughput is usually 20kbp/s and transmits using Gaussian Frequency Shift Keying (GFSK) modulation [12].

1.2.3 BLE

As seen before, the 2.4Ghz ISM band is full of all kinds of wireless communication devices, Bluetooth Low Energy, BLE, is no exception.

Being very similar to ANT, BLE is also a short-range low-power communication protocol that follows specifications of Bluetooth SIG –Special Interest Group.

This technology can support two types of networks [13]:

- **Point to Point**: used between two BLE devices, one acting as a master, the other as a slave;

- **Star topology**: used when there are multiple BLE nodes but, only one acts as master functioning as central network node.

As another user of the ISM band, the BLE communication protocol uses a simple technique to avoid interferences with all the other protocols in the same band. Besides the frequency hopping with 2 Mhz channels, the technology falls under spread-spectrum radio regulations, being able to transmit on fewer frequencies, differently from the FHSS (Frequency Hopping Spread Spectrum). In real world, this translates by the ability of having 40 channels, three for advertising and the other to exchange data. The first three channels, are allocated in different frequency space from 802.11 in order to avoid interference [14].

Figure 1.4 illustrates the exchange of messages between two BLE devices.

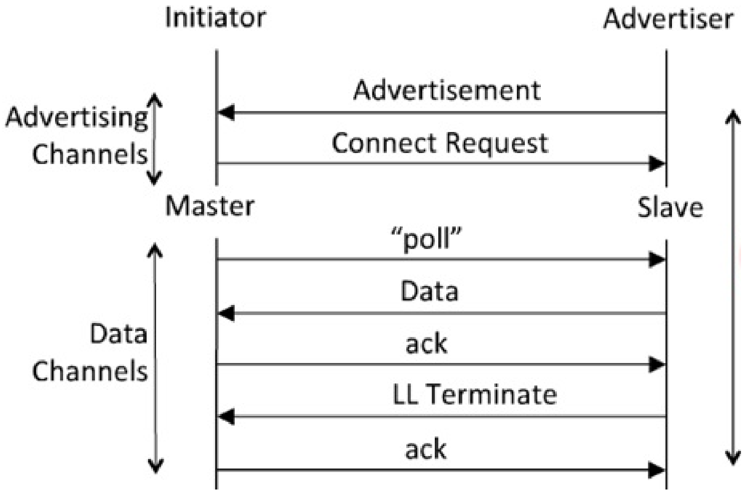


Figure 1.4: BLE protocol, image from [13].

Bluetooth Low Energy, also called Bluetooth Smart, can be applied to a large variety of applications because of its low latency and small packets[E]. Because of the ability of avoiding interference in such a crowded band, BLE is highly used in medical applications, being a secure protocol to attach to a medical vital measurement device, directly connected to a care giver [15].

1.2.4 SigFox

SigFox is the first LPWAN (Low-Power Wide Area Network) technology designed for the IoT market [16] and it is also the name of the French company that owns the technology itself.

SigFox is also emerging as one of the leaders in LTNs (Low Throughput Networks) being the main characteristics the low cost, low power consumption, long range and the Ultra Narrow Band (UNB) transmissions. the signals to be transmitted only have 100Hz of bandwidth, which is the main reason for the ability of the protocol successfully demodulate an extremely low received power signal of –142 dBm [17]. Fig 1.5 illustrates the UNB protocol used.

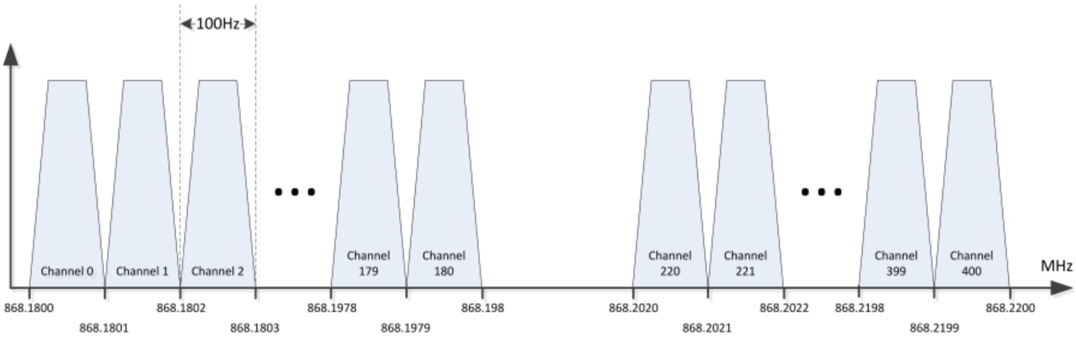


Figure 1.5: SigFox UNB protocol, image from [17].

Contrarily to the tendency of the 2.4Ghz, SigFox uses the 868Mhz ISM band which allows it to be used world wide without having to by a frequency band in every country and also long range transmissions of about 30 to 50 km in rural areas and 3 to 10 km in urban ones. In fact, [18] says that 1 to 3 fixed basic antennas are enough to cover $1000m^2$.

As a proprietary technology, there is not too much information about the protocol on the internet, although it is known that by default, every transmission is done three times, which has two main purposes:

1. As there is no acknowledge by the gateway, retransmission is a simple way to assure that the payload will reach the base station;

2. Each one of the packages are broadcasted in different frequencies, which leads to both management in time and frequency, decreasing the fading effects.

Other important aspect of the Sigfox protocol is that the nodes transmit on a random frequency within the boundaries of the channel and the base station is continuously analysing the spectrum, using signal processing algorithms to retrieve the messages. This channel accessing scheme is called Random Frequency Division Multiple Access, R-FDMA. From the usage of this scheme, results the ability to buy cheaper components, which is one of the primary objectives of IoT.

1.2.5 LoRa and LoRaWAN

This section main objective it to clarify and distinguish between two concepts that are very often confused, those are LoRa and LoRaWAN.

- **LoRa**: The Physical layer (PHY) that uses Chirp Spread Spectrum (CSS) radio modulation technique [19].

- **LoRaWAN**: The network protocol, also known as the MAC layer.

These two concepts are of extreme importance in this work context, thus an overview on both will be presented next, in order to give a better understanding of the work implemented.

LoRa

The main references to this section are Semtech's LoRa Modulation Basics [20] and a thesis by Angel Guzman-Martinez [21], every other article used is pointily referred as well.

LoRa is a Semtech proprietary Spread Spectrum modulation scheme that has its roots on Chirp Spread Spectrum modulation (CSS). One of the key factors of this modulation technique is the ability to do a trade off between data rate and sensitivity under a fixed channel bandwidth.

These characteristics comes from the utilization of orthogonal spreading factors with variable data rate, increasing LoRa robustness against interferences and giving the ability of having very low minimum Signal-to-Noise ratio (SNR) on the receiver side.

The ability of modulating different chirp rates, allows LoRa to decode many signals at the same time [22].

Spread Spectrum

To better understand the modulation technique used by Semtech's LoRa, a brief explanation of the basic principles of spread spectrum is given on this section.

In the most traditional spread spectrum technique, known as Direct Sequence Spread Spectrum (DSSS), the carrier phase of the transmitter changes accordingly to a code sequence.

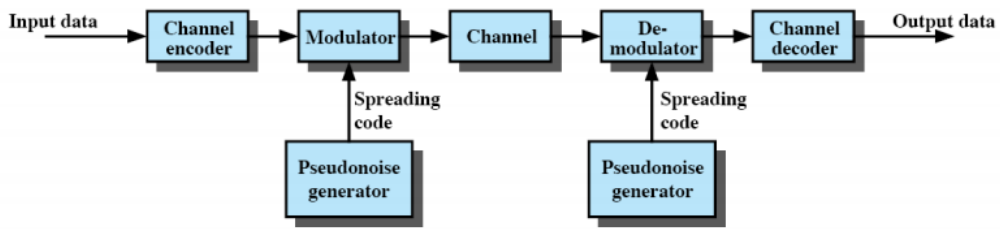


Figure 1.6: Spread spectrum communication protocol.

As shown in Fig. 1.6, one can achieve this result multiplying the wanted data by means of a pseudo–noise generator, the spreading code or chip sequence. In this process, the signal bandwidth is spread beyond the original signal bandwidth because it occurs at a much faster rate than the data signal.

To recover the data signal, the receiver has a replica of the chip sequence that is used to re-multiply with the signal received. In this process the spread signal is compressed and comes back to the original bandwidth.

As IoT devices are normally very power restricted, being the majority battery-powered devices, this technique is not the most adequate because the longer the spreading code, the longer the time that is needed for the receiver to perform a correlation, thus, more power is wasted on the communications. Besides that, the low-cost needed for the IoT nodes becomes a problem because this modulation scheme requires a very accurate and expensive clock source.

LoRa Spread Spectrum

LoRa modulation is based on Chirp spread spectrum, which consists on frequency chirps with linear frequency variation over the time in order to encode information. Because of the linearity present in this technique, the frequencies and timing offsets between transmitter and receiver are equivalent, thus, easily eliminated in the decoder. The chirp's frequency bandwidth is equivalent to the spectral bandwidth of the signal.

Besides the fact that linearity present on this technique makes the modulation less sensitive to Doppler effect, which is equivalent to a frequency offset, it also contributes a lot to the reduced price of the LoRa radios, once it does not need extremely accurate clock sources.

To establish a link with LoRa modulation, a chirp that varies in frequency is sent several times without any data modulated onto it, this synchronization mechanism is called preamble.

One important thing that is also attached to the preamble is the inverse chirp, that solves the Doppler effect and is used by the receiver to demodulate the signal.

After the synchronization process, the chirp signal continues to be used, this time to modulate the data, by shifting the phase of the chirp, as shown on Fig. 1.7.

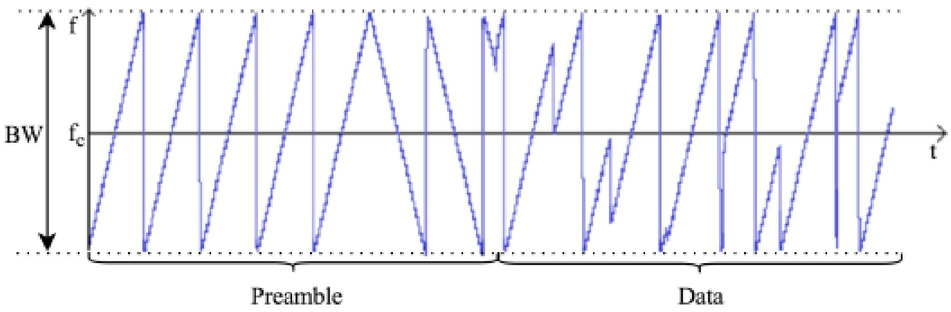


Figure 1.7: LoRa modulation, image from [19].

Fig. 1.8 illustrates the Semtech LoRa preamble.

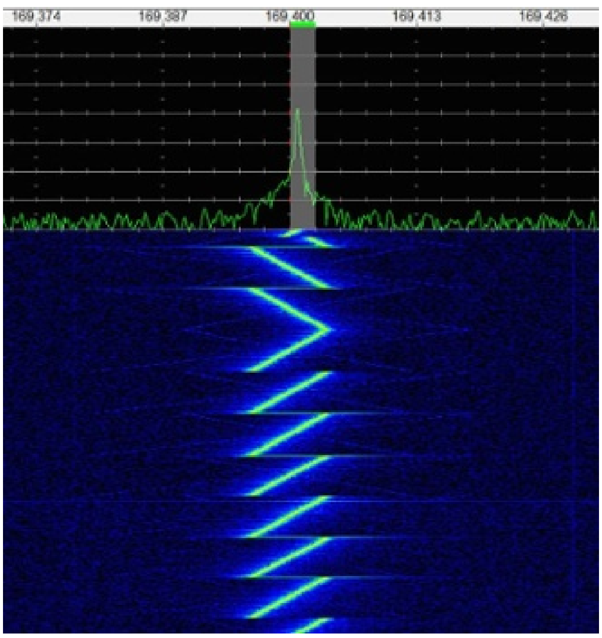


Figure 1.8: SemTech LoRa preamble, image from [23].

As said in the beginning of this section, with LoRa modulation it is possible to adapt the data rate of the transmission depending on what is needed due to the orthogonal spread spectrum factors provided by this modulation. Equation 1.1 defines the relation between the bitrate, spreading factor and bandwidth:

$$R_b = SF * \frac{1}{\frac{2^{SF}}{BW}} bits/sec \tag{1.1}$$

Where:

- $\mathbf{R}_b$: bitrate
- **SF**: spreading factor (7 to 12)
- **BW**: modulation bandwidth (Hz)

Table 1.3 shows the relation between the spreading factors and the bit rate for a 125kHz bandwidth.

Spreading factor	Symbols/second	SNR limit [dB]	Time-on-air for 10 byte packet [ms]	Bitrate [bps]
7	976	-7.5	56	5469
8	488	-10	103	3125
9	244	-12.5	205	1758
10	122	-15	371	977
11	61	-17.5	741	537
12	30	-20	1483	293

Table 1.3: Relation between spreading factors and bit rate @125kHz, table from [24].

As can be easily seen by the results on table 1, a higher spreading factor increases the robustness of the signal, lowering the bitrate. However, a higher spreading factor forces to a longer airtime for the signal, that can be seen in equation 1.2, that gives the symbol period:

$$T_s = \frac{2^{SF}}{BW} sec \tag{1.2}$$

The usage of orthogonal spreading factors gives LoRa modulation another advantage. As long as the spreading factors were different, they do not interfere with each other, which gives the opportunity to transmit several signals over the same frequency range as long as the spreading factor is different.

Adaptive Data Rate

Adaptive Data Rate, ADR, is based on Semtech's algorithm for simple data rate adaptation and is the mechanism used by LoRa to optimize data rate, airtime and energy consumption in the network [25].

This mechanism allows the network server to store the maximum SNR for each received message of one particular node. After the acquisition of twenty messages, the SNR margin is computed, according to equation 1.3:

$$SNR_{margin} = SNR_{message} - SNR_{required}(DR) - dB_{margin} \tag{1.3}$$

Table 1.3 shows the required values for each SF while the dB margin is equal to 10dB by default.

For instance, if a node sends a message with SF12 and SNR of 5, it has a margin of 25dB, reducing the SF to 7, the margin would still be 12.5dB, although, the airtime would reduce significantly and it would be a lot more energy efficient.

Data rate and transmitted power can increase or decrease based on the calculated SNR margin. That way, power consumption can be saved and less interferences are caused.

To note that ADR can only be activated when the node is fixed to a position, however, if a mobile node has the ability to notice when it is stationary for a while, it can also activate the ADR mechanism.

Link budget

In order to calculate the link budget of any wireless system, all the gains and losses from the transmitter to the receiver as well as the propagation channel are taken into account. As so, equation 1.4 express the link budget of a wireless system/network:

$$P_{rx}(dBm) = P_{tx}(dBm) + G_{system}(dB) - L_{system}(dB) - l_{channel}(dB) - M(dB) \quad (1.4)$$

Where:

- P_{rx}: the expected power incident at the receiver
- P_{tx}: the transmitted power
- G_{system}: system gains such as those associated with directional antennas, etc.
- L_{System}: losses associated with the system such as feed-lines, antennas (in the case of electrical short antennas associated with many remote devices), etc.
- $l_{channel}$: losses due to the propagation channel, either calculated via a wide range of channel models or from empirical data
- M: fading margin, again either calculated or from empirical data

However, due to LoRa's robustness against interference, the main limiting factor when talking about link budget is the SNR instead of the signal-to-interference ratio, SIR. As so, to have an example of a LoRa link budget, one can take the equation 1.5 into consideration:

$$PathLoss_{max}(dB) = Power_{tx}(dB) - Sensitivity_{rx}(dB) \quad (1.5)$$

Where:

- $PathLoss_{max}$: maximum path loss allowed by the receive
- $Power_{tx}$: Power transmited
- $Sensitivity_{rx}$: sensitivity of the receiver.

To obtain the sensitivy of the receiver, which is the minimum signal power needed in order to demodulate, equation 1.6 specifies:

$$Sensitivity(dBm) = -174 + 10log_{10}(BW) + NF + SNR \quad (1.6)$$

Where:

- -174: Boltzman constant @ 290K.
- NF: receiver noise figure (dB).
- SNR: minimum Signal–to–Noise ratio allowed by the receiver.

Converting those variables on equation 1.6 to realistic values and applying equation 1.6 and 1.5, considering the antennas gain equal to 0 dB, the results are as follows:

- Power Transmitted = 14dBm
- SNR = –20
- NF = 6dB
- Bandwidth = 125kHz

$$Sensitivity = -137dBm \quad (1.7)$$

$$PathLoss_{max} = 14 + 137 = 151dB \quad (1.8)$$

Relating the results achieved in the example with table 4 present on the Semtech's SX1272 transceiver [26], one can see that the sensitivity result in the example can be obtained in real world with LoRa spreading factor 12.

Mode	**Equivalent bit rate (kb/s)**	**Sensitivity (dBm)**
SF = 12	0.293	-137
SF = 11	0.537	-134.5
SF = 10	0.976	-132
SF = 9	1757	-129
SF = 8	3125	-126
SF = 7	5468	-123

Table 1.4: Bit rate and sensitivity according to SF, table from [20]

Taking this results into account and applying the free path loss formula present on equation 1.9:

$$FSPL(dB) = 20log_{10}(d) + 20log_{10}(f) + 32.44 \quad (1.9)$$

Where:

- d: distance between receiver and transmitter (km)

- f: signal frequency (MHz)

Applying equation 1.9 with the results obtained on equation 1.8, at a frequency of 868 MHz, the distance obtained is:

$$d = 976Km \tag{1.10}$$

This example shows how powerful LoRa is and why it is suitable for low-power, low-cost and long-range networks. Even more important in the context of this work, this results can show the capabilities of LoRa when talking about Internet of Space using HAPs or even micro satellites on LEO (Low Earth Orbit, from 200 to 1200Km [27]).

LoRaWAN

Even though LoRa physical layer is proprietary, the MAC layer designated by LoRaWAN is open being defined and maintained under a group known as LoRa Alliance [22].

According to the LoRa Alliance specifications, it operates at the ISM frequency band, which means 868Mhz for Europe and 915Mhz for United States. Once it works on the ISM band, devices should respect some rules relative to duty cycle and Effective Radiated Power (ERP). In Europe, those rules are as it follows:

- (867-868.6 MHz), (869.7 - 870 MHz): OAT with 1%duty cycle which amounts to 36 seconds per hour and an ERP cap of 14dBm.

- (868.7 - 869.2 MHz): OAT with 0.1%duty cycle which amounts to 3.6 seconds per hour and an ERP cap of 14dBm (LoRa).

- (869.4-869.65 MHz): OAT with 10%duty cycle which amounts to 360 seconds per hour and an ERP cap of 27dBm.

LoRaWAN is a Low Power Wide Area Network (LPWAN) which is mainly composed by battery powered devices being the star network topology the most used, as can be seen in Fig. 1.9 [24].

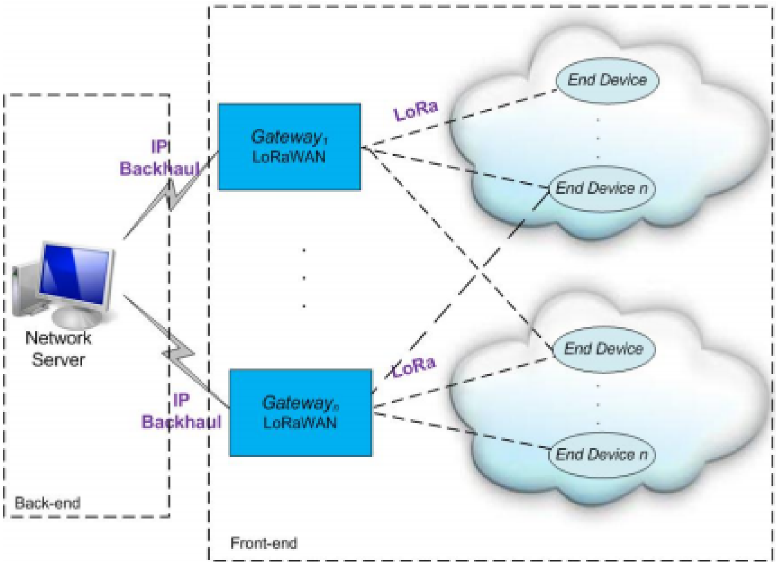


Figure 1.9: LoRaWAN architecture, image from [24].

The same Fig. 1.9 can also illustrate the separation of the architecture in two: front-end and back-end.

- **Front-end**: The communication established between the end-devices and the gateways through LoRa modulation protocol.
- **Back-end**: The network server responsible for the storage of the information prevenient from the network sensors (End-devices).

The link between the two ends is made by the gateways, acting as a bridge that receives LoRa packages and the sends it to the network server through an IP connection.

Fig. 1.10 shows the LoRaWAN topology, by LoRa Alliance.

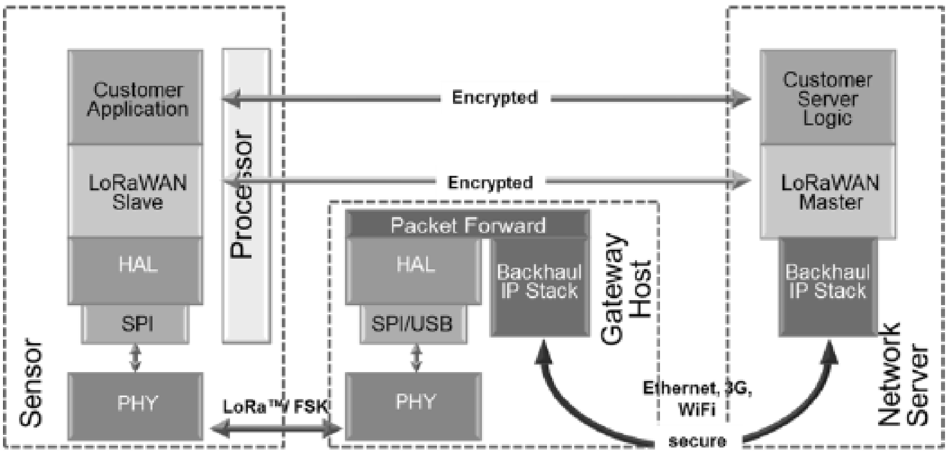


Figure 1.10: LoRaWAN topology, image from [21].

Transfer rates from 0.3kbps and 5kbps can be achieved with LoRaWAN. This transfer rates are managed through an Adaptive Data Rate (ADR) mechanism present on the nodes, as well as RF power transmission in order to extend their battery lives.

LoRaWAN end-devices can be from three different classes:

- **Class A**: Bi-directional end-devices;
- **Class B**: Bi-directional end-devices with scheduled receive slots;
- **Class C**: Bi-directional end-devices with maximal receive slots.

Fig. 1.11 illustrates the different LoRaWAN classes into the network layers.

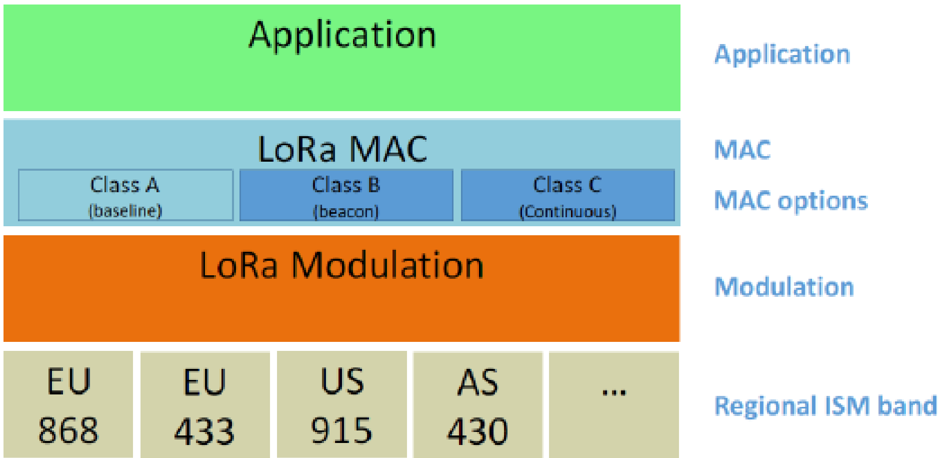


Figure 1.11: loRaWAN network layers [21].

To conclude the LoRaWAN analysis, the advantages of the usage of this kind of technology in LPWANs are presented.

1. ISM frequency band
2. Scalable
3. Bi-directional communication
4. High level of security due to encryption
5. Low-power
6. Low-cost

1.2.6 Motivation

In an era of constant technological development and advance, where everyone wants to be in touch with each other, and monitor every little thing, wireless communications have probably the most important role in our personal as well as professional lives.

For a few years, short range communication such as WiFi have been in the top of communication usage and have proven its importance and reliability. However, with the increasing number of deployed IoT devices and the urge to be globally connected with a lot of cost and power constrains, long range communications were called to play and Long Range Personal Wide Area Networks (LRPWANs) are found extremely important.

With such a large number of network users, the commonly known terrestrial base station are becoming congested. Due to that, spatial communications are evolving and becoming to be seen with new communication capabilities, increasing the strength of the so called Internet of Space.

To help Internet of Space become an everyday issue for the global community, small things as producing networks of super low-power radio transceivers with amazing low sensitivities are of great importance nowadays and in the years to come.

1.2.7 Objectives

The main goal of this project is to prove that satellite communication oriented to the IoT can be delivered with low cost "micro satellites".

In order to achieve this goal, it is proposed to build a network of sub-Ghz radios where the concentrator of the network will be attached to a main frame capable of achieving an high altitude to test the capabilities of technologies like LoRa and LoRaWAN to be applied to the internet of space.

A list with specific objectives is presented next:

- Understand the panorama of IoT and IoS;
- Learn the different options for the deployment of "micro satellites";
- Build a LPWAN;
- Pack together the network Gateway and antenna to be deployed;
- Make measurements on the distance achieved and the number of nodes reached.

With complete understanding of all the themes involved and with the tests realized, it is expected to generate valuable considerations about development of reliable low cost "micro satellites".

Chapter 2

State of Art

2.1 Internet of Space

The so called Internet of Things (IoT) is becoming more and more a normal thing in everyone's daily lives. The desire of connecting everyday objects to the internet and to each other, to interact with other users and machines is no longer a dream but a reality.

The number of applications that IoT can provide is endless. It can be in wearables, cars, highways, smart homes, smart cities, smart workspaces and one of the most important, the emergency systems. Once it has such a large amount of uses, it seems logic that the number of users will also be astronomical, because of that, it is estimated that this technology will connect 50 billion of devices using the internet around 2020 [28].

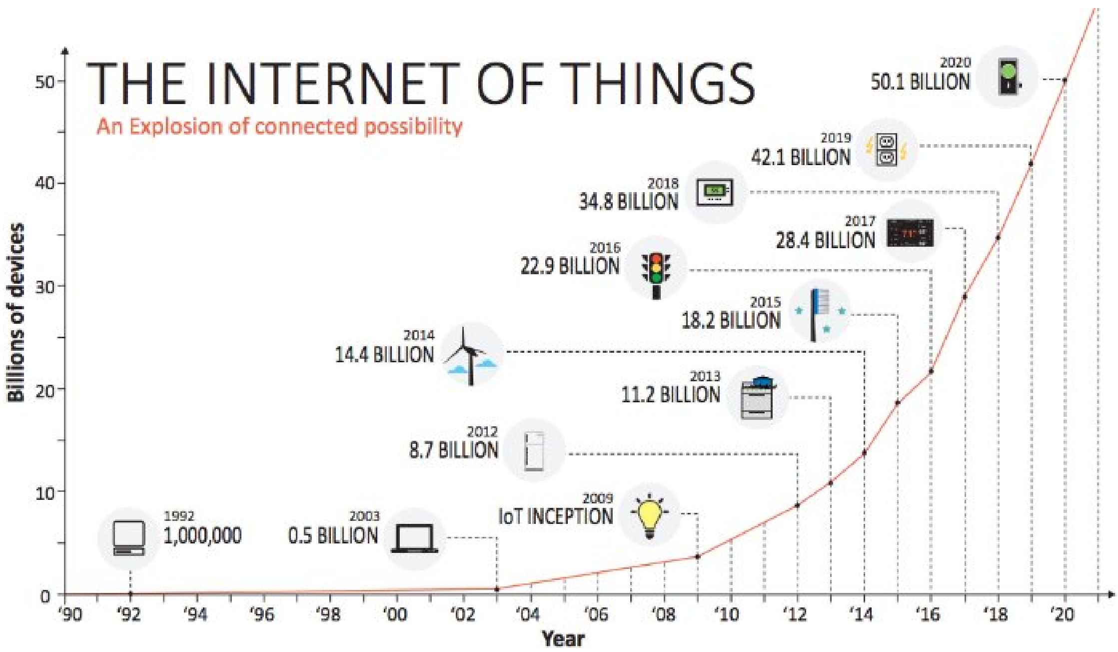


Figure 2.1: IoT device evolution, image from [29].

As the IoT devices continues to increase and evolve, all that concerns communications go in the same direction, which leads to higher data rate communications and data services. Thus, it becomes easy to understand that in order to IoT succeed, scalable and robust communications systems are essential [30]. Currently, the IoT devices typically use the already existing wired and wireless network infrastructures, however, because of all the reasons said before, those existing networks will become increasingly congested, mainly in the underserved regions of the globe.

To fight this situation, the interest and investment in space has been increasing, leading the Internet of Things to the Internet of Space.

The major problem of the current networks is the host-centric model that is used and does not match the principal objective, which is the exchange of information and service access, independent of its root. However, the satellite networks can counter those situations because of their broadcasting support and wide-area coverage, allowing underserved regions to get a better coverage and that way supporting IoT over satellite [31].

These type of networks will have an huge impact on humanity, because the 2016 report of the International Telecommunication Union said that 53%of the world population was not using the internet –3.9 billion people. Which leads to the question, "quality of life for the selected few, or for all mankind?".

Some years ago, launching a satellite had a super high cost associated and the data rate values were low, however, the time has changed and dozens of micro-satellites (also called "toaster-sized" satellites) can be launched at a time to a low earth orbit (LEO), reducing not only the costs, but also the communication latency since it is much closer to the ground stations [32]. It will also introduce some engineering challenges, as handoff issues, synchronization and tracking.

To note that these networks will not replace the terrestrial ones but work alongside with them, providing a global connectivity.

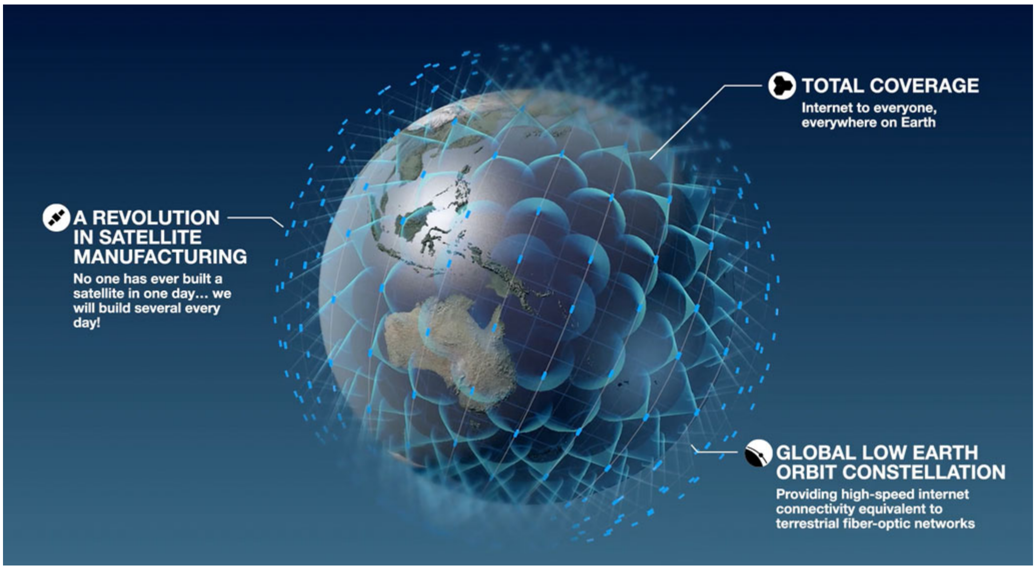


Figure 2.2: One Web satellite constellation prototype, image from [33].

From an industrial point of view, Internet of Space represents a fantastic opportunity for the satellite and communication market. With the consistent growing need of global business and governments to monitor and exercise control over geographically dispersed areas and assets, this market is expected to reach 1.7 billion dollars by 2017 [34].

Due to the obvious reasons said in the previous paragraph, big companies like Facebook or Google have already started their own projects, taking different paths, but aiming to the same goal, grant internet access to the 2/3 of the population that is deprived of it.

The so called Project Loon (started by Google X) consists on a network of high-altitude balloons, launched from the ground directly to altitudes between 18 and 23 km, right in the stratosphere [35]. A single balloon can navigate up to 100 days using only the wind, covering $5000km^2$ and powered exclusively by renewable energy.

The balloon receives a wireless internet signal from the nearest telecommunication ground station, is relayed across the balloon network and then sent back down to people in remote areas.

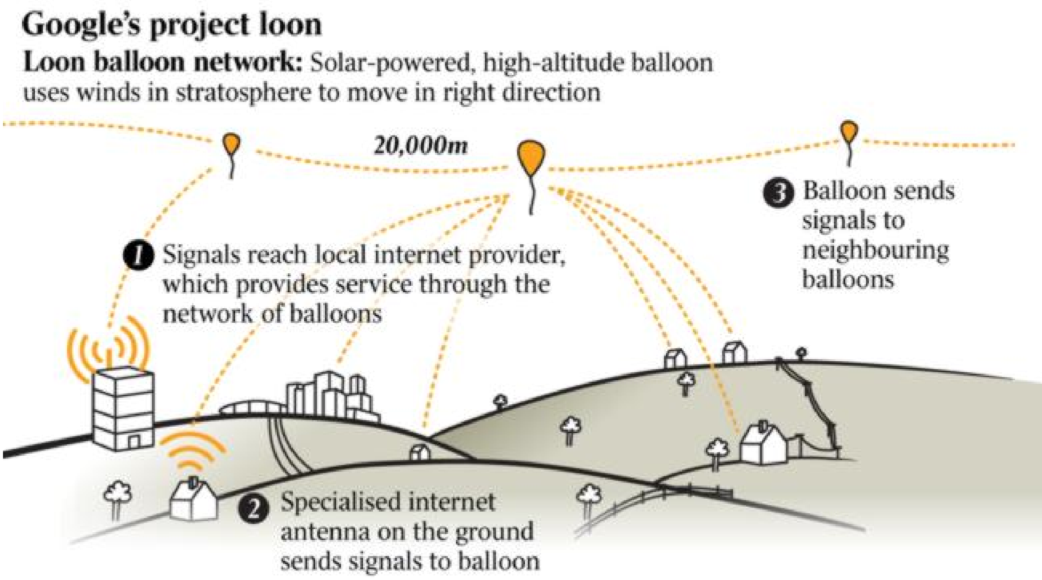


Figure 2.3: Project Loon explanation, image from [35].

On the other hand, the Facebook's project called Aquila tries to achieve the same goal as Loon, but instead of balloons it uses a fixed-wing high-altitude long-endurance unmanned aircraft. This aircraft flies at 18 to 28km and provides coverage to approximately $2830km^2$.

Figure 2.4: Facebook's UAV - Aquila, image from [36].

2.1.1 Different approaches to satellite communication

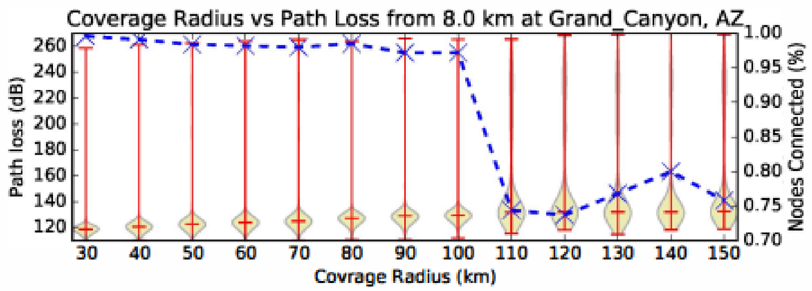
It is fact that only three GEO satellites are needed to cover almost the whole world, however, such a long distance implies significant free path loss [37]. Among the large variety of uses that IoT has, some of them require almost real time data transfer, which is impossible using GEO.

Besides from Zigbee, IEEE 802.15.4 or Bluetooth, which the maximum range was typically less than 100 meters, cellular networks seemed to be the a good option, yet, that solution is expensive and power hungry, because those networks were not designed to support IoT devices. Because of this, new low-cost low-power long-range technologies have been developed, like LoRa, which claim 5 to 15km range on earth, considering all the multiple reflections and every other real world RF communication problem.

As saw in Chapter 1, these devices have very high sensitivities, which leads to high link budgets, so, if these devices are used with line of sight, as long as the path loss is less than the link budget of the radio (LoRa device), a network connection is possible.

A study presented this year at the *First International Workshop on Mobile and Pervasive Internet of Things'17* has shown simulation results that prove that an area of 30km radius can be covered with those kinds of transmitters at an altitude of 8km [30].

If the height of the transmitter is increased, also the radius of the area it will cover will increase, and the study shows an approximately 95 per cent coverage for an area of 150km radius ($70000km^2$)at the same 8km to an area with adverse characteristics for communications such as the Grand Canyon in the USA.



(a) Path Loss and Connectivity.

(b) 50 km. (c) 100 km. (d) 150 km.

Figure 2.5: Comparison between the covered percentage and the simulation radius at Grand Canyon, USA. Results from [30].

The high sensitivity of LoRa devices enables their use for numerous applications not only on terrestrial LPWANs, but also in satellite communications, because, their link budget allows them to work at stratosphere altitudes (1). This can be a game changer in the satellite industry, providing even better conditions to IoT and IoS to succeed.

2.2 LoRa Gateways

As said in chapter 1, the main goal of this work is to prove that LoRaWAN can be suitable for LEO satellite communication. In order to achieve that, the network's "toaster size" satellite is the concentrator of the signals in the network, the **gateway**.

This section aims to present some of the most important commercial and custom-made gateways, as well as the antennas used for the communications.

2.2.1 Commercial Gateways

Nowadays, IoT and LoRa/LoRaWAN are becoming a familiar concept for engineers working with smart electronics, there are several commercial "plug and play" gateways, however, the prices between them varies a lot, mainly because of the range they can achieve.

When talking about industry standards, there are two main gateways: Kerlink LoRa IoT station [38] and MultiTech Conduit [39].

Although both are industry top choices, the achievable range differs a lot from one to another. Kerlink LoRa IoT station, which can be obtained by a price of 1500$, advertises around 9km of range, while MultiTech Conduit, provides 4km (less than half of the kerlink solution) for exchange of 500$.

Knowing that both gateways have the same hardware base, the SemTech base-band concentrator coupled with SemTech LoRa chips [22], and the two are based in Linux models, the main reason for such a range and cost difference stands in the components chosen and how the hardware is designed.

To note that compared with the theoretical results obtained in section 1, the presented ranges by industry Gateways are extremely lower, however, there is the need to consider that the environment where the gateways are mounted are normally extremely "anti-RF", promoting losses by multipath and fading.

One of the key factors to increase the gateway's range is the place where the antenna is installed,being preferred a high place, even in indoor cases, to reduce the losses phrased previously.

If one wants to have their own LoRa gateway, to start a small network or to increase the LoRaWAN coverage in the area, a "plug and play" and cheaper solution is also available. It is called The Thing Gateway [40]. For the price of 300$this device made by The Things Network (TTN), claims a network coverage up to 10km radius, being the perfect choice for LoRa enthusiasts.

Fig. 2.6 illustrates the hardware used on this board, which is again based on the SemTech's solutions, and runs open source software.

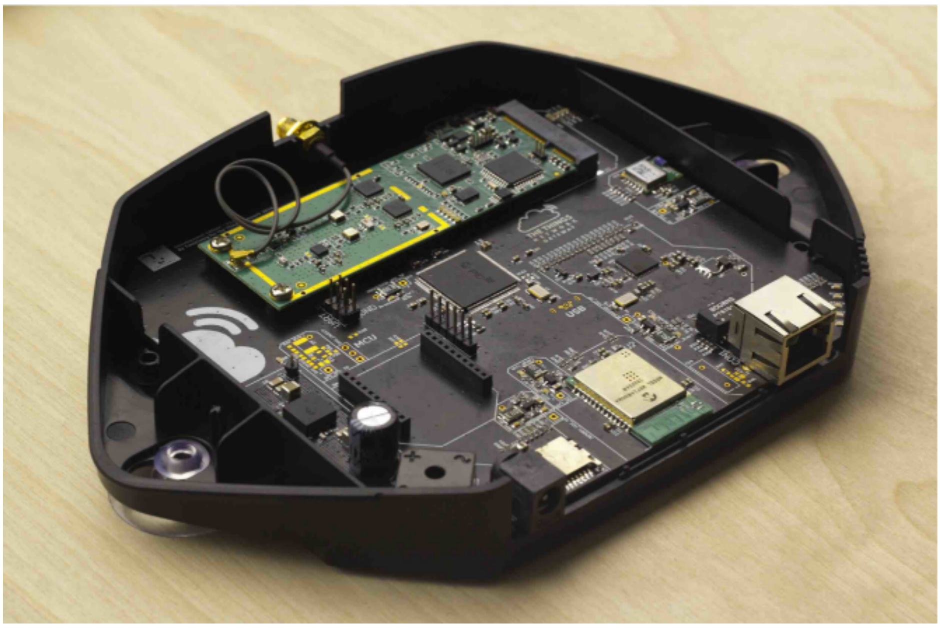


Figure 2.6: The Things Gateway, image from [41].

2.2.2 Custom Gateways

Despite the commercial gateways options, one of the purposes of this work is to better understand the functioning of LoRa and LoRaWAN. For that reason, the gateway used in this work's context is based on the iC880A-SPI - LoRaWAN Concentrator 868 MHz [42] and a Linux model.

Although the divice is simple and DIY (Do it Yourself), these gateways are extremely powerful once the LoRa concentrator is able to receive packets from different end-devices, with different spreading factors simultaneously on up to eight channels.

A detailed revision on all the distinct parts of the gateway device is provided on Chapter 3.

2.2.3 Antennas

All the fantastic characteristics provided by LoRa concentrators will value nothing if there were no antennas. As so, this section briefly describes some of the most used antennas for gateways.

One of the basics and most viewed antennas for LoRa gateways are the quarter wavelength monopoles, such as the one on Fig. 2.7 by IMST, which has about 2DBi of gain [43].

Figure 2.7: Quarter wave length monopole, image from [44].

In order to get better coverage results, outdoor antennas are the option. As so, there are plenty of different formats, which are going to be presented next.

Fig. 2.8 illustrates a quarter wavelength ground plane antenna, perfectly suited for outdoor applications, the normal quarter wave ground plane antenna consists on a vertical radiator which is insulated and centered between 4 horizontal surrounding radials which extend out from the base of the antenna. Each radial is evenly spaced (90 degrees apart from each other) around the vertical element[45]. This antennas have an omni-directional radiation pattern, and should be close to 3 dBi of gain.

Figure 2.8: quarter wavelength ground plane antenna, image from [46].

Other commonly used example, also for outdoor applications, is a dipole array, with omnidirectional radiation and 5 dBi of maximum gain.

Figure 2.9: Dipole array, image from [47].

The last two examples are great choices to external use with LoRa gateways that are going to be fixed somewhere. The fact that they are very easy to understand and implement, such antennas are accessible to anyone and can even be built at home, increasing considerably the network coverage of the gateway to be installed.

Again, as said in section 2.2.1, the height at which the antenna is mounted, directly influences the range that it can achieve. Other important fact that directly influences the range coverage is the environment where the gateway is placed, the same antenna will perform better in rural spaces than in urban spaces, as result of the many RF losses caused by buildings, cars, and lots of other infrastructures, there exist in a far higher number than in rural regions.

2.3 The Things Network

As already mentioned in section 2.2.1 of this chapter, TTN has a huge impact on the development of LoRaWAN, providing accessible products for everyone who wants to start a journey on smart "things".

Basically, The Things Network is a global, crowdsourced, open, free and decentralized internet of things network. Right now, using LoRaWAN technology, TTN is building a network for the internet of things, allowing LoRaWAN's end–devices to communicate with the internet, without the need of wifi or 3G.

One major key in the flourishing of TTN is that everyone can contribute to enlarge the coverage, by just building or buying a gateway and placing it in their houses.

Although TTN sells hardware products such as gateways and end devices, completely "plug and play", it also provides all the backend system. The backend system is responsible for routing the IoT broadcasted data between nodes and applications [48].

The used methods by the network will not be discussed here as it is not an important factor for this work, however, in a first implementation, the free services provided by TTN are a great help and a fast way to connect all the system and to begin to see results.

Chapter 3

System Architecture

After the first two chapters introducing theoretical concepts and the state of the art of the most important technologies involved in this project, this chapter aims to present all the different blocks that leads the project to its objective, the creation of a smart city.

Although it is only the first prototype, this work aims to prove that LoRaWAN can be a solution for a LEO spatial communications protocol, which has a variety of functionalities, like monitoring routes, control the temperature, humidity or pressure in different city spots, or even monitor the capacity of trash cans.

The main purpose of this chapter is to present a design of the project general architecture and its functionalities. A detailed description of all the system components is shown, not only in terms of technical characteristics but also in terms of expected performance and functions.

3.1 General Architecture

The practical part of this work consists on a LoRaWAN network divided in three distinct groups: gateway, end devices and software.

Each of this groups has a vital function for the correct operation of the entire project. Fig. 3.1 shows the general architecture and how those three groups are also subdivided.

The following sections will present a more detailed overview of the project subsystems, where their internal division is also approached.

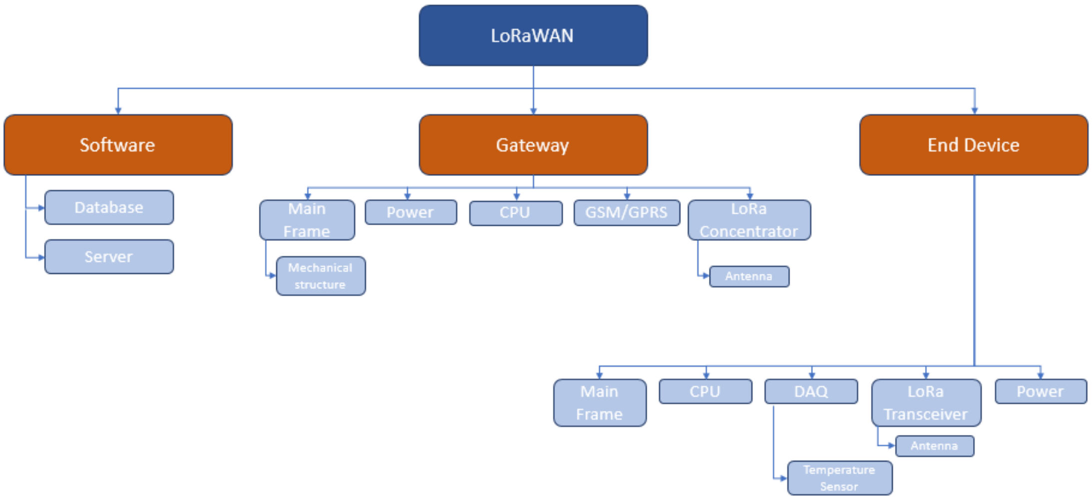


Figure 3.1: General architecture.

3.2 Gateway

Like it was said in section 2.2.2 one of the project objectives is to understand each and every step of the communication system, as so, the gateway will not be a commercial product like the ones from Kerlink or Multitech, but it will be custom build, giving that way the possibility to understand and adequate all the hardware to the project's needs.

The custom build gateway is divided in five main groups, which will be explained next.

3.2.1 LoRa Concentrator

The LoRa concentrator picked is the iC800A from IMST. This board is commonly used as the RF frontend of LoRa gateways because of its capability to receive packets from different end devices sent with different spreading factors on up to eight channels in parallel. This aspect is extremely important to the project because of the amount of end devices spread among the city, which can send packets that arrive exactly at the same time on the RF frontend. Those packages, arriving from different parts of the city have also different spreading factors, which allows the LoRa concentrator to demodulate at the same time, minimizing the probability of being lost. This characteristic, allied with the ADR can monitor a large number of end devices (+500,[49]) and even making it more efficient, managing each node airtime and transmission power.

iC800A was also chosen because of its low cost and great specifications, which allows to build and handle easily a star topology network without any routers or repeaters, just with the combination with an embedded Linux CPU.

Fig. 3.2 shows an iC880A LoRaWAN concentrator board by itself, to note that an antenna is missing on the image, which is a vital key in order to achieve better performance on the overall reception system.

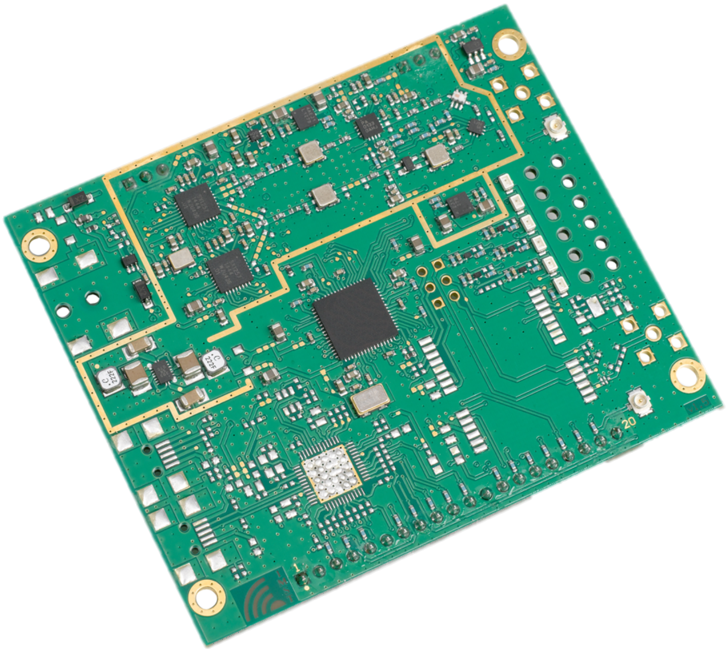


Figure 3.2: iC800A LoRaWAN Concentrator, image from [50].

3.2.2 LoRa Concentrator Antenna

Along with the LoRa concentrator board, the antenna is probably one of the most important pieces of the all system because it is the main link between the RF signals sent by the end devices and the gateway.

In order to make the right choice when it comes to the antenna to use, there are some system characteristics that need to be taken into account, they are:

- Wide area coverage;
- Minimum 5dBi (considering the end-device antenna, section 3.3.2);
- Small size;
- Printed.

The idea of a single gateway receiving data from every corner of a city, with end devices at different distance from each other and from the gateway itself, obligate the first requisite listed above, Wide area coverage. It is very important to understand that the number of end devices in the network is related to the radiation diagram of the chosen antenna. Since the first prototype of the project pretends only to make temperature acquisition, it is not needed to have end devices near to each other, but to spread them along the city. Ideally, for an application like that, the perfect suit is an antenna with omnidirectional radiation pattern.

Monopoles are probably the simplest antennas that one could build. It consists on a simple $\lambda/4$ conductor with a ground plane that can have several forms, according to the application purpose (see Fig.2.7). In addition to the simple form, monopoles have also a omni-directional radiation pattern, which leads to a wide coverage area.

Despite the great characteristic of monopoles, they do not fit the application due to their physical aspect, the vertical conductor, which could in some point prejudice the flight of the main frame. The printed ones also do not fit the application for the same reason. To use the whole radiation pattern provided by the antenna, it had to be perpendicular to the flying main frame, which also excludes from the possibilities. However, if one was considering a real satellite communication, due to the angle between the Earth and the satellite, that kind of radiation pattern is the most adequate in order to cover the biggest area possible.

Has this project main objective rests on a drone application, a different pattern is not only possible but also more applicable to this case. Although it has a much more directional radiation pattern, patch antennas could be a solution, not only because of its high gain, but also because the gateway will rise in altitude, making the directional beam pointed to the ground cover a considerable area, related to the altitude, just like happens in satellite communications.

However, to 868MHz, a patch antenna would be extremely large for the application.

Other probable solution are printed Planar Inverted F Antennas (PIFA). Although PIFA antennas have an almost omni-directional radiation pattern like monopoles they can be printed. In addition, the fact that the radiating part of the antenna is shortened to the ground plane, it provides the possibility of reaching much smaller dimensions, which is extremely important to the project, once the antenna must fit the gateway main frame (explained in chapter 3.2.5) and be parallel to it.

Despite the advantages of patch and PIFA antennas, those solutions were excluded from the project. The reasons are presented in chapter 4.

The final solution is between PIFAs and patch antennas when it comes to size and gain, being more pondered and suitable for the application. A biquad antenna, like the one presented in Fig. 3.3, can achieve gains up to 10 dBi, without being extremely large, around 180x180 mm.

Fig. 3.3 shows a biquad antenna, designed in CST simulation software.

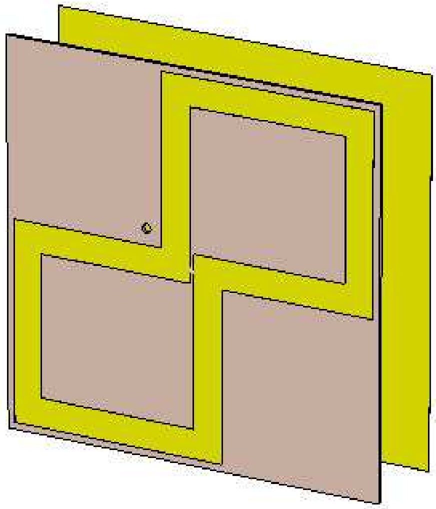


Figure 3.3: Biquad antenna (CST design).

As one can observe in Fig. 3.3, a reflector is used, placed at 40mm away from the substrate in order to increase the antenna gain and maximize its coverage. Chapter 4 makes a careful evaluation of the antenna characteristics, supporting the choice made.

3.2.3 GSM/GPRS

Besides the LoRaWAN communication protocol implemented on the gateway, there's also a GSM/GPRS protocol to do the communication link between the CPU (see chapter 3.2.4) and the network server. This will be the link between the network front and back end.

The implementation of this protocol is done with SIM900 quad-band GSM/GPRS module, shown in fig. 3.4.

Figure 3.4: SIM900 quad-band GSM/GPRS module, image from [51].

The SIM900 is a Quad-Band module prepared to work at 850/900/1800/1900 MHz, controlled by AT commands sent through serial port from the CPU. Those commands provide the ability to send and receive messages or even access the internet through GPRS.

In the project context, this functionality is very useful to establish the communication between the data acquired/stored in the gateway and the database stowed in the network server.

As the gateway has an internal storage unity, the database does not need a real-time update, what makes the GSM protocol a suitable idea to do this link, not only because of the world-wide coverage due to all the base stations implemented by the telecommunications companies but also it is not expensive to send the data, since it is only expectable to send somewhere between ten to twenty messages maximum a day.

The SIM900 module has another specification that fits the system requirements, which is the power consumption. Although the typical consumption is around 500mA, in sleep mode, which is the state it will be most of the time, it consumes 1.5mA.

3.2.4 CPU

On the gateway system, the CPU chosen was a Raspberry Pi 2 model B (RPi). This choice was made considering the iC880A LoRa concentrator manufacturer recommendation and because it is the most cost-effective solution on the market. Also, the RPi offers the possibility to easily integrate the GSM/GPRS module to communicate with the server database once the module has a specific add on to the RPi.

Other important aspect is the fact that RPi runs on an open source software, which makes it even more accessible and simple to customize and upgrade, due to the vast community of users.

Fig. 3.5 illustrates the CPU chosen RPi 2 model B.

Figure 3.5: RPi 2 model B, image from [52].

3.2.5 Main Frame

All the electronics and antenna mentioned on the previous chapters need a main frame to be attached to. This main frame will strongly depend on the project real implementation, which can lead to two different options:

- **Building top**;
- **Drone**.

Both need a mechanical structure to enclosure and protect all the hardware but, through the application in question it has different specifications.

To the first one, the building top, a simple case to protect from rain and wind is sufficient, like the example on fig. 3.6.

On the other hand, to attach the gateway to a drone, there's the need to minimize the size and weight of the mechanical structure, to reduce to minimum the impact it will have on the drone's flight.

On a first basis, in order to reduce the weight of the overall system, an option is to use the battery of the drone itself, instead of a gateway's dedicated battery. This solution will decrease the weight which could influence the flight stability, but will also reduce the flight time, once the battery will be shared by both systems.

Figure 3.6: Gateway external case example.

3.2.6 Power

As explained in section 3.2.5, the power supply will also depend on the system application. In the case of the building top, it can easily be linked to the building power supply network, which is by far the simplest method.

On the other hand, when considering the gateway attached to a drone, the power supply is something extremely important to take care of. For the proper functioning of the system, a battery with some particular specifications is needed like, small size, low weight and the capability to power up the system for at least twenty to thirty minutes.

3.3 End Device

Internet of Things strongly depends on the capability of every "little thing" to communicate somehow to somewhere. End devices are those "little things" that are attached to the daily objects and are responsible to acquire data to be sent, raw or processed, to the gateways.

Besides the gateway, one of the objectives of the project, at a mid/long term, is to build a network composed by a minimum of twenty end devices, responsible to acquire temperature data and send it to the gateway.

Besides the fact that the custom build end-devices hardware is already fabricated (architecture presented and explained at section 3.3.2), the main goal of this work is to prove the concept of a super low-cost satellite, thus, in order to facilitate the development of the project, the end devices used and tested are from STMicroelectronics and are presented in the next section.

3.3.1 STMicroelectronics End Device

The P–NUCLEO–LRWAN1 is an STMicroelectronics Nucleo pack designed to develop low–power solutions based on LoRa technologies.

This tool is composed by an ultra–low–power STM32L0 microcontroller responsible to control and manage the end device. Regarding the LoRa communication, the STM32LA MCU is coupled to a LoRa extension board, which is based on the Semtech SX1272MB2xAS.

In association with the I–CUBE –LRWAN, a certified software solution developed by STMicrocontrollers together with the eclipse IDE (Integrated Development Environment), all the variables are fulfilled to obtain a LoRaWAN end device.

The P–NUCLEO–LRWAN1 comes with a built–in temperature sensor, which makes this board ideal to a fast and easy application and proof of concept.

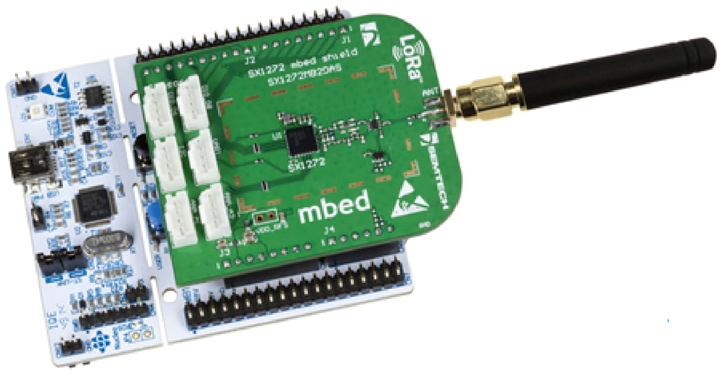


Figure 3.7: Nucleo-L073RZ and LoRa expansion board, image from [53].

In order to better understand the capabilities of the Nucleo test board, acoording to the fabricator datasheet, it is capable of:

- 14 dBm high efficiency PA;
- Programmable bit rate up to 300 kbps;

- Ability to work at 868 MHz and 915 MHz.

For all the reasons presented along this section, this was the choosen end device to use in this primary stage of this work's project.

3.3.2 Custom build End Devices

In order to optimize all the parts of the system, a custom made prototype of an end device was projected and built. the main objective of this prototype is to decrease the power consumption of each node, as well as design a dedicated hardware tool, with better specification and even more project oriented.

The project's end devices are very simple and can be divided into five groups:

- Main frame;
- Power;
- CPU;
- DAQ;
- LoRa transceiver.

Every group will be described in the next sections.

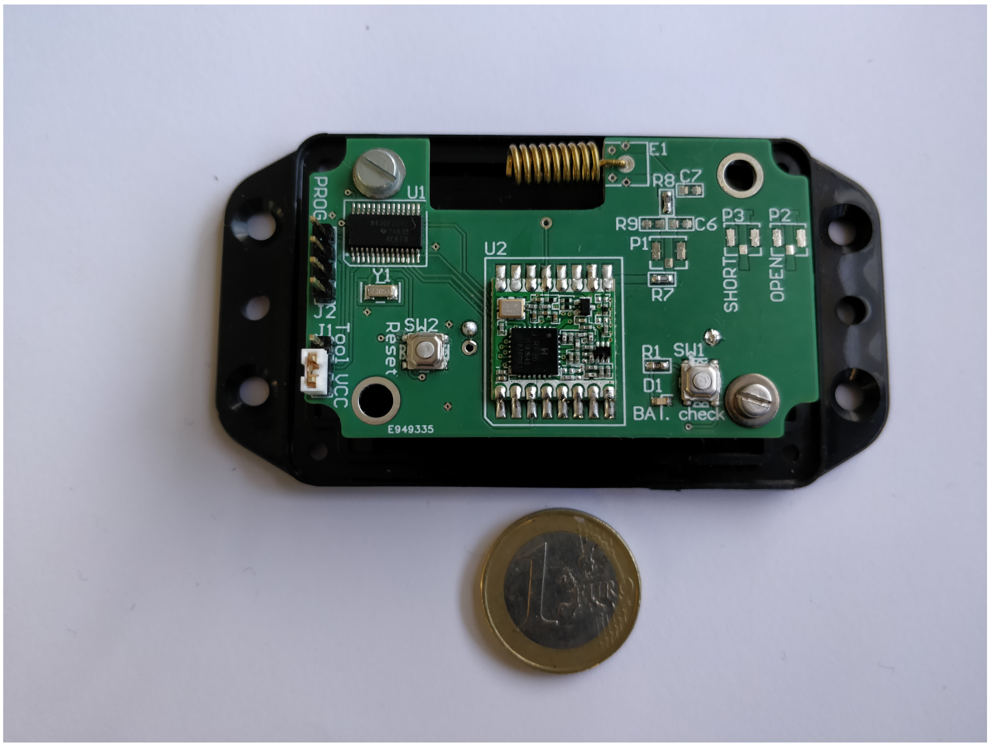


Figure 3.8: End device final prototype.

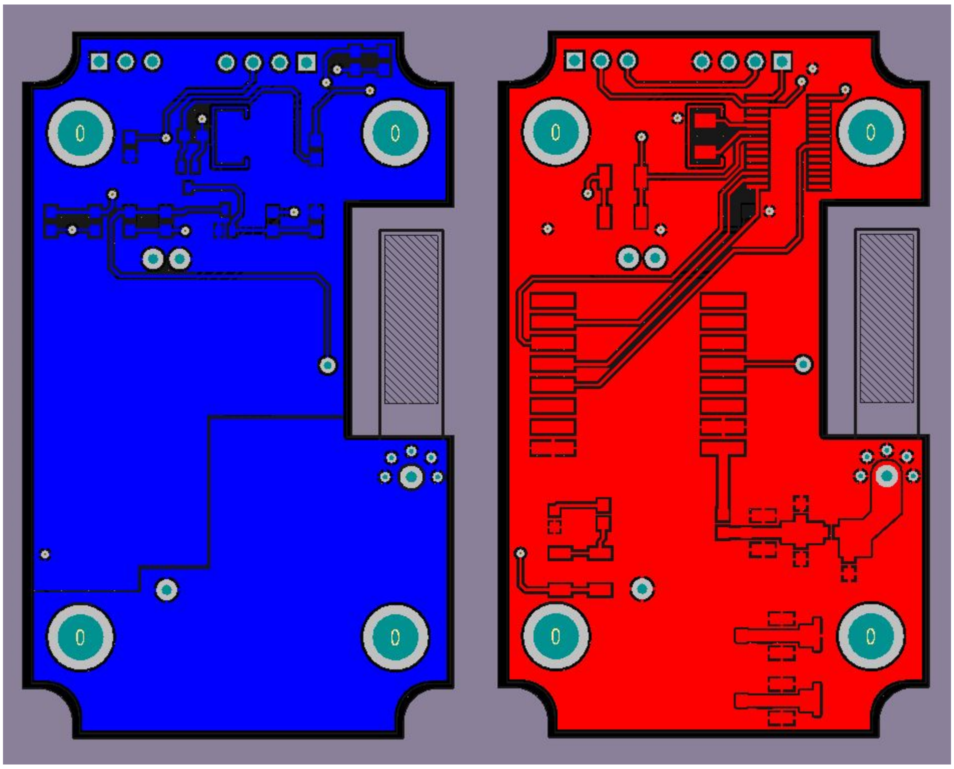


Figure 3.9: End device PCB layout.

LoRa Transceiver

The LoRa radio solution to be implemented resides on a Hope RF component called RFM95. The LoRa long range modem featured in the transceiver, based on SemTech's sx1272 provides ultra–long range communications with low current consumption and high interference immunity.

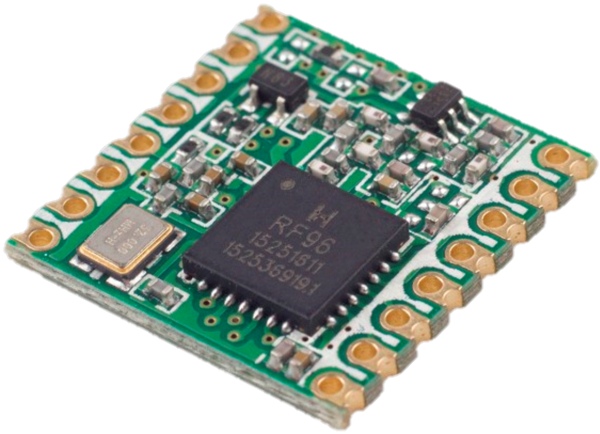


Figure 3.10: RFM95 module, image from [54].

Ultra–long range spectrum communications are only possible with this device because of the integrated +20dBm PA, making it suitable for any IoT applications requiring range and robustness. The radio will operate at 868 MHz, with a bandwidth of 125 kHz, a spreading factor of 7 to 12 and an output transmission power of 14 dBm.

As a transceiver, this device can not only transmit but also receive data packets and it has a high sensitivity down to -148 dBm and a low RX current of 10.3 mA. However, in the project context the RFM95 will be mainly used to transmit LoRa packets, so, a more detailed description of the transmission system will be given.

Figure 3.11, taken from the device's datasheet, illustrates the architecture of the RF front–end, showing the internal power amplifier configuration.

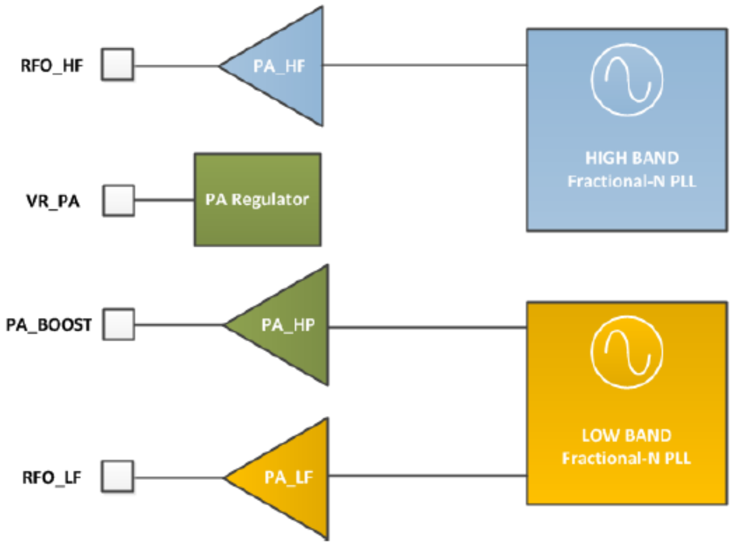


Figure 3.11: RF front–end architecture, image from [54].

RF Output Power	Current
+20 dBm, on PA_BOOST	120 mA
+17 dBm, on PA_BOOST	87 mA
+13 dBm, on RFO_LO/HF pin	29 mA
+7 dBm, onRFO_LF/HF pin	20 mA

Table 3.1: Supply current in Transmit mode.

PA_HF and PA_LF are high efficiency amplifiers used to high frequencies, from 860 MHz, and low frequencies, down to 525 MHz respectively. Both power amplifiers (PA) are programmable to yield RF power up to +14 dBm directly to a 50Ω load with low current consumption. To note that the output power is sensitive to the supply voltages, typically 3V3. As said before, the frequency to be used is the 868 MHz so the PA_LF will not be used.

The other PA listed in the figure 3.11, PA_HP, is a high-power amplifier linked to the PA_BOOST pin that can continuously operate at +17 dBm and duty cycled operate at +20 dBm, however, it will not be used as well due to the legal limit values by law in the ISM band.

The power consumption varies upon the operation mode of the device and the output power to be transmitted. Despite the fact that in sleep mode the transceiver only consumes 0.2 μA, this value can be reduce to nothing if the VDD is disconnected from the RFM95. To note that in that case, after the re-connection, a 10ms delay must be applied before trying to initiate any communication over the SPI bus, which is the protocol used to communicate between the CPU and the RFM95.

In transmit mode with a matching 50Ω load, depending on the output power, there are four different consumptions, listed in table 3.1. From all the options available, the third entry is the best solution for the application: +13 dBm with a current consumption of 29 mA.

LoRa Transceiver Antenna

It is intended that the project end devices be as small and discreet as possible so they can fit anywhere without damaging the landscape or anyone even notices them. Because of those specifications, the antenna must be as compact as possible, without sacrificing the omnidirectional radiation characteristic and high efficiency (¿75 %), once the node can be deployed on a random place without necessarily knowing in which direction the gateway will be.

A helical antenna is one of the most used antennas on end devices. Fig. 3.12 represents a simple helical antenna with the respective radiation diagram where it is possible to understand its small size: for an 868Mhz helical antenna the expected size is about 23 mm long by 5 mm diameter.

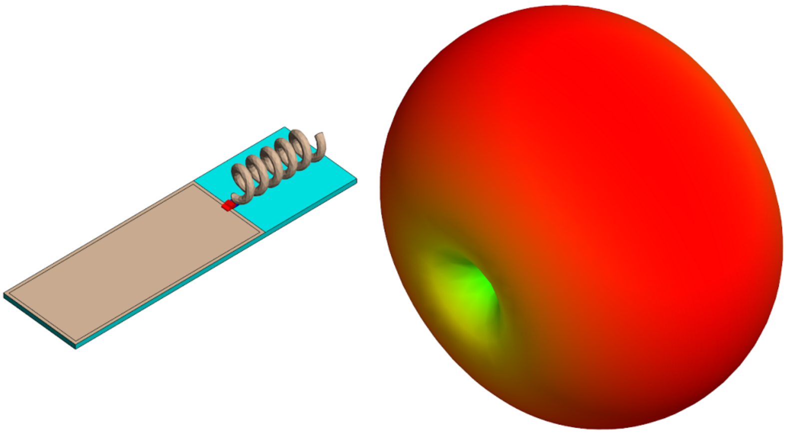


Figure 3.12: 868Mhz helical antenna, image from [55].

Another great aspect of helical antennas is the fact that can achieve around +1dBi of gain, which can maximize the link between the end device and the gateway.

As so, the choice for the node antennas falls for a commercial 868Mhz helical antenna, reducing the costs of the implementation on the PCB itself and also keeping the process a lot easier.

CPU

With the goal of minimizing the power consumption of the entire system and extend the lifetime of the end devices to the most possible, Texas Instrument MSP430F2132 was chosen because it is perfectly suitable for ultra-low power applications, as it has an active mode consumption of 250 μA at 1 MHz and sleep modes can reach consumptions as low as 0.1 μA.

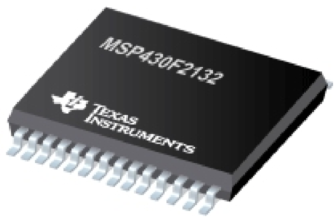


Figure 3.13: TI MSP430F2132 package, image from [56].

In order to achieve such low power consumptions, an external low frequency crystal oscillator is needed to provide external clock signal to the microcontroller. To this specific microcontroller, 32.768 kHz is the required frequency for the external crystal.

It has several communication protocols, being SPI the most important to the project, once it is the communication protocol used by the RFM95, LoRa radio.

MSP430F2132 has 8 input ports capable of receive analog signals to be converted to digital in the internal ADC. This is a great advantage because it gives the possibility to upgrade the system to monitor other type of data with different sensors like, gas or light sensors.

Once end devices are mean to work just several times a day, around 10 to 20, it is intended to spend most of the time in sleep mode, consuming as less power as possible. To achieve this goal, from all the low-power modes that the microcontroller offers, LPM3 will be the used because of its capability to awake with an internal interruption. Table 3.2 shows in more detail the consumption characteristics of this mode.

<table>
<tr><th>Parameter</th><th>Test Conditions</th><th>T_A</th><th>V_{CC}</th><th>TYP</th><th>Unit</th></tr>
<tr><td rowspan="6">Low-Power mode 3 current (LPM3)</td><td rowspan="6">•$f_{DCO} = f_{MCLK} = f_{SMCLK} = 0$ MHz
•f_{ACKL} = from internal LF oscillator (VLO)
• CPUOFF = 1, SCG0 = 1, OSCOFF = 0</td><td>-40ºC to 25ºC</td><td rowspan="3">2.2 V</td><td>0.3</td><td rowspan="6">μA</td></tr>
<tr><td>85ºC</td><td>1.2</td></tr>
<tr><td>105ºC</td><td>2</td></tr>
<tr><td>-40ºC to 25ºC</td><td rowspan="3">3 V</td><td>0.7</td></tr>
<tr><td>85ºC</td><td>1.4</td></tr>
<tr><td>105ºC</td><td>2.5</td></tr>
</table>

Table 3.2: LPM3 power consumption details.

Data Acquisition - DAQ

For the initial application, the only data to be acquired and sent to the gateway by the end devices is just a simple environment temperature.

As said in section 3.3.2, the microcontroller to be used, MSP430F2132, has an internal temperature sensor that can and be used to the application once it has a low power consumption, important for the application, and it is easier and cheaper to implement once all the connections to the microcontroller are already internally made. There is no need to buy other component and spend more money once the first component has all of it already assembled.

.

Power

Concerning the power supply of the end devices, there are two major factors, the great lifetime expected and the small size it must have.

Considering that the system will be in deep sleep most of the time, just consuming 0.7 μA with the microcontroller in low power mode and everything else completely shut down, there is no need for a large battery.

In active state, the system is expected to have the consumptions listed on table 3.3.

<table>
<tr><th>Device</th><th colspan="2">Consumption</th></tr>
<tr><td>MSP430F2132 –active mode (100 kHz)</td><td>72</td><td rowspan="2">uA</td></tr>
<tr><td>MSP430F2132 –built–in temperature sensor</td><td>40</td></tr>
<tr><td>RFM95 –+13dBm RF output power</td><td>29</td><td>mA</td></tr>
</table>

Table 3.3: ED active mode expected power consumptions.

Considering those values, the chosen battery was a IEC standard CR2450. It has 3V, a typical capacity of 610 to 620 mAh and small dimensions around 24.5 x 5.0 mm, fitting perfectly the size requisites and providing a good first prototype in terms of lifetime.

Assuming that each device has to do one transmission per hour which takes typically 1.5 seconds from beginning to end, with the power consumptions presented on table 3.3 and knowing that in sleep mode it has a power consumption of 0.7 μA, the estimated life time of the first prototype is superior to 3 years.

Main Frame

End devices are meant to be very small and discrete, however, as it is intended to be exposed to atmospheric conditions, there is the need to encapsulate the whole system in a mechanical case in such a way that the device is protected from external conditions. However, this case must be plastic, so it does not interfere with the electric field generated by the helical antenna.

Fig. 3.14 illustrates the capsule containing the end device. The flange IP65 certificates the enclosure against dust and water ingress [57].

Figure 3.14: final end–device package.

3.4 Software

Despite the fact that it is not the work main focus, the software is very important because it is responsible for the storage and organization of all the received data on the gateway, making the bridge between the RF packets and the human readable data.

3.4.1 Server

On this embryonic phase of the project, the data storage in the gateway is send to the things network (TTN) public server (see chapter 2), in order to facilitate the implementation, once it is not the main focus. However, with the evolution of the project, a private server is required to have full and private access to the data sent by the different EDs. Even though the data to be acquired does not need that much privacy, once it is only temperature, the goal of the private server is to prepare the project for future implementations, where there's the need of privacy in the data sent.

3.4.2 Database

A database is extremely necessary to better analyse the data received. With that purpose, this work needs a simple database with a table containing a weekly temperature history, organized by the descendant end device with the respective date and time of the incoming data.

Chapter 4

Experimental Results

4.1 Gateway Antenna

As discussed in chapter 3, the gateway antenna needs to respect some requisites in order to suit the application in the best way possible. To achieve the best conditions considering all the constrains applied to the project, such as size and weight specifications, three different antennas were designed and simulated:

- **Patch**;
- **Printed PIFA array**;
- **Biquad**.

This section aims to expose and compare the simulation results obtained for the three antennas, as well as justify the fabrication of the biquad antenna.

Further down this section, a more detailed analysis on the biquad antenna is made, containing a comparison between the simulated and the measured results.

4.1.1 Patch

Considering the application goals, to prove the concept that it is possible to build a super low-cost micro-satellite, the antenna for the gateway (project "micro satellite"), needs to perform as a real satellite antenna, however, in a tiny size.

Due to the directivity, in normal urban applications, a patch antenna wouldn't be a great option once it was impossible to reach all the end devices, however, in this work application as the gateway rises, the antenna beam pointed to the ground increases the covered area, creating a well-defined circle. The bigger the amplitude of the beam, the larger the area covered.

Fig. 4.1 shows the layout of the patch antenna designed and simulated on CST software.

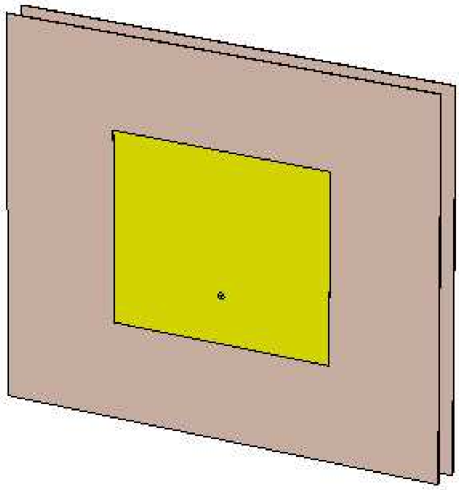


Figure 4.1: Patch antenna layout.

To achieve better performance and results on the antenna, the substrate selected is the RO4730JXR from Rogers which has as main characteristics:

- Permittivity = 3.0;
- Dissipation factor = 0.027;
- Thickness = 0.762mm.

However, considering the project's central frequency, 868MHz, a normal patch antenna designed only with this substrate would have approximate dimensions of 300 x 366 mm (considering the substrate size).

The results presented above are much bigger than the ones required for the gateway, once it can prejudice the gateway flight. To overcome this problem, a second layer of substrate was placed 20mm away from the initial one (see Fig. 4.1), containing the ground plane. With the gap between one can understand that the majority of the antenna substrate is now air, which in this case has:

- Permittivity = 1.0;
- Dissipation factor $\approx$ 0;
- Thickness = 20mm.

This addition to the first antenna decreases the dimensions of the antenna, that after an optimization process, achieve its final dimensions: 340 x 280mm.

With this design a radiation efficiency of -0.05 dB as well as a gain of 9.17 dB were achieved for the central frequency of 868Mhz. Fig. 4.2 shows the radiation pattern obtained.

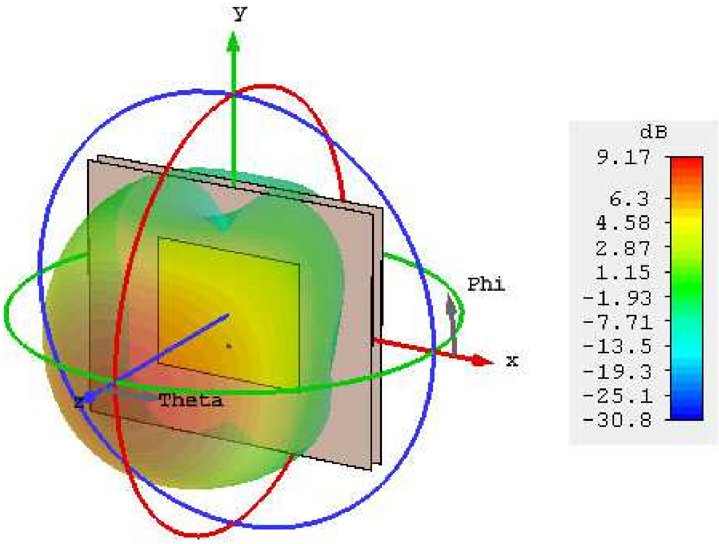


Figure 4.2: Patch radiation pattern.

In terms of bandwidth, simulations results presented a value of 100 MHz considering the S11 parameter at -10 dB (see Fig. 4.9).

At first sight, all the conditions for a good and simple antenna are compiled in this patch design, however, one crucial characteristic of the system is neglected, the dimensions of the antenna make it incompatible with the application.

4.1.2 Printed PIFA Array

To overcome the dimension problem noticed on the patch antenna, the second design attempt was a printed PIFA array.

Any PIFA printed design can reduce their dimensions significantly because of the shunt pin. Comparing to patch designs, this brings a great advantage to PIFAs, because the size is much smaller, however, the performance is nothing comparable.

When designing a printed PIFA it is expectable to reach around 1.8 dB of gain with an omnidirectional radiation pattern. Remembering chapter 3 and the antenna specifications mentioned there, those two are extremely far away from the expected. To fulfil one of the specifications, the gain, instead of one PIFA, an array of four elements was simulated. This increase in the number of antennas improved the performance of all the set.

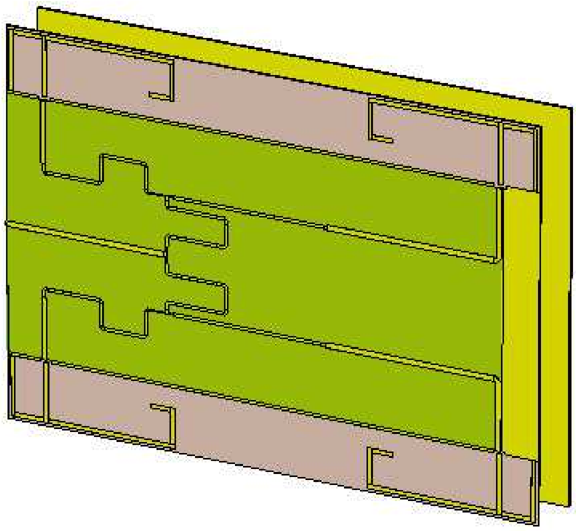


Figure 4.3: PIFA array layout.

Observing Fig. 4.3 it is easy to notice the second plane placed behind the PIFA array. Contrarily to the patch antenna where the second plane was the ground plane and was placed to use a thick layer of air as substrate, in this case, it is a reflective plane used to overcome the loss of half the radiation pattern of each antenna. Due to the application purpose, the antenna must be parallel to the main frame, which means that an omnidirectional radiation pattern has half of it waisted pointing up. The reflective plane, placed at 20 mm of the antenna, not only forces all the radiation to be pointed to the ground, as it also increases the gain of each individual antenna, contributing to the overall performance.

In Fig. 4.4 one can observe the four individual radiation patterns of the array, and their contributions to the main goal.

Due to the location of the antennas, each has its own center beam, which collides in a central one, when the feed point is only one, exciting all the antennas.

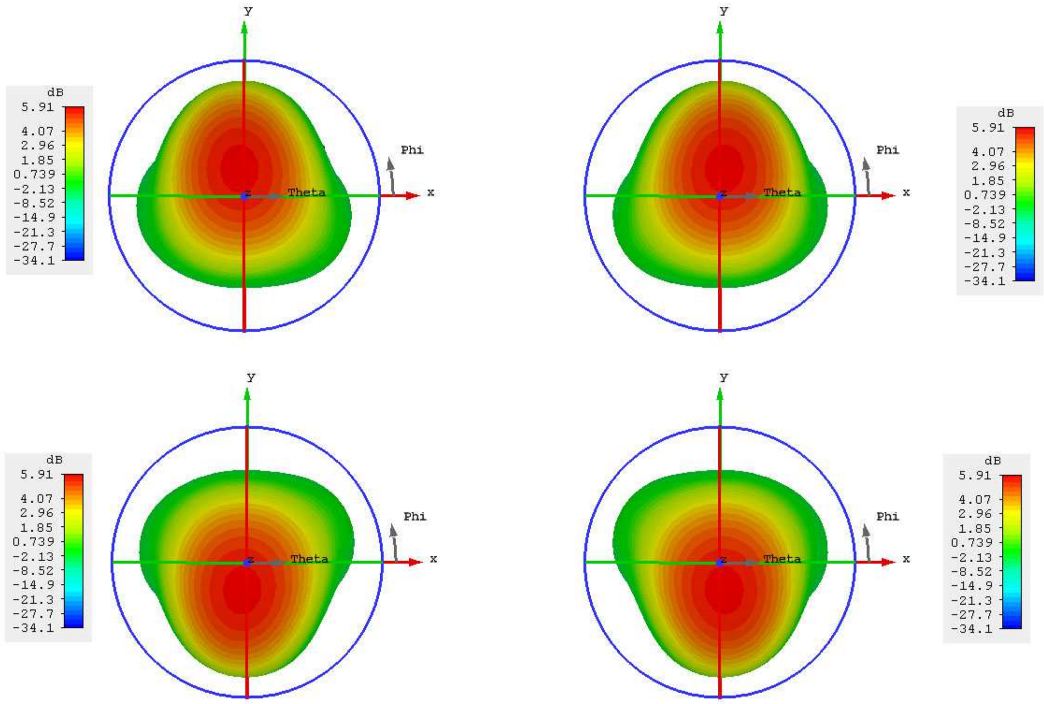


Figure 4.4: PIFA individual element radiation patterns.

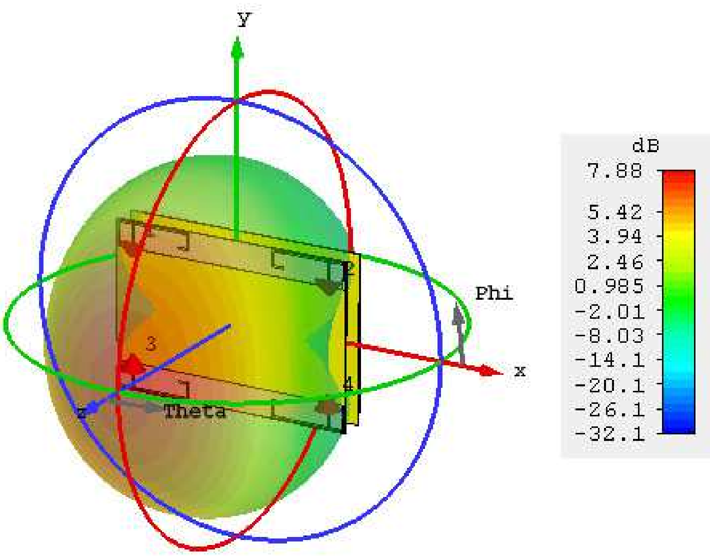


Figure 4.5: PIFA array radiation pattern.

To notice that the feed location is closer to the first two antennas. This fact has a major implication on the performance of the antenna array, decreasing the gain obtained. To overcome that situation, the two antennas placed further apart, are fed with 180°of phase shift, in order to achieve the antennas best results.

To understand if this antenna is a satisfactory solution to the project, one must analyse the S_{11} parameters.

Fig. 4.6 presents the S_{11} parameters of the antenna, with and without the matching network. As one can observe, without the matching network, the antenna wasn't even matched at the work central frequency. Using the simulation software ADS, the matching network was built with a series capacitor, with the respective value of 1.8 nF. analysing once more Fig. 4.6, after the placement of the matching network, a perfectly matched antenna was obtained.

Although the S_{11} parameters showed a perfectly matched antenna at 868Mhz, one must consider that this are only simulation results, which will certainly differ from the results obtained after the fabrications. Due to that, this design was pushed back because of the extremely narrow bandwidth presented. If after fabrication, the matching point was a bit to the sides, the antenna would be irrelevant to the project's goal.

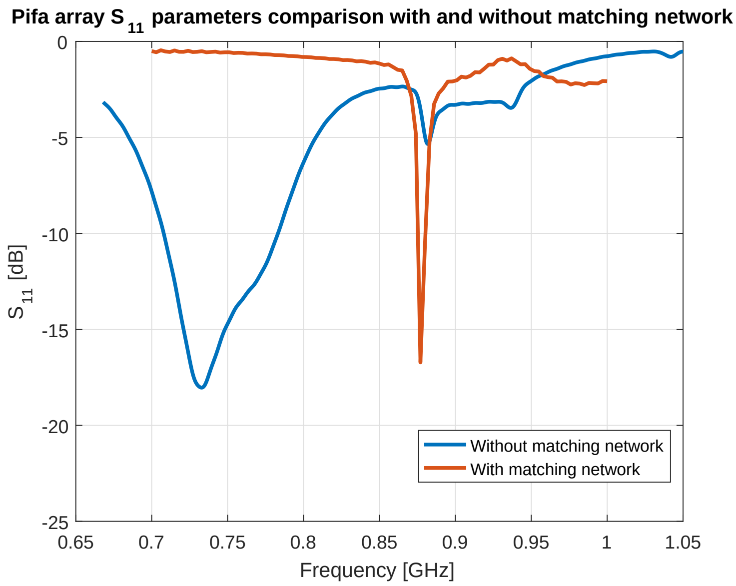


Figure 4.6: PIFA array S_{11} parameters with and without matching network comparison.

In conclusion, besides the fact that the antenna would be reduced from 340 x 280mm (patch antenna dimensions) to 197 x 135mm (PIFA array dimensions), it is too risky to narrow the bandwidth to such a thin interval. With that said, PIFA array is also not an appropriate solution to the problem.

4.1.3 Biquad Antenna

The third and final attempt was a biquad antenna. The theoretical concept of the antenna consists of two connected squares in which all individual edges have length equal to $\lambda/4$. In practice and in order to obtain the best results, those dimensions suffer alterations, however, the initial experiments are based on those concept dimensions, which means an edge equal to $\lambda/4$, equal to 86.40 mm.

Based on the assumption that those are the initial values, even if the optimal edge dimension decreases, it means an increase of the overall antenna dimension comparing to the PIFA array, however, it is still smaller than the patch. After the optimization process, the antenna final dimensions are 171 x 168 mm.

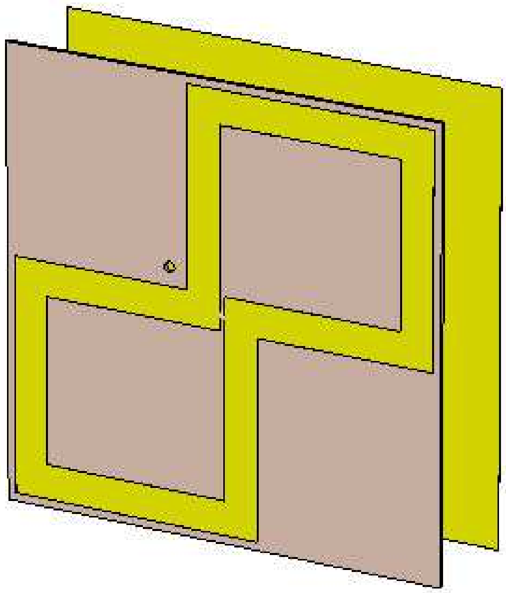


Figure 4.7: Biquad antenna layout.

As can be observed in Fig. 4.7, similarly to the patch antenna, the biquad, for the application purpose, also has the need for a reflective plane, for the same reasons. Since the radiation pattern of the printed biquad antenna has two main lobes, one to the front and other to the back of the antenna, half of the radiation would be lost. Using the reflective plane at the optimized distance of 40 mm from the antenna, not only the back lobe was not waisted, as it increases the gain on the main lobe, increasing the radiation efficiency of the antenna in what concerns the project.

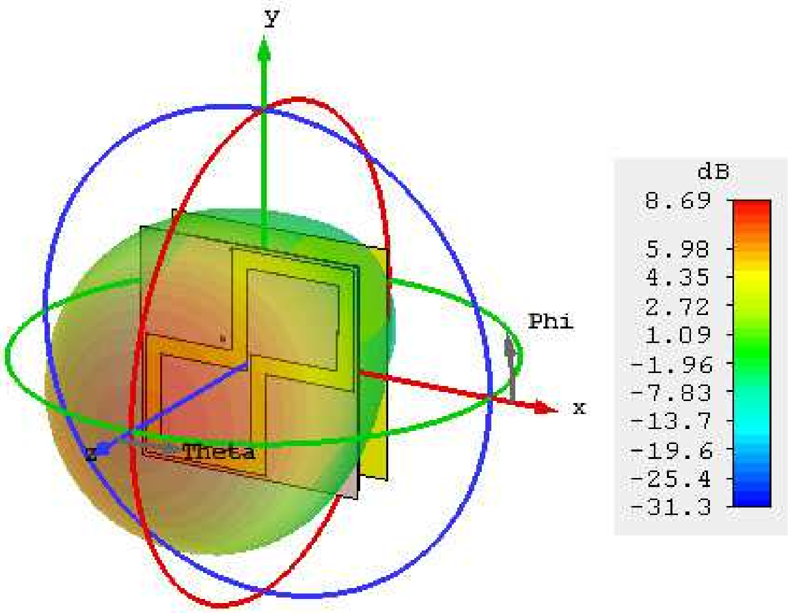


Figure 4.8: Biquad antenna radiation pattern.

The simulation results showed a radiation efficiency of -0.35 dB and a gain of 8.69 dB. This value comes right between the values obtained for the patch and the PIFA array, which gives the first two reasons for the choice of this antenna: acceptable gain and small size.

Analyzing the S_{11} parameters in Fig. 4.9, it is possible to see that from all the three antennas, the biquad is the most well matched, -23.94 dB, and has a bandwidth of 95 Mhz. Once again, comparing to the PIFA array, the biquad has a much larger bandwidth, making it much more suitable to the application. The fact that the bandwidth and the gain of the biquad is similar to the patch, reveals that it is the antenna to fabricate, because of its smaller dimensions and resembling performance.

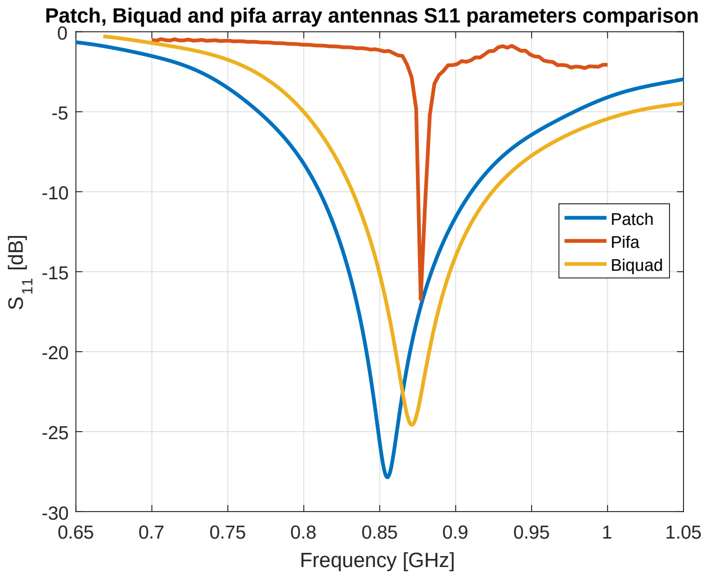


Figure 4.9: S_{11} parameter comparison.

Other reason to choose the biquad over the other two antennas is the wide coverage provided by its beam. The two images below, Fig. 4.10 and Fig. 4.11 illustrates the comparison in a cartesian plot between the radiation pattern of the three antennas when $\phi = 90°$and $\phi = 0°$. It is possible to understand how close to a patch this implementation is, even in terms of beam apperture, reducing the total size.

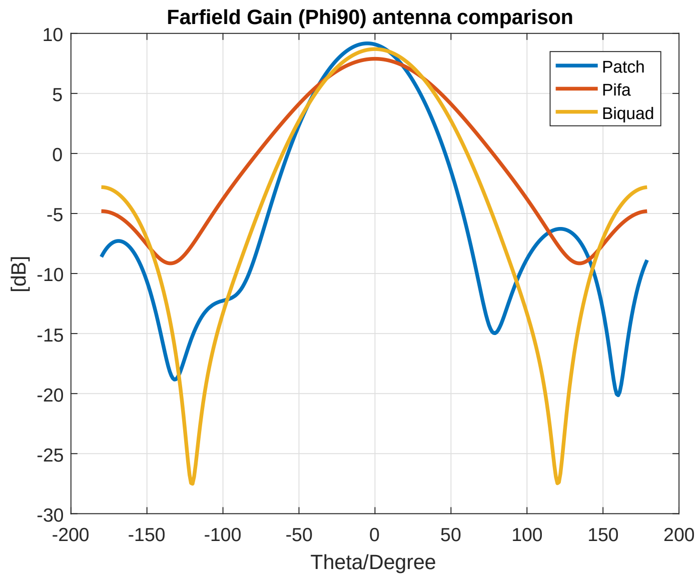


Figure 4.10: Radiation pattern $\phi = 90$.

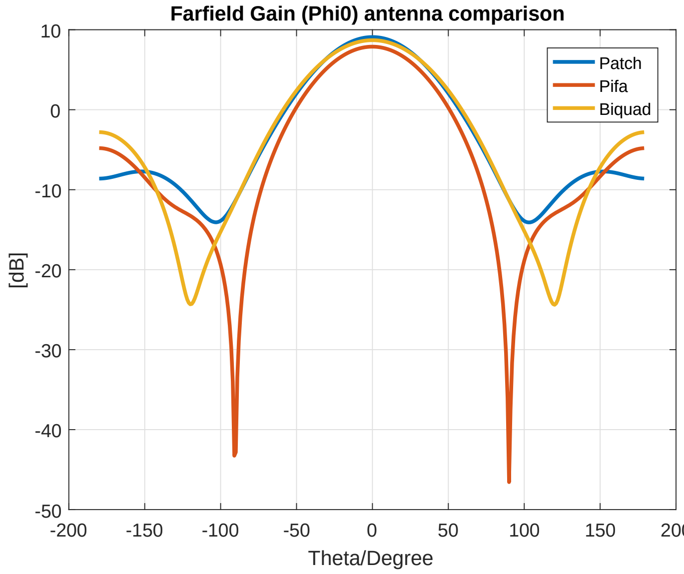


Figure 4.11: Radiation pattern $\phi = 0$.

Hereupon, the final result of the fabricated biquad antenna, represented on Figs. 4.12 and 4.13

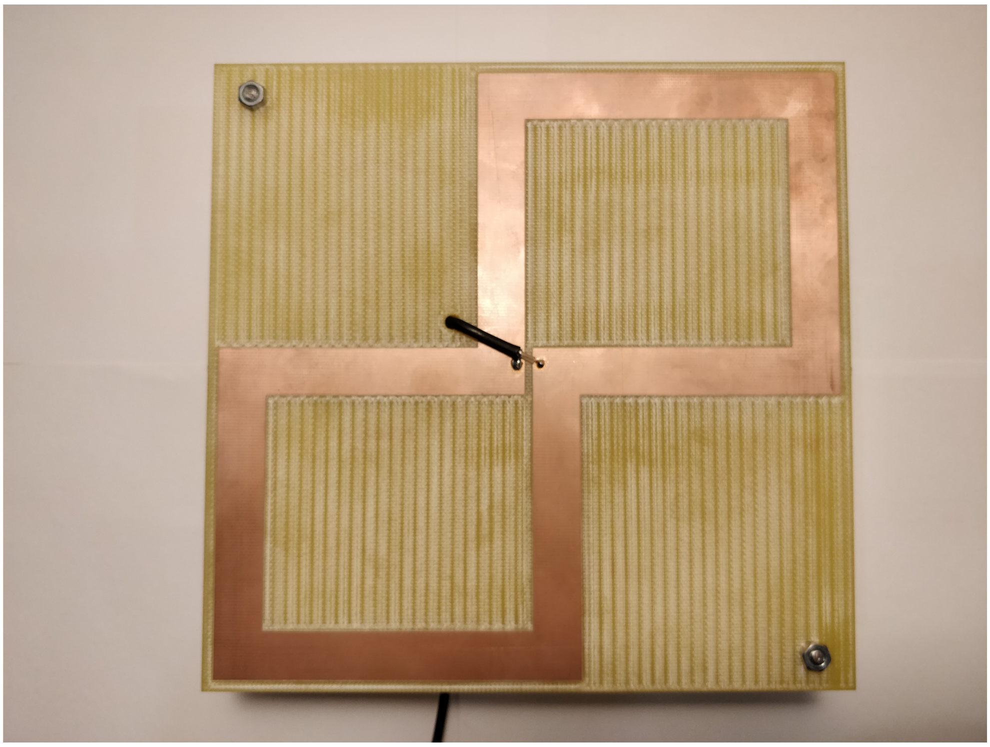


Figure 4.12: Biquad prototype front view.

Figure 4.13: Biquad prototype side view.

4.1.4 Biquad Antenna practical results

After the fabrication of the antenna represented on Fig. 4.12, a test procedure was followed in order to make comparisons between the simulation and the practical results obtained.

The most important results to discuss and analyse are the S_{11} parameters and the radiation pattern.

Figs. 4.14 and 4.15 show the setup implemented to measure the biquad antenna S_{11} parameters.

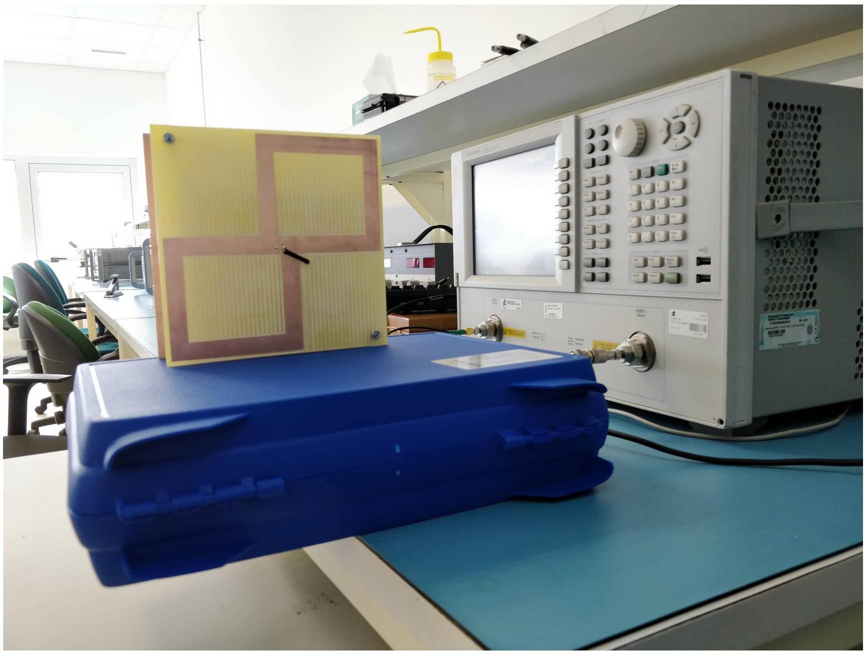


Figure 4.14: Biquad S_{11} measurement setup (front view).

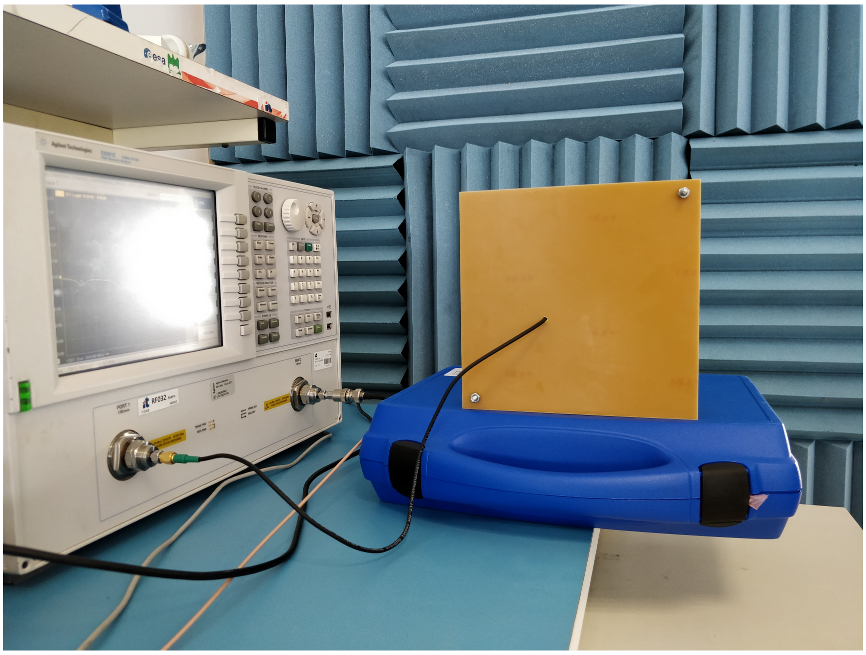


Figure 4.15: Biquad S_{11} measurement setup (back view).

The measurements done with the setup presented below lead to the results illustrated on Fig. 4.16, where the comparison between the simulation and practical results is done.

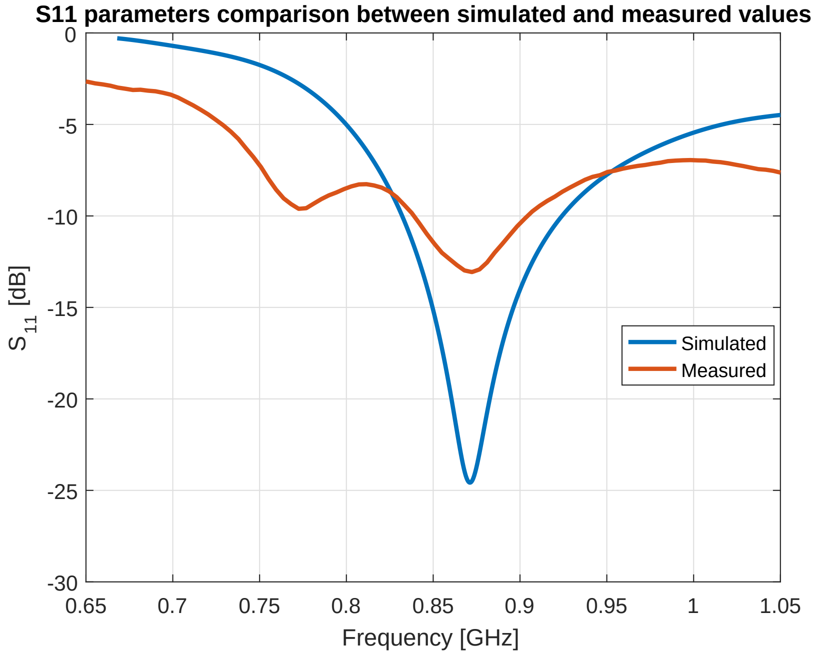


Figure 4.16: Comparison between simulation and measured S_{11} results.

As one can see, the practical results do not match exactly what is expected from the simulation results, mainly when it comes to the magnitude of the S_{11} parameters, as the practical result only reaches -13dB contrarily from the -25dB presented on the simulation.

However, considering the antenna adaptation at -10dB, one can observe that the bandwidth is reduced by -25 MHz. The simulation result showed a bandwidth of 95MHz and the physical antenna presented around 70MHz of bandwidth.

The differences between the simulated and the practical results are considerable, for instance, at the frequency band of interest, where the reflection coefficient has a difference of more than 10 dB. Nevertheless, those differences were expected to happen due to the simulation of the feed port. To obtain more accurate simulation results, the effort applied to the simulation model would be much bigger, once it would require the simulation of the coaxial cable that feeds the antenna. Although the presented results would be much more similar, the effort and time it would take would not be beneficial, since it is not possible to build the antenna in other way.

Besides that, the setup used to measure the radiation pattern of the antenna on the anechoic chamber required a relatively long feed cable. As it is expected, this 50Ω cable inserts a certain inductance, which will have direct repercussions on the antenna adaptation. The variations along the rest of the presented spectrum are also accentuated due to the noise introduced by the 50Ω coaxial cable

Considering that a biquad antenna can not have a matching network to help on the adaptation process, because of the lack of ground plane, the results are very satisfying with the manufacturing of an antenna well matched to the project's central frequency, 868MHz.

The following practical tests executed were performed at the anechoic chamber, with the setup presented on Fig.4.17, once it was supposed to study the radiation characteristics of the built antenna.

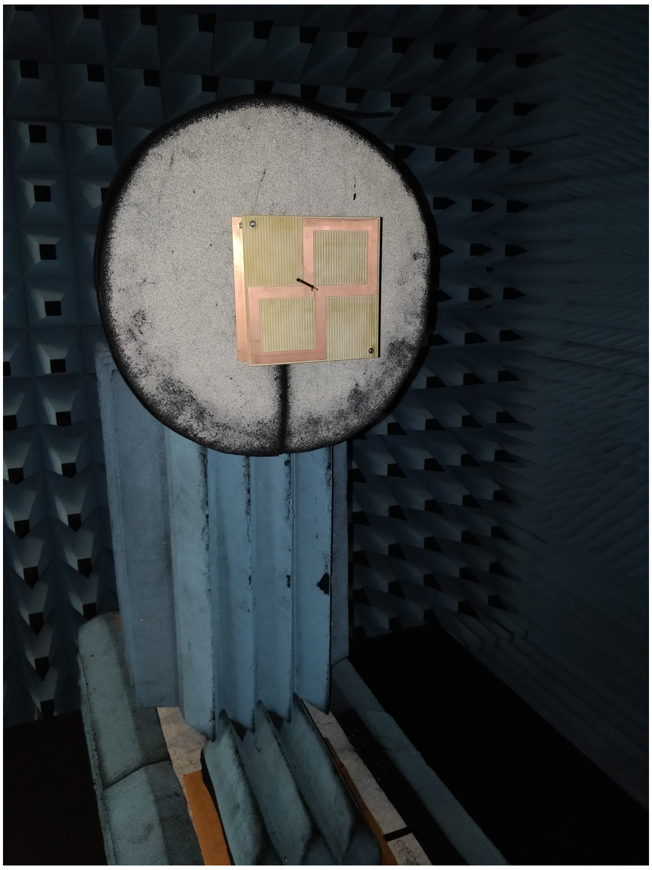


Figure 4.17: Anechoic chamber setup.

The observed values in Fig. 4.18 present a diagonal linear polarization, however, the fabricated biquad antenna has a vertical linear polarization. The diagonal appearance is related to the fact that the simulation and measured results were taken according to the antenna geometry, in this specific case, a square. When the antenna is at its "natural" position, like a bow–tie, $\phi = 45$ or $\phi = 135$, it is possible to observe the vertical linear polarization.

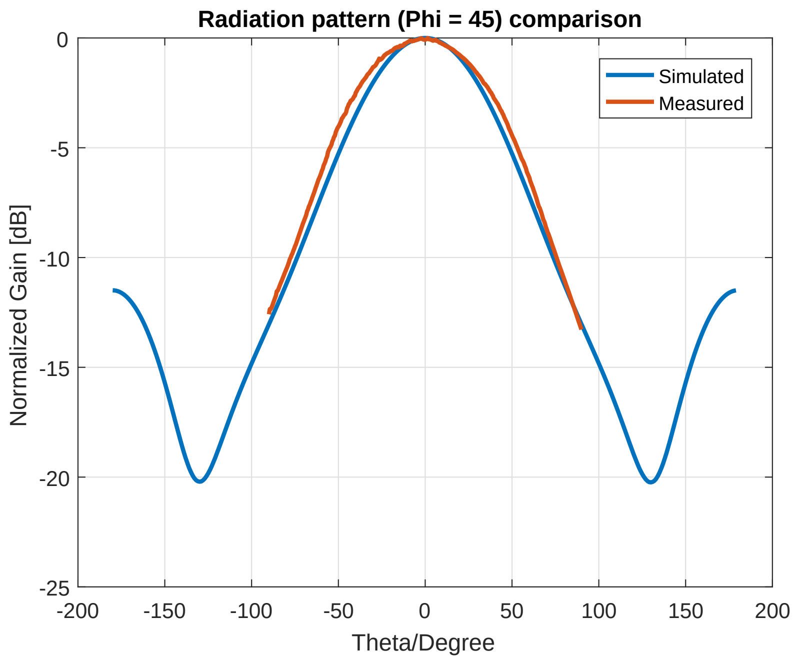


Figure 4.18: Radiation pattern (ϕ=45) comparison between simulated and practical results.

Fig. 4.18 shows the comparison between the simulation and the measured results obtained, clarifying the polarization orientation and the similarity between what was expected and obtained.

On one hand, observing the measured results for $\phi = 0$ (Fig. 4.19 top left corner), one can see that both components, E_θ and E_ϕ are extremely similar, which indicates the presence of a circular polarization, however, observing the bottom left corner of the same figure, it reinforces the linear polarization. In this case, it is possible to see that RHCP and LHCP are also very similar, which contradicts the circular polarization, where one of the components would have to be clearly superior to the other. On the other hand, for $\phi = 45$ (top right corner), the linear polarization is evident due to the difference between the E_θ and E_ϕ values. In this case, the bottom right corner of Fig. 4.19, shows once again the similarity between RHCP and LHCP.

Fig. 4.20, has, on the left, the values plotted for $\phi = 0$ and $\phi = 45$, that are supported with the 3D plot on the right, to reach a better understanding of the linear polarization, with a diagonal appearance.

4.2 Network Application

As said in the previous chapters, the main goal of this project was to prove that the LoRa /LoRaWAN technology was capable of establishing a LEO satellite link. Even though that a link like that was not possible to test on the scope of this dissertation, some simpler tests were made in order to understand what was achieved.

Referring to chapter 3.2, the solution implemented for the gateway is different from the initially designed. Essentially due to time aspects, related to some difficulties with the initial synchronization and operation with the TTN. The solution presented in this work does not

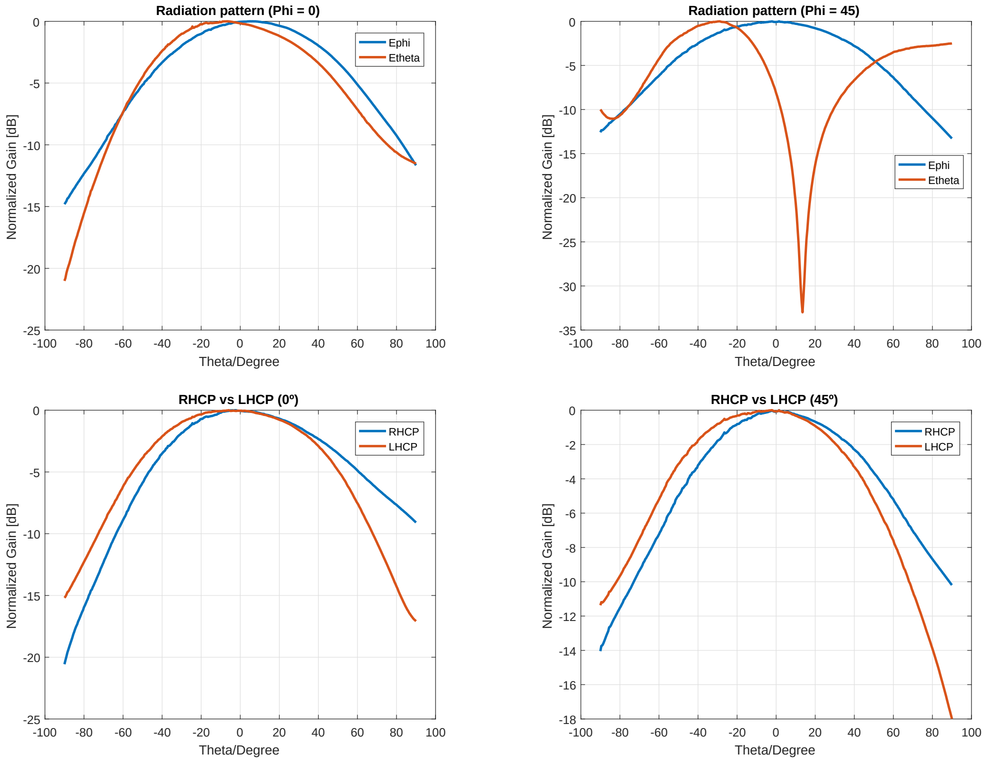


Figure 4.19: E_θ and E_ϕ components for ϕ=0 and ϕ=45, relation with RHCP and LHCP values.

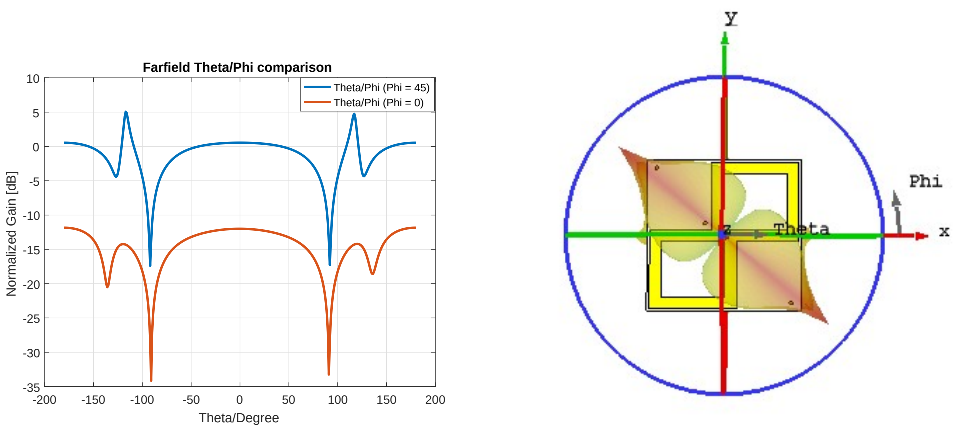


Figure 4.20: θ/ϕ comparison between ϕ=0 and ϕ=45, cartesian plot on the left and 3D on the right.

contain the GSM/GPRS module, that would be necessary for the link between the gateway and the TTN server, right now, this link is being established through ethernet.

The cable needed to implement the ethernet link, obviously prevents the application of the gateway system on a drone or at any other flying main frame. The effort necessary to set up the previous link with resource to wi-fi was considered, however, it was not put into work because on a real implementation, that link would not be capable of sending down the packages received by the LoRa concentrator due to the long distance it is supposed to be. The ethernet was the solution to go, with the view to simplify the system, and having a more reliable link, since the gateway was placed at a fixed location.

As explained on the previous paragraph, the fact that the gateway was placed at a fixed location during the test procedure, the power supply used was not a battery, but the house's electrical system, which also simplified the system.

On the other side of the application, as explained in chapter 3.3.1, the end device tested was the P–NUCLEO–LRWAN1, using a Semtech/MBED firmware, called LoRaWAN-Demo-72, which is a sample code containing all the structure needed to set up a simple end-device. The structure mentioned before has all the functions and software macros that link the microcontroller to the LoRa module on the nucleo pack and its responsible to concatenate the information requested and then send it.

Once again, in order to simplify and expedite the process, this open-source firmware was used off-the-shelf, being the modifications only the necessary to implement a working application on the TTN server and the selection of the proper macros to be used.

To test the link between the end-device and the gateway, the parameters that needed a revision and actualization were:

- Activation method: Activation By Personalization (ABP) –instead of Over-the-Air Activation (OTAA), ABP was chosen to, once again, make the connection simpler, however, skipping the join procedure has some downsides related to security;

- Frequency: The European ISM band of 868MHz;

- Adaptive Data Rate: ADR can be set ON if the end-device is at a fixed location. In this case, as the test procedure involved a moving end-device, this parameter was set to OFF.

- Default Data Rate: As a consequence of the previous parameter, the data rate cannot be dynamic neither estimated by the network, because the SNR values calculated on the reception side can be prevenient from different locations. To overcome that, the data rate chosen was the one correspondent to a spreading factor of 12 with 125 kHz of bandwidth.

Fig. 4.21 presents the serial output menu provided by the firmware used on the end-device, where it is possible to observe the configuration parameters used such as the activation method chosen, the state of ADR and even uplink information, as the data rate, port used to communicate, how many packages sent since ON and the actual data sent on the last package.

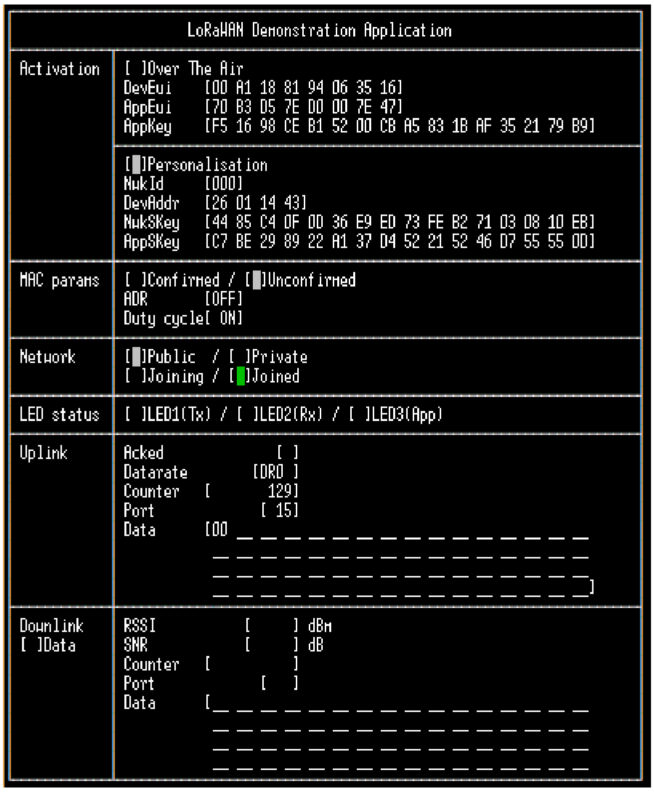


Figure 4.21: LoRaWAN-Demo-72 serial output.

To give the user the possibility of visualizing and understand the network dataflow, all the data is sent to the TTN servers, where can be displayed and analyzed on the specific application.

A TTN application is where one can register its own devices and see the messages flow, as well as their content. To note that the LoRa efficiency is yet low, so, the number of packages received by one gateway and displayed on the application, is normally well above from the number of packages sent by the end-devices.

Fig. 4.22 presents a general view of messages sent to TTN by a gateway, from devices registered to that application.

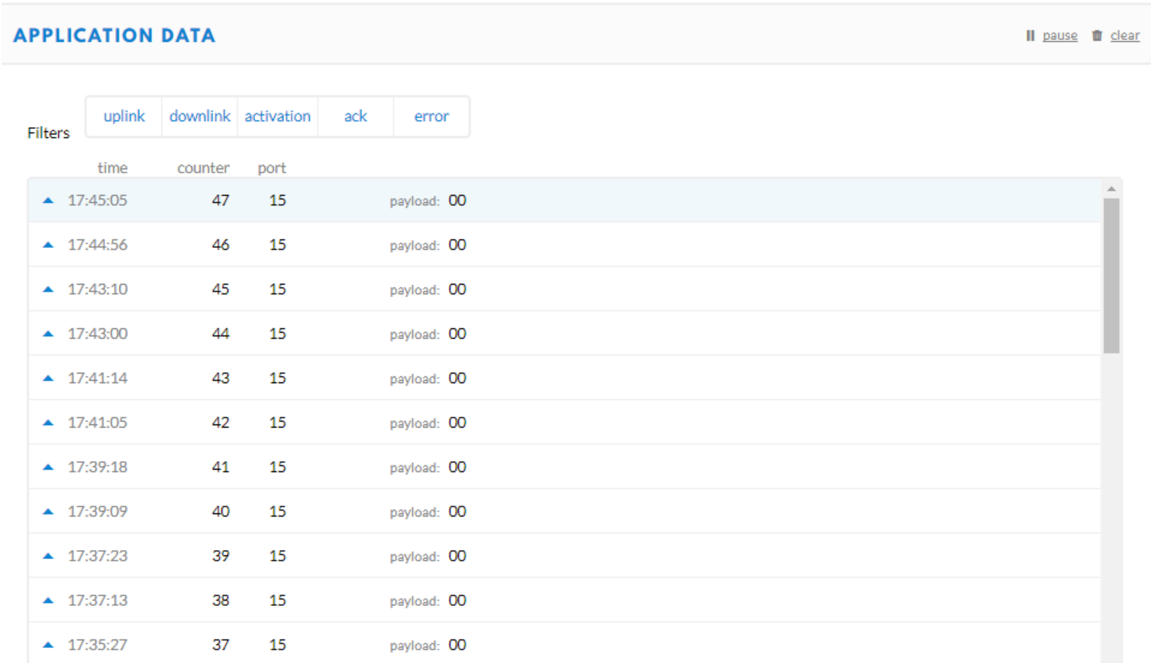


Figure 4.22: List of received messages on TTN application.

4.2.1 Test Procedure

This work subsection presents the results obtained for the two types of realized tests, indoor and outdoor.

After everything up and running, an initial indoor, close distance test was performed. Fig. 4.23 shows the setup used on this performance evaluation.

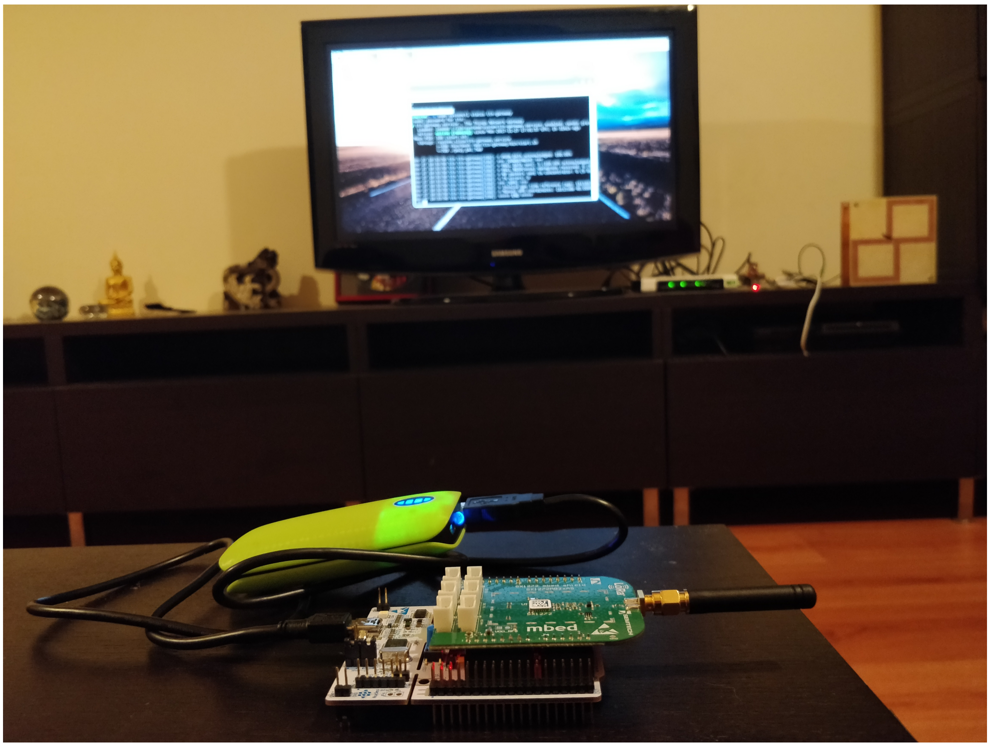


Figure 4.23: Gateway and end-device setup to the close distance test.

Due to the close distance to which this test was performed, the loss package rate was very low, and almost 100%of the packages sent by the end-device were received by the gateway and sent to the TTN. To note that not all the packages were received due to the low efficiency of LoRa, what makes it loss some data even though the receiver and emitter system were very close. Fig. 4.24 shows the information displayed on the TTN about every single package received. In there it is possible to observe the data rate and bandwidth with which package was sent, the time stamp, modulation technique used and from which device that package comes from. Besides that, it is also possible to see how many gateways have received that individual package.

Figure 4.24: Package information, indoor close distance test.

Furthermore, a much more useful information presented on those packages are the estimated values for RSSI and SNR. To note that the values presented are calculated by the gateway firmware, from which one does not have access to better understand how the values are calculated, seeing this values as relatives to each other, and not as absolute values.

For the indoor test, considering a distance of two meters between the end-device and the gateway, the average values of RSSI and SNR were -66 dB and 8.5 respectively.

Referring to table 1.3, the SNR limit which a signal can be demodulated if it is sent with a SP of 12 is -20 dB. The average SNR values are well above, as expected. However, the RSSI values achieved for such a small distance are above the expectations, which is mainly due to the gateway antenna adaptation and directivity.

The second test was performed on the outdoor and had the main purpose of understand the range capabilities of the application.

The gateway system remains fixed on the same spot. On the end-device side, a little battery was used power up the node, and it was placed inside a moving car. Although that were not the better conditions to test a radio link, because of the car's building materials, it was the best way to find the range limits of the application, allied with the urban obstacles. Fig. 4.25 presents the end-device setup.

Figure 4.25: End-device setup for the outdoor test.

Once again, the different received packages were displayed on the TTN application, as shown on Fig. 4.26.

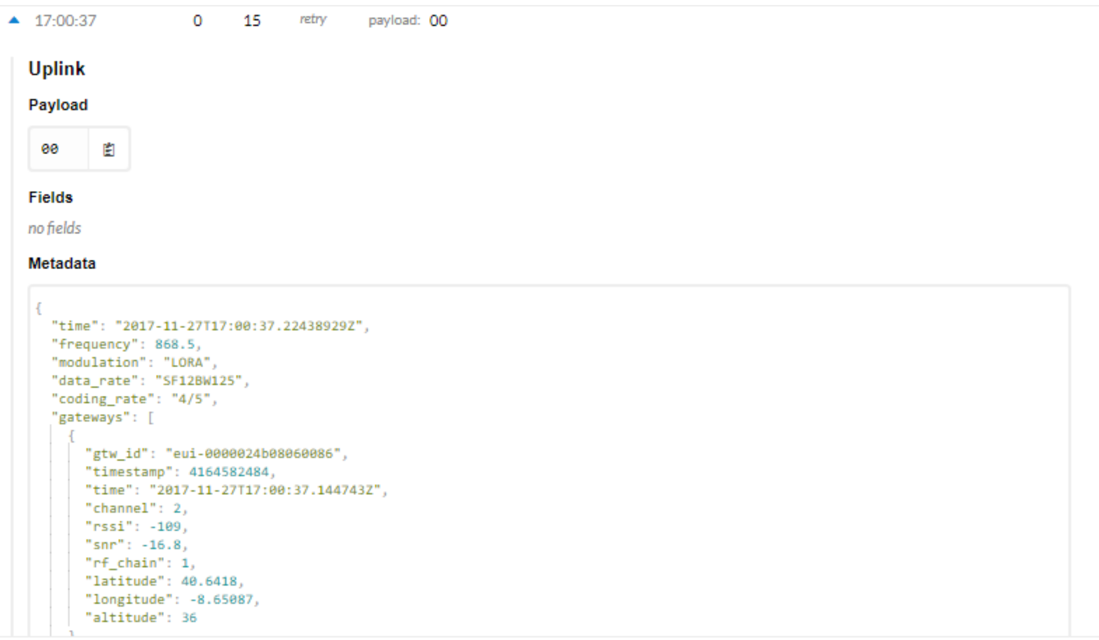


Figure 4.26: Received package from the outdoor test.

Considering the location of the gateway, the package sent from the most distant point, was at 500 m in a straight line. That package had an RSSI = -109 and SNR = -16.8.

It is obvious that those values are well below then the ones needed for a LEO satellite link, but it is pretty clear as well that, the path conditions in both cases are completely different, being the one tested much more conducive to failure because there are far fewer (or even none) links with straight line of sight.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

Referring the abstract of this work, where is said that "This dissertation arises with the purpose of developing a super low-cost micro satellite for an Internet of Things network, using LoRa technology", one can easily understand that the main goal was not achieved.

In first place, the incapacity due to time related aspects and difficulties on basic but vital processes, made it impossible to assemble both final systems, end-devices and gateway, as expected in the initial architecture design.

On the end-device system, although the hardware was built, it was never used, mainly because the chosen LoRa radio, RFM95, does not have the LoRaWAN protocol implemented. Due to that, the CPU must have a bigger memory, to implement that layer, which requires a great amount of effort that was not possible to spend. This problem was only diagnosed after the purchase of materials, making the ST board the solution to test on this work, however, having the hardware almost ready for a future implementation.

On a second version, in order to simplify the system and reduce the effort, the solution comes to change the LoRa radio, to one with the LoRaWAN layer already implemented, like the RN2483 from Microship. This solution is better because it is much more effortless than trying to use the raw LoRa modulation and demodulate it after on the gateway.

On the reception side, the gateway system, as said in the previous chapter, suffered some modifications, which affected directly the project's main goal. The fact that the GSM/GPRS link was not built made it impossible to assemble a "flying" system.

Regarding the test done at a close distance, the system had a great performance, with an average RSSI of -66dB and an SNR of 8.5, which makes it a very good solution for indoor applications, however, has seen on chapters 1 and 2, it is not the main objective of this technology.

The second test performed, that intended to evaluate the system range, fell far short of expectations. The longest link obtained had the two systems only separated by approximately 500 m, with an SNR of -16.8. One has to take into account that the test conditions were not the best, considering that the end-device was placed inside a car, which affects the electromagnetic field due to its metal composition and because of the indoor placement of the gateway antenna.

The fact that there was not line of sight between the systems and the test was performed on an urban environment, the reflections and obstacles present on this scenario greatly affected the overall system performance.

With regard to the studies made on the antenna to build for the gateway, observing the results on chapter 4, the biquad antenna was clearly the best option, however, due to its unusual form, the practical results were far below than the ones simulated, which also affected the system performance.

One can conclude that for the application it was supposed to serve, the physical aspect of the antenna was completely reached, presenting an 171 x 168 x 40 mm antenna, considering the initial premise, however, to the conditions it ended up being tested, it is not suitable. The directivity presented by the antenna, assembled on the underside of a flying mechanical main frame, would provide a considerable coverage area to the application. On earth, and with obstacles in the surroundings, the antenna applicability would be reduced.

In conclusion, one can understand that the main goal of this work, to create a micro-satellite network for IoS, was not reached, however, with future work, the proof of concept that the technology used is capable of this link is still possible to be achieved.

5.2 Future Work

With all the conclusions taken, it is easy to understand that there is a lot of room and need for future work.

Although the results were not the ones expected, there are a lot of lessons to be taken in order to improve the quality and applicability of this work, to its primary goal.

First of all, the end-device system, must be modified taken into account what said in section 5.1. Although it can make the device slightly more power hungry, because the Microship module has bigger power consumption, it will enable the manufacturing of a tiny yet powerful and versatile IoT/IoS end-device. To note reference to not only internet of space, but also to internet of things, because once made, the panoply of applications is huge.

The way the gateway system is implemented right now, although not suitable for an IoS application as it should be, it is ready to be implemented in other solutions, as industries or at agriculture fields. To become part of a near space solution, again, the GSM/GPRS link is fundamental and one of the things to do as future work.

Regarding the antennas, trying to explore another layout or improve the adaptation of the existing one is a major key to the success of a future application. To other applications, as the ones mentioned above, the antenna would need to be totally different, suggesting omnidirectional radiation patterns as a solution.

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