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Trabajo Fin de Grado

Evaluación del rango de cobertura de una red LoRaWAN utilizando un dispositivo personalizado

(*Evaluation of LoRaWAN Network Coverage Using Custom Made Device*)

Para acceder al Título de

Graduado en Ingeniería de Tecnologías de Telecomunicación

Autor: Andrea Fernández Sierra

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FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION

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BRNO UNIVERSITY OF TECHNOLOGY

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FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION

FAKULTA ELEKTROTECHNIKY A KOMUNIKACNÍCH TECHNOLOGIÍ

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ÚSTAV TELEKOMUNIKACÍ

EVALUATION OF LORAWAN NETWORK COVERAGE USING CUSTOM MADE DEVICE

VYHODNOCENÍ LORAWANOVÉ SÍTOVÉHO PROVOZU S POUŽITÍM ZARZENÍ PRO UŽIVATELE

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- Porovnejte výsledky simulace s výsledky naměřenými na reálných sy
- Dosažené výsledky zhodnoťte

DOPORUČENÁ LITERATURA:

[1] CHRISTIANSEN, Donald. *Electronics engineers' handbook*. 4th ed. New York: McGraw Hill, 1997. ISBN 0070210772.

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Abstract

The topic of this thesis is to study the Low Power Wide Area (LPWA) networks. It will be focused on the different LPWA technologies that will be explained later in detail: SigFox, LoRaWAN and NB-IoT. In the practical part, the functionality and coverage of BUT gateway (gateway of the University of Brno) will be evaluated using custom made device. These results will be further compared with the public The Things Network (formed by three gateways, the University gateway and other two). The outcome of this thesis will be to evaluate the real-life implementation of LoRaWAN technology in terms of coverage.

El tema de este proyecto es estudiar las redes de área extensa de baja potencia (LPWAN). En primer lugar, se prestará atención a las tecnologías LPWA que se describirán en detalle: SigFox, LoRaWAN y NB-IoT. En la parte práctica, con un dispositivo personalizado se evaluará la funcionalidad y la cobertura de la puerta de enlace BUT (puerta de enlace de la Universidad de Brno). Estos resultados serán comparados con la red pública TTN (formada por tres puertas de enlace, puerta de enlace de la Universidad y dos más). El resultado de este proyecto será la evaluación de la implementación en la vida real de la tecnología LoRaWAN en términos de cobertura.

Key words

IoT, LPWA , LPWAN, SigFox, LoRa, LoRaWAN, NB-IoT, Lora Module, RN2483, Coverage.

1 Introduction

Nowadays, we live in a connected world in where the Internet of Things (IoT) is becoming increasingly important. IoT is a concept that identifies the connection of devices to the network and the subsequent compilation processing of data. In the case of IoT, these devices are connected to the Internet, allowing them not only to communicate with each other, also access to Internet services, or interact directly with people.

In the area of IoT, the Low Power Wide Area Networks (LPWAN) are emerging, centralizing the interest of industry and standardization bodies. LPWAN are characterized by offering long-range wireless connectivity, low power consumption and low cost between connected devices, such as sensors powered by batteries.

LPWAN technologies are designed for Machine to Machine (M2M) environments. When a machine communicates with another machine to accumulate information and exchange data, it is called machine to machine communication (M2M). When a human communicates with human via signs and languages, this is called human to human communication (H2H). M2M and IoT are the fastest growing technology for the future, but without H2H, we will never be able to unlock its full potential. M2M will always call for H2H. M2M implementations without H2H can not generate the expected returns unless humans are able to defy distance instantly to address issues, solve problems and handle cases (real-time).

Fig. 1.1: Human to Human communication[1].

Making use of the Internet of Things (IoT) model to the industry, we obtain Industry 4.0 or Industrial Internet of Things (IIoT). The manufacture processes are in a digital transformation, produced by the advancement of information technologies and, particularly, the software.

This thesis is divided in two parts, a first theoretical part and a second part of implementation and measures.

In the first section of this chapter an introduction to the LPWA networks. In the second chapter a detailed description of SigFox, LoRa (WAN) and NB-IoT will be offered, where its definitions and most relevant characteristics will be defined.

In the practical part, third chapter, the main objective is to connect the custom made device to the network of the Brno University of Technology, and the exchange of information between them. The obtained results in the tests carried out (in real conditions included) and the conclusions will be explained.

A fourth chapter will be dedicated to interpretate the conclusions of this thesis[1] [3].

1.1 LPWA Networks: Description of differences between licensed and unlicensed M2M communication technologies

This section gives a detailed overview of LPWAN, covering the characteristics of LPWAN as well as Licenced vs Unlicensed LPWAN.

The widely used short-range radio technologies (e.g. ZigBee, Bluetooth) are not adapted for scenarios that require long range transmission. Solutions based on cellular communications (e.g. 2G, 3G, and 4G) can provide larger coverage, but they consume excessive device energy. Therefore, IoT applications requirements have driven the emergence of a new wireless communication technology: low power wide area network (LPWAN).

LPWAN is increasingly gaining popularity in industrial and research communities because of its low power, long range, and low-cost communication characteristics. It provides long-range communication up to 10–40 km in rural zones and 1–5 km in urban zones. In addition, it is highly energy efficient(i.e. more than 10 years of battery lifetime) and inexpensive. In summary, LPWAN is highly suitable for IoT applications that only need to transmit tiny amounts of data in long range. Many of the LPWA technologies depicted in Fig. 1.2 have arisen as well as unlicensed frequency bandwidth. Among them, LoRa and NB-IoT are today's leading emergent technologies which involve many technical differences[2] [3].

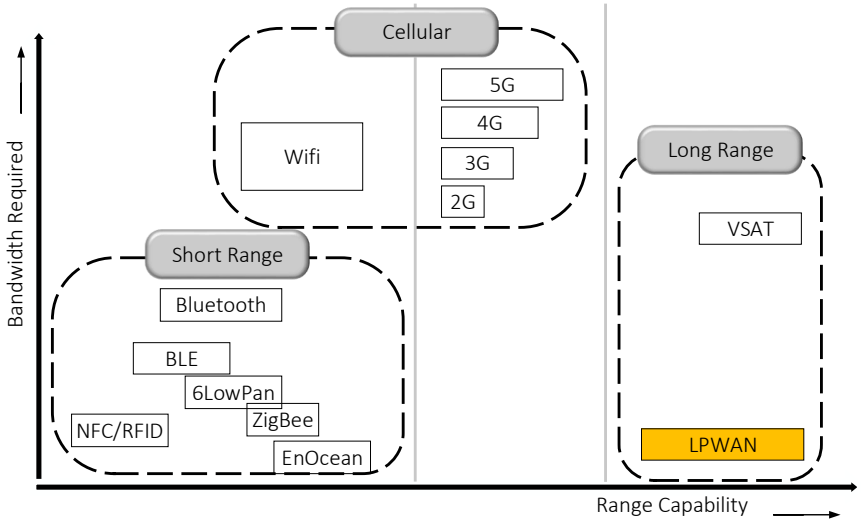


Fig. 1.2: Required bandwidth vs. range capacity of short distance, cellular, and LPWA[2].

Finally in Fig. 1.3 it can be seen how each technology is located compared to other existing technologies in key points such as coverage, range, power consumption...

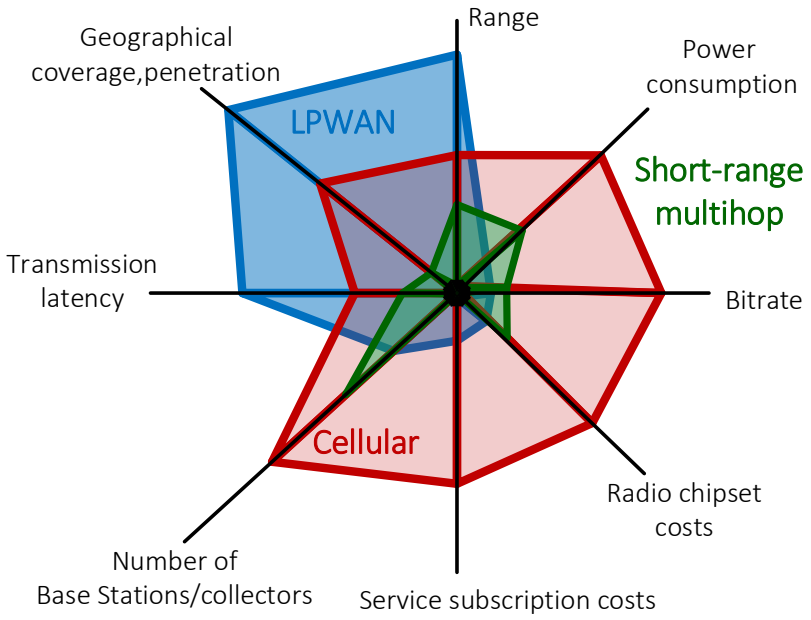


Fig. 1.3: Comparative networks[3].

2 LPWA Technologies

This chapter will be focused on the aforementioned emerging patented technologies and its technical aspects: Sigfox, LoRa and NB-IoT. They will be summarised in a comparative table 2.1.

2.1 SigFox

Sigfox is a communication technology standard of LPWAN which gives an end to end connectivity solution. Sigfox allows end devices to connect with patented base stations which are equipped with software defined cognitive radios using an IP based network[2].

2.1.1 Frequency spectrum utilization and access to the RAN

Sigfox uses the unlicensed ISM bands, 868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia.

The spectrum is divided into 400 channels of 100 Hz each one. 40 Channels are reserved and not used.

The transmissions do not choose a specific channel to send the messages, the frequencies will be randomly chosen from the allocated spectrum according to the channel bandwidth and the allocated spectrum mentioned before. Each message is transmitted by three times by default, this has two objectives:

At first, Sigfox supported uplink communications only. Later on, it was progressing into a bidirectional technology. Downlink transmissions are not very frequent, retransmissions are the existing way to check that the message will reach the base station. The number of messages over the uplink is limited to 140 messages per day. However, the number of messages over the downlink is limited to 4 messages per day, which means that the acknowledgement of every uplink message is not supported.

On the other hand, each transmission is broadcasted in a different frequency. So, the effects of fading are diminished. The reliability is ensured by the use of time and frequency diversity[5] [2] [6].

2.1.2 Physical layer (modulation, frame, subframe, . . .)

Sigfox uses ultra-narrowband technology (UNB). It utilises a digital modulation process named as binary phase-shift keying (BPSK) in an ultra-narrow band (100 Hz) sub-GHz ISM band carrier (Fig. 2.1).

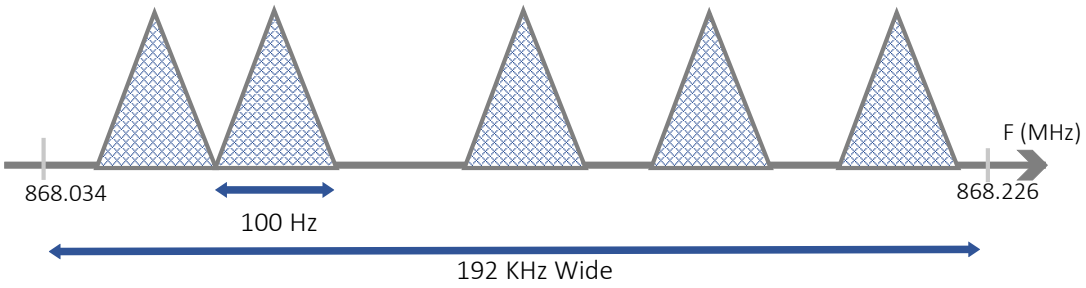


Fig. 2.1: Sigfox technology based on Ultra-Narrow Band [9].

Due to ultra-narrow spectral occupation, the noise contribution is very low; it has a very low power consumption, high receiver sensitivity and low-cost antenna design. The system is able to demodulate a low power signal up to 142 dBm.

The frame structure is formed by a physical header, a MAC header, the user data packet, a hash of variable length and the CRC (Cyclic Redundancy Check). The CRC is an error-detecting code commonly used in digital networks and storage devices to detect accidental changes to raw data.

The physical header is formed by a preamble of 4 bytes for synchronization with the receiver and frame synchronization of 2 bytes that express a unique device ID which it is issued as a sender address.

The user data packet is up to 12 bytes. The hash is generated from a secret key that every end point has stored and it is used to authenticate the payload at the receiver. The CRC of the error control is 2 bytes [5] [2] [6] [7].

2.1.3 Higher layers in ISO/OSI or TCP/IP models

SigFox protocol stack is formed by three main layers: Frame, MAC and Physical layers. Figure 2.2 below shows a comparison between SigFox and the OSI reference model.

The physical layer handles the modulation, the bit rate and transmission power control, and the radio resource occupation. Ultra-narrowband technology is identified by using a technique named as Random Frequency and Time Division Multiple Access (RFTDMA) (section 2.1).

The Medium Access Control layer header adds a field for identification device and detecting code errors. The MAC layer can identify and order the generation of the radio frames with an included sequence number.

The purpose of the frame layer is to receive the payload that comes from the application layer, to do the segmentation and delivery of the fragments to the MAC layer[8].

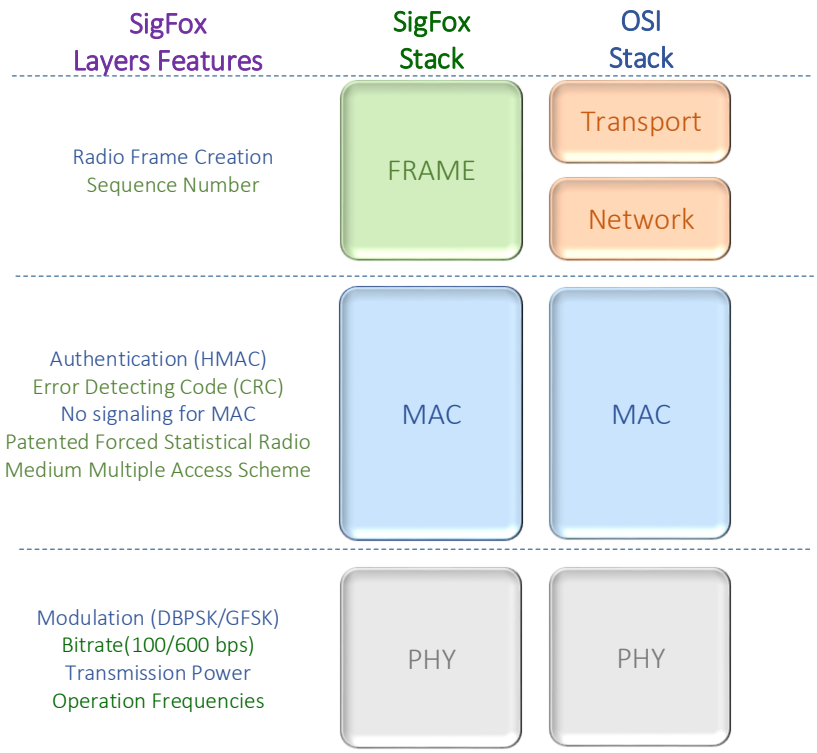


Fig. 2.2: Sigfox protocol Stack[8].

2.1.4 Security

Sigfox is mostly dedicated in protecting against attacks on the integrity of the network, employing sequencing, message scrambling and antireplay techniques.

Security of the payload is left to the customer. It is the customer's responsibility to structure and encrypt the payload because as Sigfox is only a transport channel.

Furthermore, Sigfox is applying security by default principles in all the components it offers to Sigfox users, Sigfox operators, device manufacturers and end-customers:

- Cryptography based on Advanced Encryption Standard (AES) with no key OTA transmission.
- Payload encryption, as an option to ensure the confidentiality of the data.
- Isolation of each part of the network and assess the risks. In case of a hack minor segment of the network is impacted.

On the device side, three levels of security are defined. Depending on its use and sensitivity, the device maker will decide what level will be implemented: medium, high or very high.

The data transferred over the network is encrypted by the secure element. The secret key is only known by the device and the end customer[6] [9].

2.2 LoRa(WAN)

LoRa is the abbreviation of Long Range. LoRa defines a physical layer technology developed in 2010 by Cycleo. LoRa has been designed to communicate over long distances with low power consumptions performance and high immunity to interference. LoRaWAN is a network specification proposed in 2015 by LoRa Alliance, which offers a MAC layer based on LoRa modulation[10].

2.2.1 Frequency spectrum utilization and access to the RAN

LoRa modulates the signals in sub-GHz ISM band using a proprietary spread spectrum technique. LoRa uses unlicensed ISM bands as Sigfox. The bidirectional communication is provided by the chirp spread spectrum (CSS) modulation which we will explain in the following subsection.

Depending on which part of the world we are located, LoRa works in different bands. In Europe, the frequency band used is the 863-870 MHz ISM Band regulated by ETSI (European Telecommunications Standards Institute). It uses 8 randomly choosen channels, all of them are separated by 0.3 MHz in relation to the adjacent channels.The Fig. 2.3 shown 8 channels of the European frequency band. The frequency band used in the USA, Canada, Australia, Singapore or Israel is the ISM band of 902 - 928 MHz, using 13 channels. All the channels are separated by 2.16 MHz in relation to the adjacent channels. These channels are chosen randomly, adjusting to the channels used for the use of XBee of 900 MHz. This thesis aims to use the 868 MHz band.

Regarding the network architecture, LoRaWAN uses a long-range star topology where the gateways are used to relay messages between end-devices and a central core network. Each data message is transmitted by a node and it is received by all the gateways in the range. The nodes are not associated with a specific gateway. This redundant reception improves the number of messages received successfully. However, this feature requires multiple gateways, which may increase the network deployment cost. The received packet is forwarded by each gateway from the end node to the cloud-based network server via backhaul. The network server is able

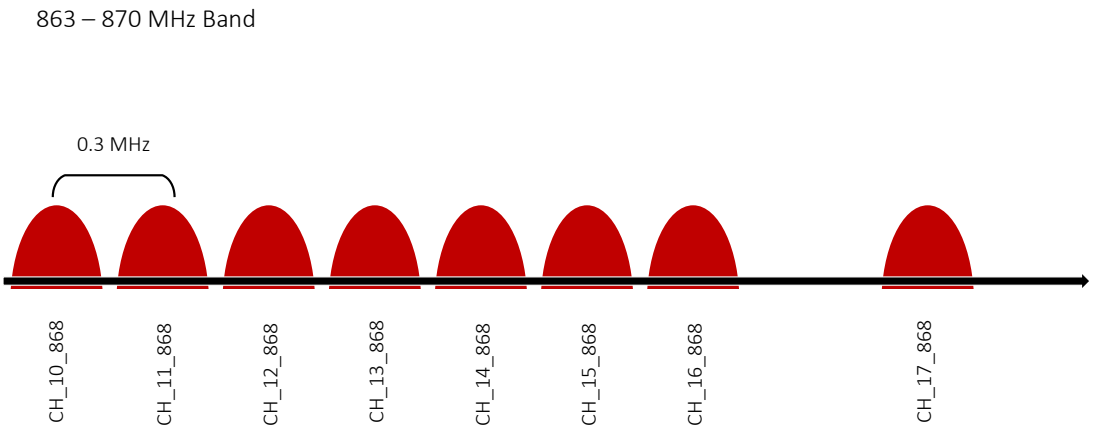


Fig. 2.3: European frequency band used for LoRa[10].

to filter the duplicate receptions from different gateways, to check security, to send ACKs to the gateways and the messages to the specific application server.

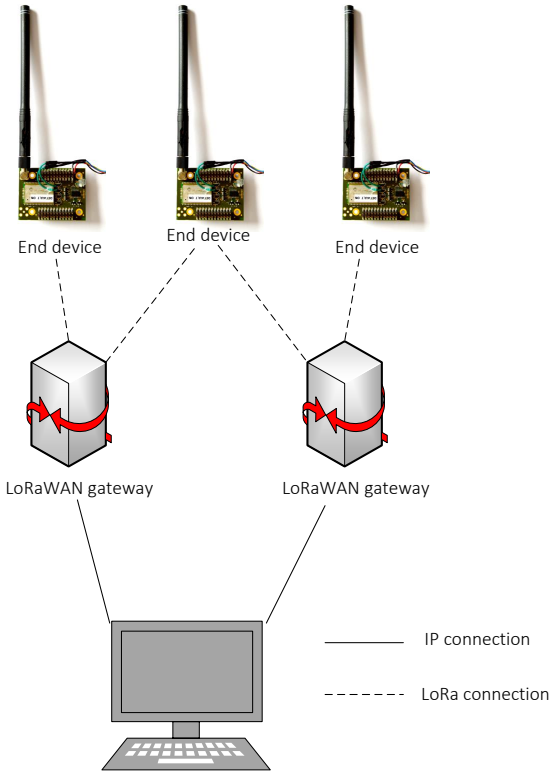


Fig. 2.4: LoRa network architecture[12].

The gateways connect to the server through a standard IP connection while the nodes connect to the gateway or to the server, through a direct link using LoRa or

FSK (Fig. 2.4). The communication can be unidirectional or bidirectional, in the last case, upward traffic predominates.

The LoRaWAN standard specifies how an end node can join the network. There are two methods, the end devices can be activated over the air (OTAA) or by personalization (ABP) Different keys and identifiers are needed during the joining procedure, also to communicate during session [2] [5] [10] [11] [12].

- **OTAA**: The node and the server negotiate the encryption keys when the node joins the network. The node sends:
  - **the DevEUI, (Device EUI)**: is a global end-device ID in IEEE EUI64 address space that uniquely identifies the end-device.
  - **the AppEUI (Application EUI)**: is an application Identifier, uniquely identifies the application globally. It is assigned by network server.
  - **the Appkey, (Application Key)**: is AES-128 root key specific to the end-device that is assigned to the end-device during fabrication. It is used to generate two session keys which are called NwkSKey and AppSKey.

  Afterwards, the server sends you the address of the device and both keys. All this procedure is necessary before the packets transmission.
- **ABP**: The packets transmission starts from the beginning of the join. The node and the server, both know:
  - **The NwkSKey**: is an specific network session key of the end-device. It is used for interaction between the Node and the Network Server. This key is used to check the validity of the messages (MIC check).
  - **The AppSKey**: is an specific application session key of the end-device. It is used by the application server and the end-device to encrypt and decrypt the payload field of the application. It provides specific data messages.
  - **The DevAddr**: consists of 32 bits. It identifies the end-device within the current network. The DevAddr is allocated by the Network Server of the end-device.

Additional to the two methods to join the end nodes to a the LoRaWAN network, LoRaWAN devices can operate in two different ways:

- **P2P mode**: The nodes can connect between each other directly (LoRa networks).
- **Hybrid mode**: Combination between P2P and LoRaWAN modes to send messages through LoRaWAN networks. In this mode a LoRaWAN license is required. A gateway in hybrid mode (central node) and the others nodes in P2P mode. The idea is that the gateway listens to P2P packets and relay them to the LoRaWAN infrastructure [13] [14] [15].

Picture below shows the Hybrid mode scheme (Fig. 2.5):

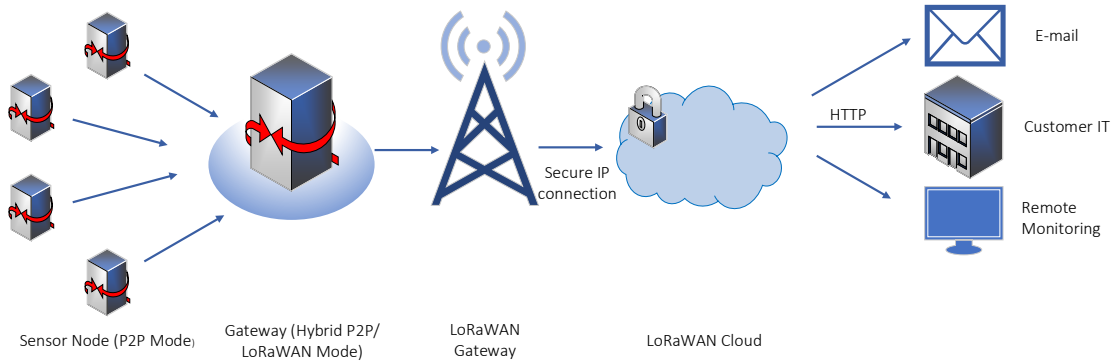


Fig. 2.5: Hybrid mode scheme [10].

2.2.2 Physical layer (modulation, frame, subframe, . . .)

LoRa is a spread spectrum modulation technique based on Chirp spread spectrum (CSS). It is a technique that uses chirp pulses to encode information. Data is modulated on different channels and speeds (section 2.2.1) with forward error correction (FEC). The signal resulted has low noise levels, enabling high interference resilience.

Due to the linearity of the chirp pulses, the frequency offsets between the receiver and the transmitter are equivalent to timing offsets, and they are eliminated easily in the decoder. This makes this modulation immune to the Doppler effect, equivalent to a frequency offset.

LoRa is described as a modulated chirp frequency which maintains the same low power characteristics as the FSK modulation with significantly increases of communication range. It uses coding gain to increase the sensitivity of the receiver and it is capable of reaching transmission speeds between 0.3 and 50 Kbps. It makes it suitable for P2P communications between nodes.

LoRa uses six spreading factors from SF7 to SF12. The spreading factors are the duration of the chirp. SF7 is the shortest time on the air and SF12 is the longest. Each step in spreading factor multiply by two the time on the air to transmit the same amount of data (Fig.2.6). The messages transmitted by using different spreading factors can be received simultaneously by LoRa base stations.

LoRa uses three bandwidths: 125kHz, 250kHz and 500kHz in the HF ISM 868. The chirp uses the entire bandwidth. If the same bandwidth is using during a longer period of time on the air, the results in less data transmitted per unit of time.

The data rate is the number of bits to encode the data. It is an integer value between 0 and 15, it affects modulation, spreading factor and the bandwidth. Depending on the SF in use, LoRaWAN data rate ranges from 0.3 Kbps to 27 kbps.

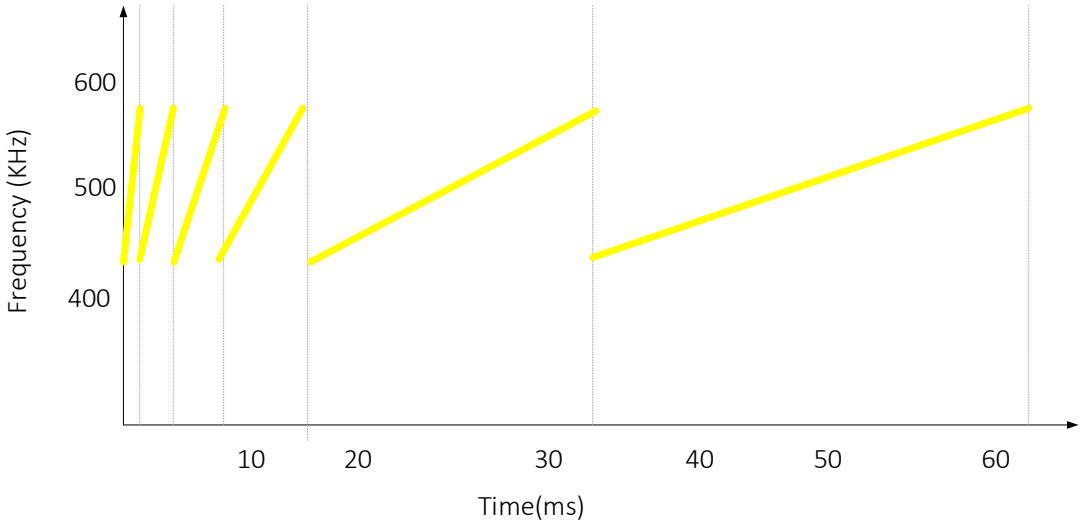


Fig. 2.6: LoRa Spreading Factors SF7 - SF12 [16].

In the practical part, the data rate will be set to 0, which implies an SF of 12 a bandwidth of 125 KHz.

The maximum duty cycle, is defined as the maximum percentage of time during an end-device occupies a channel. The selection of the channel must be implemented pseudo-random channel hopping at each transmission and to be compliant with the maximum duty cycle. Messages per day are unlimited[2] [10] [12].

2.2.3 Higher layers in ISO/OSI or TCP/IP models

It is known that LoRa defines the physical layer while LoRaWAN defines the MAC communication protocol. MAC (Media Access Control) layer is one of two sublayers that make the Data Link Layer of the OSI model (Fig. 2.7).

LoRaWAN defines three types of devices (Classes A, B, and C) with different capabilities.

- **Class A**: End-devices of class A allow bidirectional communications where each end-devices uplink transmission followed by two short downlinks receive windows (Fig. 2.8). These devices use for the uplink pure ALOHA access. Pure ALOHA is a random-access protocol that is implemented within the MAC layer, a sublayer of the link layer. Its purpose is to determine which station of the competition can have the opportunity to access the multiple access channel in the MAC layer.
  Each receive window is defined by the duration, an offset time, and a data rate. The offset time recommended for each receive is 1 s and 2 s, although it can be configurable. Downlink transmission is allowed only after a successful uplink

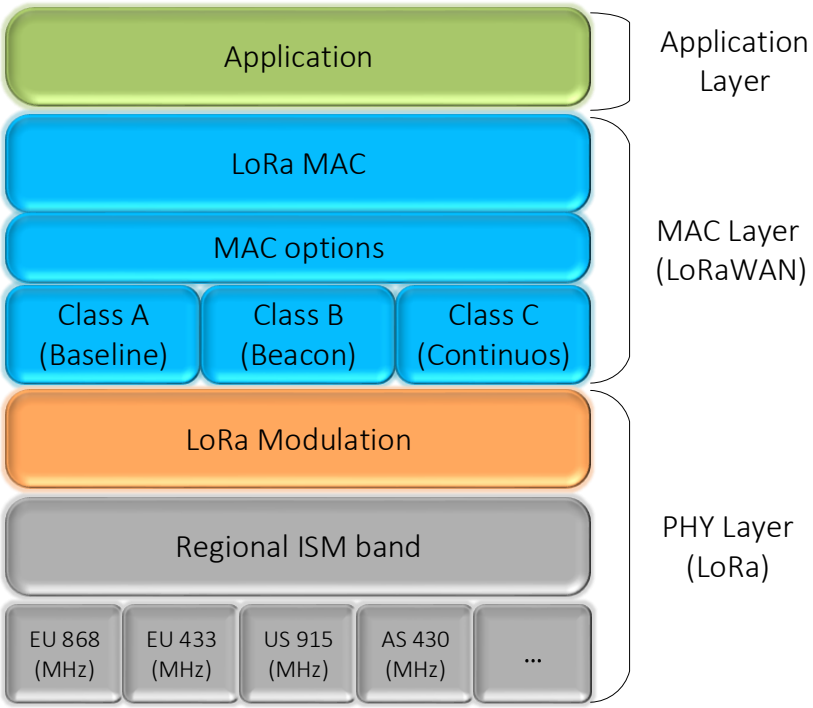


Fig. 2.7: LoRa Protocol Stack [11].

transmission. The data rate used in the first downlink window is calculated. In the second window, the data rate is fixed to the minimum, 0.3 Kbps. Downlink traffic cannot be transmitted until a successful uplink transmission is decoded by the gateway. The second receive window is disabled when downlink traffic is received by the end device in the first window. Class A is the class of LoRaWAN devices with the lowest power consumption.

- **Class B**: these devices are designed for applications with additional downlink traffic. These devices are synchronized by using periodic beacons that are sent by the gateway, the scheduling of additional receive windows for downlink traffic as long as the previous transmissions have not been successful.
- **Class C**: end devices are always listening to the channel except when they are transmitting. The rest of classes are compatible with Class A. Class C devices cannot implement class B. The three classes can coexist in the same network, and devices can switch from one class to another.

  The following figure 2.8 shows the three classes of the current end devices. In class A, the first receive window R×1 comes exactly Receive Delay 1 s after the end of the uplink modulation. The second slot R×2 comes exactly Receive Delay 2 s after the end of the uplink modulation. As shown in Fig. 2.8 in class B, the gateway sends a beacon on a regular beacon delay to synchronize

all the end devices in the network. When an end device receives the beacon, it can open a short reception window named as ping slot predictably during a periodic time slot. For Class C devices, reference to Fig. 2.8 end devices not only open two receive windows as class A, also they open a continuous receive window up to the end of transmission. These class devices are used for applications that have enough power available and thus that do not need to minimize reception time windows [5] [13] [17].

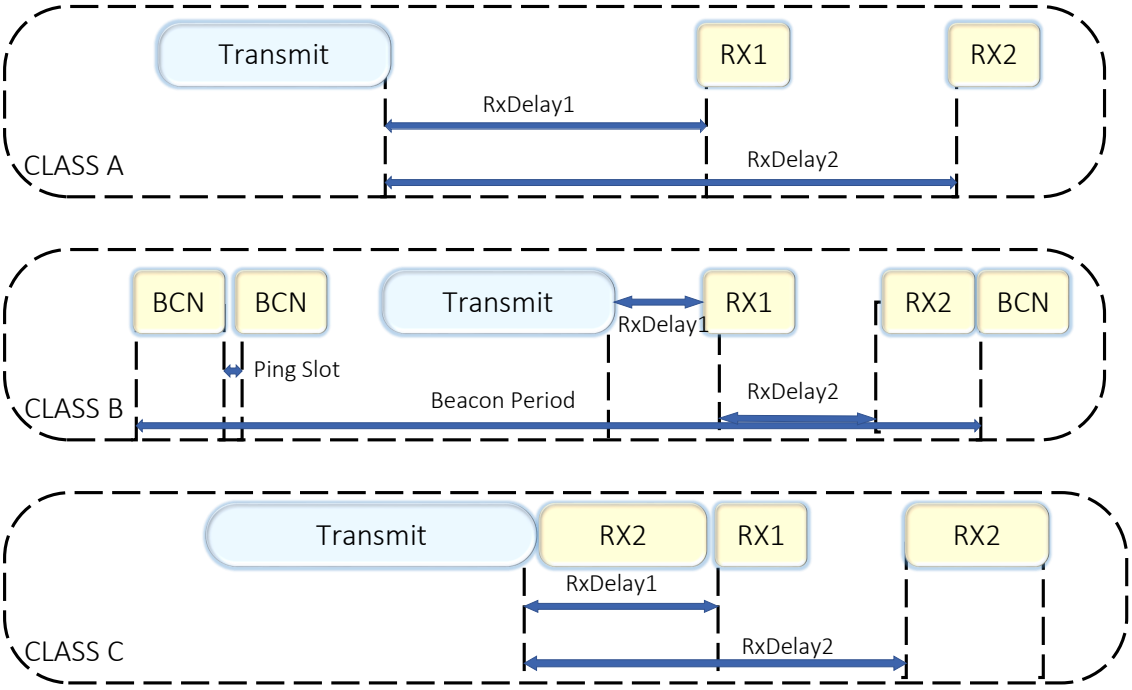


Fig. 2.8: LoRaWAN communication classes[18].

2.2.4 Security

It is extremely important for any LPWAN to incorporate security. LoRaWAN utilizes two layers of security: one for the network and another one for the application. This allows nodes to perform routing and network maintenance tasks while preserving the confidentiality of application data.

The LoRaWAN network solution comes with an authentication and security frameworks based on the AES128 (Advanced Encryption Standard) encryption scheme (Fig. 2.9). The AES-128 encrypts the frame for confidentiality and generates a MIC (Message Integrity Code) for integrity. Each end-device has assigned keys that is done by device manufacturers or the application owners (section 2.2.1).

Authentication and encryption are separated so it is possible to authenticate packets and provide integrity protection.

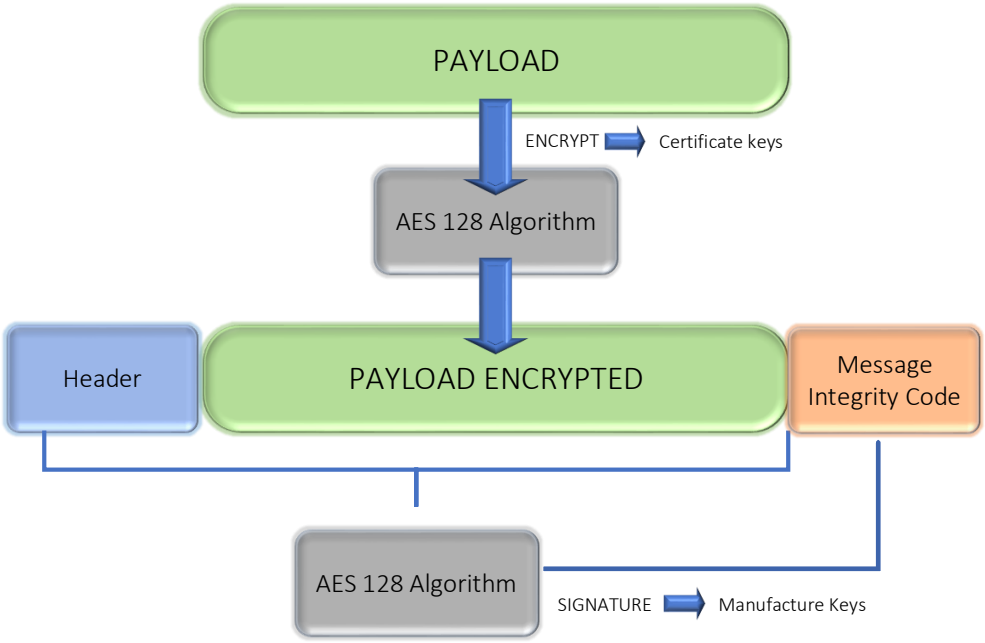


Fig. 2.9: AES-128 encryption scheme [18].

Each message is encrypted by using the XOR operation with the corresponding key (from the key stream) to generate the encrypted payload. The payload length is always the same before and after the encryption. This can be used together with overflowing counters by a malicious entity to restore the key stream from the encrypted messages [5] [11] [18] [19].

2.3 NB-IoT

Narrow-Band Internet of Things (NB-IoT) is a Low Power Wide Area (LPWA) technology proposed in Release 13 of the 3GPP in June 2016 for data perception and acquisition intended for intelligent low-data-rate applications[2].

2.3.1 Frequency spectrum utilization and access to the RAN

NB-IoT uses licensed bands. NB-IoT which can coexist with GSM (global system for mobile communications) and LTE (long-term evolution). NB-IoT only requires a bandwidth of 180 kHz, and LTE devices can use from 1 to 18 MHz. The difference between them is the use of narrowband to reduce device complexity, cost, and power. NB-IoT can only be used and deployed by service providers that have already a frequency license on LTE bands or that have it rented. To improve the capacity

achieved and also,reuse the existing LTE infrastructures. It allows connectivity of end devices up to 100K per cell.

It may be deployed inside an LTE carrier or in the guard band. Figure 2.10 shows the possible operation modes:

- **Stand-alone operation**: Use of current used GSM frequencies.
- **Guard-band operation**: Use of the unused blocks resource within an LTE carrier's guard-band.
- **In-band operation**: Uses of block resources within an LTE carrier. The assignment of resources between LTE and NB-IoT is not fixed.

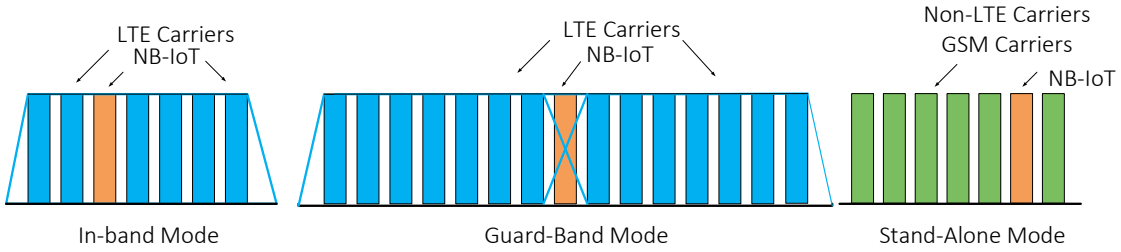


Fig. 2.10: Operation Modes for NB-IoT [23].

The 3GPP recommends the integration of NB-IoT with the LTE cellular networks. NB-IoT is only accepted with a software update and the existing LTE infrastructure. The NB-IoT communication protocol is based on the LTE protocol. NB-IoT reduces LTE protocol functionalities to the minimum and it improves them as required for IoT applications[20] [21] [22] [23].

2.3.2 Physical layer (modulation, frame, subframe, . . .)

NB-IoT uses modulation QPSK, with different methods for downlink or uplink:

- **Downlink**: we use Orthogonal Frequency-Division Multiple Access (OFDMA).
- **Uplink**: the method is single-carrier frequency division multiple access (SC-FDMA).

The data rate is limited to 200 kbps for the downlink and to 20 kbps for the uplink. The maximum payload size for each message is 1600 bytes.

OFDMA and SC-FDMA modulate in time and frequency the signal. The attribution is not the identical for the two methods. The difference between both methods is represented in the figure 2.11 below:

OFDM each subcarrier is attributed with a user dynamically; the 4 symbols are sent at the same time. However, SC-FDMA, instead of sending 4 symbols at the same time, it sends one by one only. This method provides a lower peak power ratio which improves the autonomy of the battery [2] [21] [23] [24].

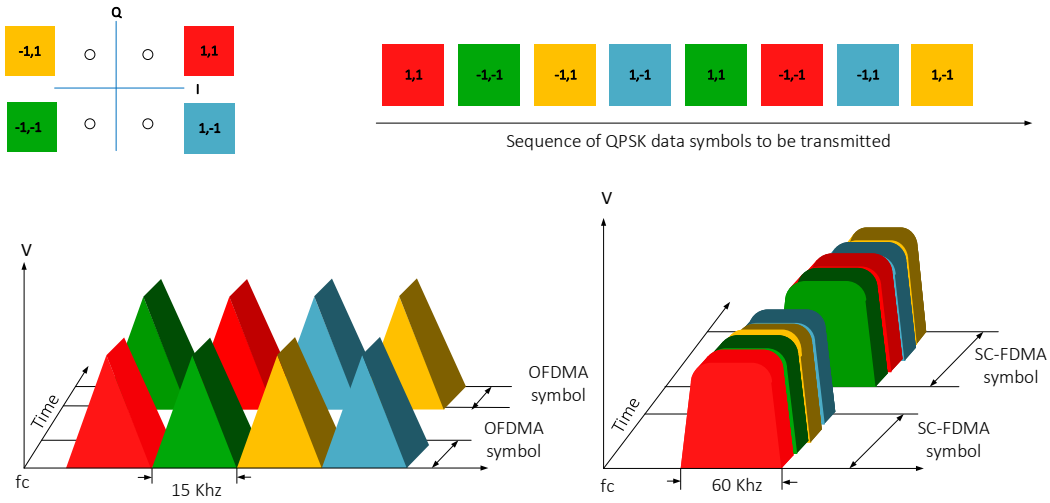


Fig. 2.11: Comparation of OFDMA and SC-FDMA transmitting a series of QPSK data symbols[21].

2.3.3 Higher layers in ISO/OSI or TCP/IP models

In this subsection it has been decided not to go into depth due to its complexity, an overview of each technology with its basic characteristics is intended.

2.3.4 Security

NB-IoT security model is inherited from LTE. The SIM card (USIM (Universal Subscriber Identity Module) since 3G) is the stepping stone for the device authentication and encryption. This card contains subscribers information and keys, however the decive is only identified by the IMEI (International Mobile Equipment Identity) in three-way handshake. This process authenticates device and subscriber on the network and it sets up cryptographic keys, that are used to protect next communications. The benefits of this technology cover massive deployment over the years without any major vulnerability, excluding in earlier 2G standards (A5/1 attack) that have been deprecated and on which NB-IoT devices are not vulnerable. Operators backhauls are protected traditionally with IPSec tunnels.

Most of the end-applications also make use of encryption. They use TLS with an application of servers/cloud. TLS capabilities for IoT and constrained environment are significant increased, including microcontrollers that embeds AES/RSA hardware acceleration engines to offer good security for low no computational cost [21].

	SigFox	**LoRaWAN**	**NB-IoT**
Modulation	BPSK	CSS	QPSK
Frequency	Unlicensed ISM bands (868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia)	Unlicensed ISM bands (868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia)	Licensed LTE frequency
Bandwidth	100 Hz	250 KHz and 125 kHz	180 KHz
Maximum data rate	100 bps	50 kbps	200 kbps
Bidirectional	Limited/Half-duplex	Yes/Half-duplex	Yes/Half-duplex
Maximum messages/day	140(UL),4(DL)	Unlimited	Unlimited
Maximum payload length	12 bytes (UL),8 bytes (DL)	243 bytes	1600 bytes
Range	10 Km (urban), 40 Km (rural)	5 Km (urban), 20 Km (rural)	1 Km (urban), 10 Km (rural)
Interference immunity	Very high	Very high	Low
Authentication and encryption	Not supported	Yes (AES 128b)	Yes (LTE encryption)
Adaptive data rate	No	Yes	No
Handover	End-devices do not join a single base station	End-devices do not join a single base station	End-devices join a single base station
Localization	Yes (RSSI)	Yes (TDOA)	No (under specification)
Allow private network	No	Yes	No
Standardization	Sigfox company is collaborating with ETSI on the standardization of SigFox-based network	LoRa-Alliance	3GPP

Tab. 2.1: Comparative Table [2].

3 Practical Part

This chapter is focused on a detailed description of the practical part of the thesis. It evaluates if the technology achieves expectations according to the specification. LoRaWAN technology is verified in real conditions. The tools used are explained below.

A LoRaWAN infrastructure is implemented to send data automatically.

An Arduino board has been chosen together with a LoRa module to set up the infrastructure mentioned before. As part of this thesis, a "C++ code" has been created to send ten data messages with the selected software (automated process). This “C++ code” is uploaded to the Arduino board.

The connection between LoRa module and the network gateways has been verified as the messages have been successfully received.

In the last part of this chapter, the LoRaWAN technology coverage is discussed based on the results.

3.1 Evaluation of the LoRaWAN module adherence to the standard

This section describes the tools used and the verification of how the technology is adhered to the standard, based on the standard described in the theoretical part of the thesis. At the end of the section, this has been verified with the results obtained.

3.1.1 Utilized hardware and software

To confirm and to evaluate the technology used, different software and hardware tools have been needed. Each of the tools are described in the following subsubsection.

LoRa Module

The LoRa microchip selected has been the RN2483 microchip that works at 868 MHz frequency. It is located inside the LoRa module.

The RN2483 microchip provides LoRaWAN connection through a simple UART interface. This module works with the LoRaWAN class A protocol.

To get access to LoRa technology network, a minimal configuration is required. This configuration can be stored in the EEPROM of the module.

The RN2483 transceiver module features LoRa technology RF modulation, which provides long-range spread spectrum communication with high interference immunity [25].

General features table (Tab. 3.1) is shown:

Modulation	FSK, GFSK, and LoRa Technology modulation
Frequency Band	863.000 MHz to 870.000 MHz ; 433.050 MHz to 434.790 MHz
Maximum Over-the-Air Data Rate	300 Kbps with FSK modulation; 10937 bps with LoRa Technology modulation
Interface	UART
Operation Range	Up to 15 km coverage at suburban ; up to 5 km coverage at urban area
Sensitivity	at 1% PER -146 dBm
RF TX Power	max. 10 dBm on 433 MHz band ; max. 14 dBm on the 868 MHz band
Temperature (operating)	-40 °C to +85 °C

Tab. 3.1: General features RN2483 [25].

Picture below shows the LoRa module (Fig. 3.1) in which the RN2483 microchip is focused, main part of the module:

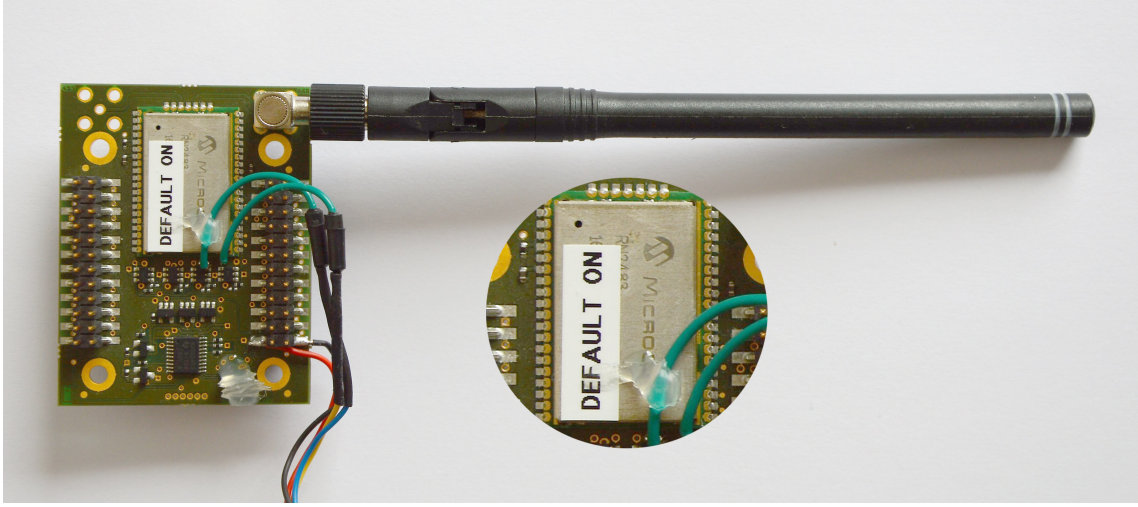


Fig. 3.1: Microchip RN2483 in LoRa module.

Termite Software

Termite 3.4 was the software selected for the first part of this thesis. Termite 3.4 is a software which uses the RS-232 (Recommended Standard 232); it is easy to use in relation with other software. Its interface presents a window where the sent/received information is displayed where a line space is located to write the messages. It is similar to a messaging client.

Its main characteristics are:

- Plug-in interface for data pre-processing.

- History of commands that were written with autocomplete.
- Ability to run with pre-configured settings from a read-only medium.
- Support for non-standard baud rates (MIDI, DMX512).
- Different colour for the transmitted data (blue) and the received data (green).

Laptop HP Pavilion x360

Personal laptop with Windows 10 operating system, Intel Pentium N3520 processor and internal storage of 500 GB. Any computer with similar characteristics would be acceptable.

3.1.2 Verification methodology

Once the software and hardware tools have been explained, the module is evaluated according to the standard. Commands are sent to the module to verify if it works as expected.

The current scenario is shown on the figure 3.2 where you can see the laptop, the LoRa module and the gateway. The laptop is connected with the LoRa module via USB and the LoRa module with the gateway through LoRa technology (wireless technology).

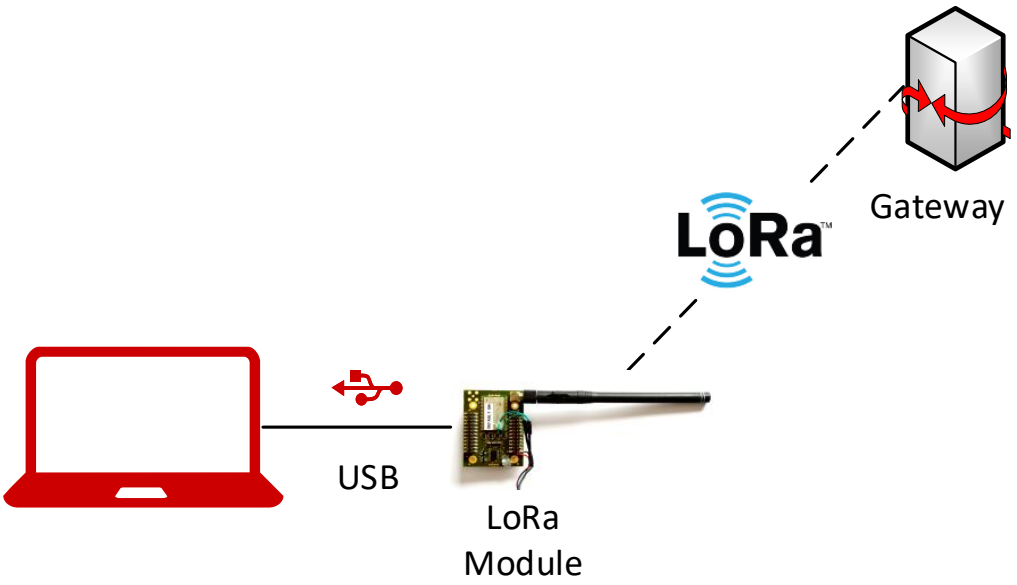


Fig. 3.2: Required scenario to evaluate the module according to the standard.

Default settings for the UART interface are 57600 bps, 8 bits, no parity, 1 stop bit, no flow control are used to communicate with the module.

It must be verified that the port has been recognised in Termite, we must see at the top of the screen: “COM5 57600 bps, 8N1, no flow control".

The version of the module is checked to verify the connection between the computer and the module is working properly. The following command is executed:

```
sys get ver
RN2483 1.0.4 Oct 12 2017 14:59:25
```

This command returns the information related to the hardware platform, firmware version, release date and time stamp on firmware creation.

After getting the communication between the two ends, it must pause the MAC level. The following command pauses the LoRaWAN stack functionality to allow transceiver (radio) configuration. This command replies the time interval in milliseconds that the transceiver can be used without affecting the LoRaWAN functionality.

```
mac pause
4294967245
```

The maximum value 4294967245 is returned whenever the LoRaWAN stack functionality is in the Idle state and the transceiver can be used without restrictions.

Besides, we will check the default configuration:

```
radio get mod
lora
```

This command reads back the current mode of operation of the module, LoRa.

```
radio get freq
868100000
```

This command reads back the current operation frequency of the module in Hz.

Next command reads back the current spreading factor being used by the transceiver. Parameters values can be from SF7 to SF12.

```
radio get sf
sf12
```

This command read back the current operating radio bandwidth used by the transceiver in KHz. The parameter values can be 125, 250 or 500.

```
radio get bw
125
```

At last, to get the coding rate used by the radio. The parameter values can be 4/5, 4/6, 4/7 and 4/8. It uses the following command:

```
radio get cr
4/5
```

As we expected, the module is configured as a LoRa device with a transmit and retransmit frequency of 868.1 MHz. A spreading factor of 12 defines the sensibility of the reception. A bandwidth of 125 KHz which determine the time on air, in our

case 1 second. The coding rate 4/5 is the best error correction mechanism. Each parameter stablished conform the standard EU-868.

The device mode will be configured. There are two possible modes we have mentioned before, OTAA and ABP. In our case, we will configure it in ABP mode. For this, it is necessary to know the keys: DevEUI, DevAddr, nwkskey, and appskey (keys already explained in subsection 2.2.1).

This command reads the preprogramme EUI node address from RN2483 module. The value returned by this command is a globally unique number provided by Microchip.

```
sys get hweui
0004A30B001C6E01
```

The following commands set the different keys for the RN2483 module:

```
mac set nwkskey CB1B6F00D50842A66124BEEE21EB5FA4
ok
mac set appskey AFD26A29452FFDE64B09215DBAA21528
ok
```

This command set the unique network device address for the RN2483 module.

```
mac set devaddr 26011813
ok
```

Finally, it saves the LoRaWAN configuration parameters.

```
mac save
ok
```

There are two modes to join to the network: ABP or OTAA (2.2.1). For this thesis the ABP method has been selected as it is easy to carry out its setup. The following attempts to join the network using ABP mode:

```
mac join abp
ok
accepted
```

We are already joined to the network.

3.1.3 Results

At the end, it is verified that the technology works as we expect according to the standard, sending and receiving data.

There are two options to send data with LoRa:

- Confirmed: it will be confirmed by a downlink frame.
- Unconfirmed: it will not be confirmed.

The allowed format of sending data for RN2483 is:

```
mac tx <type><FPort><payload>
```

This command may reply two responses. The first response is received immediately after entering the command. In case the command is valid (ok reply received). The second reply is received after the end of the uplink transmission. If the response is mac_tx_ok the uplink transmission was successful and not downlink data was received back from the server.

Some of the messages sent are:

```
mac tx uncnf 1 AF
ok
mac_tx_ok
mac tx uncnf 4 AB
ok
mac_tx_ok
mac tx cnf 1 BEEF
ok
mac tx cnf 4 5A5B5B
ok
```

In addition to the response obtained by Termite in which it is possible to verify if the messages have been received correctly. Messages are received on the gateways too.

3.2 Evaluation of the LoRaWAN gateway range

The first section of this chapter was focused to verify that LoRaWAN technology works as we expected. In this second section, LoRaWAN technology is verified in real conditions. We have the opportunity to evaluate the LoRaWAN gateway range sending automated data messages.

3.2.1 Utilized hardware and software tools

As mentioned before, to effectively evaluate the technology used, several software and hardware tools have been needed. To implement them it uses an Arduino Board with the current LoRa Module in used. The tools used are described in the following subsection:

Arduino UNO Board

The Arduino Board choosen to carry out this thesis has been the Arduino UNO Board. The main reason for your choice is that it is the most appropriate to start with electronics and coding because it is one of the most robust systems[26].

Arduino UNO is a microcontroller board based on the ATmega328P. It has 14 digital input/output pins, 6 analog inputs, a 16 MHz quartz crystal, a USB connection, a power jack, an ICSP header and a reset button.

It connects to the computer with a USB cable and it contains everything is needed to perform this thesis.

The general features table of Arduino UNO (Tab 3.2) is shown:

Microcontroller	ATmega328P
Operating Voltage	5 V
Input Voltage (recommended)	7-12 V
Input Voltage (limit)	6-20 V
Digital I/O Pins	14(of which 6 provide PWM output)
PWM Digital I/O Pins	6
Analog Input Pins	6
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB (ATmega328P) of which 0.5 KB used by bootloader
SRAM	2 KB (ATmega328P)
EEPROM	1 KB (ATmega328P)
Clock Speed	16 MHz

Tab. 3.2: General Features Arduino UNO [26].

Figure 3.3 shows the main part of an Arduino UNO Board,the microcontroller in which the ATmega328P is focused:

IDE Arduino Software

The Arduino IDE software has been used to program the Arduino board as its ease of programming for beginners.

Arduino IDE is a cross-platform application that is written in the programming language Java. The Arduino IDE supports the languages C and C++. The code is written by the user that requires two basic functions to start the sketch and the main cycle of the program: to compile and link it to a main ( ) program appendix. Arduino IDE uses the avrdude program to convert executable code into a text file an also, into a hexadecimal encoding that is uploaded on the Arduino board.

Arduino IDE features are:

- **Multi-platform application**: Arduino IDE works on the three most popular operating systems: Windows, Mac OS, and Linux. Also it gives programmers the option to create and save their sketches in the cloud, or create their programs locally.

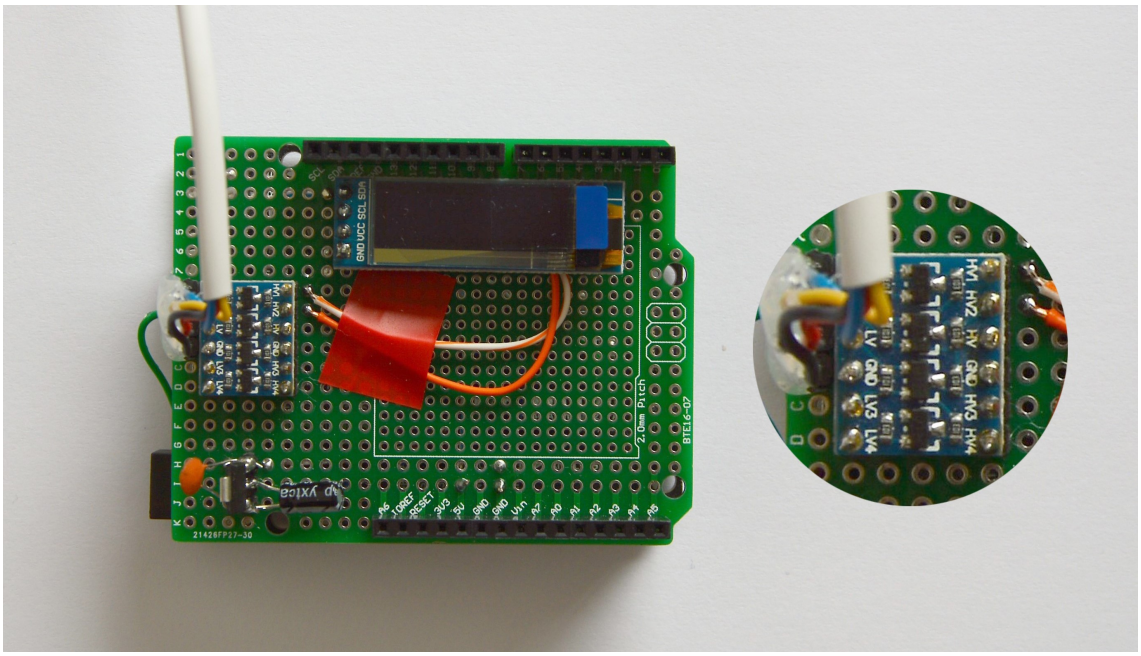


Fig. 3.3: ATmega328P microcontroller in Arduino UNO Board.

- **Board Management**: Arduino IDE comes with a multiplatform management module where users can select, at the moment, the board that they want to work with.
- **Vast Library**: Arduino IDE has more than 700 integrated libraries. These have been written and shared by the Arduino community, which allows other users to use them in their own projects without having to install any additional software.
- **Third party Hardware Support:** Arduino IDE supports connections with third-party hardwares. This makes the use of the application more extensive than limited to the proprietary plates.

3.2.2 Verification methodology

Once the software and hardware tools have been explained, the process of sending data messages is automated. 11 messages are sent, the first message to check the connection and the remaining 10 data messages. It has been decided to send ten data messages because in that way you get more accurate results. In the first section, the sending of data messages has been made individually. The results obtained in this section are subsequently used.

Picture of the complete infrastructure is shown in (Fig. 3.4) The Arduino UNO board has the function of controlling the module.

The code used in this infrastructure is explained. It is a C ++ code, programmed

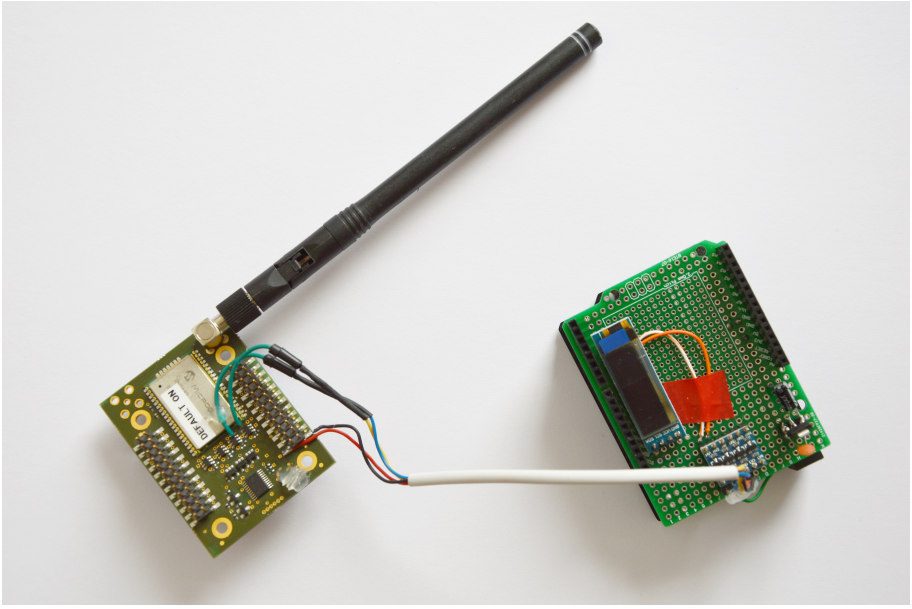


Fig. 3.4: LoRaWAN infrastructure.

in Arduino IDE Software. This code has been written in order to send data repeatedly, as in a loop.

One of the advantages of automating the process, including the precision, it would be the reduction of sending time. That way, LoRa module can delete unnecessary tasks and focus on sending data.

As mentioned before, this code sends an initial message and ten data messages. When the ten messages are sent, the program stops.

The code begins including the necessary libraries for the implementation:

```
1 #include "rn2xx3.h"
2 #include "SoftwareSerial.h"
3 #include "U8glib.h"
4
5 U8GLIB_SSD1306_128X32 u8g(U8G_I2C_OPT_NO_ACK);
6
7 SoftwareSerial LoraSerial(9, 8);
8
9 rn2xx3 myLora(LoraSerial);
```

Listing 3.1: Libraries.

The listing 3.1 shows on line 5, the definition of used display (128x32 pixels) over I2C. On line 7 it defines the software serial, LoRa RX pin is connected to the pin 9 of the Arduino and the TX pin is connected to the pin 8. Last, on line 9, it creates an instance of the rn2xx3 library, giving the software serial as a port to use.

The listing below (Lst. 3.2) shows the draw function:

```
void draw(String text) {
    u8g.firstPage();
    do {
        u8g.setFont(u8g_font_unifont);
        u8g.setPrintPos(0, 20);
        u8g.print(text);
    } while( u8g.nextPage() );
}
```

Listing 3.2: Draw function.

The needed to create the draw function is due to our interest to work independently of the computer when the measurements are carried out.

The next function that was performed is "initialize_module" the module joins the network and the keys are negotiated.

```
void initialize_module(){
    delay(100);
    LoraSerial.flush();

    String hweui = myLora.hweui();

    while(hweui.length() != 16){

        Serial.println("Communication with RN2483 unsuccessful");
        Serial.println(hweui);
        delay(10000);
        hweui = myLora.hweui();
    }

    Serial.println("Firmware version:");
    Serial.println(myLora.sysver());

    Serial.println("The DevEUI is: ");
    Serial.println(myLora.hweui());

    Serial.println("Join to the network");
    bool result = false;

    //Modo ABP: initABP(Addr,AppSKey,NwkSKey);
    result = myLora.initABP("26011813",
    "AFD26A29452FFDE64B09215DBAA21528", "
    CB1B6F00D50842A66124BEEE21EB5FA4");

    while(!result){
        Serial.println("Unable to join");
        delay(60000);
        result = myLora.init();
```

```
32
33          String text="Unable to join";
34          draw(text);
35      }
36
37      Serial.println("Successfully joined");
38
39      String text="Succesfully joined";
40      draw(text);
41  }
```

Listing 3.3: Initialize_module function.

On line 5 of the listing 3.3, the hweui of our device is obtained. The length of the hweui must be 16 bytes if this is not satisfied "Communication with RN2483 unsuccessful".

“Serial.println” is used to print in the serial port in ASCII code through the code. Also, delay (x), is used to add a milliseconds delay where x is the time in milliseconds.

The listing 3.3 shows the configuration in ABP mode and the negotiation of the LoRa keys as mentioned above.

From line 28 to 40 of the listing 3.3, it is displayed that if the value of the result is different, the union is not. It is shown on the display “Unable to join”. Also, if the result value is the same, the connection to the network is successfully achieved. This is shown on the display too.

The last function to analyze is “send” (Lst. 3.4). In this function, the ten data messages are sent.

```
1  void send(){
2
3      Serial.print("Transmission");
4
5      String text="Transmission";
6      draw(text);
7
8      switch(myLora.tx("21")){
9
10         case TX_FAIL:{ //It the transmission fail
11             Serial.println("TX unsuccessful or not acknowledged");
12             break;
13         }
14
15         case TX_SUCCESS:{
16             Serial.println("TX successful and acknowledged");
17             break;
18         }
```

```
19
20          case TX_WITH_RX:{
21
22              String received = myLora.getRx();
23              received = myLora.base16decode(received);
24              Serial.print("Received: " + received);
25              break;
26          }
27
28          default:{
29              Serial.println("Unknown response from TX ");
30          }
31      }
32  }
```

Listing 3.4: Send function.

On line 8 of the listing 3.4, a message unconfirmed is sent. The value sent “21” is the hexadecimal value of the “!”. The sending of the message is inside a switch so depending of the confirmation obtained, the string written on the serial port is different.

For example, if the confirmation is TX_FAIL, it is written to the serial port "TX unsuccessful or not acknowledged".

The void setup( ) is explained. The setup is the part that runs first when the program is started (Lst. 3.5).

```
1  void setup() {
2
3      Serial.begin(57600);
4      LoraSerial.begin(57600);
5      Serial.println("Startup");
6
7      initialize_module();
8
9      delay(1000);
10
11     myLora.setFrequencyPlan(TTN_EU);
12
13     myLora.setDR(0);
14
15     myLora.tx("Andrea");
16
17     delay(10000);
18
19     int counter=1;
20
21     while(counter<=10){
```

```
22          send();
23          counter=counter+1;
24          delay(10000);
25      }
26      String text=( "10 Messages sent");
27      draw(text);
28      delay(6000);
29  }
30  void loop() {
31
32  }
```

Listing 3.5: Void setup( ) and void loop( ).

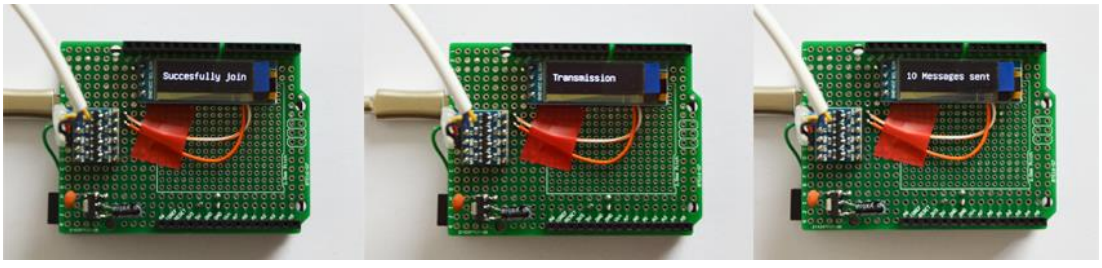
On line 3 in Fig 3.5 opens the hardware serial (USB port) with proper baud rate 57600 bps, also line 4 opens the software serial on pins 8 and 9. The call to the function is made “initialize_module”.

The frequency plan is setup to TTN_EU. The objective of this is to establish limits of use. Finally, the data rate is set to 0. This implies an SF of 12 and 125 KHz of bandwidth as it has been verified in the initial configuration. On line 15, the initial unconfirmed message is sent “Andrea”.

The variable counter is declared, which quantifies the number of messages sent. For this, a loop is made inside the setup, in which the send( ) function is called. When this loop finishes, "10 Messages send" is shown on the display.

The void loop( ) is empty. The presence of this function has been considered as part of this code development, although it has not been used, the code works successfully.

The figure 3.5 shows the changes that the display experiences during the sending of data messages.



Succesfully join Transmission 10 Messages sent

Fig. 3.5: Display changes during the transmission.

3.2.3 Results of the measurements and comparison with the TTN network

The measurements have been performed in the city of Brno. In the figure below (Fig. 3.6), it can be seen the coordinate map where the tests have been carried out. They have been selected taking into account terrain areas with different characteristics. Obtaining in that way, accurate results (forty-eight points).

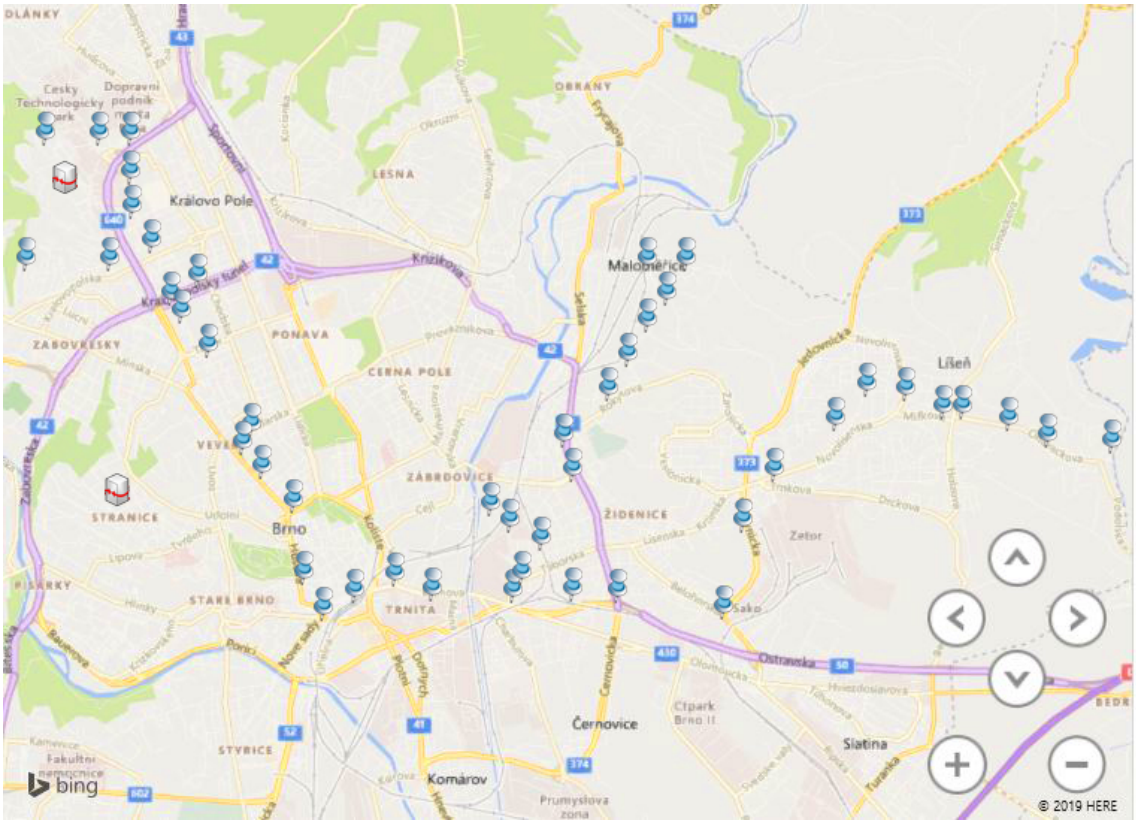


Fig. 3.6: Coordinate map.

In each point, the LoRaWAN infrastructure has been kept connected via USB cable to an external battery (Fig. 3.7). The sending point would change and the receiving gateways would remain constant.

The current scenario is shown on the picture (Fig. 3.8) where it can be seen the external battery, the LoRaWAN infrastructure and the gateway. The battery is connected with the LoRaWAN infrastructure via USB and the LoRaWAN infrastructure with the gateway through LoRa technology.

Once the measurements have been made, the resulting files will be obtained from the gateways. The generated file is a JSON file (JavaScript Object Notation) in which you can see the value of the counter, the location of the gateway and many other sending parameters. An example of JSON file is shown below (Lst. 3.6):

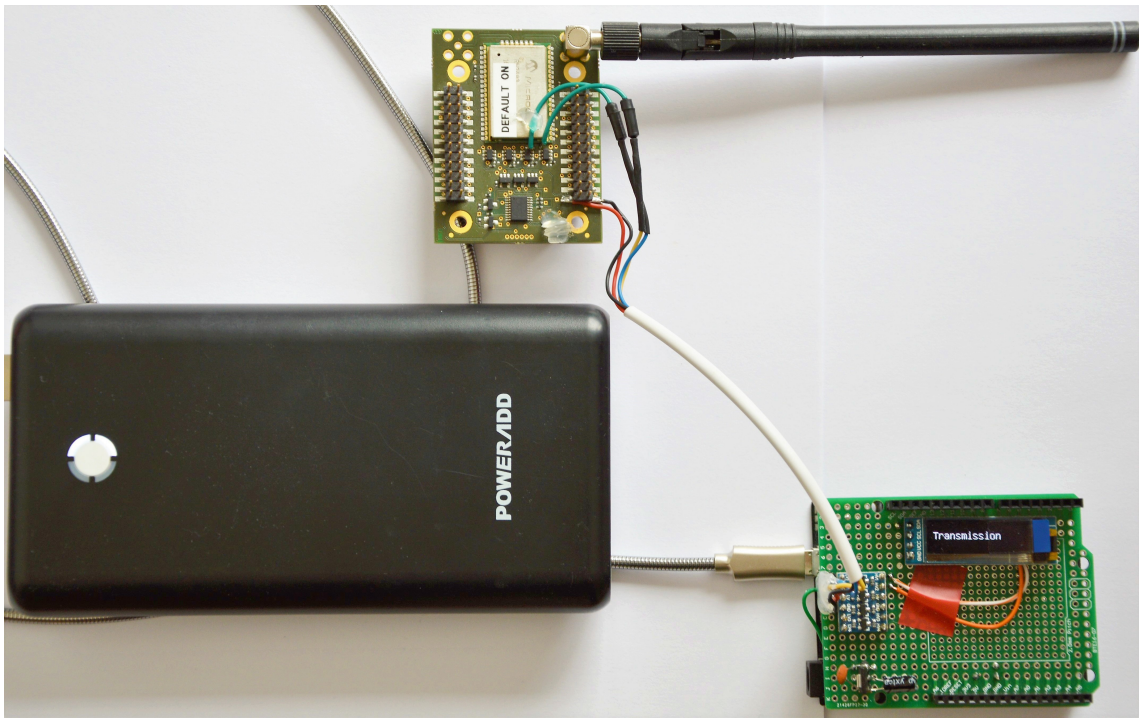


Fig. 3.7: Hardware equipment.

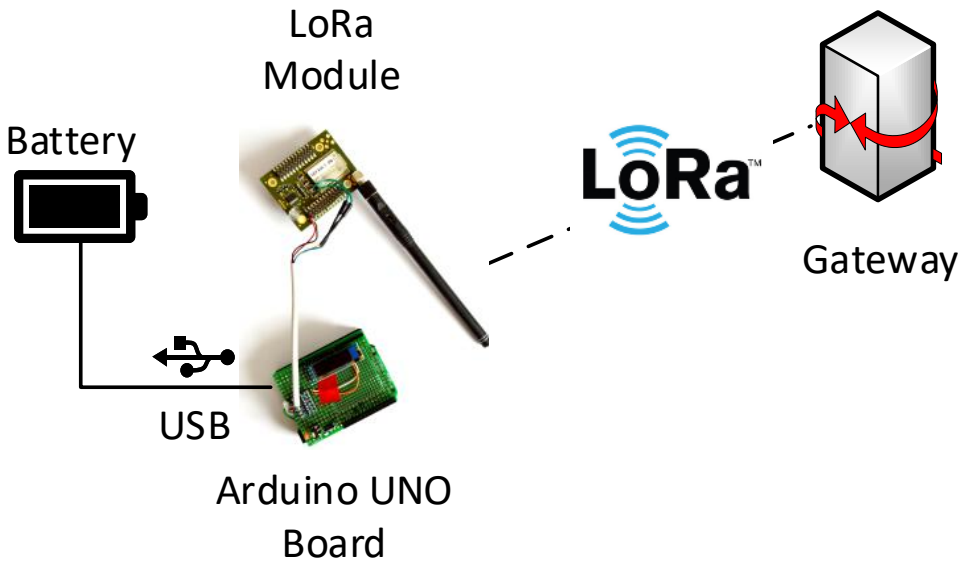


Fig. 3.8: Automated communication with LoRaWAN infrastructure.

```
 {
"counter": 1,
"app_id": "b_iot",
"port": 1,
"metadata": {
   "time": "2019-03-29T10:42:05.98409484Z",
   "coding\_rate": "4/5",
   "frequency": 867.1,
   "airtime": 1155072000,
   "modulation": "LORA",
   "gateways": [
      {
         "time": "2019-03-29T10:42:05.956711Z",
         "rf_chain": 0,
         "gtw_id": "eui-b827ebfffec6e5d0",
         "channel": 3,
         "rssi": -119,
         "latitude": 49.19936,
         "longitude": 16.57975,
         "altitude": 320,
         "timestamp": 2269981292,
         "snr": -5.2
      },
      {
         "time": "2019-03-29T10:42:29.536815Z",
         "rf_chain": 0,
         "gtw_id": "eui-1dee0933d840ee1b",
         "channel": 3,
         "rssi": -117,
         "timestamp": 2543574716,
         "snr": -13
      }
   ],
   "data_rate": "SF12BW125"
},
"dev_id": "andrea",
"hardware_serial": "0004A30B001C6E01",
"payload_raw": "MjE="
 }
```


Listing 3.6: JSON file appearance.

In the JSON files there are three gateways that receive the information (gtw_id). These gateways are:

- 'gtw_id': 'but_biot'.
- 'gtw_id': 'eui-b827ebfffec6e5d0'.
- 'gtw_id': 'eui-1dee0933d840ee1b'.

Depending on the position where the sending is made, the gateway that receives the messages change.

The location of two of three gateways is known (gateway symbol Fig. 3.6). It is unknown the location of 'gtw_id': 'eui-1dee0933d840ee1b'. Even so, it has been decided to take into account that the data received by the gateway 'eui-1dee0933d840ee1b' to carry out an accurate comparison. The gateway But_Biot versus the TTN_Network (three gateways, one of them But_Biot).

In order to graphically compare the results obtained, heat maps have been performed. The latitude, the longitude and the RSSI of each coordinate have been used. The RSSI (Received Signal Strength Indicator) is a reference scale for measuring the power level of the signals received by a device in wireless networks. The scale is frequently expressed in negative values. Smaller values indicate higher signal losses.

The But_biot heat map is shown below (Fig. 3.9):

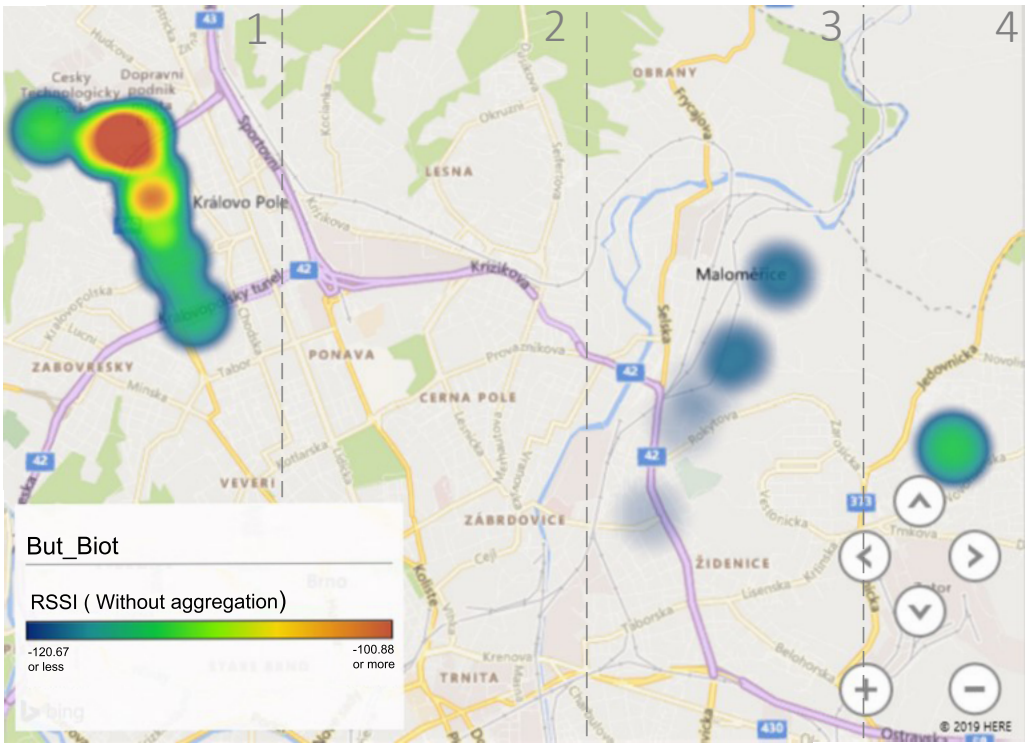


Fig. 3.9: But_Biot heat map.

The values are gradually distributed from blue to red indicating less or more activity respectively.

For a better understanding of the maps each of them is divided into 4 areas already reflected in the heat maps. First area, left part of the map, around the But_biot; second area, the city centre; third area around Masarova and finally a

fourth area, on the right part of the map. In But_Bio heat map it can be seen how the area near the But_biot is the most activate (area 1).

The area 1 is 358 meters above sea level. It is an elevated area on the ground. On the other hand, the area 3 is 284 meters above sea level, lower than the previous area but it is still in a high location. The area 4 is 302 meters above sea level. Being a little higher than area three, it differs in the image with greenish tone.

In high areas, the signal received is higher because it is transmitted with no interferences between them which implies good values of the RSSI. However, in the city centre, the area 2, the signal is attenuated and obstructed by obstacles that are in the way during the transmission: trees, buildings ... It is located in a valley, between two mountains.

Due to the aforementioned interferences and obstacles, the phenomenon known as multipath propagation occurs, the signals are received by the gateway on two or more paths and at different times which can cause problems in the reception of the signal due to the interaction between the signals. This phenomenon is reflected in the results obtained; successive measurements points, so the distance between them is very small, the results vary considerably.

The TTN_Network heat map is shown below (Fig. 3.10):

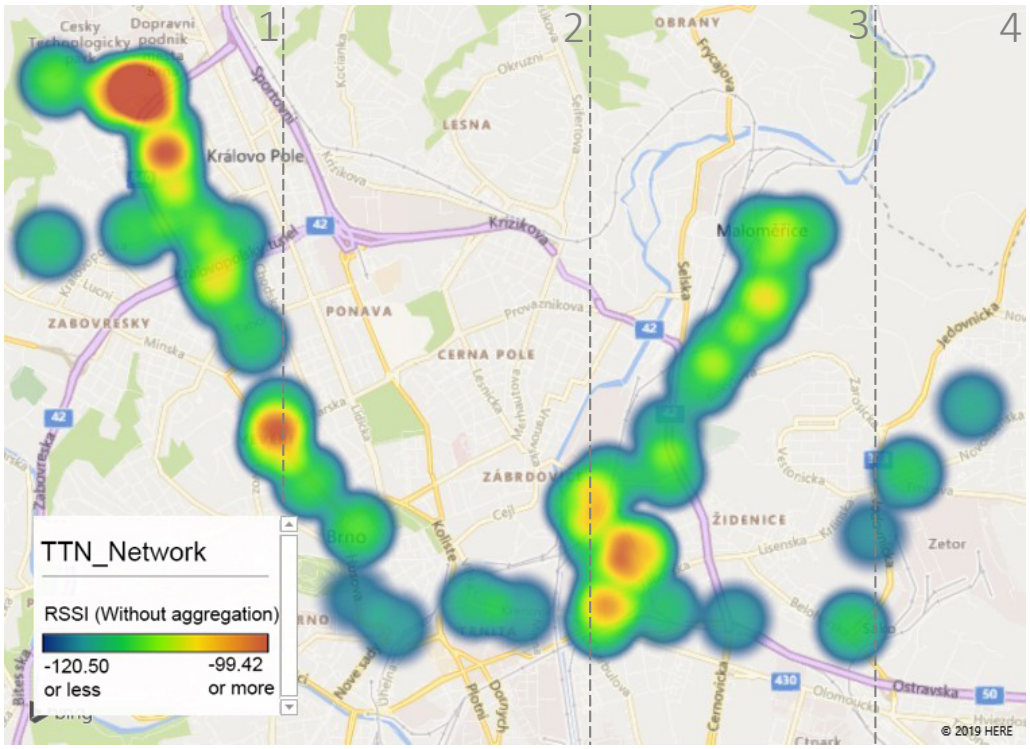


Fig. 3.10: TTN_Network heat map.

As we mentioned before, the heat map of the TTN_Network collects the information received by the three gateways (But_biot between them). Unlike the

But_Biot heat map, the activity of this heat map is higher.

The TTN_network heat map is divided again into four areas.

The area with the most activity is again area 1, the largest area. You can also see two more areas with activity (area 2 and 3), not present in the previous map.

It should be remembered, as in the previous map, that zone 3 and zone 4 are high areas of the terrain, making it easier for transmission to take place without interference.

4 Conclusions and Lessons learned

The goal of connecting the customized device to the network of the Brno University of Technlogy has been achieved as a part of this thesis.

Data has been collected and tests have been conducted with the intention that the reader can draw their own conclusions, and evaluate the types of scenarios it may be good to use LoRa(WAN) technology.

The conclusions obtained as part of this thesis are presented below:

- The importance of the configuration of our device should be highlighted. It can be seen in section 3.1.2 that depending on how you configure the parameters of the device (the SF, the bandwidth, the data rate...) with the commands mentioned before, the obtained results can be different.
- It has been verified with the map of coordinates that the messages can be received up to approximately 7 Km away, with RSSI values between -120 and -99 dBm. Even with -99 dBm, area of greatest activity, the RSSI is kept low. There are points where packages are not received practically, so communication could be totally missed although if we are closer than 7 Km away. From 7 Km, the connection would be infeasible.
- In terms of the results obtained, the expected theoretical coverage according to the specification of this technology is around 5 km. In this thesis, messages have been received from a point 7 km away. The measurements were repeated several times. It was checked again how messages were received. Point of zone 4 of the heat map of the But_Biot.
- These tests were carried out in the city of Brno, so the results make change significantly if they are carried out in an open space, without interferences or obstacles as it was the case in the city center. However, we have seen how LoRaWAN technology penetrates very well and there are few things that interfere with it.
- It is known that the TTN network is public with three gateways. The BUT_Biot network is paid with just one gateway. The TTN_network gives better results due to the presence of a greater number of gateways. Although more gateways implies higher implement cost; as the network is public, is not a paremeter to consider. The TTN network gives us better results being of public use.

In the future, I would like to continue this project by performing the same tests with other LPWA technologies to know their coverage limits, advantages and disadvantages. It can thus be assessed which of the technologies presents the best conditions in a data transmission.

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List of symbols, physical constants and abbreviations

IoT	Internet of Things
LPWAN	Low Power Wide Area Network
M2M	Machine to Machine
H2H	Human to Human
IIoT	Industrial Internet of Things
NB-IoT	Narrow Band-Internet of Things
LPWA	Low Power Wide Area
RAN	Radio Access Network
ISM band	Industrial, Scientific and Medical band
UNB	Ultra-Narrow Band
BPSK	Binary Phase Shift Keying
CRC	Cyclic Redundancy Check
ISO	International Organization for Standardization
OSI	Open System Interconnection
TCP	Transmission Control Protocol
IP	Internet Protocol
MAC	Media Access Control
RFTDMA	Random Frequency and Time Division Multiple Acces
AES	Advanced Encryption Standar
OTA	Over the Air
CSS	Chirp Spread Spectrum
ETSI	European Telecommunications Standards Institute
USA	Unites States of America
ACK	Acknowledgement
FSK	Frequency Shift Keying
OTAA	Activation Over the Air
ABP	Activation by Personalization
DevEUI	Device EUI
AppEUI	Application EUI
AppKey	Application Key
NwkSkey	Network Session Key
AppSKey	Application Session Key
MIC	Message Integrity Code
DevAddr	Device Address
P2P	Point to Point

SF	Spread Factor
HF	High Frequency
3GPP	3rd Generation Partnership Project
GSM	Global System for Mobile
LTE	Long Term Evolution
QPSK	Quadrature Phase Shift Keying
OFDMA	Orthogonal Frequency-Division Multiple Acces
SC-FDMA	Single-Carrier Frequency Division Multiple Access
SIM	Subscriber Identity Module
USIM	Universal Subscriber Identity Module
IMEI	International Mobile Equipment Identity
TLS	Transport Layer Security
IPSec	Internet Protocol security
RSA	Rivest, Shamir and Adlema
UL	Up Link
DL	Down Link
RSSI	Received Signal Strength Indicator
TDOA	Time Difference of Arrival
UART	Universal Asynchronous Receiver Transmitter
EEPROM	Electrically Erasable Programmable Read Only Memory
RF	Radio frequency
MIDI	Musical Instrument Digital Interface
UE	European Union
USB	Universal Serial Bus
ICSP	In circuit serial programming
I2C	Inter-Integrated Circuit
TX	Transmitter
ASCII	American Standard Code for Information Interchange
RX	Receiver
TTN	The Things Network
JSON	JavaScript Object Notation
BUT	Brno University of Technology

Appendices

Obtained JSON files and summary table

Measurements 1−5:

POINT 1


```
{'payload_raw': 'QW5kcmVh', 'hardware_serial': '0004A30B001C6E01', '
    counter': 0, 'metadata': {'modulation': 'LORA', 'data_rate': '
    SF12BW125', 'gateways': [{'gtw_id': 'eui-1dee0933d840ee1b', 'rssi':
     -113, 'snr': -6.5, 'timestamp': 2996088748, 'time': '2019-03-26T16
    :01:07.814805Z', 'rf_chain': 0, 'channel': 7}], 'airtime':
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    281, 'rf_chain': 0, 'location_source': 'registry', 'rssi': -113, '
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    '4/5'}, 'app_id': 'b_iot', 'port': 1, 'dev_id': 'andrea'}
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Measurements 1-12

PUNTO 1

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POINT 2

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POINT 3


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POINT 4

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POINT 6

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POINT 7


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POINT 8

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POINT 9

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POINT 10

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POINT 11

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{'dev_id': 'andrea', 'counter': 5, 'payload_raw': 'MjE=', 'port': 1, 'app_id': 'b_iot', 'metadata': {'airtime': 1155072000, 'frequency': 867.7, 'coding_rate': '4/5', 'modulation': 'LORA', 'time': '2019-04-01T10:42:19.573454949Z', 'gateways': [{'channel': 6, 'altitude': 320, 'rssi': -118, 'latitude': 49.19936, 'longitude': 16.57975, 'snr': 1, 'time': '2019-04-01T10:42:19.395806Z', 'rf_chain': 0, 'gtw_id': 'eui-b827ebfffec6e5d0', 'timestamp': 3785257612}, {'channel': 6, 'rssi': -115, 'snr': -13.5, 'time': '2019-04-01T10:42:59.898474Z', 'rf_chain': 0, 'gtw_id': 'eui-1dee0933d840ee1b', 'timestamp': 617532476}], 'data_rate': 'SF12BW125'}, 'hardware_serial': '0004A30B001C6E01'}
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POINT 12

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Measurements 1-18

PUNTO 7

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PUNTO 9

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PUNTO 10

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PUNTO 11

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PUNTO 13

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eui-1dee0933d840ee1b', 'channel': 1, 'rssi': -117, 'timestamp':
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PUNTO 14

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-b827ebfffec6e5d0', 'channel': 2, 'rssi': -107, 'latitude':
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1744531460, 'snr': 2.8}, {'time': '2019-03-29T11:45:19.294429Z', '
rf_chain': 0, 'gtw_id': 'eui-1dee0933d840ee1b', 'channel': 3, 'rssi
': -115, 'timestamp': 2018124628, 'snr': -10.5}], 'data_rate': '
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PUNTO 15

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PUNTO 16

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PUNTO 17

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PUNTO 18

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49.19936, 'longitude': 16.57975, 'altitude': 320, 'timestamp':
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eui-b827ebfffec6e5d0', 'channel': 3, 'rssi': -123, 'latitude':
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Measurements 13-25

PUNTO 13

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PUNTO 14


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    b827ebfffec6e5d0', 'rf_chain': 0, 'channel': 6, 'altitude': 320, '
    snr': -16.8}], 'time': '2019-03-28T13:55:53.658302421Z', 'data_rate
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    coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', '
    hardware_serial': '0004A30B001C6E01'}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 3, 'metadata': {
    'frequency': 868.1, 'gateways': [{'timestamp': 525499588, '
    longitude': 16.57975, 'rssi': -118, 'time': '2019-03-28T13
    :56:06.997561Z', 'latitude': 49.19936, 'gtw_id': 'eui-
    b827ebfffec6e5d0', 'rf_chain': 1, 'channel': 0, 'altitude': 320, '
    snr': -14.8}], 'time': '2019-03-28T13:56:07.026261897Z', 'data_rate
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    coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', '
    hardware_serial': '0004A30B001C6E01'}
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    longitude': 16.57975, 'rssi': -115, 'time': '2019-03-28T13
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    b827ebfffec6e5d0', 'rf_chain': 0, 'channel': 5, 'altitude': 320, '
    snr': -11}], 'time': '2019-03-28T13:56:33.756573855Z', 'data_rate':
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    coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', '
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    :56:47.092666Z', 'latitude': 49.19936, 'gtw_id': 'eui-
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    snr': -10.2}], 'time': '2019-03-28T13:56:47.122085334Z', 'data_rate
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    hardware_serial': '0004A30B001C6E01'}
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    longitude': 16.57975, 'rssi': -119, 'time': '2019-03-28T13
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    snr': -8.5}], 'time': '2019-03-28T13:57:00.487211213Z', 'data_rate'
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    hardware_serial': '0004A30B001C6E01'}
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PUNTO 15


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    snr': 0}], 'time': '2019-03-28T14:07:08.094204326Z', 'data_rate': '
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    coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', '
    hardware_serial': '0004A30B001C6E01'}
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    'frequency': 867.5, 'gateways': [{'timestamp': 1199930980, '
    longitude': 16.57975, 'rssi': -114, 'time': '2019-03-28T14
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    longitude': 16.57975, 'rssi': -115, 'time': '2019-03-28T14
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    snr': -4.2}], 'time': '2019-03-28T14:07:48.193936404Z', 'data_rate'
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    coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', '
    hardware_serial': '0004A30B001C6E01'}
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    longitude': 16.57975, 'rssi': -109, 'time': '2019-03-28T14
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    b827ebfffec6e5d0', 'rf_chain': 1, 'channel': 0, 'altitude': 320, '
    snr': -7}], 'time': '2019-03-28T14:08:28.305722366Z', 'data_rate':
    'SF12BW125', 'modulation': 'LORA', 'airtime': 1155072000, '
    coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', '
    hardware_serial': '0004A30B001C6E01'}
```


PUNTO 16


```
{'dev_id': 'andrea', 'payload_raw': 'QW5kcmVh', 'counter': 0, 'metadata
    ': {'frequency': 867.7, 'gateways': [{'timestamp': 1800508068, '
    longitude': 16.57975, 'rssi': -111, 'time': '2019-03-28T14
    :17:22.006044Z', 'latitude': 49.19936, 'gtw_id': 'eui-
    b827ebfffec6e5d0', 'rf_chain': 0, 'channel': 6, 'altitude': 320, '
```

```
    snr': -1.2}], 'time': '2019-03-28T14:17:22.036966796Z', 'data_rate'
    : 'SF12BW125', 'modulation': 'LORA', 'airtime': 1318912000, '
    coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', '
    hardware_serial': '0004A30B001C6E01'}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 1, 'metadata': {
    'frequency': 868.3, 'gateways': [{'timestamp': 1813872588, '
    longitude': 16.57975, 'rssi': -111, 'time': '2019-03-28T14
    :17:35.36668Z', 'latitude': 49.19936, 'gtw_id': 'eui-
    b827ebfffec6e5d0', 'rf_chain': 1, 'channel': 1, 'altitude': 320, '
    snr': -1.2}], 'time': '2019-03-28T14:17:35.394009877Z', 'data_rate'
    : 'SF12BW125', 'modulation': 'LORA', 'airtime': 1155072000, '
    coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', '
    hardware_serial': '0004A30B001C6E01'}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 2, 'metadata': {
    'frequency': 867.3, 'gateways': [{'timestamp': 1827237156, '
    longitude': 16.57975, 'rssi': -113, 'time': '2019-03-28T14
    :17:48.733467Z', 'latitude': 49.19936, 'gtw_id': 'eui-
    b827ebfffec6e5d0', 'rf_chain': 0, 'channel': 4, 'altitude': 320, '
    snr': 1.5}], 'time': '2019-03-28T14:17:48.784428018Z', 'data_rate':
     'SF12BW125', 'modulation': 'LORA', 'airtime': 1155072000, '
    coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', '
    hardware_serial': '0004A30B001C6E01'}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 4, 'metadata': {
    'frequency': 868.1, 'gateways': [{'timestamp': 1853966452, '
    longitude': 16.57975, 'rssi': -109, 'time': '2019-03-28T14
    :18:15.461766Z', 'latitude': 49.19936, 'gtw_id': 'eui-
    b827ebfffec6e5d0', 'rf_chain': 1, 'channel': 0, 'altitude': 320, '
    snr': -6}], 'time': '2019-03-28T14:18:15.489906891Z', 'data_rate':
    'SF12BW125', 'modulation': 'LORA', 'airtime': 1155072000, '
    coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', '
    hardware_serial': '0004A30B001C6E01'}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 5, 'metadata': {
    'frequency': 867.9, 'gateways': [{'timestamp': 1867331260, '
    longitude': 16.57975, 'rssi': -114, 'time': '2019-03-28T14
    :18:28.827023Z', 'latitude': 49.19936, 'gtw_id': 'eui-
    b827ebfffec6e5d0', 'rf_chain': 0, 'channel': 7, 'altitude': 320, '
    snr': 0}], 'time': '2019-03-28T14:18:28.854101163Z', 'data_rate': '
   SF12BW125', 'modulation': 'LORA', 'airtime': 1155072000, '
    coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', '
    hardware_serial': '0004A30B001C6E01'}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 6, 'metadata': {
    'frequency': 867.1, 'gateways': [{'timestamp': 1880696316, '
    longitude': 16.57975, 'rssi': -117, 'time': '2019-03-28T14
    :18:42.188254Z', 'latitude': 49.19936, 'gtw_id': 'eui-
    b827ebfffec6e5d0', 'rf_chain': 0, 'channel': 3, 'altitude': 320, '
    snr': -3}], 'time': '2019-03-28T14:18:42.218450435Z', 'data_rate':
    'SF12BW125', 'modulation': 'LORA', 'airtime': 1155072000, '
```

```
    coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', '
    hardware_serial': '0004A30B001C6E01'}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 7, 'metadata': {
    'frequency': 867.5, 'gateways': [{'timestamp': 1894061732, '
    longitude': 16.57975, 'rssi': -114, 'time': '2019-03-28T14
    :18:55.556975Z', 'latitude': 49.19936, 'gtw_id': 'eui-
    b827ebfffec6e5d0', 'rf_chain': 0, 'channel': 5, 'altitude': 320, '
    snr': -3}], 'time': '2019-03-28T14:18:55.584257406Z', 'data_rate':
    'SF12BW125', 'modulation': 'LORA', 'airtime': 1155072000, '
    coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', '
    hardware_serial': '0004A30B001C6E01'}
```


PUNTO 17


```
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 2, 'metadata': {
    'frequency': 868.1, 'gateways': [{'timestamp': 2042409972, 'rssi':
    -98, 'time': '2019-03-28T14:25:44.670568Z', 'gtw_id': 'eui-
    b827ebfffe114355', 'rf_chain': 1, 'channel': 0, 'snr': -14.8}], '
    time': '2019-03-28T14:25:44.702690917Z', 'data_rate': 'SF12BW125',
    'modulation': 'LORA', 'airtime': 1155072000, 'coding_rate': '4/5'},
     'port': 1, 'app_id': 'b_iot', 'hardware_serial': '0004A30B001C6E01
    '}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 3, 'metadata': {
    'frequency': 867.7, 'gateways': [{'timestamp': 2055774388, 'rssi':
    -102, 'time': '2019-03-28T14:25:58.034786Z', 'gtw_id': 'eui-
    b827ebfffe114355', 'rf_chain': 0, 'channel': 6, 'snr': -14.2}], '
    time': '2019-03-28T14:25:58.070708685Z', 'data_rate': 'SF12BW125',
    'modulation': 'LORA', 'airtime': 1155072000, 'coding_rate': '4/5'},
     'port': 1, 'app_id': 'b_iot', 'hardware_serial': '0004A30B001C6E01
    '}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 7, 'metadata': {
    'frequency': 867.9, 'gateways': [{'timestamp': 2370000556, '
    longitude': 16.57975, 'rssi': -120, 'time': '2019-03-28T14
    :26:51.49468Z', 'latitude': 49.19936, 'gtw_id': 'eui-
    b827ebfffec6e5d0', 'rf_chain': 0, 'channel': 7, 'altitude': 320, '
    snr': -13}], 'time': '2019-03-28T14:26:51.524405078Z', 'data_rate':
     'SF12BW125', 'modulation': 'LORA', 'airtime': 1155072000, '
    coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', '
    hardware_serial': '0004A30B001C6E01'}
```


PUNTO 18


```
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 2, 'metadata': {
    'frequency': 867.9, 'gateways': [{'timestamp': 2662442556, '
    longitude': 16.57975, 'rssi': -113, 'time': '2019-03-28T14
    :31:43.941281Z', 'latitude': 49.19936, 'gtw_id': 'eui-
    b827ebfffec6e5d0', 'rf_chain': 0, 'channel': 7, 'altitude': 320, '
```

```
    snr': -6}], 'time': '2019-03-28T14:31:43.969082062Z', 'data_rate':
    'SF12BW125', 'modulation': 'LORA', 'airtime': 1155072000, '
    coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', '
    hardware_serial': '0004A30B001C6E01'}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 5, 'metadata': {
    'frequency': 868.5, 'gateways': [{'timestamp': 2976140044, 'rssi':
    -106, 'time': '2019-03-28T14:32:42.815436Z', 'gtw_id': 'eui-1
    dee0933d840ee1b', 'rf_chain': 1, 'channel': 2, 'snr': -13.2}], '
    time': '2019-03-28T14:32:24.15804532Z', 'data_rate': 'SF12BW125', '
    modulation': 'LORA', 'airtime': 1155072000, 'coding_rate': '4/5'},
    'port': 1, 'app_id': 'b_iot', 'hardware_serial': '0004A30B001C6E01'
    }
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 6, 'metadata': {
    'frequency': 867.3, 'gateways': [{'timestamp': 2989505076, 'rssi':
    -113, 'time': '2019-03-28T14:32:56.173995Z', 'gtw_id': 'eui-1
    dee0933d840ee1b', 'rf_chain': 0, 'channel': 4, 'snr': -15.5}], '
    time': '2019-03-28T14:32:37.517326383Z', 'data_rate': 'SF12BW125',
    'modulation': 'LORA', 'airtime': 1155072000, 'coding_rate': '4/5'},
     'port': 1, 'app_id': 'b_iot', 'hardware_serial': '0004A30B001C6E01
    '}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 7, 'metadata': {
    'frequency': 867.7, 'gateways': [{'timestamp': 2729265756, '
    longitude': 16.57975, 'rssi': -117, 'time': '2019-03-28T14
    :32:50.767603Z', 'latitude': 49.19936, 'gtw_id': 'eui-
    b827ebfffec6e5d0', 'rf_chain': 0, 'channel': 6, 'altitude': 320, '
    snr': -2.2}, {'timestamp': 3002869756, 'rssi': -112, 'time': '
    2019-03-28T14:33:09.538929Z', 'gtw_id': 'eui-1dee0933d840ee1b', '
    rf_chain': 0, 'channel': 6, 'snr': -9.2}], 'time': '2019-03-28T14
    :32:50.794113445Z', 'data_rate': 'SF12BW125', 'modulation': 'LORA',
     'airtime': 1155072000, 'coding_rate': '4/5'}, 'port': 1, 'app_id':
     'b_iot', 'hardware_serial': '0004A30B001C6E01'}
```


PUNTO 19


```
{'dev_id': 'andrea', 'payload_raw': 'QW5kcmVh', 'counter': 0, 'metadata
    ': {'frequency': 868.1, 'gateways': [{'timestamp': 3467836172, '
    rssi': -112, 'time': '2019-03-28T14:40:54.539815Z', 'gtw_id': 'eui
    -1dee0933d840ee1b', 'rf_chain': 1, 'channel': 0, 'snr': -3.5}], '
    time': '2019-03-28T14:40:35.856965263Z', 'data_rate': 'SF12BW125',
    'modulation': 'LORA', 'airtime': 1318912000, 'coding_rate': '4/5'},
     'port': 1, 'app_id': 'b_iot', 'hardware_serial': '0004A30B001C6E01
    '}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 2, 'metadata': {
    'frequency': 867.1, 'gateways': [{'timestamp': 3220961252, '
    longitude': 16.57975, 'rssi': -120, 'time': '2019-03-28T14
    :41:02.453709Z', 'latitude': 49.19936, 'gtw_id': 'eui-
    b827ebfffec6e5d0', 'rf_chain': 0, 'channel': 3, 'altitude': 320, '
```

```
    snr': -12.2}, {'timestamp': 3494565188, 'rssi': -112, 'time': '
    2019-03-28T14:41:21.26582Z', 'gtw_id': 'eui-1dee0933d840ee1b', '
    rf_chain': 0, 'channel': 3, 'snr': -0.2}], 'time': '2019-03-28T14
    :41:02.481278903Z', 'data_rate': 'SF12BW125', 'modulation': 'LORA',
     'airtime': 1155072000, 'coding_rate': '4/5'}, 'port': 1, 'app_id':
     'b_iot', 'hardware_serial': '0004A30B001C6E01'}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 3, 'metadata': {
    'frequency': 868.5, 'gateways': [{'timestamp': 3507929900, 'rssi':
    -111, 'time': '2019-03-28T14:41:34.640729Z', 'gtw_id': 'eui-1
    dee0933d840ee1b', 'rf_chain': 1, 'channel': 2, 'snr': -5}], 'time':
     '2019-03-28T14:41:15.949124936Z', 'data_rate': 'SF12BW125', '
    modulation': 'LORA', 'airtime': 1155072000, 'coding_rate': '4/5'},
    'port': 1, 'app_id': 'b_iot', 'hardware_serial': '0004A30B001C6E01'
    }
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 4, 'metadata': {
    'frequency': 867.3, 'gateways': [{'timestamp': 3247691004, '
    longitude': 16.57975, 'rssi': -118, 'time': '2019-03-28T14
    :41:29.192329Z', 'latitude': 49.19936, 'gtw_id': 'eui-
    b827ebfffec6e5d0', 'rf_chain': 0, 'channel': 4, 'altitude': 320, '
    snr': -8}, {'timestamp': 3521294948, 'rssi': -113, 'time': '
    2019-03-28T14:41:47.997811Z', 'gtw_id': 'eui-1dee0933d840ee1b', '
    rf_chain': 0, 'channel': 4, 'snr': -6}], 'time': '2019-03-28T14
    :41:29.220529805Z', 'data_rate': 'SF12BW125', 'modulation': 'LORA',
     'airtime': 1155072000, 'coding_rate': '4/5'}, 'port': 1, 'app_id':
     'b_iot', 'hardware_serial': '0004A30B001C6E01'}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 6, 'metadata': {
    'frequency': 867.7, 'gateways': [{'timestamp': 3274421252, '
    longitude': 16.57975, 'rssi': -118, 'time': '2019-03-28T14
    :41:55.914749Z', 'latitude': 49.19936, 'gtw_id': 'eui-
    b827ebfffec6e5d0', 'rf_chain': 0, 'channel': 6, 'altitude': 320, '
    snr': -7.8}, {'timestamp': 3548025188, 'rssi': -111, 'time': '
    2019-03-28T14:42:14.731642Z', 'gtw_id': 'eui-1dee0933d840ee1b', '
    rf_chain': 0, 'channel': 6, 'snr': -6.8}], 'time': '2019-03-28T14
    :41:55.944051526Z', 'data_rate': 'SF12BW125', 'modulation': 'LORA',
     'airtime': 1155072000, 'coding_rate': '4/5'}, 'port': 1, 'app_id':
     'b_iot', 'hardware_serial': '0004A30B001C6E01'}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 7, 'metadata': {
    'frequency': 867.9, 'gateways': [{'timestamp': 3287786764, '
    longitude': 16.57975, 'rssi': -115, 'time': '2019-03-28T14
    :42:09.28888Z', 'latitude': 49.19936, 'gtw_id': 'eui-
    b827ebfffec6e5d0', 'rf_chain': 0, 'channel': 7, 'altitude': 320, '
    snr': -13.2}], 'time': '2019-03-28T14:42:09.320081469Z', 'data_rate
    ': 'SF12BW125', 'modulation': 'LORA', 'airtime': 1155072000, '
    coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', '
    hardware_serial': '0004A30B001C6E01'}
```


PUNTO 20

{'dev_id': 'andrea', 'payload_raw': 'QW5kcmVh', 'counter': 0, 'metadata': {'frequency': 867.7, 'gateways': [{'timestamp': 3686829436, 'longitude': 16.57975, 'rssi': -118, 'time': '2019-03-28T14:48:48.32662Z', 'latitude': 49.19936, 'gtw_id': 'eui-b827ebfffec6e5d0', 'rf_chain': 0, 'channel': 6, 'altitude': 320, 'snr': -1.5}, {'timestamp': 3960433332, 'rssi': -115, 'time': '2019-03-28T14:49:07.169142Z', 'gtw_id': 'eui-1dee0933d840ee1b', 'rf_chain': 0, 'channel': 6, 'snr': -8.2}], 'time': '2019-03-28T14:48:48.35764623Z', 'data_rate': 'SF12BW125', 'modulation': 'LORA', 'airtime': 1318912000, 'coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', 'hardware_serial': '0004A30B001C6E01'}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 1, 'metadata': {'frequency': 868.1, 'gateways': [{'timestamp': 3973798228, 'rssi': -109, 'time': '2019-03-28T14:49:20.532769Z', 'gtw_id': 'eui-1dee0933d840ee1b', 'rf_chain': 1, 'channel': 0, 'snr': -0.2}], 'time': '2019-03-28T14:49:01.809682049Z', 'data_rate': 'SF12BW125', 'modulation': 'LORA', 'airtime': 1155072000, 'coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', 'hardware_serial': '0004A30B001C6E01'}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 2, 'metadata': {'frequency': 867.5, 'gateways': [{'timestamp': 3987163380, 'rssi': -111, 'time': '2019-03-28T14:49:33.902399Z', 'gtw_id': 'eui-1dee0933d840ee1b', 'rf_chain': 0, 'channel': 5, 'snr': -4.2}], 'time': '2019-03-28T14:49:15.178568805Z', 'data_rate': 'SF12BW125', 'modulation': 'LORA', 'airtime': 1155072000, 'coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', 'hardware_serial': '0004A30B001C6E01'}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 3, 'metadata': {'frequency': 868.3, 'gateways': [{'timestamp': 3726924828, 'longitude': 16.57975, 'rssi': -112, 'time': '2019-03-28T14:49:28.423418Z', 'latitude': 49.19936, 'gtw_id': 'eui-b827ebfffec6e5d0', 'rf_chain': 1, 'channel': 1, 'altitude': 320, 'snr': -0.2}], 'time': '2019-03-28T14:49:28.450010338Z', 'data_rate': 'SF12BW125', 'modulation': 'LORA', 'airtime': 1155072000, 'coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', 'hardware_serial': '0004A30B001C6E01'}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 4, 'metadata': {'frequency': 867.1, 'gateways': [{'timestamp': 3740290076, 'longitude': 16.57975, 'rssi': -121, 'time': '2019-03-28T14:49:41.783726Z', 'latitude': 49.19936, 'gtw_id': 'eui-b827ebfffec6e5d0', 'rf_chain': 0, 'channel': 3, 'altitude': 320, 'snr': -10.5}, {'timestamp': 4013893980, 'rssi': -114, 'time': '2019-03-28T14:50:00.635326Z', 'gtw_id': 'eui-1dee0933d840ee1b', 'rf_chain': 0, 'channel': 3, 'snr': -6.5}], 'time': '2019-03-28T14:49:41.836994631Z', 'data_rate': 'SF12BW125', 'modulation': 'LORA', 'airtime': 1155072000, 'coding_rate': '4/5'}, 'port': 1, 'app_id':

```
    'b_iot', 'hardware_serial': '0004A30B001C6E01'}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 5, 'metadata': {
    'frequency': 867.9, 'gateways': [{'timestamp': 3753655324, '
    longitude': 16.57975, 'rssi': -114, 'time': '2019-03-28T14
    :49:55.156314Z', 'latitude': 49.19936, 'gtw_id': 'eui-
    b827ebfffec6e5d0', 'rf_chain': 0, 'channel': 7, 'altitude': 320, '
    snr': -0.8}, {'timestamp': 4027259220, 'rssi': -115, 'time': '
    2019-03-28T14:50:14.000185Z', 'gtw_id': 'eui-1dee0933d840ee1b', '
    rf_chain': 0, 'channel': 7, 'snr': -13}], 'time': '2019-03-28T14
    :49:55.185404916Z', 'data_rate': 'SF12BW125', 'modulation': 'LORA',
     'airtime': 1155072000, 'coding_rate': '4/5'}, 'port': 1, 'app_id':
     'b_iot', 'hardware_serial': '0004A30B001C6E01'}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 6, 'metadata': {
    'frequency': 867.3, 'gateways': [{'timestamp': 3767020372, '
    longitude': 16.57975, 'rssi': -117, 'time': '2019-03-28T14
    :50:08.522241Z', 'latitude': 49.19936, 'gtw_id': 'eui-
    b827ebfffec6e5d0', 'rf_chain': 0, 'channel': 4, 'altitude': 320, '
    snr': -7.5}], 'time': '2019-03-28T14:50:08.550987382Z', 'data_rate'
    : 'SF12BW125', 'modulation': 'LORA', 'airtime': 1155072000, '
    coding_rate': '4/5'}, 'port': 1, 'app_id': 'b_iot', '
    hardware_serial': '0004A30B001C6E01'}
{'dev_id': 'andrea', 'payload_raw': 'MjE=', 'counter': 7, 'metadata': {
    'frequency': 868.5, 'gateways': [{'timestamp': 3780385700, '
    longitude': 16.57975, 'rssi': -111, 'time': '2019-03-28T14
    :50:21.887352Z', 'latitude': 49.19936, 'gtw_id': 'eui-
    b827ebfffec6e5d0', 'rf_chain': 1, 'channel': 2, 'altitude': 320, '
    snr': -5.8}, {'timestamp': 4053989588, 'rssi': -113, 'time': '
    2019-03-28T14:50:40.72757Z', 'gtw_id': 'eui-1dee0933d840ee1b', '
    rf_chain': 1, 'channel': 2, 'snr': -5.8}], 'time': '2019-03-28T14
    :50:21.916639749Z', 'data_rate': 'SF12BW125', 'modulation': 'LORA',
     'airtime': 1155072000, 'coding_rate': '4/5'}, 'port': 1, 'app_id':
     'b_iot', 'hardware_serial': '0004A30B001C6E01'}
```


PUNTO 21


```
{'dev_id': 'andrea', 'payload_raw': 'QW5kcmVh', 'counter': 0, 'metadata
    ': {'frequency': 867.1, 'gateways': [{'location_source': 'registry'
    , 'rssi': -115, 'time': '2019-03-28T14:53:10Z', 'latitude':
    49.227043, 'rf_chain': 0, 'channel': 3, 'longitude': 16.575365, '
    timestamp': 3392503076, 'gtw_trusted': True, 'gtw_id': 'but_biot',
    'altitude': 281, 'snr': -13.5}], 'time': '2019-03-28T14
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Point	Name	Latitude	Longitude	RSSI But_Biot	RSSI TTN_Network	Date
1	Point_01	49.23235	16.5695922	-113	-111.8571429	26.03.2019
2	Point_02	49.231761	16.5804283	-102.125	-99.41666667	26.03.2019
3	Point_03	49.220242	16.5904492		-115.1666667	26.03.2019
4	Point_04	49.220775	16.5789478		-113.5555556	26.03.2019
5	Point_05	49.219738	16.5687339		-115.1111111	26.03.2019
13	Nové sady	49.190093	16.6094283		-117.4	28.03.2019
14	Šilingrovo náměstí	49.192337	16.6048364		-118.4	28.03.2019
15	Česká	49.197771	16.6050725		-112.25	28.03.2019
16	Grohova	49.201339	16.5993861		-112.7142857	28.03.2019
17	Konečného náměstí	49.204536	16.5954164		-106.6666667	28.03.2019
18	Nerudova	49.206561	16.5957275		-112.2	28.03.2019
19	Klusáčkova	49.212393	16.5927236		-114.4444444	28.03.2019
20	Tererova	49.21589	16.5891831		-114.1666667	28.03.2019
21	Dobrovského	49.217775	16.5878419	-115	-113.1818182	28.03.2019
22	Skácelova	49.221861	16.5850631	-114.375	-112.5	28.03.2019
23	Červinkova	49.225476	16.5826492	-110.375	-107.625	28.03.2019
24	Technické muzeum	49.228118	16.5822631	-109.375	-108.7058824	28.03.2019
25	Technologický park	49.231369	16.5771239	-100.875	-100.1666667	28.03.2019
1	Mariánské údolí	49.203333	16.7157939			29.03.2019
2	Velatická	49.204486	16.7075864			29.03.2019
3	Macháčkova	49.206291	16.7016481			29.03.2019
4	Náměstí Karla IV.	49.207028	16.6954789			29.03.2019
5	Mifkova	49.207292	16.6926681			29.03.2019
6	Jírova	49.209041	16.6865042			29.03.2019
7	Kotlanova	49.209759	16.6810164		-116.7	29.03.2019
8	Masarova	49.207064	16.6774653	-114	-114.3636364	29.03.2019
9	Novolíšeňská	49.201926	16.6699122		-118	29.03.2019
10	Líšeňská	49.197254	16.6655883		-114.2222222	29.03.2019
11	Bělohorská	49.190088	16.6633675		-117	29.03.2019
12	Krásného	49.190681	16.64942			29.03.2019
13	Židovský hřbitov	49.191487	16.6410944		-115.1111111	29.03.2019
14	Geislerova	49.192861	16.6348397		-111.2857143	29.03.2019
15	Životského	49.190638	16.6338097		-110.625	29.03.2019
16	Masná	49.191276	16.6242825		-117	29.03.2019
17	Vlhká	49.191992	16.6188108		-115.2	29.03.2019
18	Hlavní nádraží	49.191375	16.6124486		-121.5	29.03.2019
1	Červený písek	49.22055	16.6574828	-118.3333333	-113.4375	01.04.2019
2	Jarní ČD	49.220593	16.6528694	-120.6666667	-112.6666667	01.04.2019
3	Železniční stavitelstv	49.216605	16.6540389		-112.875	01.04.2019
4	Depo ČD	49.214285	16.6520861	-118.5	-112.6363636	01.04.2019
5	Kulkova	49.211671	16.6482131	-120	-113.8181818	01.04.2019
6	Podsednická	49.209155	16.6456703	-120	-113.8181818	01.04.2019
7	Svatoplukova	49.205131	16.6414217		-115.8333333	01.04.2019
8	Stará osada	49.202061	16.6417114	-120	-113.3	01.04.2019
9	Kuldova	49.201339	16.6345553		-113.3333333	01.04.2019
10	Tomáškova	49.199551	16.6316156		-110.8571429	01.04.2019
11	Uzavřená	49.196915	16.6334394		-112.5714286	01.04.2019
12	Jílkova	49.195906	16.6381064		-104.2857143	01.04.2019