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# Evaluating LoRa and LoRaWAN performance in Louvain-la-Neuve

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# Chapter 1

# Introduction

## 1.1 Context

In this era of rapid change, technology is reshaping our world so rapidly that what might have been an element of science fiction twenty years ago is the reality today. Nowadays, almost everyone possesses a smartphone millions of times more powerful than all the computing power used by NASA to send men on the moon in 1969, and no one bats an eye. If this age of constant progress has been going since before anyone on this planet was born, it does not appear to be slowing down any time soon.

Recently, our world has been more connected then ever before. From our watches to our fridges, it seems like there exists no limit to what can be connected on the internet. And this is just the beginning. It is becoming increasingly easier and cheaper to collect data not just from smartphones, but almost every item in our daily life. This is the ascent of what is called the "Internet of Things", or IoT in short.

There is no strict definition for IoT but simply put, it describes the concept of connecting everyday physical items to the internet and being able to identify themselves to other devices. With such a technology, the possibilities are almost endless. Notably, smart cities, health care, agriculture and industrial automation are among the most promising fields for IoT. In 2017, the IoT market amounted to $235 billion. It is expected to double and reach $520 billion in 2012[1].

Because of its requirements, mainstream communication technologies such as Wi-Fi, Bluetooth or 4G are not sufficient for this rising market. Long range, low battery consumption and cheap costs are also important characteristics to ensure the success of an IoT network. In response to this demand, multiple technologies have arisen, notably a network LP-WAN. Right now, the leaders in this market are Sigfox and LoRa. This thesis focuses on the latter.

## 1.2 Purpose and structure

Currently, no LoRa network is deployed in Louvain-la-Neuve. The purpose of this thesis is twofold: to explain both the main theoretical and practical aspects to take into account in the deployment of a LoRa network, and to evaluate its performance in the field.

To achieve this, the content of this document is divided into the three following chapters :

**The theoretical framework**
LoRa is first compared to its main competitor to better understand its strengths and weaknesses. Once the distinction between LoRa and LoRaWAN is made, the specifications of both of them are explained. The Things Network which acts as the back-end of LoRa is detailed: what is is, its features and its architecture. Finally, the main theoretical elements to consider when designing a wireless communication network such as the one in this thesis are explained.

**The experiments**
The hardware used for the subsequent experiments is described together with the motivation of its choice. The framework and the purpose of each experiment is depicted. Finally, the results are presented and exposed for each of these experiments.

**Related work**
An overview of the pertinent scientific literature is made, and the results obtained in the previous chapter are compared .

# Chapter 2

# Theoretical framework

This chapter describes the theoretical framework that is necessary to deploy a LoRa network, by explaining the employed technologies and the most important theoretical elements to take into account.

## 2.1 Overview of the LP-WAN technologies

Over the last few years, the demand for IoT solutions in the market has been explosive and its applications can be found in numerous fields such as air monitoring, agriculture, smart homes, and much more. Short-ranged typical radio-technologies such as Bluetooth, Wi-Fi or Zigbee are not adapted for situations where big coverage is needed, whereas cellular communications can provide larger coverage but consume excessive device energy for the needs of IoT.[2] Furthermore, IoT devices require less memory, less processing power, less bandwidth, and of course, less available energy. This is either because "things" are battery driven and maximising lifetime is a priority or because their number is expected to be massive[3].

Recently, a new paradigm called Low-Power, Wide-Area Network (LP-WAN) has arisen. As recently as early 2013, the term "LP-WAN" did not even exist. The main foundation of this technology is the deployment of highly scalable systems, employing low-cost edge-devices with low-battery consumption (i.e. 10+ years of battery lifetime), and long-range communication up to 10–40 km in rural zones and 1–5 km in urban zones.[4]. In addition, it is highly energy efficient and inexpensive, with the cost of a radio chipset being less than 2 € and an operating cost of 1 € per device per year. [2]

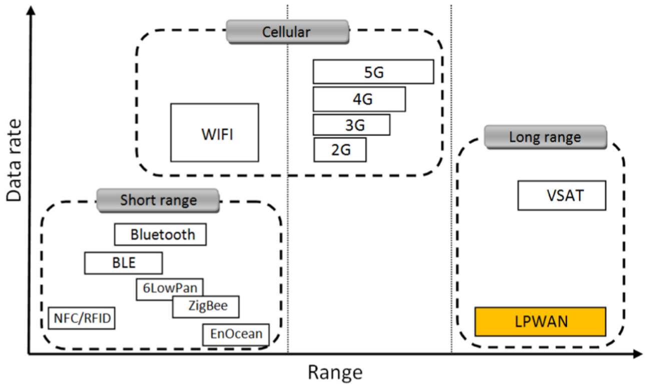

Figure 2.1: Required data rate vs. range capacity of radio communication technologies: LP-WAN positioning.[2]

### LoRa and Sigfox

Among today's leading emergent LP-WAN technologies, the main competitor of LoRa is Sigfox. While this thesis focuses on LoRa, it is noteworthy to mention their main differences, which are synthesised in table 2.1.

Lora and Sigfox have quite different business models. The Sigfox business model has a top-down approach. It possesses all of the technology from the back-end data to the endpoint software, and licenses its endpoint technology to manufacturers and vendors like Texas Instruments and STMicroelectronics. Simply put, Sigfox licenses the hardware and sells the software as a service. In most countries of western Europe, a majority of the territory is already covered by Sigfox. The deployment of the network is usually done by private operators. In Belgium for instance, the whole country is covered by ENGIEM2M, the official Sigfox operator in Belgium[5].

On the other hand, LoRa uses an opposite strategy. Its standards are maintained by the LoRa-alliance which is a non-profit association composed of more than 500 members such as Alibaba, Cisco, Orange or ARM. Anyone can manufacture LoRa gateways, deploy a LoRa network or participate to its development. The trick is that Semtech is the only manufacturer making LoRa radios.[6]

On a technological standpoint, Sigfox and LoRa both operate on the same unlicensed ISM bands, which are 868MHz for Europe, 915MHz in North America and 433MHz in Asia.

Sigfox employs a proprietary modulation called "Differential Binary Phase Shift Keying" (DBPSK) which operates on ultra-narrow bands 100Hz wide. Because of this, the maximum throughput is 100bps, with a maximum payload length

| | **Sigfox** | **LoRa** |
|---|---|---|
| **Band** | Unlicensed ISM | Unlicensed ISM |
| **Modulation** | BPSK | CSS |
| **Max. data rate** | 100 bps | 50 kbps |
| **Max. message length** | 12 bytes (UL), 8 bytes (DL) | 256 bytes |
| **Max. messages/day** | 120 (UL), 4 (DL) | Unlimited |
| **Allows private network** | No | Yes |

Table 2.1: Sigfox and LoRa main differences

of 12 bytes for each message, and a maximum of 140 uplink messages per day. Downlink messages are limited to 8 per day, which prevents the possibility of acknowledgements for each message. Due to this, Sigfox claims that the maximum range can reach up to 10km in urban environment.

Lora uses Semtech's proprietary modulation named "Chirp-Spread Spectrum" (CSS). It can use six possible different spreading factors (SF) ranging from SF7 to SF12 which allow to adapt the trade-off between range and data rate. LoRa's bandwidth is much larger, and can vary between 125 and 500kHz. Its data rate can go up to 50kbps, and the number of transmissions per day is not limited by LoRa itself. LoRa on the other hand claims its messages can be received to 5km away in urban environment[2, 4]. LoRa will be detailed further in the next section.

## 2.2 LoRa and LoRaWAN

LoRa and LoRaWAN are often used interchangeably but are two different technologies, that must thus be differentiated:

- LoRa (short for long range) is a spread spectrum modulation technique derived from chirp spread spectrum (CSS) technology, as well as the systems that support the modulation, including LoRa chips and gateways. It is proprietary and built by Semtech.
  In short, we can say it is the physical layer.

- LoRaWAN is the media access control (MAC) layer protocol designed for large-scale public networks with a single operator. It is built using Semtech's LoRa modulation scheme.[7]. It is an open standard, developed by the LoRa alliance.
  In short, we can say it is the data link layer.

### 2.2.1 LoRa

As a CSS modulation, LoRa uses frequency chirps with a linear variation of frequency over time in order to encode information. The resulting signal has low noise levels, enabling high interference resilience, and is difficult to detect or jam. The parameters affecting this technology is further developed in the next section

Like Sigfox, LoRa operates on unlicensed ISM (Industrial, Scientific and Medical) bands, i.e., 868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia. This means that anyone is allowed to use these frequencies, thus making it possible to undergo a lot of interference.

The LoRa data rate varies between 300 bps and 50 kbps depending on spreading factor and channel bandwidth. The maximum payload length for each message is 243 bytes.

The frequency offset between the transmitter and the receiver can reach 20% of the bandwidth without impacting decoding performance. This helps with reducing the price of LoRa transmitters, as the crystals embedded in the transmitters do not need to be manufactured to extreme accuracy. LoRa receivers are able to lock on to the frequency chirps received, offering a sensitivity of the order of $-130$ dBm.[3]

#### Modulation parameters

The customisation of the LoRa modulation is affected by four parameters:

- **Spreading Factor (SF)**: LoRa employs multiple spreading factors, between 7 and 12. The spreading factor provides a trade-off between data rate and range. Choice of higher spreading factor increases the range but decreases the data rate, and thus increases the airtime for a message. For example, a message with SF12 will take around 25 more time to transmit the same message than SF7.

- **Bandwidth**: LoRa allows the usage of three bandwidth, namely 125kHz, 250kHz and 500kHz. Usage of a wider band makes data rates but lowers the receiver sensitivity. Doubling the data rate divides the receiver sensitivity by two, making messages harder to decode.

- **Frequency sub-band, or channel**: the frequency at which the message is modulated. LoRa operates around the 868MHz frequency, but because of the bandwidth can be as small as 125kHz, it divides its frequency band on smaller frequencies sub-band, or channels, such as 867.3MHz or 867.5MHz for instance. This allows receivers to receive multiple messages with the same SF at the same time, provided they are on different sub-bands.

- **Code Rate** (CR): The code rate defines the amount of forward error correction which is included in LoRa. It equals $4/(4+n)$, where $n = \{1, 2, 3, 4\}$. Decreasing the code rate helps reduce the Packet Error Rate in the presence of short bursts of interference, i.e. a packet transmitted with a code rate of 4/8 will be more tolerant to interference than a signal transmitted with a code rate of 4/5.

A LoRa symbol is composed of $2^{SF}$ chips[1], which covers the entire frequency band. It starts with a series of upward chirps. When the maximum frequency of the band is reached, the frequency wraps around, and the increase in frequency starts again from the minimum frequency.

Transmitters send the spread data at a chip rate equal to the system bandwidth in chips per-second-per-Hertz. So a LoRa bandwidth of 125 kHz corresponds to a chip rate of 125 000 chips per second.

Figure 2.2 gives an example of a LoRa transmission in the frequency variation over time. The position of this discontinuity in frequency is what encodes the information transmitted. As there are $2^{SF}$ chips in a symbol, a symbol can effectively encode SF bits of information.[8, 3].

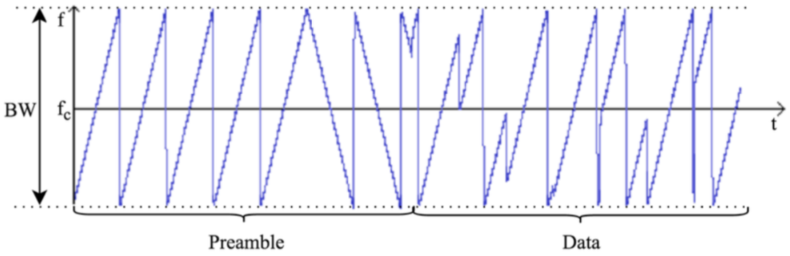

Figure 2.2: Frequency variation over time of a sample signal emitted by a LoRa transmitter. Data taken from [9]. $f_c$ is the central frequency of the channel, and BW is the bandwidth

Taking all these parameters into account, this equation allows one to compute the useful bit rate, $R_b$:

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[1] One must not confuse a chirp, a ramp from high to low-frequency or inversely, and a chip, the subdivision of a symbol.

$$R_b = SF * \frac{BW}{2^{SF}} * CR$$

Where SF is the spreading factor, BW the bandwidth and CR the code rate.

### Packet structure

While the LoRa modulation can be used to send arbitrary frames, Semtech has a physical frame format that is specified and implemented in its transmitters and receivers. The bandwidth and spreading factor are constant for a frame. A LoRa packet is structured as follows:

1. **Preamble**: it is used for the synchronisation purposes. The preamble is composed mainly of constant upchirps that cover the whole frequency band.
2. **Header** (optional): indicates the size of the payload, the code rates used for the transmission and a presence of CRC in the frame. It is optional to allow disabling it in situations where these parameters are already known by the receiver. The header also includes a CRC, and its coding rate is 4/8.
3. **Payload**: Maximum payload varies between 2 and 255 bytes.
4. **Payload CRC** (optional): its length depends on the coding rate.

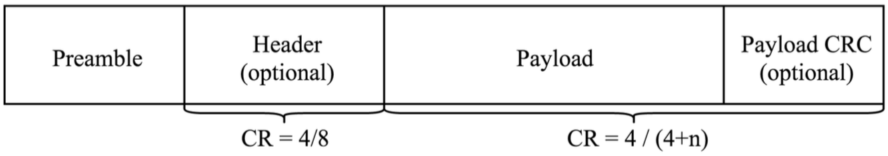


Figure 2.3: Structure of a LoRa frame, from [3]. $n = \{1, 2, 3, 4\}$

### Rules and regulations

As LoRa operates on the unlicensed ISM that can be used by everyone, some rules are set in the European Union concerning its usage. In Belgium, we use the standards set by the European Telecommunications Standards Institute.

These limitations concern duty cycle which indicates the fraction of time a resource is busy, and the maximum transmission power of a device. For example, a single device on a channel for 2 time units every 10 time units will have a duty cycle of 20%.

The ISM band is divided into smaller channels, where the duty cycle limitations vary from 0.1 to 1%, and maximum transmission power ranges from 5mW to 25mW, except on the 869.4 to 869.65 MHz intended for gateways, which has a 10% duty cycle limitation and a maximum transmission power range of 500mW. [10, 11]

### 2.2.2 LoRaWAN

As a MAC protocol, LoRaWAN is built to use the LoRa physical layer. It is designed mainly for sensor networks, wherein sensors exchange packets with the server with a low data rate and relatively long time intervals (one transmission per hour or even days). This section describes the LoRaWAN V1.1 specification[12], as released in 2017.

LoRaWAN defines the communication protocol and system architecture for the network while the LoRa physical layer enables the long-range communication link. The protocol and network architecture have the most influence in determining the battery lifetime of a node, the network capacity, the quality of service, the security, and the variety of applications served by the network.

#### Network architecture

A LoRaWAN network is mainly composed of three distinct elements:

1. **End-devices** or **end-nodes** that are low-power consumption sensors communicating with the gateways using LoRa
2. **Gateways** are the intermediate devices that forward packets coming from end-devices to a network server over an IP backhaul interface allowing a bigger throughput, such as Ethernet or 3G. There can be multiple gateways in a LoRa deployment, and the same data packet can be received (and forwarded) by more than one gateway. A single gateway can serve thousands of devices.
3. A **network server** that is responsible for de-duplicating and decoding the packets sent by the devices and generating the packets that should be sent back to the devices[3]. This is explaine in more details in section 2.3.

LoRaWAN network architecture is deployed in a star-of-stars topology in which the gateways relay messages between end-devices and the central network server.

The gateways are connected to the network server via standard IP connections and act as a transparent bridge, simply converting RF packets to IP packets and vice versa. The wireless communication takes advantage of the Long Range characteristics of the LoRa physical layer, allowing a single-hop link between the end-device and one or many gateways. All modes are capable of bi-directional communication.[13]

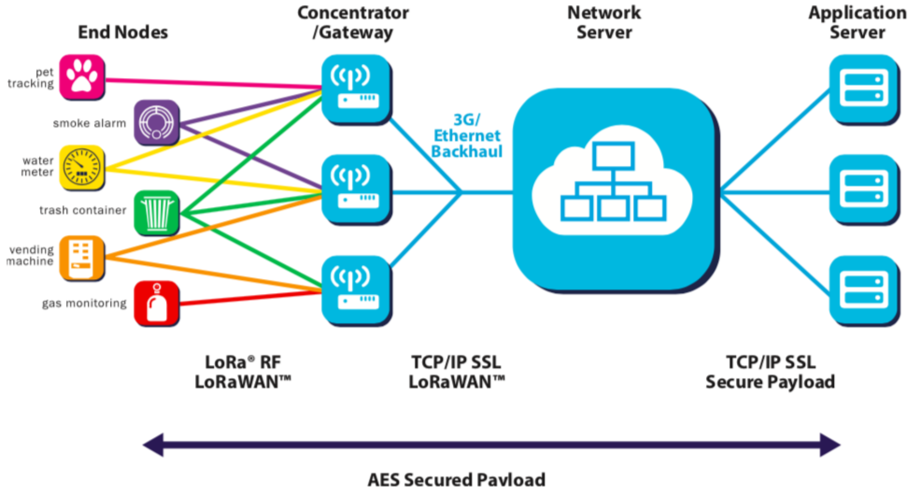


Figure 2.4: LoRaWAN network architecture, from [12]

Because of this topology, direct communication between end-nodes is not possible. This network configuration was chosen instead of a mesh network (where individual end-nodes forward the information of other nodes, which increases the communication range and cell size of the network) because while increasing the range, it also adds complexity, reduces network capacity, and reduces battery lifetime as nodes receive and forward information from other nodes that is likely irrelevant for them. Long range star architecture makes the most sense for preserving battery lifetime when long-range connectivity can be achieved.[12]

It should be noted that the end-devices are not associated with a particular gateway in order to have access to the network. The gateways serve simply as a link layer relay and forward the packet received from the end-devices to the network server after adding information regarding the reception quality.

### LoRaWAN classes

LoRaWAN has three different classes of end-node devices to address the different needs reflected in the wide range of applications. These classes distinguishes between a basic end-node (Class A) and optional features (Class B, Class C), and trade off network downlink communication latency versus battery lifetime

- **Class A**: this is the default class which must be supported by all LoRaWAN end-devices. Each end-device's uplink transmission is followed by two short downlink receive windows, giving the opportunity for bi-directional communication. This is an ALOHA type of protocol. Class A operation is the lowest power end-device system but offers less flexibility, as downlink communications can only happen shortly after an uplink communication which can happen without notice.
- **Class B**: In addition to the Class A, the class B devices open extra receive windows at scheduled times. The gateway has thus to send time-synchronised beacon to the end-device, so that the end-device knows when it should be listening.
- **Class C**: class C further reduces latency on the downlink by keeping the receiver of the end-device open at all times, even when the device is not transmitting. This increases the power consumption, and should be used in situations where continuous power is provided.

## 2.3 The Things Network

The Things Network is the provider used for the network server in thesis, which means it provides the interface between the gateways and the applications (see figure 2.4. First, the precise role of a network server is explained. Then, because the Things Network does not only provide this service but also other tools, these are explained in this section.

### 2.3.1 Network server

When a gateway successfully receives a message, the data must be transferred to the corresponding application. In the same fashion, when an application wants to send a message to a node, a gateway must be chosen to broadcast the message.

This is where the Network Server come is place; just like LoRa and LoRaWAN allow the end nodes to communicate with the gateways, the Network Server is responsible for routing data between devices and applications, as shown in figure 2.4.

While the LoRa alliance provides certain specifications for the back-end interfaces such as controlling the MAC layer, end-point authentication, or applications behind the scenes in the core network[14], there is no official release for the back-end part of a LoRaWAN network.

As such, multiple solutions already exist to run a LoRaWAN network server, such as LoRaServer, an open-source network-server sponsored by CableLabs[15], ResIOT, developed by Ublsoftware[16], and The Things Network, developed by The Things Industries.

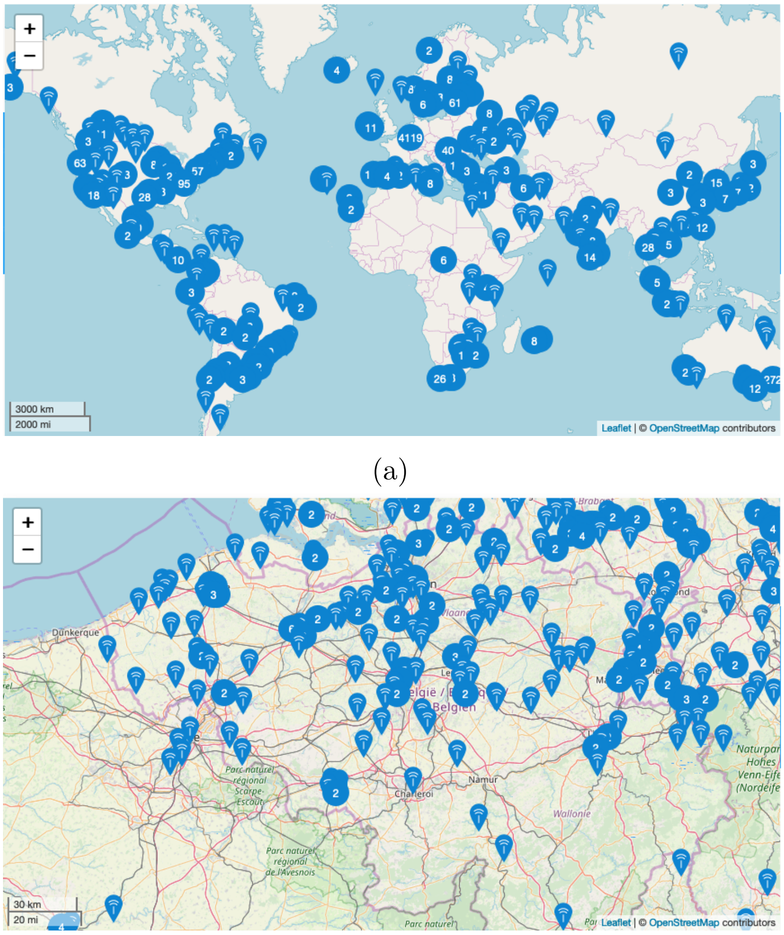
For this thesis, The Things Network (TTN) was used as the back-end for the experiments.

### 2.3.2 Features

The Things Network is a worldwide open source community network for the Internet of Things using LoRa technology. Currently, TTN is composed of more than 7600 gateways throughout 138 countries, and more than 160 gateways in Belgium, as shown in figure 2.5. Anyone can connect a device and use this network freely, but it is also possible to help extend the network by deploying gateways.

To use the network, one has to create a TTN account on their website and register their end node. TTN then provides keys for the node to encrypt and send data to the gateways. A gateway can be easily connected to TTN in the same fashion, by registering it on TTN and configuring the gateway with the correct settings. When a gateway is online, it forwards any LoRa message it receives to TTN, which takes care of forwarding it to the correct owner. Because the data of the packet is encrypted, only himself can access the data. The end node and gateway status can be monitored online on TTN console, as well as the data recently received.

It is also possible to connect any application to TTN. TTN provides SDKs in Java, Python, Node.js and other languages to easily communicate with their servers and build applications. There already exists multiple applications that are ready to use. For instance, "TTN Mapper" allows to map the coverage of a gateway with an Android smartphone. This application was used in the experiments described in section 3.2.



(a)

(b)

Figure 2.5: The Things Network coverage worldwide (a) and in Belgium (b)

### 2.3.3 Architecture

In this section, we will detail The Things Network architecture. Its aim is to perform all its routing in a distributed and decentralised way. For this purpose, the network is split in distinct components, each with its specific responsibilities[17]:

- A **Router** is responsible for communicating with the gateways. When they receive a message transmitted over LoRa, the gateways forward it to the router, which translates each vendor-specific protocol to TTN's internal protocol, and sends it to the correct brokers. Each gateway is connected to one router. Alongside, it adds meta-data such as the GPS coordinates and

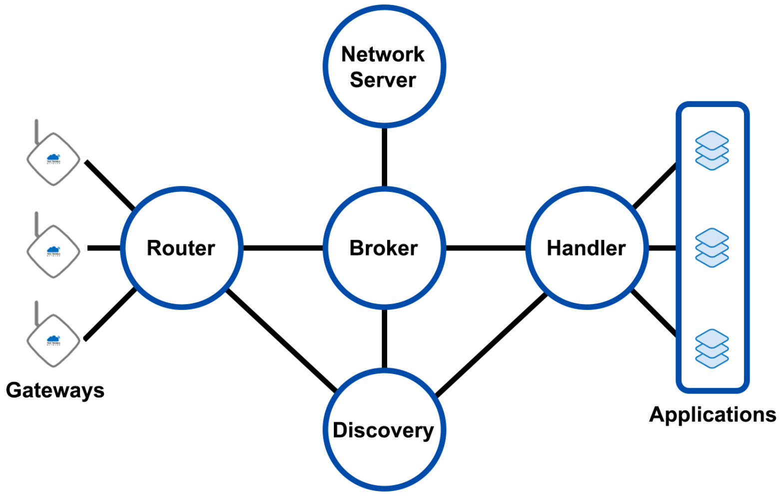


Figure 2.6: The Things Network architecture (simplified)

the gateway status to each uplink message[2]. The Router is responsible for the scheduling of the gateways i.e. when a gateway should send downlink messages.

- A **Broker** is responsible for finding the right handler for each uplink message. When the same LoRa packet is received by multiple gateways, the Broker deduplicates it by only keeping once redundant meta-data (such as frequency and modulation) and keeping signal strength, reception time and GPs coordinates of each gateway. Based on a score calculated by the Router for each gateway, it also chooses the best option for sending a downlink message.
- The **Network Server** monitors the state of all devices. Before a Broker forwards an uplink message to the Handler, it is the Network Server that receives it first to update the state of a device.
- The **Handler** takes care of the decryption of uplink messages and encryption of downlink messages (messages in TTN are end-to-end encrypted). It converts the payload to a format easily accessible by the user's application. The Handler determines whether an uplink message should receive a downlink response, either to send data, confirmation or instruction to a device.

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[2] An uplink message is a message from a node to an application, a downlink message is the opposite.

- The **Discovery Server** helps components to determine where traffic should be routed to as TTN is decentralised service. This is where routers, brokers and handlers announce themselves.

While these components are hosted by The Things Network, it is also possible to deploy a private network, as they can be run in a private environment. This allows for the data to stay in a private environment.

## 2.4 Radio communication theory

Before placing antennas, some theoretical aspects of radio communications must be taken into account to understand the results, and to obtain the best range in practical conditions.

### 2.4.1 Decibel and decibel-milliwatt

The decibel and decibel-milliwatt are two units that are important to understand and will often be used in these calculation:

- The decibel (**dB**) is used to measure a ratio of electrical powers on a logarithmic scale.

  $$G = 10 * \log \frac{P_o}{P_i} \tag{2.1}$$

  Where $G$ is the gain, $P_i$ is the input power, and $P_o$ the output power.
  For example, for an input of 8mW and an input of 10mW, we say that the gain is 0.96dB

- The decibel-milliwatts (**dBm**) is an unit of power. It is defined as the gain relative to an electrical power input of 1mW. Values expressed in dBm can thus always be translated to mW, and conversely.

  $$P(\text{dBm}) = 10 * \log \frac{P(\text{mW})}{1\text{mW}} \tag{2.2}$$

  For example, 80dBm is equal to 100kW and -73dBm is equal to $5 * 10^{-8}$dBm

### 2.4.2 Free-space loss

The free-space loss can be defined as the loss incurred by an electromagnetic wave as it propagates in a straight line through a vacuum with no absorption or reflection of energy from nearby objects.[18]. This assumes that the energy only spreads out as it propagates, does not dissipate and is not lost. This "loss" only occurs because of the inverse square law. Its mathematical expression is

$$L_p = \left(\frac{4\pi D}{\lambda}\right)^2 \tag{2.3}$$

which with $\lambda = \frac{c}{f}$ can be written as

$$L_p = \left(\frac{4\pi f D}{c}\right)^2 \tag{2.4}$$

where

$L_p$ = free-space path loss (unitless)
$D$ = distance (kilometres)
$f$ = frequency (hertz)
$\lambda$ = wavelength (metres)
$c$ = speed of light in free space ($3 * 10^8$m/s)

By converting to dB, separating the constants from the variables and for frequencies in MHz, the free space loss becomes:

$$L_p = 32.45 + 20\log f_{\mathrm{MHz}} + 20\log D \tag{2.5}$$

For LoRa which has a frequency of 868MHz in Europe, the equation simply becomes:

$$L_p = 91.22 + 20\log D \tag{2.6}$$

### 2.4.3 Fresnel zone

During radio transmissions, one might intuitively think that a direct line of sight would be enough to get a good reception of the signal. However, more clearance with respect to the surrounding objects is required.

To understand this, consider an antenna A transmitting to another antenna B, and an obstacle reflecting the electromagnetic waves at point C, as shown in figure 2.7. Path AB is line-of-sight path, where as path ACB is a secondary transmission path via reflection from the obstacle located at C. In the case where there is no phase reversal at the point of reflection, the signal will cancel if AB and ACB differ by an odd multiple of a half wavelength.

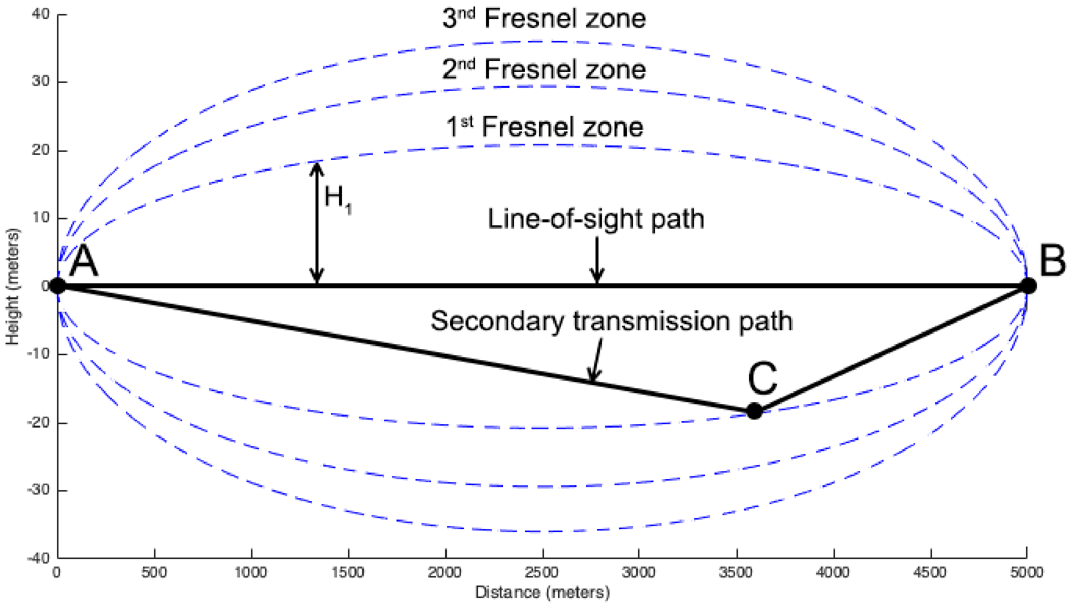

Figure 2.7: Line-of-sight and secondary transmission in the 3 first Fresnel zone. Path ACB is half a wavelength longer than path AB.

Typically however, the angle of incidence is high and a phase reversal happens. In this case, if the distances AB and ACB differ by an odd amount of half the wavelength, the signals will add up. Conversely, if their distances differ by a whole number of half wavelengths, the signals will tend to cancel.

The first Fresnel zone is delimited by an ellipse from which a wave could be reflected to the end point with an additional path length of a half wavelength. In the same fashion, the $n$th Fresnel zone is delimited by the ellipse where a reflection from this ellipse would cause a propagation delay that is $n/2$ the wavelength.

The height $H_n$ from the line-of-sight path to the boundary of the $n$th Fresnel zone depending on distance $x$ from antenna A is described as :

$$H_n = \sqrt{\frac{n\lambda x(d-x)}{d}} \tag{2.7}$$

where $\lambda$ is the wavelength, and d the distance between antenna A and antenna B[18, Chapter 13].

In the case of LoRa, experiments show that a reasonable expected maximum range in an urban environment is 5km[4]. The 3 first Fresnel zones in this case are plotted in figure 2.7. From this figure, we can see that the maximum height for the first Fresnel zone is close to 20 meters.

Measures show that in order to achieve a normal loss of transmission approximately equal to the loss of the free space path, the transmission path should cross all obstacles with a clearance of at least 0.6 times the distance from the first Fresnel zone and preferably a distance to or greater than the first Fresnel zone distance. When placing antennas, it is important to keep this in mind in order to obtain a good reception.

### 2.4.4 Link budget and link margin

In order to determine if a link between two devices is possible, a calculation called the link budget calculation must be performed. It accounts for all the gains and losses during a transmission, and this allows to understand which parameters in a basic communication system can be modified, and which cannot.

A basic communication systems is composed of one transmitter and one receiver, each with an antenna, the two being separated by the path. Five elements must be taken into account for a link budget calculation[19] :

1. The **transmission power** is the power used to send a transmission. It is expressed in dBm.
2. The **antenna gain** describes how much power in the direction of peak radiation is transmitted antennas create an effect of amplification thanks to their physical shape. This effect is the same when transmitting or receiving. The higher the gain, the more "directional" is the antenna.
3. The **cable loss** happens because some of the signal's energy is lost in the cables and connectors going from the radio to the antenna. This depends on its length and the type of cable.
4. The **path loss** contains all the losses between the two communicating antennas. It is mainly caused by free-space loss, attenuation and scattering due to obstacles present in the Fresnel zones, as discussed in the two previous sections.
5. The **minimum receiver sensitivity** denotes the lowest signal level that the radio can distinguish. It is expressed in dBm.

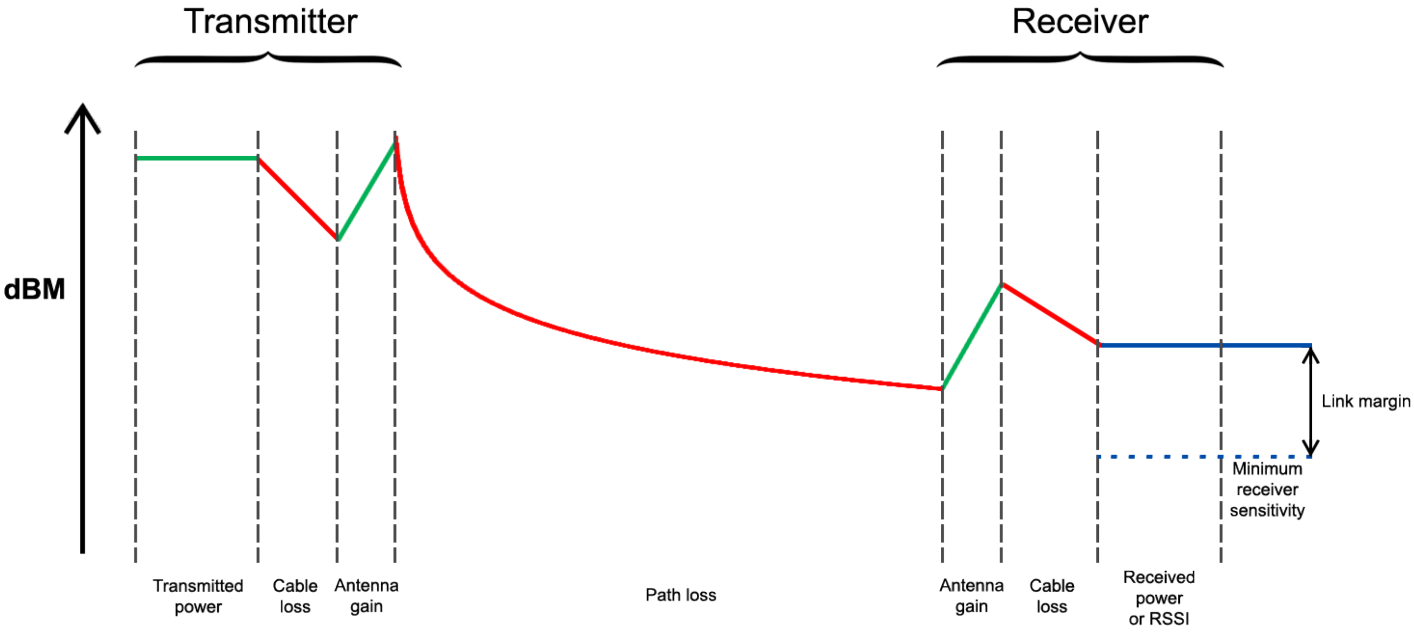

Figure 2.8: Components of a basic communication system to calculate the link budget

Putting all these parameters together gives the link budget calculation, and an illustration of this concept can be shown in figure 2.8. The sum of all these leads to the signal level at the receiver. If it is higher than the minimum receiver sensitivity, then the link is feasible.

Regulations exist for the maximum "Effective Isotropic Radiated Power" or EIRP, which is the sum of transmission power, cable loss and antenna gain. In Europe, the maximum EIRP varies between 11.84dBm and 24.84dBm[10][3]. .

### 2.4.5 RSSI and SNR

Throughout the experiments, RSSI and SNR are two metrics that will often be used to characterise signal quality. It is thus necessary that these are well understood.

**Received Signal Strength Indication** or RSSI is the intensity of the signal received. It is usually expressed in dBm. In figure 2.8, this is the sum of all the gains and losses, and corresponds to the blue line. Typical RSSI values for LoRa

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[3] In the ETSI regulations, the limitation is actually written in terms of Effective Radiated Power or ERP. These values differ by a value of 2.15; $EIRP(dB) = ERP(dB) + 2.15$

varies between -30dBm and -120dBm, which means it can receive signals weaker than $10^{-12}$mW!

**Signal-to-Noise Ratio** or SNR is a measure comparing the RSSI to the background noise. It is usually expressed in dB. With logarithmic units, its expression is:

$$\mathrm{SNR}_{dB} = \mathrm{RSSI}_{dB} - \mathrm{N}_{dB} \tag{2.8}$$

Where $\mathrm{N}_{dB}$ is the noise level in dB. The higher the SNR, the easier it is to decode the signal. Usually, the SNR needs to be positive for the signal to be readable. For LoRa, packets can have negative SNR, going as low as -14dB[20] and still be transmitted!

# Chapter 3

# Experiments

In this chapter, the field evaluation of LoRa and LoRaWAN performances are shown. First by explaining and justifying the hardware used, then by describing the context of the experiments, and finally by showing and discussing the results.

## 3.1 Hardware

### 3.1.1 Gateway

When deploying a LoRa network, the choice of the gateway is one of the first question that comes to mind. Multiple companies such as Kerlink, LORIX, Multitech and The Things Industries (the creators of The Things Network) propose commercially available gateways, with prices ranging from 500 € to 1500 € depending on their functionalities and weather resistance. These have the advantage of being easy to set up and are ready to use for industrial applications.

It is possible, however, to build a gateway by buying the different components, assembling them and configuring the gateway. This option is of course cheaper, and because the goal of this thesis is to evaluate LoRa and LoRaWAN performance and not to deploy a ready-to-use IoT solution in Louvain-la-Neuve, a home-made gateway was chosen for the experiments.

It should be noted that between the ordering of the gateways and the redaction of this thesis, new commercially available gateways have been released by The Things Industries, namely "The Things Indoor Gateway" and "The Things Outdoor Gateway". Their cost is reasonable (respectively 100 € and 490 €), they support Listen Before Talk, can connect to 4G and are trivial to set up. This would have been very exciting to test, but unfortunately they were made available a few months too late.[21, 22]

The components of the home-made gateway used for the experiments are the following:

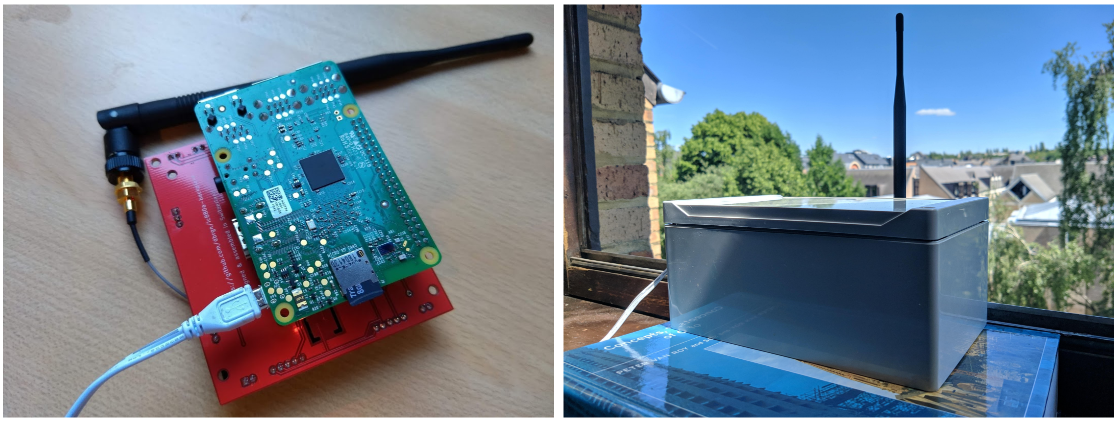
- A iC880A concentrator, built by IMST: this is the centre piece of the gateway as it is responsible for radio modulation and demodulation, thus sending and receiving LoRa packets. The iC880A is one of the most popular LoRa concentrator. It is able to receive packets of different end devices and send with different spreading factors on up to 8 channels in parallel.

- An antenna, built by IMST as well. The one used here as a gain of 2dB, and a pigtail to connect the antenna to the concentrator.

- A raspberry Pi3 host (as well as its power supply and an SD card): is is responsible for running the software which connects the gateway to The Things Network and runs the packet forwarder.

- An adaptor board to connect the iC880A to the raspberry Pi3: the one used here is built by a small Swiss enterprise named "Coredump" that sells electronics. For a cheaper alternative, jumper wires could have been used, but this is known to cause interference which affects the gateway's performances.

- A plastic enclosure to protect the gateway.

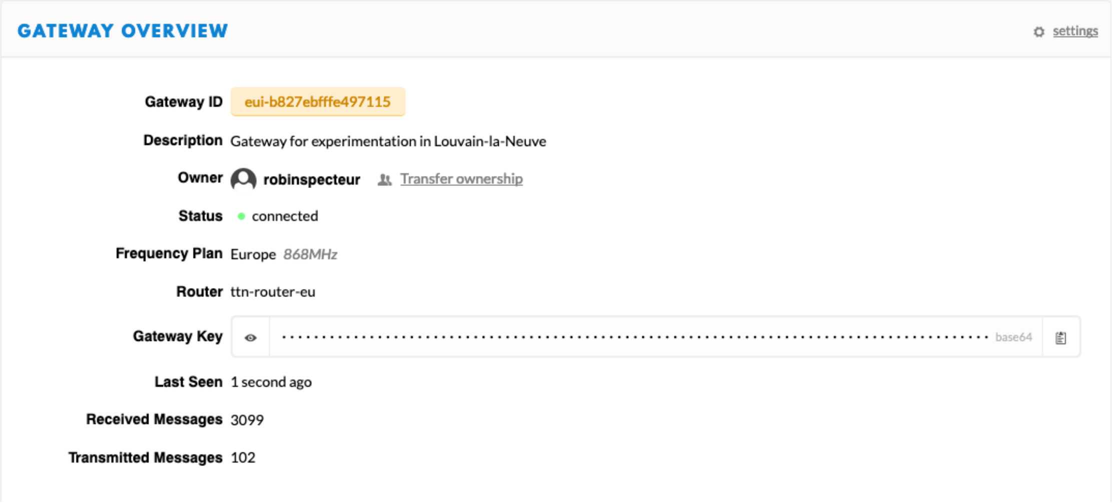


(a) The gateway's electronic boards (b) The gateway up and running

Figure 3.1: LoRa gateway built with the components described in this section

The gateway uses Raspbian Stretch Lite as the operating system, and runs the legacy Semtech packet forwarder that forwards radio frequency packets received by the concentrator to a server through an IP/UDP link, and emits radio frequency packets that are sent by the server. It connects to the internet via Wi-Fi, but can also connect via Ethernet.

Once the gateway is configured, it has to be registered on The Things Network. Its status can be seen on The Things Network's console, as shown in figure 3.2. Because TTN gateways are usable by everyone, it sometimes receives LoRa packets from unknown owners and forwards them to the TTN server.



**Gateway ID** eui-b827ebfffe497115

**Description** Gateway for experimentation in Louvain-la-Neuve

**Owner** robinspecteur

**Status** ● connected

**Frequency Plan** Europe *868MHz*

**Router** ttn-router-eu

**Gateway Key** ····································································

**Last Seen** 1 second ago

**Received Messages** 3099

**Transmitted Messages** 102

Figure 3.2: The gateway's satus

Regarding the link budget values, the gateway can transmit with a power up to 20dBm and has a minimum sensitivity ranging between -120dBm and -137dBm[23]. Its cable loss is -1.5dB, whereas the antenna gain is +2.15dB.

### 3.1.2 End node

Now that the gateways is operational, any device broadcasting LoRa messages near the gateway can be seen on The Things Network's console.

A wide range of certified products are available to meet LoRaWAN's wide range of IoT use cases. The Things Node was chosen for the experiments. It is developed by The Things Industries, is a cheap (approximately 50 €) LoRa node which is perfect to prototype ideas without having to deal with bread boards, wires and sensors. It is a class A device based on the SparkFun Pro Micro - 3.3V/8Mhz Arduino board and Microchip's RN2483 LoRaWAN module. As sensors, it possesses a digital accelerometer, a light sensor and a temperature sensor. A button and an

Figure 3.3: TTN node in its box and its casing, and the Printed circuit board

RGB LED allow the device to take input and give output to the user. All this is packaged in a waterproof (IP54) case with 3 AAA batteries for months of use.

The Things Network developed an Arduino library dedicated to connect devices like The Things Node to The Things Network. The node used here is thus programmable with the Arduino IDE. This allows for almost infinite possibilities with the node; LoRa parameters such as the spreading factor or the bandwidth, message format, input by the sensors and the button, etc. can be programmed according to the user's intentions.

Once the node is registered on The Things Network, messages are successfully sent by the node, received by the gateway, forwarded to The Things Network and finally appear on its console.

Regarding the link budget calculations, The Things Node can transmit with a power up to 14dBm and claims to have a sensitivity that can go as low as -146dBm[24]. The cable loss and antenna gain couldn't be found anywhere. For the former, it can be assumed that it is negligible given the antenna is embedded in the circuit board. Concerning the antenna, several antennas that were very similar to the one found on board had a gain ranging between -2dB and 1dB. For this reasons, it also can be neglected.

## 3.2 Experimental framework

When developing a LoRa network in the real world, many factors have to be taken into account: topology of the terrain, modulation parameters, economic constraints, usage of the bandwidth etc. LoRa is also a recent technology, and no study has yet been done concerning its performances in Louvain-la-Neuve.

The purpose of the experiments was to study the influence of four different variables:

- The position of the gateways and the according coverage in Louvain-la-Neuve.
- The evolution of the signal over time, and depending on the weather.
- The impact of varying Spreading Factors.
- The importance of interference during simultaneous transmissions.

A last experiment was dedicated to find the furthest point from which communication with a gateway was possible. A more thorough description of each experiment is done in subsection 3.2.2.

### 3.2.1 Gateway positions

For each experiment, the gateways were placed in either or both of the two following locations:

A. From the window of the author's accommodation.
   Latitude: 50°40'14.3"N
   Longitude: 4°36'33.5"E
   Altitude: 134m

B. At the roof of the "Réaumur" building.
   Latitude: 50°40'06.8"N
   Longitude: 4°37'16.6"E
   Altitude: 145m

From now on, these locations will be referred as location A and location B (or gateway A and gateway B). These are shown in figure 3.4, which also illustrates the topography of Louvain-la-Neuve. There are two reasons for the choice of these positions:

1. The first and the most obvious is the (supposed) good range they offer. The city of Louvain-la-Neuve has a "valley" topography, with the centre of the city being at a lower altitude as can be seen on figure 3.4. Each gateway is placed on a "side" of the valley. Furthermore, they both had a relatively good "view" of Louvain-la-Neuve, thus offering the clearest Fresnel zone for many places.

2. The second is the ease of access. This is an important factor when of experimenting: in case of malfunction, the gateway can easily be accessed to find the origin of the problem. Some experiments also spanned over different days and thus required the gateway to be placed and removed several times.

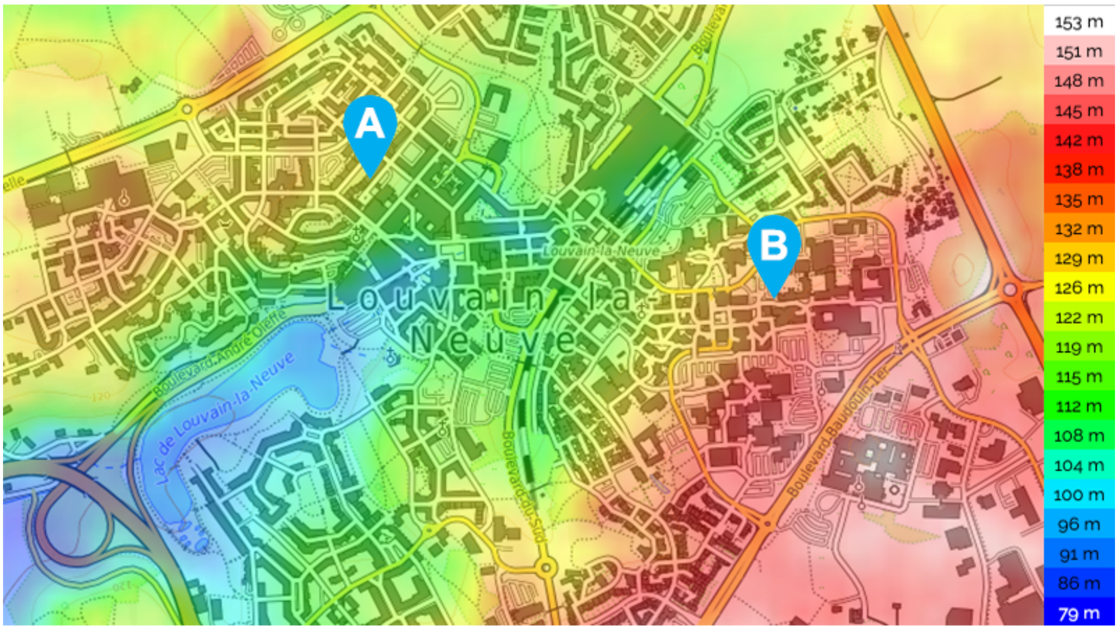


Figure 3.4: Gateway positions on a topographic map [25]. The gateway A is positioned at the author's accommodation, and the gateway B at the Réaumur building. Note the city's "valley" topography.

### 3.2.2 Experience descriptions

#### Antenna coverage

The purpose of this experiment is to get a map of the coverage of each antenna individually, and together. This gives an idea about how many antennas would be needed for a total coverage and how much the coverage can vary according to distance in real conditions.

To achieve this, precise GPS coordinates and metadata with RSSI and SNR for each transmission are needed to map the quality of the coverage. The challenge is that the node used in this thesis don't have a GPS antenna.

Fortunately, an application called "TTN Mapper"[26] was developed specifically for this problem. It requires a node transmitting to The Things Network and an

Android phone running the TTN Mapper app. The node must be connected to the TTN mapper application on The Things Network's console[1], and one simply has to connect to its TTN account on the TTN mapper android app to begin mapping.

When mapping, all of the data and metadata such as payload, RSSI value, data rate, time, GPS coordinates etc. of each successfully transmitted packet is stored on the phone. A provisional coverage map is also accessible on the spot to allow for a visualisation of the data. Once the coverage is mapped, the data can be accessed on TTN mapper's website for everyone to look at, as gateways to The Things Network can be used by every TTN user.

The spreading factor used to transmit packets was SF7, as recommended by TTN Mapper's developer[26]. Being the smallest spreading factor, it gives the smallest range and thus shows the "worst case" scenario for the coverage. But it also has the fastest data rate, therefore the smallest transmission time (approximately 50ms), and allows for more frequent messages. Comparatively, a higher spreading factor such as SF12 can take more than 1 second for a transmission. As explained in section 2.2.1 about European regulations of LoRa frequency bands, a duty cycle limitation of 1% means that a node transmitting at SF12 must wait at least 100 seconds between each message, which is not practical when mapping the coverage of an area.

A script for the node was programmed to broadcast a message approximately[2] every 10 second. This node operated on a battery and was carried around most of Louvain-la-Neuve urban area. To cover most of the city, a distance of approximately 20km had to be travelled. This experiment was repeated three times: once with gateway A, once with gateway B, and once with both. Their positions are shown at figure 3.4. The total distance travelled for this experiment accounts to roughly 60km.

This experiment was conducted between late March and early May, between 8AM and 7PM. The weather conditions were relatively calm; partially cloudy, moderate wind, temperature ranging between 10°C and 15°C, and no precipitation.

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[1] One should not confuse the "TTN mapper" android application, running on a smartphone, the "TTN mapper" TTN application running on the TTN server, and the TTN mapper website to visualise the coverage.

[2] For an unknown reason, the delay between each message could vary by a few seconds, but this does not have an impact on the results.

### Maximum range

The purpose of this experiment was to find the furthest point from where it was still possible to send messages from a gateway. This was not done in conjunction with the first experiment detailed in section 3.2.2, because the spreading factor was set in order to SF12 to maximise the reach of the transmission. The two gateways were placed simultaneously at position A and B. To find the furthest point, the node broadcast messages starting from Ottignies' train station, exploring different roads until a message was consistently received.

### Signal quality evolution

When deploying a device, achieving to successfully transmit few packets is not enough. One must make sure that the signal will not be lost, or at least not too often. To test this, a gateway was placed at position A, and the two nodes were placed at two different locations, shown in figure 3.5:

1. The first one - called node 1 - was placed near gateway A, at a distance of approximately 100 meters.
   Latitude: 50°40'17.1"N
   Longitude: 4°36'36.2"E
2. The second one, node 2, was placed further, 500 meters away gateway A.
   Latitude: 50°40'06.8"N
   Longitude: 4°36'59.1"E

These two positions were chosen to compare the evolution of a strong signal, coming from location n°1, and a weak signal, coming from location n°2. Each node broadcast a message every minute during two different days in early April, each time during more than 12 hours. The weather was clear the first day, while the other had some heavy rain and a lot of wind.

### Spreading Factor variation

As discussed in section 2.2.1, multiple parameters can be toggled in the LoRa modulation. The Spreading Factor is the setting that has the most impact on transmission rate and range, and this impact of its different value was examined in this experiment. For this experiment, transmissions were made using the 6 different Spreading Factors (from SF7 to SF12). For each Spreading Factor, 30 to 60 messages were sent.

Figure 3.5: Position of the two nodes and the gateway in Louvain-la-Neuve

The locations of the nodes and the gateway was the same than in previous experiment; they are illustrated in figure 3.5. They were chosen for similar reasons.

**Interference between nearby nodes**

In case of a large LoRa network, interference between nodes emitting simultaneously, or between other devices using the same frequency band, is a legitimate concern.

For this last experiment, two nodes were placed 30 centimetres next to each other, and simultaneously broadcast a total of 50 messages on the same Spreading Factor, for each Spreading Factor. The frequency sub-band used was automatically chosen by each individual node, as in real-world conditions.The two nodes were positioned at location 2 (see figure 3.5), and the gateway at location A.

## 3.3 Results and discussions

### 3.3.1 Antenna coverage

The coverage of each and both gateways is illustrated on figure 3.6. The signal varied between -30dBm and -120dBm, but for the sake of clarity and because a signal higher than -100dBm can be considered of good quality, the colour only corresponds to RSSI values ranging between -100dBm and -120dBm. Red and orange can be considered as a "good signal", yellow and green as "mediocre", and turquoise and blue as weak.

Each square's colour represents the average RSSI of the area covered by the square; this allows for a better readability as there might be many points of different colours close to each other. Figure 3.6a has more squares than figures 3.6b and 3.6c. This might give the impression that the gateway at position A gives excellent result compared to the other, but this is because the first map was realised while moving by foot. While this gives a better resolution, it is very time consuming and does not especially yield more useful information; figures 3.6b and 3.6c were realised while moving on bike which increased the distance between each transmission. Figure 3.6a was made with approximately 1400 data points; figures 3.6b and 3.6c with approximately 700 each.

These maps should not be taken as an exact coverage of the gateways in Louvain-la-Neuve; the absence of colour at some places does not necessarily mean the absence of signal. While efforts were made to cover most of the city, a complete coverage map is impossible to make due to restricted or impossible access to many places. Instead, it should be taken as a guideline concerning the quality one might expect in a specific area. Furthermore, all measurements were realised outdoors. Indoors, a smaller RSSI value can be expected, as it was noticed that the difference can vary substantially depending on the building

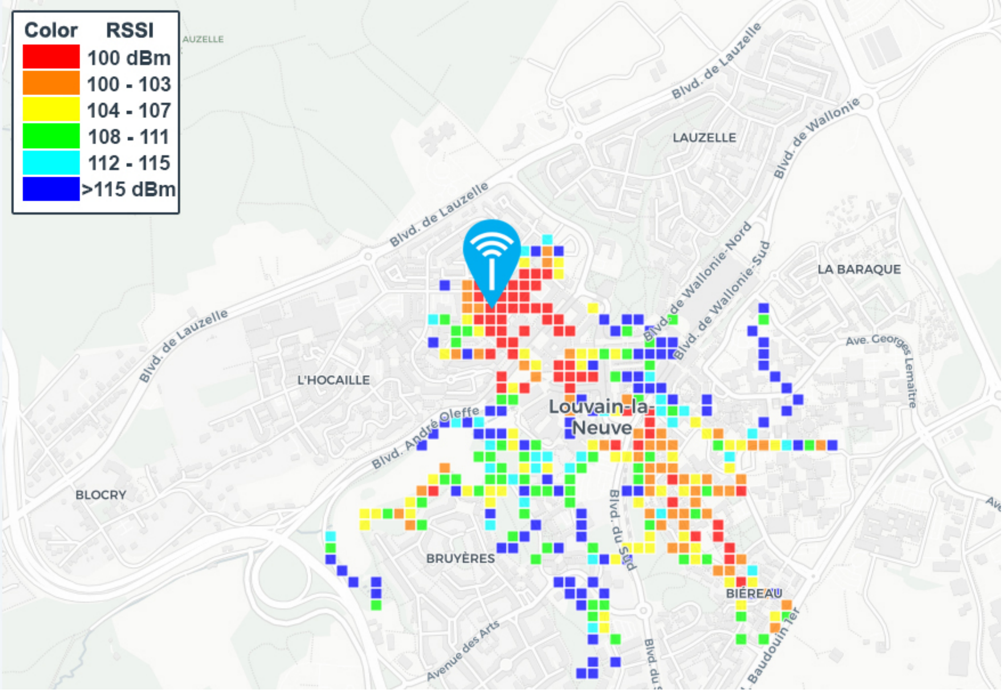
Two main conclusions can be drawn from these 3 figures:

- Signal quality can vary considerably depending on topography and buildings obstructing the signal, more than distance. For instance, in figure 3.6a, the antenna was placed facing the south-east direction (the antenna is omnidirectional, but the window from which it transmitted face south-east) and the signal is lost after only a few hundred metres up north. Conversely, on the same figure, there is still a good signal 1km south-east of the gateway.

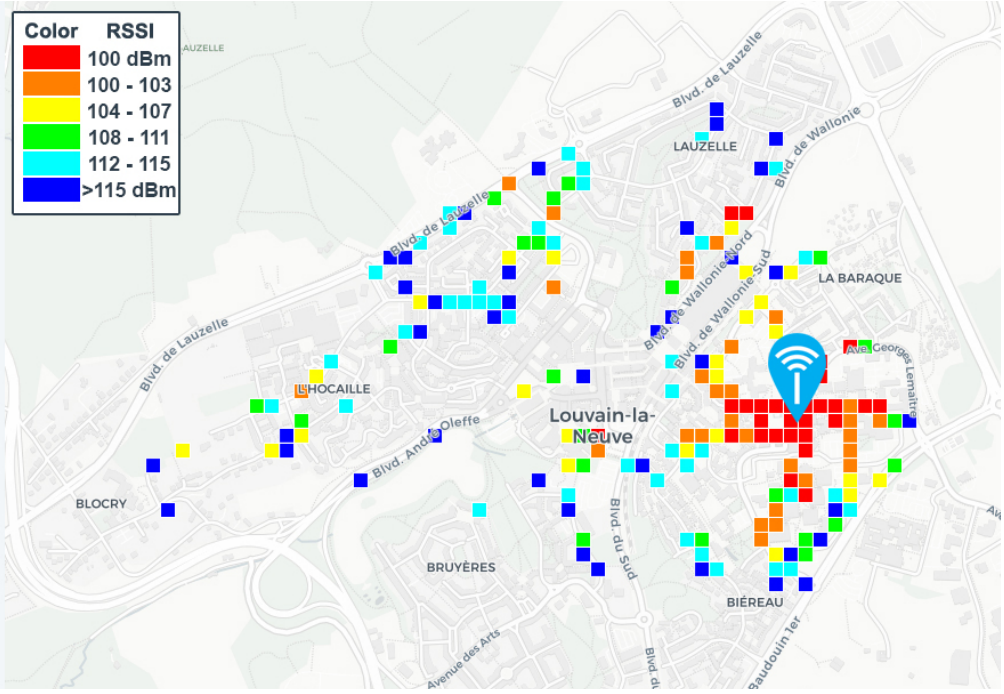
  In the same fashion, gateway B covers that area north and west of gateway A better than gateway A. This is more than likely due to these areas being higher in altitude (see figure 3.4) and obstructed by many obstacles from gateway A, whereas gateway B is much further but has a much "clearer" Fresnel zone.

  This is especially visible in figure 3.7: after 200 meters, RSSI values are unpredictable using the distance as an indicator.

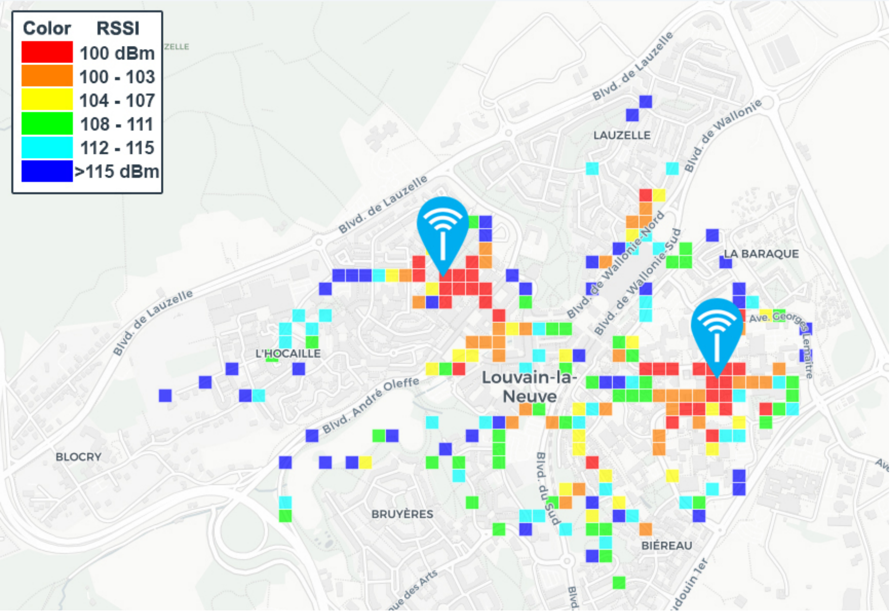
- Combined together, the two gateways provide coverage in most of Louvain-la-Neuve, and are complementary in their coverage. However, coverage from



(a) Coverage for gateway at position A



(b) Coverage for gateway at position B



(c) Coverage for gateways at position A and position B

Figure 3.6: Coverage for each and both gateways. The colour of each square describes the average value of the RSSI in this square.

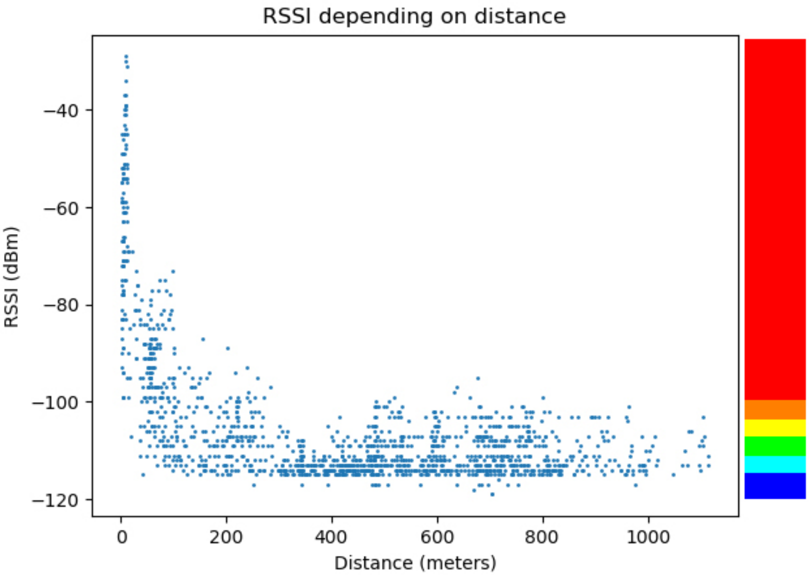


Figure 3.7: RSSI depending on distance for gateway at position A. The colours on the right correspond to the colours on figures 3.6

figure 3.6c does not seem to be different than the coverage from figures 3.6a and 3.6b combined together. However, some areas while being covered, have weak coverage and transmissions might be inconsistent in them while using the same modulation parameters.

### 3.3.2 Maximum range

A transmission was successfully made from the Blocry parish to gateway B, the parish being one of the furthest points in the city of Louvain-la-Neuve from gateway B. The church is precisely at a distance of 2km from the gateway.

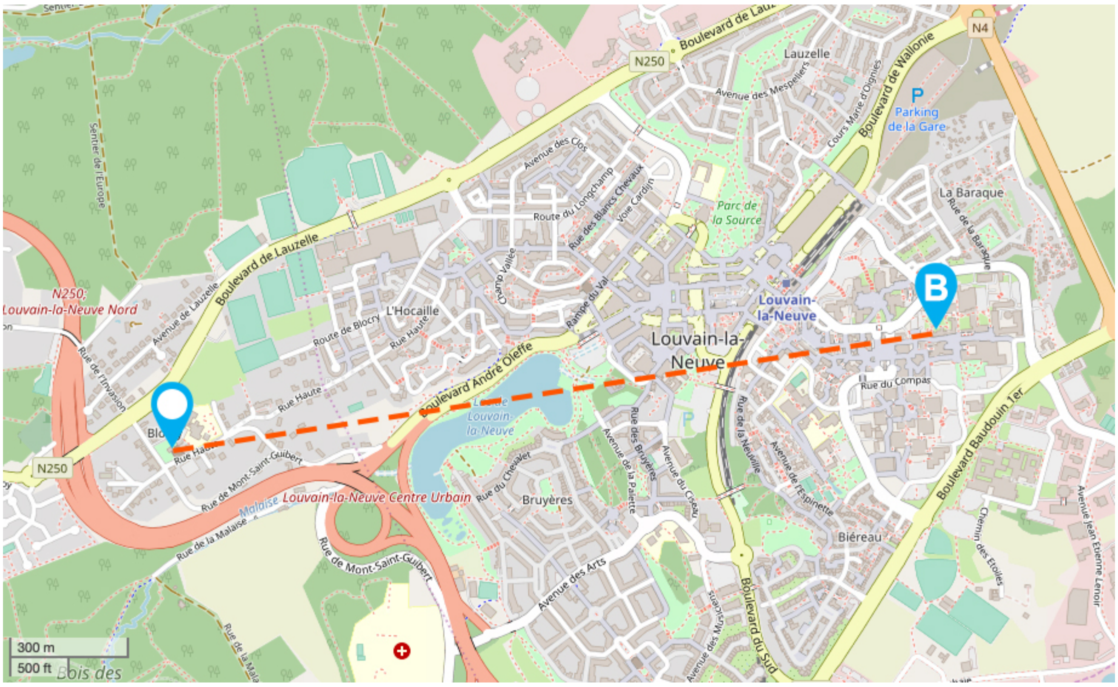


Figure 3.8: Furthest transmission

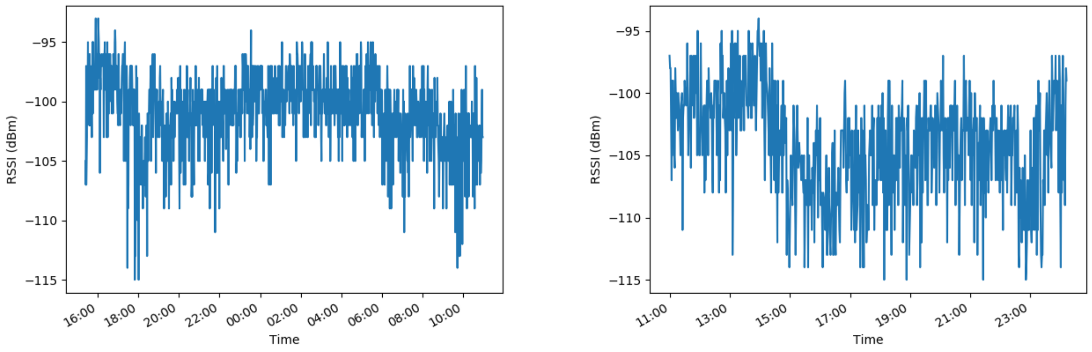
### 3.3.3 Signal quality evolution

A graph of the RSSI signal for each node and for each day can be seen in figure 3.9, and table 3.3 shows a compilation of the data of each graph. From these, three conclusions can be drawn:

1. Even in stable conditions, the signal intensity can widely vary. For instance, in figures 3.9a and 3.9b, RSSI ranges between -115dBm and -95dBm.

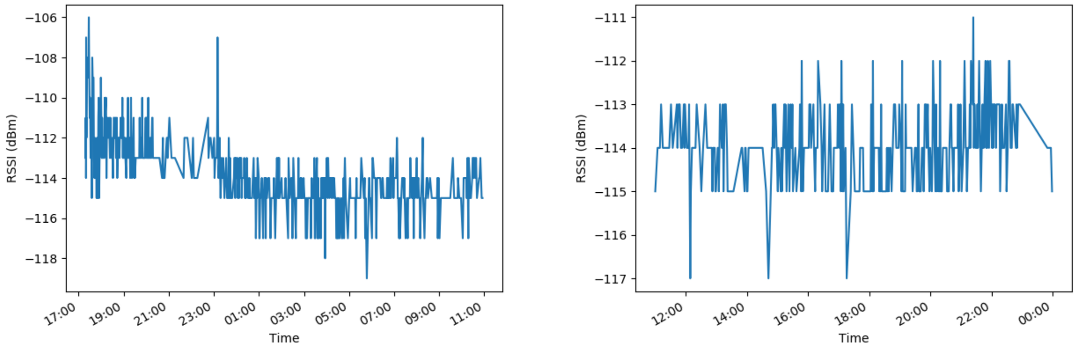
2. Even in poor link conditions such as the one between node 2 and the gateway, communication is still possible, albeit not successful on each transmission. This also explains the low variability for RSSI and SNR with node 2: the values in the dataset correspond to only half the packets, those who reached the gateway.

3. Weather visibly had an impact on the transmission. The first day was sunny whereas the second was rainy, 5 to 10°C colder. At 3pm, strong winds even began and a small storm declared itself. By all means, the values in table 3.1 are worse the second day. RSSI and SNR were also less predictable (ignoring the second node due to the reasons explained before).



(a) Node 1, day 1

(b) Node 1, day 2



(c) Node 2, day 1

(d) Node 2, day 2

Figure 3.9: RSSI variation over time for each node.

| | **Node 1** | |
|---|---|---|
| | **Day 1** | **Day 2** |
| **# of messages sent** | 1112 | 762 |
| **Transmission rate** | 98.32% | 94.23% |
| **RSSI (mean ± sd)** | -100.832 ± 3.290 | -104.173 ± 4.389 |
| **SNR (mean ± sd)** | 7.545 ± 1.746 | 5.710 ± 3.005 |

| | **Node 2** | |
|---|---|---|
| | **Day 1** | **Day 2** |
| **# of messages sent** | 933 | 684 |
| **Transmission rate** | 60,08% | 47,5% |
| **RSSI (mean ± sd)** | -113.837 ± 1.767 | -113.95 ± 0.880 |
| **SNR (mean ± sd)** | -3.996 ± 2.850 | -5.894 ± 1.785 |

Table 3.1: Transmission statistics for node 1 and node 2

### 3.3.4 Spreading Factor variation

The results for node 1 are summarised in table 3.2, and in table 3.3 for node 2. Surprisingly, the Spreading Factor had little impact on the transmission rate during this experiment, even though the setting was exactly the same than in the previous experiment. Especially for node 2 at SF7, the transmission rate is unexpectedly high. This goes to show how variable transmissions can be.

It can also be observed that the Spreading Factor has little impact on both RSSI and SNR values. This is in line with the theory: a higher spreading factor gives a longer transmission time and thus higher receiver sensitivity, but the message is still emitted with the same power.

### 3.3.5 Interference between nearby nodes

In this experiment, the transmission rates denoted in figure 3.10 were significantly lower than in the previous experiment, even though the conditions were mostly similar (same position and almost same average RSSI). These lower transmission rates are obviously caused by the interference between the two nodes. For SF7 and SF8, the simultaneous transmission rates are particularly affected, much more than the other spreading factors.

Among the 80 successful simultaneous transmissions, none were broadcast on

| | **Transmission rate** | **RSSI (avg ± sd)** | **SNR (avg ± sd)** |
|---|---|---|---|
| **SF7** | 97.78% | -100,75 ± 3,50 | 7.65 ± 1,45 |
| **SF8** | 83.78% | -101,48 ± 3,50 | 8,80 ± 2,17 |
| **SF9** | 88.89% | -105,04 ± 3,44 | 8,65 ± 1,57 |
| **SF10** | 100% | -96,41 ± 1,68 | 9,48 ± 1,73 |
| **SF11** | 94.55% | -108,81 ± 3,56 | 4,52 ± 2,64 |
| **SF12** | 93.61% | -100,02 ± 2,45 | 7,63 ± 1,09 |

Table 3.2: Node 1 transmission statistics

| | **Transmission rate** | **RSSI (avg ± sd)** | **SNR (avg ± sd)** |
|---|---|---|---|
| **SF7** | 97.83% | -112,89±1,90 | 1,32±2,30 |
| **SF8** | 88.57% | -112,55±1,77 | 1,35±1,98 |
| **SF9** | 84.21% | -111,63±1,78 | 4,04±1,68 |
| **SF10** | 100% | -111,90±2,59 | 2,14±2,18 |
| **SF11** | 100% | -109,43±2,71 | 3,82±1,30 |
| **SF12** | 97.5% | -113,31±1,67 | -3,38±4,12 |

Table 3.3: Node 2 transmission statistics

the same channel, even though simultaneous transmissions on the same channel represented around 12.5% of the transmissions[3]. Even

The average SNR values are shown in table 3.4. They show how resistant to noise LoRa is. Especially, at SF12, the average SNR of -10dB deserves to be highlighted! One message was even transmitted with a SNR as low as -17.8dB.

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[3] When broadcasting, each node decides by default pseudo-randomly on which of the 8 channel to broadcast, thus broadcasting 12.5% of the time on each channel on average

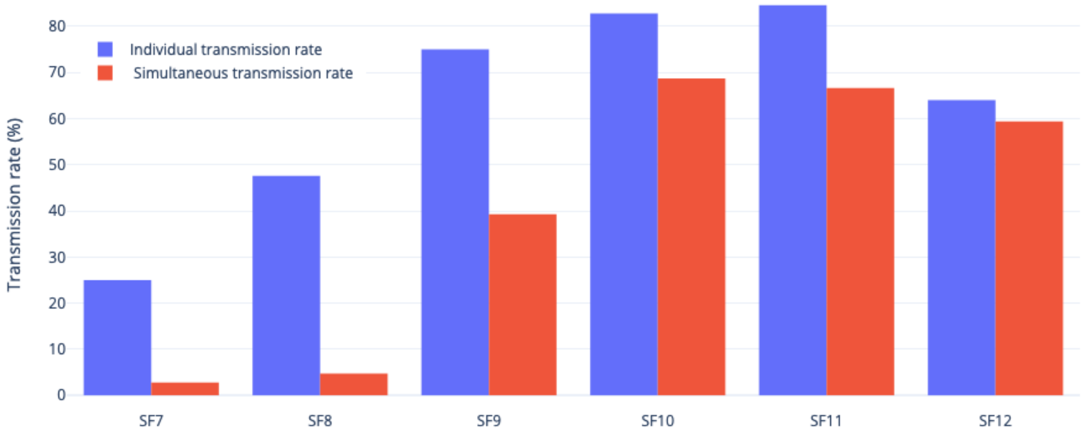

Figure 3.10: Transmission rates depending on Spreading factor. The individual transmission rate is the total number of messages received over the number of messages sent i.e. the usual transmission rate. The simultaneous transmission rate is the number of messages simultaneously received over the number of messages simultaneously sent.

| **SF** | **SNR (avg. ± sd)** | **"Usual" SNR (avg. ± sd)** |
|---|---|---|
| 7 | -4.34 ± 2.52 | 1.31 ± 2.30 |
| 8 | -7.29 ± 2.85 | 1.35 ± 1.98 |
| 9 | -9.17 ± 2.92 | 4.04 ± 1.68 |
| 10 | -6.70 ± 4.09 | 2.14 ± 2.18 |
| 11 | -9.11 ± 3.48 | 3.82 ± 1.30 |
| 12 | -10.11 ± 3.55 | -3.38 ± 4.12 |

Table 3.4: Transmission rates (TR) and Signal-to-Noise Ratio depending on Spreading Factor. "Usual" SNR is the SNR from node 2 in the experiment described in section 3.3.4, to give a point of comparison

# Chapter 4

# Related work

LoRa and LoRaWAN, and The Internet of Things in general, have gain interest over the last few years. As such, most of the scientific publications are recent, and the earliest paper dedicated to LoRa only dates back to 2014[27].

Numerous papers have studied LoRa range in real world conditions, under diverse propagation and environmental conditions, with varying results [20, 3, 28, 29, 30].

In Oulu, Finland, a mapping of the RSSI received from a single gateway was also made, as shown in figure 4.1[28]. A better coverage was achieved than in this thesis: they found that a single gateway could cover an area of few kilometres in the urban zone and achieved communication as far as 30 kilometres away on sea. This can be explained by two factors. Firstly, they had an antenna tower at disposition, elevating the gateway 12 metres above ground level and at a total altitude of 24 metres. Secondly, the topology of the ground is flatter, being close the sea. They also analysed the performance of LoRa communications in presence the of Doppler shift. They found that with a Spreading Factor of 12 and a speed higher than 40km/h, performance deteriorated, but that under 25km/h, performances were reliable.

Another study in Paris, France, also measured the coverage of LoRa in urban environment. For approximately similar distance and spreading factors, they found transmission rates quite in line with similar conditions, getting around 60% of transmission rate at a distance of 1400m with SF7, and reaching close to 100% with SF9 and 12.[3]

In [20], researchers compared the performance of a LoRa network in three environments: open space with at least 1km of free sight, dense forest with a flat terrain and urban environment. They found that the urban environment had the

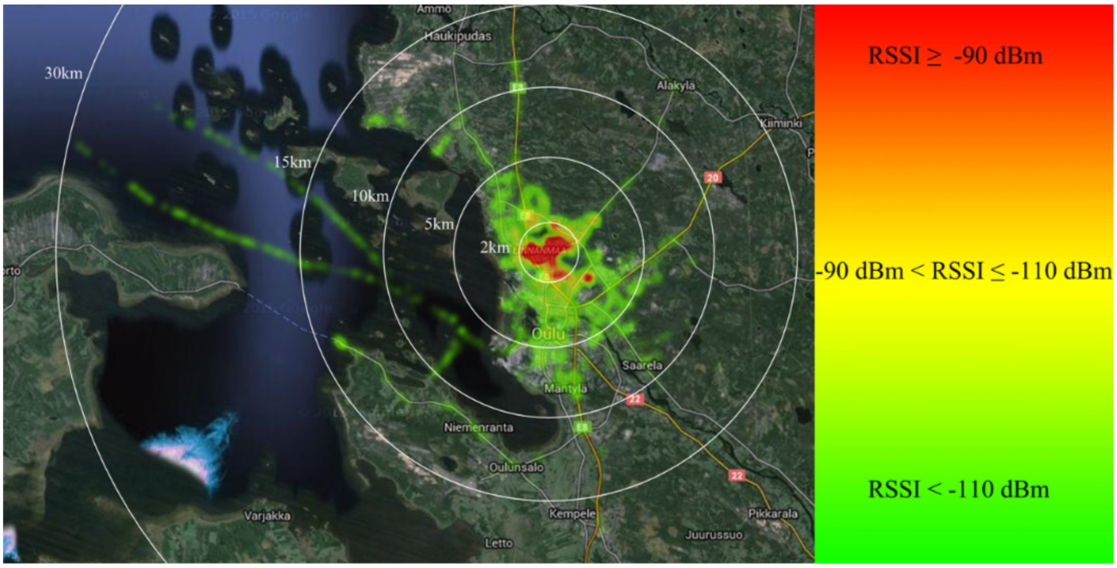

Figure 4.1: RSSI map of a gateway in Oulu, Finland[28].

most drastic drop in both RSSI and SNR. After only 150 metres, the transmission rate dropped staunchly. They also measured RSSI and SNR values for varying gateway elevations. As expected, they found that the elevation was decisive to obtain better RSSI values, with an increase of almost 30dB when elevating the antenna from 0 metres to 20 metres above ground level, as shown in figure 4.2.

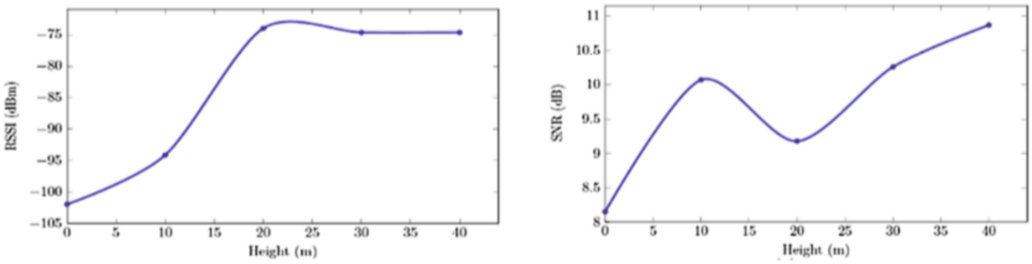

Figure 4.2: Gateway elevation experiment results from [20]

In [4], it was also found that while LoRa was very reliable at short-range, it was very terrain dependent. Researchers found a lot of variance in results with a very small variation in distance and altitude.

With regard to the impact of interference between LoRa nodes, a stochastic geometry framework for modelling the performance of a single gateway LoRa network was used to show the negative impact of highly populated LoRa networks in [31]. They compared two link-outage conditions: one due to a high SNR, the other due to interference when using different LoRa channels. They found that the latter is the essential limiting factor for LoRa scalability, and that the coverage probability dropped exponentially with the number of devices due to interfering signals using the same SF, more than other limitations such as the spectrum bandwidth limitations. This was not observed during the experiments as Louvain-la-Neuve is almost clear of LoRa packets, but this could become an issue was a network to deploy heavily.

Another study evaluated the interference depending on the spreading factor [32]. First, they studied interference between identical SF. In the simulation, they found that larger SF clearly yielded better resistance to interference, whereas messages with SF7 could barely be transmitted. The experiment confirmed the simulations. Then, they compared interference between different SF. In the simulation, they found that using a high spreading factor always provided better immunity to interference from other SF. However, they also found that transmissions using a large SF were more vulnerable to interference coming from low SF than from large SF e.g. a transmission using SF12 is more vulnerable to interference with a transmission on SF7 than on SF10. The experiment confirmed again these results.

In [33], researchers also studied interference between different spreading factors. While they did conclude that higher SF were more resilient to interference, they did not note that the SF of the interferer had an impact on interference like in [32]. They also concluded that SF7 was very prone to interference.

This is consistent with the observations done in section 3.3.3.

# Chapter 5

# Conclusion

The Internet of Things is rapidly growing, with LoRa being on the forefront of the technologies that will carry it. Understanding its strengths and limitations is important is a LoRa network to be deployed in Louvain-la-Neuve.

This thesis aims to present a clear explanation of all the elements to take into account when deploying a LoRa network, whether they be theoretical or practical, and to evaluate LoRa performance in Louvain-la-Neuve.

To do this, gateways were assembled, configured, and put into place. In the same fashion, devices capable of sensing useful data were configured and made able to communicate with these gateways. To collect the data, The Things Network was used, thus forming the prototype of a LoRa network in Louvain-la-Neuve.

Thanks to this network, it was possible to evaluate the performance of LoRa on different aspects. First, by looking at what range three configurations of gateways could offer. This produced three different maps, giving a clear view of the signal coverage in Louvain-la-Neuve. It was found that the promises made of a coverage over 5km in urban environment were exaggerated, and that this value was highly dependant on antenna position and elevation, as well as the devices situation. The signal could be lost after only a few hundred metres and could be heard 2 kilometres away from the same gateway.

As well as terrain conditions and clearance in the Fresnel zone, it was also shown that other factors could significantly affect LoRa transmission. From one day to another, results could considerably vary. Factors such as weather seemed to play a heavy role.

While studying the impact of the spreading factor, the impressive resilience of LoRa to interference and noise was demonstrated. Under harsh interference conditions, it was able to decode a majority of the signals, achieving a transmission rate over 80% with some parameters.

Finally, these results were compared to the existing literature to evaluate their coherence with the existing knowledge. With respects to range, multiple studies obtained better results than those in this thesis, while some obtained worse. But it was also shown that due to the importance of factors such as elevation, these results could easily be improved. Other studies also confirmed the findings done on the resilience from interference of LoRa.

LoRa is a promising technology, and might very well be used widely in Louvain-la-Neuve in some future. However, the designers of such a network should be aware of its strengths and weaknesses.

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