

# Expanding a LoRaWAN network for cost efficiency improvement

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MASTER'S THESIS

DEPARTMENT OF ELECTRICAL AND INFORMATION TECHNOLOGY

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Master's Thesis

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## Abstract

LoRaWAN is a new technology whose presence in Smart Cities is increasing. It provides benefits to daily life, however, battery consumption of end-devices is one of the limiting factors that must be recognized. The lower the consumption, the better the network quality.

The battery life of a specified end-device depends on the power needed for the transmission. To improve it, the distance from every end-device to the gateway should be minimum. Optimizing this distance, the overall consumption decreases and the global network performance improves, reducing the economic cost. The number of gateways in the network is another factor that changes the consumption, however, in this network, this number is fixed.

In the network deployed in Lund, a new gateway is going to be introduced. The aim of this thesis is to find the optimal location for this new gateway in order to reduce the end-devices' consumption. The aim has been achieved by deploying an optimization algorithm over the power consumption in the network. Considering some difficulties to place the gateway in the resulting location, the best location to place the new gateway has been obtained by applying the optimization algorithm over a list of existing and accessible locations.

## Acknowledgments

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## List of acronyms

LoRa	Long Range
LoRaWAN	Long Range Wide Area Network
LPWAN	Low Power Wide Area Network
ADR	Adaptive Data Rate
SNR	Signal to Noise Ratio
RSSI	Received Signal Strength Indicator
IoT	Internet of Things
NB-IoT	Narrow Band Internet of Things
FSK	Frequency Shift Keying
MAC	Media Access Protocol
IP	Internet Protocol
CRC	Cyclic Redundant Check
CSS	Chirp Spread Spectrum
SF	Spreading Factor
CR	Coding Rate
BW	Bandwidth
LTE	Long Term Evolution
Cat	Category
WSN	Wireless Sensor Network
PL	Path Loss
EPL	Expected Path Loss
OS	Operative System
GPRS	General Packet Radio Service
EDGE	Enhanced Data Rates for GSM Evolution
3G	Third Generation
IFC	The Industry Foundation Classes

## Popular Science Summary

LoRaWAN is a specification developed to connect devices within an Internet of Things network that are wirelessly connected. The main scope of this technology is to simplify the connectivity among devices. The devices used, mainly sensors, are connected to the Internet through gateways that, at the same time, are connected to servers. The communication with the end-devices can be unidirectional or bidirectional depending on the application. This communication utilizes LoRa technology to connect the device and the gateway. Also, the communication between the gateway and the server can use any other type of technology. [1]

Each end-device could have a different frequency channel and a different data rate. The data rate variability depends on the device's location and on the messages' duration; this may vary from 0.3 kbps to 50 kbps. The system uses an Adaptive Data Rate (ADR) scheme in order to handle these changing data rates. As it uses spread spectrum techniques, it ensures that each device's channel does not interfere with each other. This technology has three security layers at different levels which protect the data transferred through these networks: Unique Network key (EUI64), Unique Application key (EUI64), and Device specific key (EUI128). [2]

There are three defined classes of end-devices: Class A, Class B, and Class C. Class A focuses on covering bidirectional communications where the uplink communication has higher priority. The end-device decides when to send information depending on its needs. Right after this uplink communication is created, two downlink windows are able to be used. Only the end-device can initiate the communication, thus it saves energy. For this reason, Class A is the class type that consumes the lowest amount of energy, and is the one discussed in this thesis. Class B reserves some windows to the downlink in order to send beacons that allow the server to send messages to devices that are mostly asleep. Class C provides constant capability of receiving information as it always keeps the window open. Only when it is necessary to transmit information, it closes the window. As a result, Class C has the highest power consumption of the three classes. [1] [2]

# 1. INTRODUCTION

## 1.1. Background

LoRaWAN is a Low Power Wide Area Network (LPWAN) which means that end-nodes should consume minimal power in order to reduce the maintenance cost of end-nodes. However, when deploying a gateway, it has a varying distance to every sensor. For example, a sensor far away needs to send information consuming more battery power compared to a sensor closer to the gateway. In LoRaWAN, a feature called Adaptive Data Rate is used, which can reconfigure sensors to a higher or lower data rate when sending. Considering Sensefarm's data, a message containing the same information can take from 40 ms to 1.4 seconds to transmit. Figure 1 shows a typical LoRaWAN network.

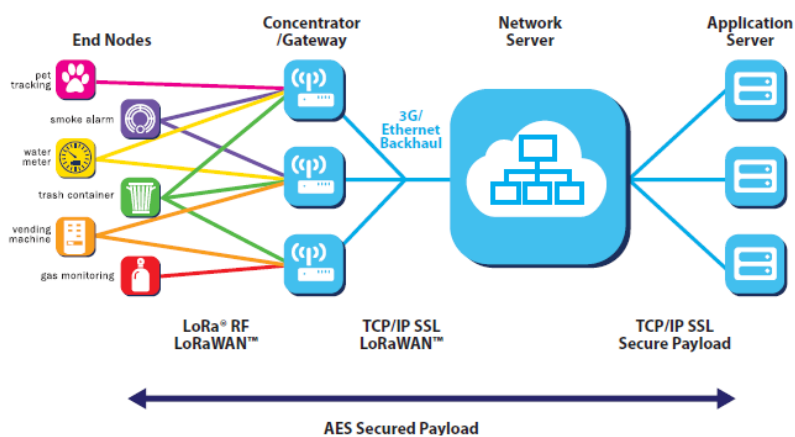


Figure 1: LoRaWAN network [16]

Battery replacement is costly, especially inside apartments which have significant administration overhead in the range of 600 SEK/entrance following Sensefarm's data. It might be cost effective to put gateways in certain locations as it increases the sensors' battery life by increasing the link-budget (reducing the power consumed) and reducing transmission times. It is important to note that as the number of sensors is expected to increase over time, the cost of maintaining them will also increase.

However, there are no methods which can minimize the maintenance costs by placing the gateways of a network at appropriate locations. To do that, one has to determine the optimum gateways' placement. By determining the optimum gateways' location, the sensors' battery life will increase; it is known as reducing the gateway load.

## 1.2. Project aims

The main aim is to save the sensors' batteries. This is done by increasing the SNR at the gateways, which leads to a lower spreading factor. With a lower spreading factor, the data rate increases, and the needed time for sending the message and the power consumed decrease; this is the main challenge. To get these results, the modelling of a wireless sensor network has to be known. Previous works on this field are considered and it is explained in more detail throughout the thesis.

The data collected in the city of Lund is used to develop the optimization. There is an open platform (Lunds Open City Sensor Network) which provides information about RSSI, SNR,

bandwidth, frequency, size, code rate, spreading factor and location of the three, distinct gateways, and of the measurements done through the city. Considering this data and the channel model, an SNR expression is optimized.

SNR depends on the noise, which is a random variable and cannot be modified, and the received power. The received power depends on the transmitted power, which is a fixed value dependant on the spreading factor used, and the path loss. Thus, maximizing the SNR is the same as minimizing the path loss.

If the optimization procedure would need more time than the settled time for the optimization, it is possible to apply approximation methodologies that define an error margin in which the optimization solution (in this case, the gateway's position) is as close to the best solution as possible.

After applying the optimization procedure, the result is the addition of a new gateway in the optimal location. A portable gateway and a power level measurement tool is used to go to the location, establish the gateway, and take measurements around the city. When the resulting location is not accessible (walls, buildings, etc.), a suboptimal location is analysed. The gateway to add is an outdoor gateway as it provides more coverage than an indoor gateway.

The aim of this Master's thesis will consist on finding the optimal location of a new outdoor gateway in Lund Open City Sensor Network by applying optimization techniques [section 2.3].

### 1.3. Approach

The thesis project is based on a theoretical study, a software implementation, and a testing phase. The initial phase has been the proper documentation for the theoretical part. It consisted of studying relevant material in statistics (optimization) and wireless sensor networks (a deep understanding of the LoRaWAN technology and the channel modelling).

The next step was to develop the optimization methodology using Matlab as a tool. In this step, the optimization methods that Matlab provides was researched.

The testing phase consisted of checking the measurements taken on the city when the gateway is placed at the resulting optimal location.

### 1.4. Limitations

The used channel model, which is widely applied in the literature [5] and [6], is considered the best approach to the estimation of the path losses in a LoRaWAN network. The lack of stability of the environment does not calculate the exact path loss results but it is the best approach to the channel estimation as shown in [5] and [6].

Another difficulty is the gateway's placement. The optimization gets an optimal location but this location may not always be accessible. A potential solution to this issue is applying the optimization over a list of possible locations that are accessible and finding the best gateway location among these options.

## 1.5. Thesis outline

This thesis is divided in eight chapters. The first chapter covers an introduction to the thesis and to the work. The second chapter provides an overview about the theory used. Chapter 3 develops the optimization implementation using all the knowledge acquired in previous chapters. Chapter 4 evaluates the results of placing the new gateway in different locations and faces a new way to approach the research. Chapter 5 provides a conclusion for the thesis. Chapter 6 has the thesis' annexes and chapter 7 contains the references to the bibliography used.

## 1.6. Related work

As the network is a wireless sensor network with LPWAN, mobile communications channel models such as Hata or SUI cannot be used in this scenario. Because there has been some research on this topic, it has been established that the best way to model a LPWAN with LoRaWAN technology is by using a log-normal definition for the path losses based on [5] and [6] experiments. Studies [5] and [6] are more similar to Lund's scenario, they were developed in Oulu (Finland) and Dortmund (Germany). They are similar scenarios because they are sub-urban areas and they have used LoRa technology as well. [7] uses a log-normal model too, but it applies a mathematical approach, which is useful to consider.

Further research supports the idea of using log-normal distributions. In [8], the use of a one slope with two slopes log-normal model is compared in a wireless sensor network. There is a tendency to use larger number of slopes in the model when the environment has worse propagating properties (urban, indoor, buildings, etc.).

A similar technology that is used in IoT scenarios is NB-IoT. One of the most relevant differences is that LoRaWAN uses unlicensed spectrum meanwhile NB-IoT connects to an operator network through licensed spectrum. The advantage that LoRaWAN has compared to NB-IoT is that it does not need a mobile operator to work; nevertheless, it uses a proprietary modulation (LoRa) which may complicate its development. [9]

There is a deep research on the optimization field applied to sensor networks, for example [10] studies how to distribute the gateways over surface in order to connect underwater sensors. [11], [12] and [13] analyse how to distribute the gateways in a non-LoRaWAN network to make it more efficient. [14] and [15] get a similar approach as they optimize the gateway's placement in a wireless sensor network; however, as it is an ordinary wireless sensor network, it sends the information by several hops. The sensors do not directly send the information to the gateway because they cannot reach it, so they send the data to other sensors jumping from one sensor to another until the gateway is reached. [14] and [15] optimize the gateway's placement by minimizing the number of hops. This is not a problem in LoRaWAN networks as they directly reach the gateway due to the large coverage of LoRaWAN networks.

## 1.7. Advancements and outcome

The advancement of this Master's thesis is the development of a methodology that can be implemented over any LoRaWAN wireless sensor network to get a better, overall performance.

The outcome of this Master's thesis is a detailed study on the improvement of a current IoT network by reducing the power consumed on its devices that use LoRaWAN technology.

## 1.8. Resources

The work of the Master's thesis has been done at the Sensefarm office in Lund. Sensefarm is a company focusing on sustainability in agriculture and green cities, which achieves it with sensor network technology. It is a star-up with 6 employees.

A workstation was provided to work in the company facilities as well as to use their prior research. All the sensors, gateways and technology that Sensefarm has deployed in Lund has been accessible in order to test the studies and to verify the procedures.



## 2. THEORETICAL REVIEW

Chapter 2 makes an overview of the three main concepts used in this thesis: the type of network (LoRaWAN – section 2.1), the channel analysis for the communication (section 2.2) and the way of getting the results (optimization theory – section 2.3).

### 2.1. LoRaWAN

LoRa is the physical layer used in LoRaWAN networks. It uses Frequency Shift Keying (FSK) modulation in order to achieve low power consumption, and it uses Chirp Spread Spectrum in order to cover a large area. The biggest outcome from LoRa is its capability of long communication ranges because its link budget is higher than most other technologies.

LoRa is used in Low Power Wide Area Networks (LPWAN) because it reaches long distances consuming low power. Thus, it is mainly used in IoT applications where the end-devices in the network only transmit small, infrequent, information amounts. Hence, this technology extends their battery life. [16]

LoRaWAN is a MAC (Media Access Protocol) protocol used when the LoRa physical layer is applied. [16] [17]. *Figure 2* shows LoRa distribution in the protocol layers.

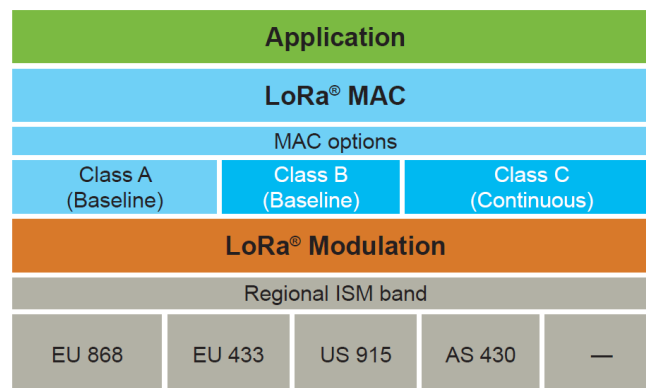


Figure 2: Protocol layers [16]

#### 2.1.1. Network architecture

The network architecture generally used in LoRaWAN is a mesh network architecture with a star topology. It consists of end-devices that are connected to some gateways with one hop (no repeaters needed) and these gateways are connected to a server through another technology (IP, Ethernet, WiFi, etc.). This allows for the access of a long-range network. [16][18] This is shown in *Figure 3*.

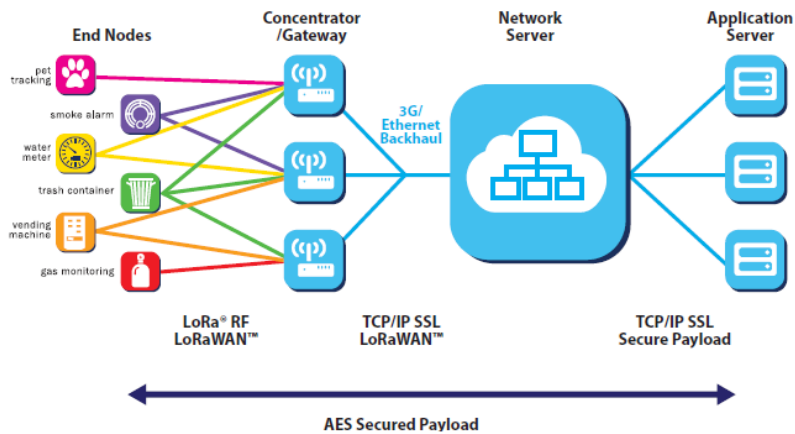


Figure 3: Network architecture of LoRaWAN [16]

In a LoRaWAN network, one node transmits the information to more than one gateway. Every gateway sends all the information received to the server (even if it is repeated), and the server is responsible for filtering repeated content.

In IoT applications, since the gateways receive loads of data from a large number of sensors, they have high capacity to manage it. High capacity is attained by applying Adaptive Data Rate (ADR) and having multichannel transceivers at the gateway. The number of concurrent channels, the time on air, the payload length and the way that nodes transmit are all factors affecting this capacity. [16]

### 2.1.2. Frames

The frames in LoRaWAN at the physical layer are constituted by a preamble (approximately  $12.25 T_s$ , it carries out synchronization functions and defines the modulation used), a header (it includes a Header Cyclic Redundant Check (CRC), consists of 20 bits in total, and it has a coding rate of 4/8 to be more reliable while the rest of the frame has another coding rate), the payload (from 51 Bytes to 222 Bytes), and a CRC field. [18] [19] These fields are easier to identify in *Figure 4*.

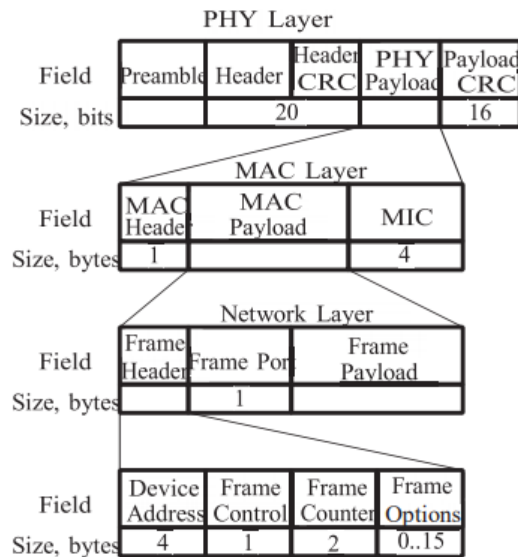


Figure 4: LoRa frames [19]

### 2.1.3. Adaptive Data Rate

LoRa uses Chirp Spread Spectrum (CSS) modulation in order to avoid interference, Doppler Effect, and multipath. [18] This means that the signals are orthogonal to each other. A spreading factor change results in a data rate change. The spread factor can be changed in order to get better data rates for transmissions where the link is better. Hence, the transceivers can manage receiving different data rates in different channels. [16]

The spread factor is defined as:

$$SF = \log_2\left(\frac{R_c}{R_s}\right)$$

Equation 1: Spreading factor

where  $R_s$  is the symbol rate and  $R_c$  is the chip rate. [18]

A data rate change is also translated in a change on the Time on Air of the information sent. Lowering the spreading factor means increasing the data rate and it means lowering the Time on Air. If a node needs less Time on Air, this time is available for other nodes to transmit. If the Time on Air is low, it results in battery consumption savings. This capability of changing the spreading factor, and consequently the data rate and the Time on Air is the Adaptive Data Rate (ADR). Adaptive Data Rate works with symmetrical uplink and downlink conditions. [16]

Figure 5 shows an example of how much the Time on Air can change using different spreading factors.

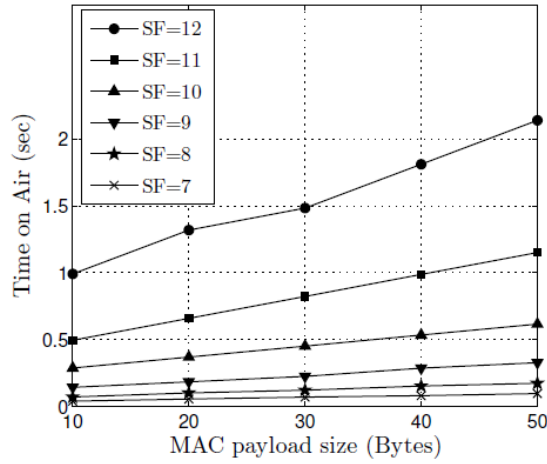


Figure 5: Time on air [18]

The relation between the data rate and the spreading factor is shown in *Equation 2*:

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

Equation 2: Data rate

Where CR is the rate of the forward error correction code (4/5, 4/6, 4/7 or 4/8) and  $T_s$  is the symbol duration.

*Equation 1* shows that as the spreading factor increases, the data rate decreases; however, at the same time the sensitivity is higher. *Table 1* shows some examples of these relations between spreading factor, channel bandwidth, coding rate, bit rate and sensitivity:

Spreading factor	Bandwidth (kHz)	Coding rate	Bit rate (bps)	Sensitivity (dBm)
12	125	4/6	250	-137
11	125	4/6	440	-136
10	125	4/5	980	-134
9	125	4/5	1760	-131
8	125	4/5	3125	-128
7	125	4/5	5470	-125
7	250	4/5	11000	-122

Table 1: Relation SF - bandwidth - coding rate - bit rate - sensitivity [19]

*Figure 6* shows how LoRa parameters vary altogether.

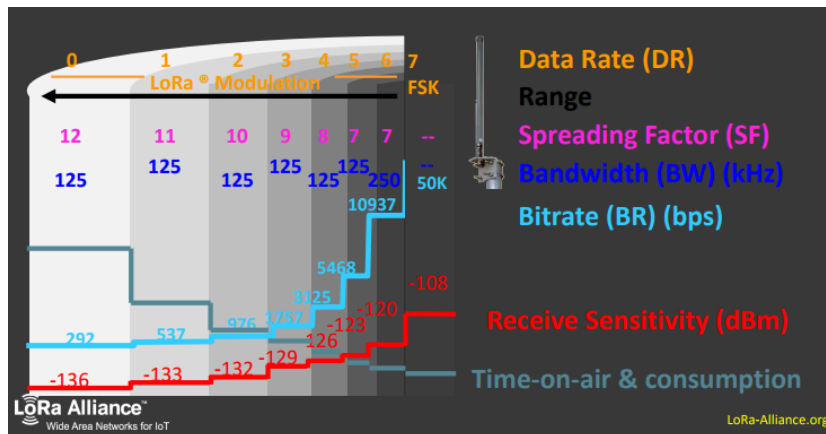


Figure 6: LoRa parameters [20]

Thanks to LoRa properties, a LoRaWAN network can increase its size and capacity using the Adaptive Data Rate feature. If a capacity increase is needed, the addition of gateways would solve this issue. [16]

### 2.1.4. Device classes

There are three defined classes of end-devices used for different applications.

Class A covers bidirectional communications, but the uplink communication has higher priority. The end-device decides when to send information depending on its needs. [1][2] This is known as ALOHA mode. Here, the device transmits the uplink as soon as information is to be sent, does not have to wait for a certain time slot, and has priority over downlink messages. [19] Right after this uplink communication is established, there are two downlink windows. The communication can only be initiated by the end-device, thus it saves energy. Class A is the class type which consumes the lowest power.

Class B reserves some windows to the downlink data in order to send beacons that allows the server to send messages to mostly asleep devices. A device is sleeping when it is not taking measurements, sending information or waiting to receive it.

Class C provides constant capability of receiving information as it always keeps the window open. Only when it is necessary to transmit information, it closes the window. Class C has the highest power consumption of the three classes. [1] [2]

Figure 7 compares the main features of the three class types and how they vary regarding battery lifetime and downlink latency.

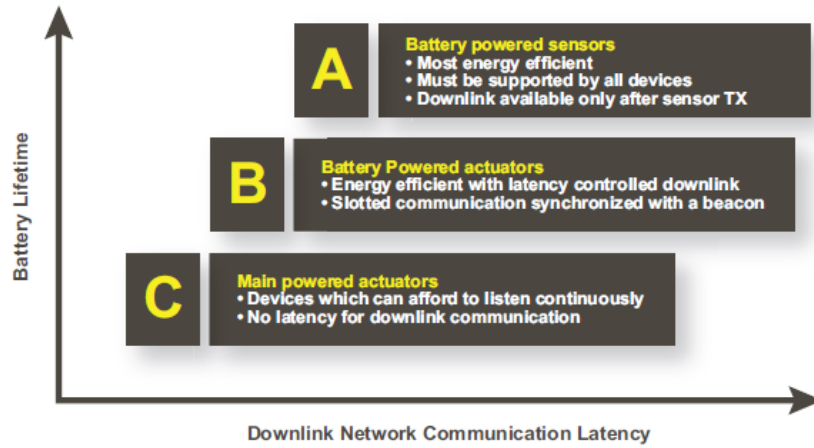


Figure 7: Device classes [1]

### 2.1.5. Security

LoRaWAN uses two security layers: one for the network (Network Session Key – NwkSKey) to authenticate the node, and one for the application (Application Session Key – AppSKey) to save user’s application data. [16] The security protocol is based on the 802.15.4 protocol (AES-128). [20] Both security layers are shown in *Figure 8*.

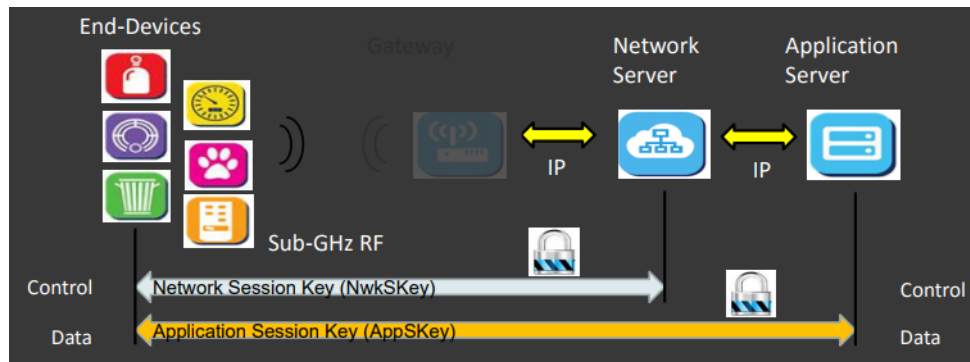


Figure 8: Security topology [16]

### 2.1.6. Specifications

Depending on the region, there are different specifications on LoRa. As this master’s thesis is done in Lund, the analysis uses European specifications:

Frequency band	867-869 MHz
Channels	10
Channel Bandwidth uplink	125/250 kHz
Channel Bandwidth downlink	125 kHz
Transmitted power uplink (maximum)	14 dBm
Transmitted power downlink (maximum)	14 dBm
Spreading Factor uplink	7 – 12
Data rate	250 bps – 50 kbps
Link Budget uplink	155 dB
Link Budget downlink	155 dB

Table 2: LoRa specifications

Of the ten channels, eight are used to transmit information, one is used with high data rate at 11 kbps, and the last is used with FSK at 50 kbps. [16] The eight channels dedicated to transmit information are used uplink, another is used downlink to provide responses from the gateway to the device, and the other is used to transmit a device's request to the gateway uplink. [19]

The transmitted power varies depending on the spreading factor and bit rate used. As the spreading factor decreases by steps of 1, the transmitted power also does by steps of 2dB. *Table 3* shows this relation.

SF	Bandwidth (kHz)	Transmitted power	Transmitted power (dBm)
12	125	Maximum transmitted power	14
11	125	Maximum transmitted power – 2dB	12
10	125	Maximum transmitted power – 4dB	10
9	125	Maximum transmitted power – 6dB	8
8	125	Maximum transmitted power - 8dB	6
7	125	Maximum transmitted power – 10dB	4
7	250	Maximum transmitted power – 12dB	2

Table 3: Relation SF - transmitted power

Specifically, the steps are of 2.15 dB as it is referred to a half-wave dipole but it is always referred as 2dB. [21]

### 2.1.7. Comparison with other technologies for LPWAN

*Table 4* compares LoRaWAN with Narrow-Band IoT, LTE Cat-1, LTE Cat-M, NB-LTE and SigFox. LoRaWAN data rate is not the highest, however, the type of applications that use LoRaWAN do not require high data rates. Its batteries last longer than other technologies, it saves more power, and it is more immune against interferences. [16] [22] Its main competitor is NB-IoT. Comparing them, LoRa is focused on lower-cost, high-volume applications, whereas NB-IoT is focused on high-value applications in which it is possible to pay more in order to get a better quality of service. [23]

	LoRaWAN	NB-IoT	LTE Cat-1	LTE Cat-M	NB-LTE	SigFox
Modulation	SS Chirp	UNB / GFSK / BPSK	OFDMA	OFDMA	OFDMA	GFSK / DBPSK
Bandwidth	125 – 500 kHz	100 Hz	20 MHz	1.4 – 20 MHz	200 kHz	
Data rate	290 bps – 50 kbps	100 bps	10 Mbps	200 kbps – 1 Mbps	20 kbps	100 bps
Maximum Output power	20 dBm	20 dBm	23 – 46 dBm	23 – 30 dBm	20 dBm	
Link budget	154 dB	151 dB	130 dB	146 dB	150 dB	146 dB
Battery	105 months	90 months		18 months		7 to 8 years
Power efficiency	Very high	Very high	Low	Medium	Medium / High	Very high
Interference immunity	Very high	Low	Medium	Medium	Low	Yes
Security	Yes	No	Yes	Yes	Yes	Yes
Range	2 – 5 km urban 15km sub-urban 45 km rural	1.5 km urban 20 – 40 km rural		35 km 2G 200 km 3G and 4G		3 – 10 km urban 30 – 50 km rural

Table 4: Comparison with other technologies for LPWAN [16] [22]

Some other competitors are: Ingenu and Weightless. Ingenu uses the 2.4 GHz band, and its main feature is its high data rate up to 624 kbps for uplink and 156 kbps for downlink; however, its range extends up to 6 kilometres, and it consumes more energy because of the band used. The Weightless Special Interest Group has developed three standards: Weightless-W, Weightless-N and Weightless-P. Weightless-W uses the whitespaces left by television (470–790 MHz), its data rates go from 1 kbps to 1 Mbps and its battery lasts from 3 to 5 years. Weightless-P covers multiple band frequencies and its battery life ranges from 3 to 8 years. [18] (These last three standards are not included in the table).

### 2.1.8. Applications

The use of LoRa is widespread in several environments due to its versatility and great coverage. These applications can include, but are not limited to the following: parking management, air pollution monitoring, asset tracking, agriculture processing, cattle tracking, energy management and sustainability, fall detection, fire detection, fleet management, fleet tracking, home security, indoor air quality, industrial temperature monitoring, liquid presence detection, stolen vehicles location, medical refrigerators, precision farming, predictive maintenance, radiation leak detection, shipment quality, smart home asset tracking, smart lighting, smart parking, tank flow monitoring, waste management, water flow monitoring, water management and protection or wireless gas level monitoring. [19]

### 2.1.9. Battery life

This thesis is focused on decreasing power consumption. *Figure 9* shows a battery consumption approach in a cycle measured by a digital oscilloscope. The process starts by waking up the end-device, taking the measurements, transmitting the information to the gateway, waiting to check if the gateway sends information back and, finally, returning to sleep. The transmission to the gateway is the step that consumes the most power; the bigger the spreading factor, the higher the consumption. Therefore, the main objective is improving this part of the transmission. [24]

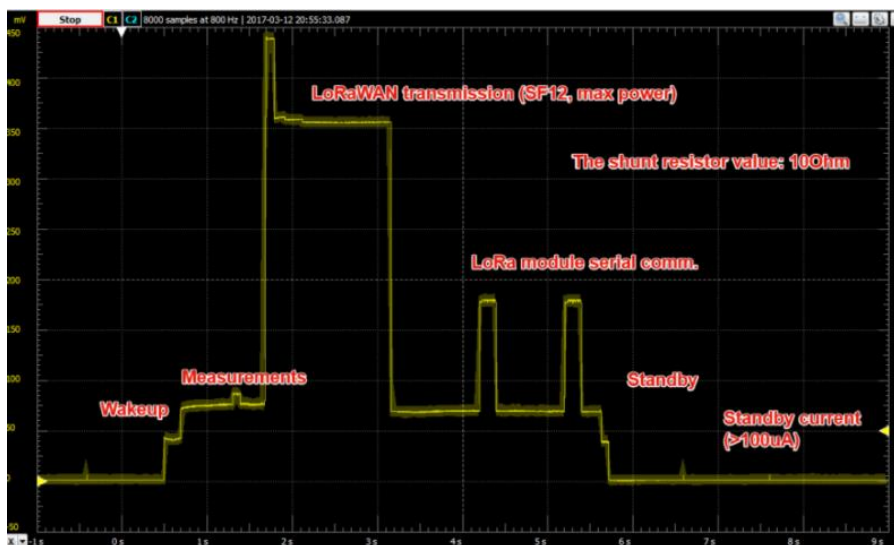


Figure 9: Battery life [24]



## 2.2. Channel model

As it is a Wireless Sensor Network (WSN) of a Low Power Wide Area Network (LPWAN), mobile communication channel models such as Hata or SUI cannot be used with LoRaWAN technology. There has been some previous research on this topic, the main conclusion obtained from them is that the best way to model a LoRaWAN network is using a log-normal definition of the path losses. [5] [6]

The log-normal definition can use one or more slopes. The use of more slopes leads to results that are more accurate. This is necessary when there is a difficult propagation environment such as in urban areas, indoor propagation, hills and buildings, etc. Thus, it is going to be considered the one slope definition as Lund is a sub-urban area without indoor propagation and it is flat.

There are some studies already done to estimate the channel model in a network that uses LoRaWAN. Their definition of the measured path loss is shown in *Equation 3*.

$$PL(dB) = |RSSI|(dB) + SNR(dB) + P_{TX}(dB) + G_{RX}(dB)$$

Equation 3: Path loss

Where RSSI is the Received Signal Strength Indicator,  $P_{TX}$  is the transmitted power and  $G_{RX}$  is the received gain. [5]

*Equation 3* is generalized by the expression of the expected path loss [6] which is shown in *Equation 4*.

$$EPL(dB) = B + 10n \log_{10}\left(\frac{d}{d_0}\right)$$

Equation 4: Expected path loss

Where  $B$  is the path loss at the reference distance of  $d_0$ ,  $n$  is the path loss exponent,  $d$  is the distance in kilometres and  $d_0$  is the reference distance of 1 km.

As a reference, through EPL equation, the free space equation that comes from Friis formula can be computed with  $n=2$  and  $B$  will vary depending on the frequency used; for 868 MHz,  $B$  is 91.22. However, as the free space conditions are just ideal and not real, these values can only be considered as a reference. [5]

A more complete channel model analysis can be found in the section 6.1.

## 2.3. Optimization theory

Optimization consists of reaching the optimal solution of a problem where cost and profit are the variables considered. The objective is to reduce the cost and to increase the profit which means increasing the difference profit – cost.

Following a mathematical approach, optimization is the process of getting the best solution under certain circumstances. The objective is to minimize a negative effect or to maximize a positive effect. These effects are mathematically represented by a function (objective function) that depends on some design variables. These design variables may have some restrictions; hence, the optimization process is defined as the process of looking for the maximum or

minimum value of the objective function and its variables' values where the maximum or minimum values are reached.

The general optimization problem structure is shown in *Equation 5*.

$$\begin{aligned} \min_x f(x) \\ g_j(x) \leq 0 \quad j = 1, 2, \dots, m \\ h_k(x) = 0 \quad k = 1, 2, \dots, p \end{aligned}$$

Equation 5: Optimization function and constraints

In *Equation 5*, the components that are defined are:  $f(x)$ ,  $x$ ,  $g_j(x)$  and  $h_k(x)$ .

$f(x)$  is the objective function to be minimized that depends on  $n$  variables, and it can be linear or not.

$x$  is the design vector, an  $n$ -component vector that contains the variables of  $f(x)$ :  $x = [x_1, x_2, \dots, x_n]^T$

$g_j(x)$  defines the inequality constraints and  $h_k(x)$  defines the equality constraints.  $g_j(x)$  and  $h_k(x)$  may be more than one or they may not be present. The set of values from  $x$  that satisfy all the restrictions is known as possible region or possible set, thus, the solution has to be a vector  $x$  that is in this region.

The goal is to find the vector  $x$  where the function  $f(x)$  reaches its minimum. This is a general way of expressing an optimization problem. If it were a maximization problem, it would consist of minimizing the negative version of the objective function. Similarly, if the inequalities had the opposite sign, it would acquire the same structure using the negative expression of the constraint. [26]

An optimization analysis of the problem in this thesis can be found in annex 6.2 and a continuation of the mathematical approach in annex 6.3.

## 3. IMPLEMENTATION

Chapter 3 starts providing information about the gateways used in the network and continues with the explanation of the optimization implementation.

### 3.1. Gateways' information

The three gateways used are the Wirnet Station from Kerlink, this device is shown in *Figure 10*.

It is designed for outdoor usage, has a gain of 3dB, and it can reach up to -141 dBm of sensitivity, which is lower than the minimum sensitivity with a spreading factor 12. Also, it operates in 868 MHz band for bidirectional communications, has embedded, remote and open low power communication stations, an open development framework (Linux OS), and it can connect to the network by GPRS/EDGE/3G or Ethernet. [27]



Figure 10: Wirnet Station [27]

### 3.2. Optimization

#### 3.2.1. Process overview

The following steps have been followed in order to proceed with the optimization; they are going to be explained in detail from section 3.2.2 to section 3.2.5:

- Measurements data extraction from the environment under study
- Data preparation to be analysed
- Relevant values' calculation over the data
- Deployment of the optimization

#### 3.2.2. Measurements data extraction

To proceed with the optimization, there are some previous steps to follow. First, all the data obtained from measurements have been sorted out in Excel: EUI (measurement identifier), latitude (of the measurement), longitude (of the measurement), RSSI, SNR, time and gateway connection (identifier).

A coloured dot indicates each measurement. *Figure 11* shows the three gateways coverage in which the worst measurements are shown by a red dot. When the RSSI is higher than -102.6 dBm there is a green dot, when the RSSI is between -102.6 dBm and -106.6 dBm there is a yellow dot, and when the RSSI is equal to or below -106.6 dBm there is a red dot. These values have been defined by the developers of the tool that displays the taken measurements.

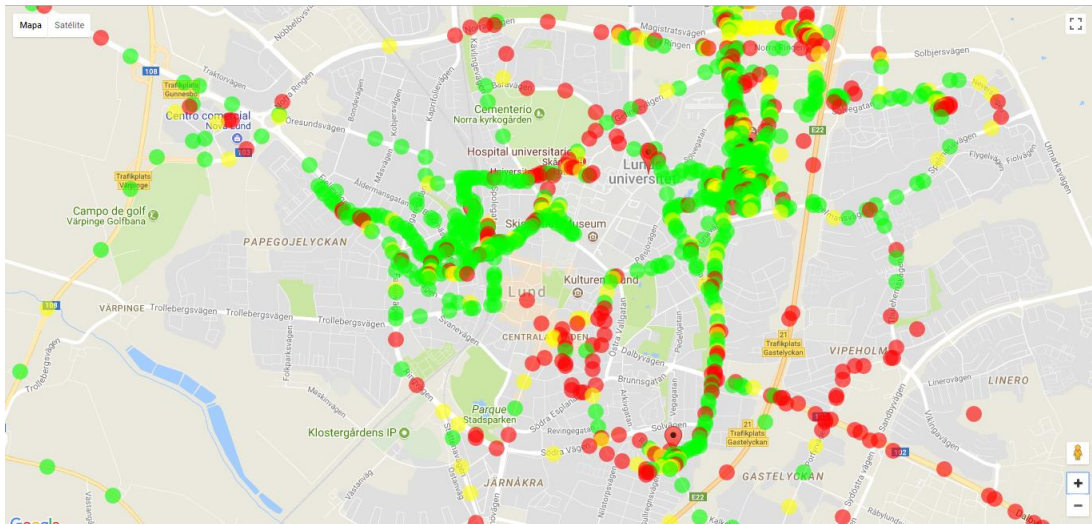


Figure 11: Map of measurements

It is easy to identify where the gateways are located as there is a dense, green area around them. In the north, this is the Vattentornet gateway, in the west, this is the Kristallen gateway and, in the south, this is the Rabyvagen gateway. *Figure 12* shows the maximum reach of the gateways, the network catches up to 22 km and the outskirts of Malmö.

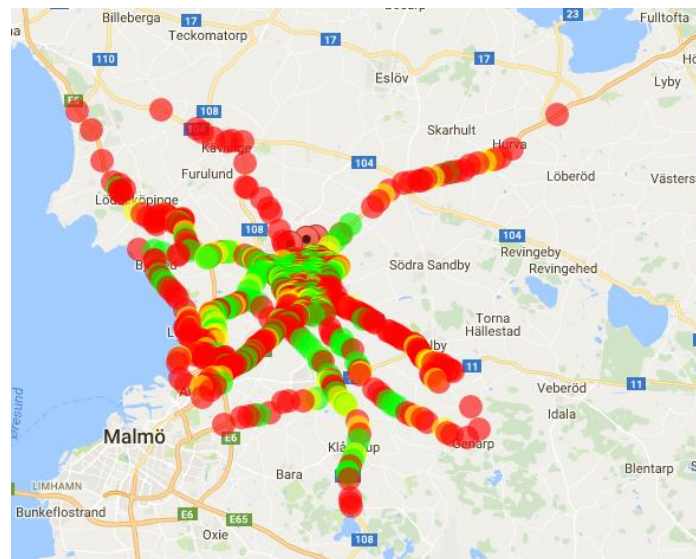


Figure 12: Maximum reach

### 3.2.2.1 Analysis of measurements with a low signal strength

There is a certain area in the central-north portion of the map mainly covered in red. Although the Vattentornet gateway is not too far from there, this gateway has been placed on the eastern tower area. The gateway's antenna is omnidirectional but it does not have line of sight with this area due to the dome over the tower. Therefore, this northern area is not properly covered either by the Vattentornet gateway or by the Kristallen gateway.

In the north east, the accumulation of measurements with a low signal strength is caused by shadowing due to Elite Hotel Ideon. It is the only building in this area that is taller than the tower and avoids further propagation.

In the south, there are more areas with low signal strength. The gateway placed in Rabyvagen has not a large coverage, it gets bad measurements nearby its location. It has a lower height than the other gateways, 20.35 m and in front of it there is a taller building which absorbs the majority of the radiation avoiding the gateway to connect with further points.

### 3.2.3. Data preparation

In order to estimate the channel, the values of B and n (path loss coefficient) from *Equation 4* for every taken measurement have been calculated. Firstly, the path loss (PL(dB)) and the distance (d) are calculated.

#### 3.2.3.1 Path loss

The path loss is obtained from *Equation 3*, where RSSI and SNR are measured values,  $P_{TX}$  is always 14 dBm as all the measurements have been taken with spreading factor 12 and the gain of the gateway is 3 dB [27].

#### 3.2.3.2 Distance

The distance requires more complex operations than the path loss as the positioning data given is the latitude and longitude. The equation needed to obtain the distance between two points knowing their latitudes and longitudes is the law of cosines expressed in *Equation 6*.

$$d = \text{acos}(\sin\varphi_1 * \sin\varphi_2 + \cos\varphi_1 * \cos\varphi_2 * \cos\Delta\lambda) * R$$

Equation 6: Distance – law of cosines

Where  $\varphi_1$  and  $\varphi_2$  are both points' latitudes,  $\Delta\lambda$  is the difference between both point's longitudes and R is the Earth radius  $R = 6,371 \text{ km}$  being d the total distance. [28]

Even though, the distance expression depends on sines and cosines and an expression that uses trigonometric functions cannot be easily minimized; the solution is to apply the Euclidean distance expression. This change does not have a great impact over the result as the area under study can be considered flat and there is no need to consider the Earth curvature. *Equation 7* shows the Euclidean distance expression. [29]

$$\bar{d} = \sqrt{(\bar{x}_m - x_{GW})^2 + (\bar{y}_m - y_{GW})^2}$$

Equation 7: Euclidean distance

$\bar{x}_m$  and  $\bar{y}_m$  are the measurement coordinates in the city and  $x_{GW}$  and  $y_{GW}$  the gateway coordinates (being a scalar) in meters. d is the distance from the measurement to the gateway.

To get the coordinates in meters, the equivalence between degrees and meters has been used:

$1^\circ = 111.32 \text{ km}$  at the Equator, as Lund is between  $55^\circ$  and  $56^\circ$ .

One degree in Lund for the distance in the east-west direction is:

$$1^\circ = R * \left( \sin\left(\frac{56\pi}{180}\right) - \sin\left(\frac{55\pi}{180}\right) \right) = 63.05 \text{ km}$$

Equation 8: Degree to kilometers conversion in Lund [30]

In order to calculate the distance between a measurement and the gateway, the Euclidean distance equation is applied and it only uses the data in meters, the coordinates have to be converted from degrees to meters. This coordinates' definition in meters is only applied to calculate distances among points, hence it is not representative over a map because coordinates (longitude and latitude) are expressed in degrees.

An example is included to see that there is not as a large of a difference between the two methodologies:

Latitude (°)	Longitude (°)	Gateway latitude (°)	Gateway longitude (°)
55.71243	13.21483	55.71174	13.20399

Table 5: Positioning values in degrees

Y (km)	X (km)	Y Gateway (km)	X Gateway (km)	d XY (km)	d (km)
6201.90807	1471.0752	6201.831676	1469.869057	0.604303	0.68378

Table 6: Positioning values in meters

### 3.2.3.3 Path loss exponent - n

The n estimation follows Equation 9.

$$n = a - b * h_{GW} + \frac{c}{h_{GW}}$$

Equation 9: n value

where  $h_{GW}$  is the gateway's height and the values a, b and c are variables that depend on the type of terrain. Terrain type A is for hilly areas with moderate to high tree density, terrain type B is for intermediate conditions, and terrain type C is for flat areas with light tree densities. [31]

Table 7 contains the current gateways' heights in the network and Table 8 shows the constant values a, b, and c from Equation 9 at every terrain type.

Gateway's names	Height (m)
lund-kristallen [32]	26.66
lund-rabyvagen [32]	20.356
lund-vattentornet [33]	34

Table 7: Gateways' height

	Terrain type A	Terrain type B	Terrain type C
a	4.6	4	3.6
b	0.0075	0.0065	0.005
c	12.6	17.1	20

Table 8: Terrain types

The terrain type in Lund is B because the terrain is between hilly and flat and the tree density is medium. Table 9 shows the n values of the gateways applying Equation 9.

Gateway's names	Height (m)	n
lund-kristallen	26.66	4.46812
lund-rabyvagen	20.356	4.70773
lund-vattentornet	34	4.28194

Table 9: Gateways - height - n

The path loss exponent can be estimated in several ways, it also depend on the type of city. However, as Lund is a sub-urban area and the range for sub-urban areas is from 3 to 5, the results fit these requirements. [34]

### 3.2.3.4 B value

With the path loss value, the distance and the path loss exponent (n), the B parameter for the path loss equation of every measurement is obtained with Equation 10.

$$\overline{PL(dB)} = \bar{B} + 10n \log_{10}\left(\frac{\bar{d}}{d_0}\right) \rightarrow \bar{B} = \overline{PL(dB)} - 10n \log_{10}\left(\frac{\bar{d}}{d_0}\right)$$

Equation 10: Path loss – B value

## 3.2.4. Calculation of relevant values over the data

In this section, the procedure of data collection and processing before the optimization is carried out. All the calculations in this section have been performed using R.

### 3.2.4.1 Step 1

Figure 11 shows that the areas with poorer coverage are a central zone and the road 102. As the central zone covers the city center and more populated areas, the objective is to improve this region. The area of interest is limited in the north by Norra Ringen (55.7211° latitude), in the south by an area close to Sodra vägen (55.694606° latitude), to the west by the central station (13.1885° longitude), and to the east by the Rabyvagen gateway (13.201396° longitude) as shown in Figure 13.

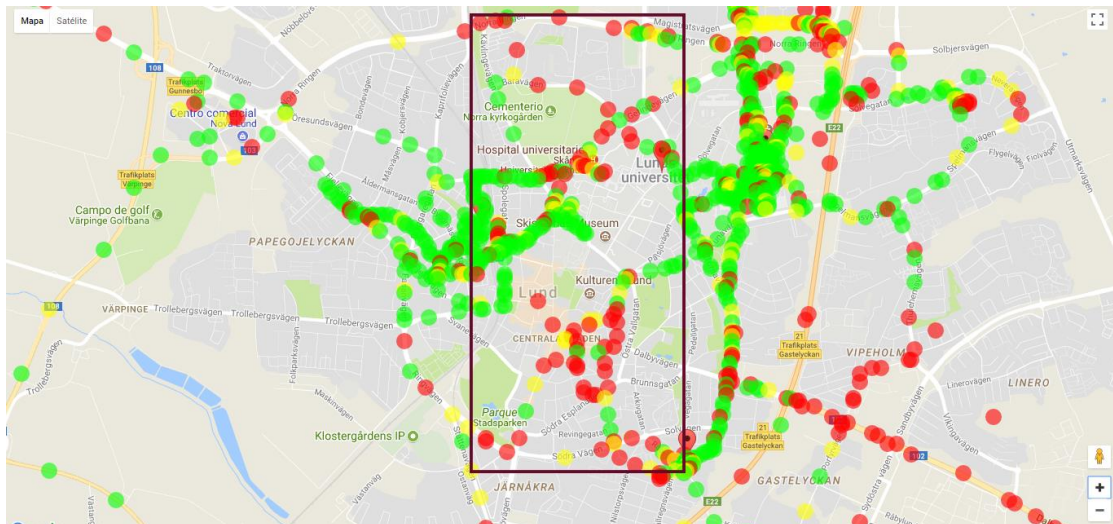


Figure 13: Interest area coverage

From Figure 13, it is possible to get the central point of the interest area 55.7078°, 13.194948°. This value is going to be useful further afield to start the optimization iterations in that point.

From the area in Figure 13, named from now on as interest area, the green and yellow points are not going to be considered in the optimization, as the goal is to improve the worse cases (red points).

### 3.2.4.2 Step 2

Following Equation 10, the  $B$  value of each path has been estimated, from each measurement to the gateway that it was connected. Nevertheless, if a new gateway is placed, the path loss will not be the same, as each end-device would be connected to a different gateway with a different location, different path losses and different gateway's height. Channel estimation is a procedure that cannot be accurately predicted, but it is possible to estimate it based on previous data.

The approach followed in this thesis in order to estimate the channel has consisted in dividing the interest area to improve in 16 small regions, and the  $B$  factor in each small area has been estimated as an average of the previous measurements of  $B$  in that area. For example, if there are two measurements in region 1, the average of these two values is the  $B$  value for every measurement in region 1. As a result, it generates a vector of 16 values of  $B$  called  $B_p$ .

### 3.2.4.3 Step 3

The new gateway has been considered to be placed in one of the four central areas to have more or less an equal distance to every location. The structure is represented in Table 10.

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

Table 10: Interest area division

The path losses are different regarding the gateway location, thus the  $B$  value will vary considering both the gateway and the measurement location.

To clarify the procedure followed, an example is included to explain the way to obtain the new  $B$  values vector,  $B_p$ . If the measurement were placed in region 5 and the gateway were placed in region 6, the new  $B$  value would be the average between the  $B$  value in 5 and 6. If the measurement were located in region 14 and the gateway were placed in region 6 too, the  $B$  value would be the average between the  $B$  value in 6, 10 and 14.

The collected measurements show RSSI values that reach up to -119 dBm.

## 3.2.5. Deployment of the optimization

### 3.2.5.1 Methodology used

Once all the data has been arranged, the next step is to deploy the optimization. It is run in Matlab. Despite the initial idea of using the toolbox 'cvx' [4], it has been tested that it does not allow to implement optimizations with vector information, hence, the function 'patternsearch' has been used to minimize the objective function. [36] There are other functions in Matlab that allow to minimize functions, however, 'patternsearch' is the one that fits better the requirements as it allows to introduce constraints and it can consider all the measurements for the optimization. The feasibility of other options is going to be analysed in section 6.4.



### 3.2.5.2 Objective function definition

The goal is to minimize the network path losses, thus the objective function is the product of all the path losses of every measurement in natural units. It has been used natural units instead of the expression in decibels due to the unfeasibility of minimizing logarithmic expressions. *Equation 11* is the path loss expression used in natural units, it represents the path loss between every measurement and the gateway to which it is connected.

$$\overline{PL(dB)} = \bar{B} + 10n \log_{10}\left(\frac{\bar{d}}{d_0}\right) \rightarrow PL = 10^{\overline{B(dB)}/10} * \bar{d}^n$$

Equation 11: Path loss in natural units

*Equation 12* results as the *Equation 7* and *Equation 11* combination.

$$\overline{PL} = 10^{\overline{B(dB)}/10} * ((\bar{x}_m - x_{GW})^2 + (\bar{y}_m - y_{GW})^2)^{n/2}$$

Equation 12: Path loss with distance equation

The optimization design variables are the location coordinates of the new gateway ( $x_{GW}$  and  $y_{GW}$ ). The goal is to determine the value of  $x_{GW}$  and  $y_{GW}$  that minimize the objective function value. The optimization tests which the value of the optimization function is in every point in the study area. From all these values, it takes the lowest one as its optimal point (minimum value).

*Equation 13* shows the final objective function, the path loss is multiplied by every measurement location.

$$\min_{x_{GW}, y_{GW}} \prod_{k=1}^{length(\bar{x}_m)} 10^{\overline{B_P(dB)}(k)/10} * ((\bar{x}_m(k) - x_{GW})^2 + (\bar{y}_m(k) - y_{GW})^2)^{n/2}$$

Equation 13: Objective function

*Equation 13* components are:

$\overline{B_P}$  is the vector of the 16 values of averaged  $B$  then,  $\overline{B_P(dB)}(k)$  is a constant value and it gets the  $B_P$  value used at the measurement  $k$ .

$x_{GW}$  and  $y_{GW}$  are the new gateway coordinates to be determined (a constant value).

$\bar{x}_m$  and  $\bar{y}_m$  are both vectors,  $\bar{x}_m(k)$  and  $\bar{y}_m(k)$  are constant coordinates values of the measurement  $k$ , all the measurements create the vectors  $\bar{x}_m$  and  $\bar{y}_m$ .

$n$  is a constant value that does not vary. Its value will depend on the new gateway height. As the height cannot be known beforehand, it has been estimated that the new gateway is going to be placed over a 5-floor building. The height of a 5-floor building has been calculated with the tool [36] and it is 23.5 m. *Equation 14* shows the  $n$  value for the new gateway estimation.

$$n = 4 - 0.0065 * h + \frac{17.1}{h} = 4.5749$$

Equation 14:  $n$  value at 23.5 m

### 3.3. Results

Matlab provides algorithms for optimization; the selected algorithm for this application is *patternsearch*. The selection has been made based on its possibility of minimizing constrained problems (the new gateway has to be placed inside Lund, which limits/constrains the region) and it allows considering large amounts of data. Section 6.4 compares *patternsearch* with other algorithms providing support to consider *patternsearch* as the best algorithm to optimize this network.

#### 3.3.1. GPS algorithm

Patternsearch is a technique that requires the discretization of the space study. In the current scenario, this technique applies GPS algorithm, where the mesh represents the area under study (Lund). The iterative algorithm takes into account the Lund area, and the process reduces the area until it reaches a single point, being this point the solution of the considered problem. The mesh size value shows the degree of reduction being mesh size 1 the whole area. [37]

The process is started at the initial point. In this experiment, the initial point is the central point of the interest area as it is more likely to have an optimal result centred in the area under study. In each iteration, the algorithm considers a set of points inside the mesh area called mesh points. The mesh points are equidistant points to the initial point and their distance to the initial point varies as the mesh size does.

*Figure 14* shows the initial structure of this methodology. The mesh points (in red) are equidistant points from the initial point covering the area under study, in this example, it is the whole circumference (mesh size 1).

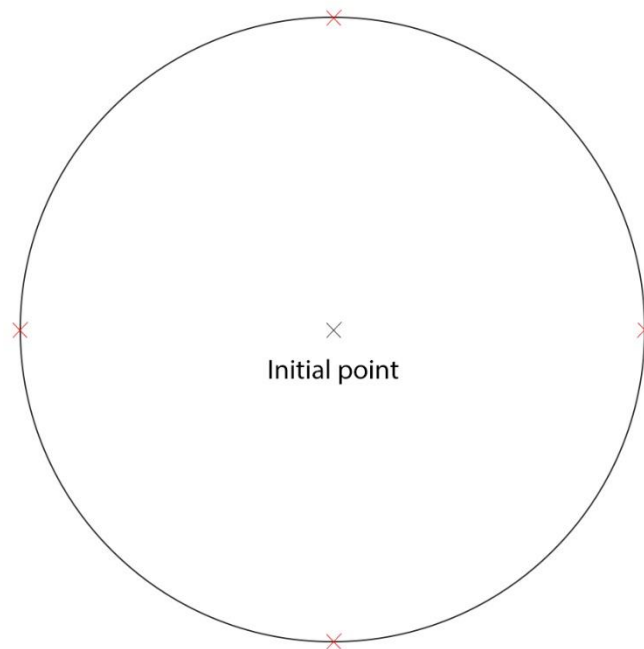


Figure 14: GPS algorithm first step

The first step calculates the value of the objective function at the initial point and at the mesh points. The algorithm polls the mesh points by computing their objective function values. The poll may be successful or not.

If the poll is successful (*Successful poll*), an objective function value lower than the value of the objective function for the initial point has been found at one of the mesh points. For the next iteration, the point that has obtained a lower value of the objective function is used as the new initial point and the mesh size is doubled. Doubling the mesh size makes the next set of mesh points to be chosen equidistantly to the new initial point, but at double the distance compared to the previous distance. The area considered is increased by the square root of two.

Figure 15 shows that if one of the mesh points reaches a lower path loss value than the initial point path loss, this mesh point is the new initial point for the next iteration and the new area under study (blue circumference) is double the previous area but centred in the new initial point.

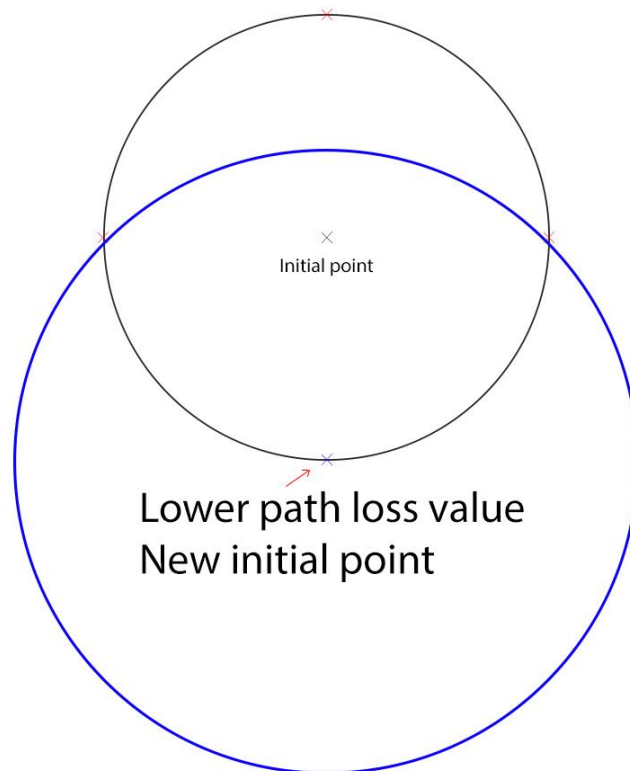


Figure 15: GPS algorithm Successful poll result

If the poll is not successful, it is necessary to refine the mesh (*Refine Mesh*). Under this circumstance, none of the mesh points get a lower objective function value than at the initial point. For the next iteration, the size of the mesh is reduced to the half and the procedure is repeated until it reaches a *Successful poll*. The new set of mesh points for the next iteration is at half distance from the initial point. The initial point remains the same.

Figure 16 shows how the new area under study is reduced to the half (blue circumference), the new set of mesh points are over the new area limits, and the initial point remains the same for the next iteration.

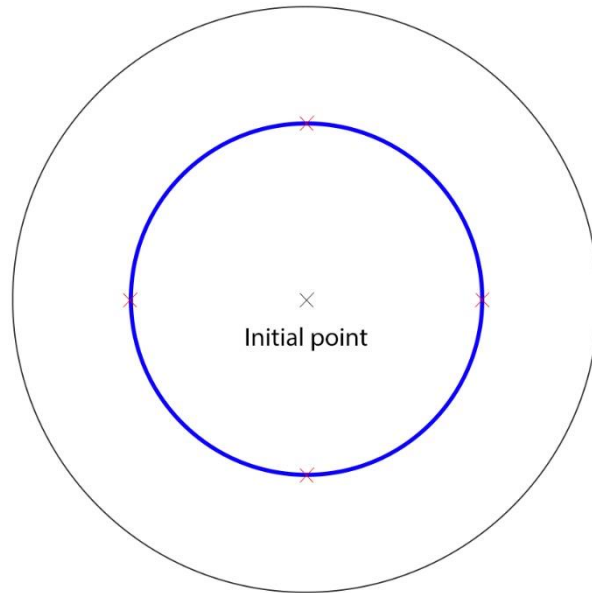


Figure 16: GPS algorithm Refine mesh result

The procedure continues until the stopping criteria is satisfied, these conditions are:

- The mesh size reaches the Mesh tolerance ( $10^{-6}$ ).
- The number of maximum iterations is reached ( $100 * \text{number of variables} \rightarrow 200$ ).
- The total number of function evaluations is reached ( $100 * \text{number of variables} \rightarrow 200$ ).
- The time limitation is reached (set to infinite).

These conditions are set by default with the values between brackets, but can be changed. In this experiment, they have been settled to default values. [37]

A comparison with other Matlab functions for optimization can be found in the annex 6.4.

### 3.3.2. Matlab execution

The iteration process stops after 36 iterations because the mesh tolerance has been reached. The result obtained in the optimization satisfies all the constraints, being the solution of the optimization algorithm  $55.7018^\circ$ ,  $13.1952^\circ$ . Table 11 shows the iteration evolution in the optimization. It can be seen how the objective function value decreases and how the mesh size is doubled when there are *Successful poll* events. Nevertheless, it can be seen that the mesh size is reduced to the half when there is a *Refine mesh* event.

Initially, the algorithm considers the whole area under study, but after the first *Successful poll* event it is reduced to the half around the new initial point. The refinements are more accurate as the iterations advance because the mesh size is progressively reduced limiting the area to poll. Thus, the selection of the initial point is influential in the solution as the result of the

optimization is near the initial point. It is confirmed that the central point is 55.70123°, 13.197125°, and it is at 190 m from the solution of the optimization algorithm.

Iteration	f(x)	Mesh size	Method
0	3.13231e+179	1	
1	3.13231e+179	0.5	Refine mesh
2	3.13231e+179	0.25	Refine mesh
3	3.13231e+179	0.125	Refine mesh
4	3.13231e+179	0.0625	Refine mesh
5	3.13231e+179	0.03125	Refine mesh
6	3.13231e+179	0.01563	Refine mesh
7	3.13231e+179	0.007813	Refine mesh
8	3.13231e+179	0.003906	Refine mesh
9	3.13231e+179	0.001953	Refine mesh
10	5.43941e+170	0.003906	Successful Poll
11	5.43941e+170	0.001953	Refine Mesh
12	5.43941e+170	0.0009766	Refine Mesh
13	5.43941e+170	0.0004883	Refine Mesh
14	2.09851e+168	0.0009766	Successful Poll
15	2.09851e+168	0.0004883	Refine Mesh
16	2.09851e+168	0.0002441	Refine Mesh
17	2.09851e+168	0.0001221	Refine Mesh
18	6.89953e+165	0.0002441	Successful Poll
19	6.89953e+165	0.0001221	Refine Mesh
20	6.89953e+165	6.104e-05	Refine Mesh
21	6.89953e+165	3.052e-05	Refine Mesh
22	6.87273e+163	6.104e-05	Successful Poll
23	6.87273e+163	3.052e-05	Refine Mesh
24	6.87273e+163	1.526e-05	Refine Mesh
25	6.87273e+163	7.629e-06	Refine Mesh
26	3.20995e+163	1.526e-05	Successful Poll
27	3.20995e+163	7.629e-06	Refine Mesh
28	3.38149e+161	1.526e-05	Successful Poll
29	3.38149e+161	7.629e-06	Refine Mesh
30	3.38149e+161	3.815e-06	Refine Mesh
31	4.44822e+160	7.629e-06	Successful Poll
32	4.44822e+160	3.815e-06	Refine Mesh
33	4.44822e+160	1.907e-06	Refine Mesh
34	4.45181e+159	3.815e-06	Successful Poll
35	4.45181e+159	1.907e-06	Refine Mesh
36	4.45181e+159	9.537e-07	Refine Mesh

Table 11: Iterations

Table 12 and Table 13 show the amount of worse (red) measurements distributed in the 16 regions.

B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16
2	1	1	5	1	9	9	3	2	4	5	8	2	2	9	4

Table 12: Amount of bad measurements in each region

2	1	1	5
1	9	9	3
2	4	5	8

2	2	9	4
---	---	---	---

Table 13: Amount of bad measurements in each region

Seeing this distribution, since the red measurements in our dataset are concentrated in the middle and South-Eastern region, a central location for a new access point is reasonable.

### 3.4. Procedure overview

In order to clarify all the necessary steps to find the optimal location, the list below summarizes the process:

- Obtaining the measurements' data in Excel: location of the measurements, its signal level (RSSI), and its SNR.
- Definition for each measurement: its gateway location (where the gateway is in relation to the connected measurement) and the gateway height, the transmitted power, the path loss exponent (which has been calculated, considering a sub-urban environment), the gateway gain, the measured path loss, the distance to the gateway, and the  $B$  estimation.
- $R$  script execution. It selects the interest area where the worse measurements are, it defines the 16 regions, and the  $B_p$  vector value (vector with the averaged  $B$  value in each region).
- Matlab script execution. It deploys the optimization using the script resulting from the  $R$  execution and gets the optimal location.

### 3.5. Considerations

In the whole procedure, some assumptions have been taken into account.

- The path loss exponent ( $n$ ) is obtained from a formula that depends on the terrain type and the height. The terrain type has been estimated to be the one of a sub-urban area, however, it is not possible to get a more accurate value. The new gateway height cannot be determined before knowing the optimization result; the obtained value is valid at the estimated height.
- It is not possible to perfectly measure the environment effect in a channel. The  $B$  value has been calculated based on it and it cannot have an accurate result either.
- In order to simplify the procedure, the averaged  $B$  value has been considered instead of real measurements. To get an idea of how representative the measurements are in each area, the variance and the standard deviation have been calculated. They are shown in *Table 14*.

	Variance	Standard deviation	Standard deviation (dB)
B1	5.724877	2.39	3.78397901
B2	0	0	-
B3	0	0	-
B4	86.894058	9.32	9.69415912
B5	0	0	-
B6	39.297785	6.26	7.96574333
B7	46.241767	6.8	8.32508913

B8	65.375655	8.08	9.07411361
B9	47.714835	6.9	8.38849091
B10	10.59466	3.25	5.11883361
B11	27.596423	5.25	7.20159303
B12	15.012056	3.87	5.87710965
B13	53.052222	7.28	8.62131379
B14	40.967405	6.4	8.06179974
B15	164.733305	12.83	11.0822666
B16	16.570736	4.07	6.09594409

Table 14: B variance and standard deviation

The smaller the standard deviation, the closer these values are to the mean. Hence, it is possible to test how accurate the  $B$  value estimation is in each region. If the standard deviation is low, all the values in the area can be approximated to the mean, however, if not, the approximation would be incongruous. [39] The zero values on the variance are because there is only one measurement in that region. As region 15 is the one with the highest standard deviation, this area should be covered by the gateway in Rabyvagen, but its coverage is worse than the others and it leaves this area improperly attended.

### 3.6. Implementation with spreading factor data measurements

In the previous analysis in this chapter, the spreading factor was fixed to 12, then, the transmitted power was always 14 dBm. Some new measurements have been taken considering the possibility of variable spreading factor. From now on, the new measurements taken in the city considering the spreading factor data are going to be used. The location of the three gateways remains the same.

The device used to take the new measurements is a Field Test Device from Adeunis for LoRaWAN which measures the RSSI, SNR, and spreading factor in a certain location for uplink and downlink. [40] The majority of these measurements have been taken in the interest area. This device is shown in *Figure 17*.

The minimum RSSI reached has been -121 dBm. The data extraction procedure, the optimization implementation technique, and the minimization function (patternsearch) remain the same.

Section 3.6.1 shows the optimization results defining the best location to place a new gateway in Lund considering the possibility that the LoRaWAN network applies the Adaptive Data Rate functionality changing the value of the spreading factors when the measurements are taken.



Figure 17: Field Test Device [40]

### 3.6.1. Results

The iteration process stops after 56 iterations because the mesh tolerance has been reached. The result obtained in the optimization satisfies all the constraints, being the solution of the optimization algorithm **55.7021º**, **13.1933º**. The procedure followed is analogous as in section 3.3.2. The distance from the result of the optimization to the initial point is bigger, 261 m, which explains why it has taken more iterations to converge to a solution.

Table 15 and Table 16 show the amount of worse (red) measurements distribution in the 16 regions.

B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16
-	-	-	6	3	16	10	7	10	64	37	38	10	2	-	-

Table 15: B values in each region

-	-	-	6
3	16	10	7
10	64	37	38
10	2	-	-

Table 16: B values in each region

Figure 18 shows the comparison between the previously calculated optimal location (marked in red) and the new one (marked with a green dot). Both results are around the same area.

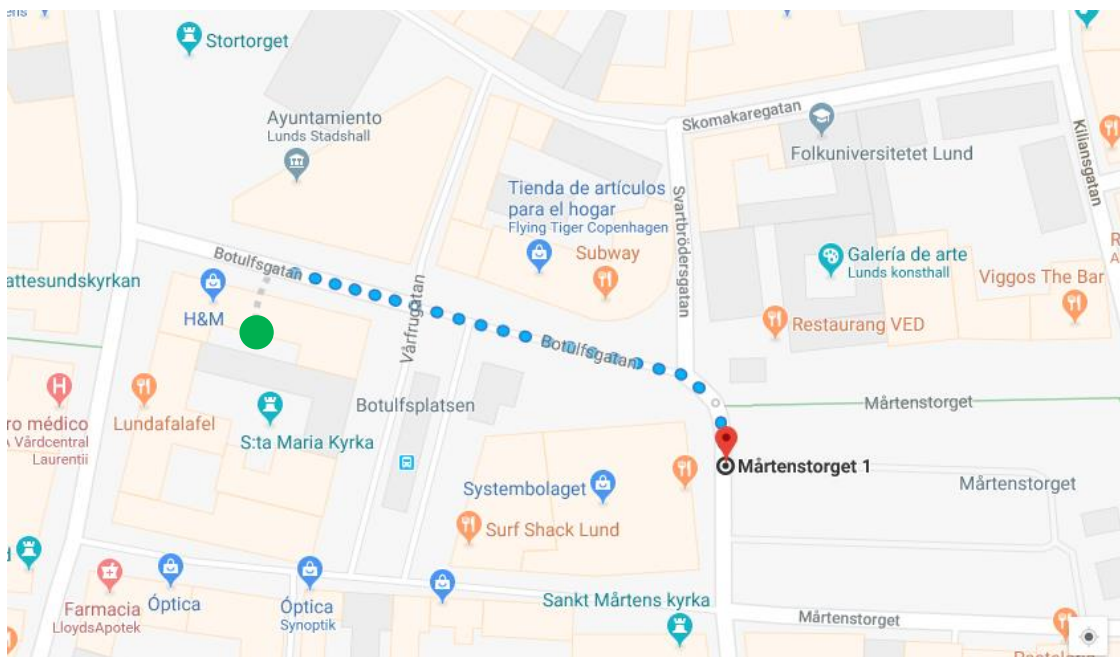


Figure 18: Optimal location change



## 4. EVALUATION

In this chapter, the gateway coverage in two locations is evaluated. The procedure followed is as follows:

- Checking where it is possible to access in the optimal location surroundings
- Going to the location
- Placing the gateway
- Going around the city and taking some measurements

### 4.1. Test 1

In the first trial, the gateway is in Mårtenstorget at street level over a parking meter machine (55.701513<sup>o</sup>, 13.195974<sup>o</sup>). This gateway's placement is shown in *Figure 19*.



Figure 19: Test 1 gateway placement

The measurements that have been connected to this gateway are shown in *Table 17*.

RSSI (dBm)	SNR (dB)	SF	Measurement Latitude (°)	Measurement Longitude (°)
-106	-3.5	7	55.7057667	13.2008333
-107	-10.2	10	55.7021667	13.2008333
-106	-2.5	10	55.7014333	13.2006667
-107	-14	12	55.7004167	13.2
-108	-11	12	55.70045	13.2011667
-110	-10.8	8	55.6994833	13.1995
-107	-4.8	12	55.7038667	13.1943333
-108	-8.5	10	55.7042333	13.1945
-105	-5.5	7	55.70545	13.1951667
-106	-7.2	8	55.70835	13.197

Table 17: Test 1 results

*Figure 20* shows the location of the measurements from *Table 17* in a map. Despite the gateway being placed at ground level, it has reached a latitude of 55.708315<sup>o</sup> to the north and

55.699416° to the south. The measurements taken inside Mårtenstorget with direct line of sight with the gateway were connected to Kristallen gateway. At ground level, there are more interfering obstacles in the propagation than over a building, and therefore the measurements are the result of interferences, reflections, shadowing and constructive/destructive signals.

Looking at the RSSI values, four of them are not below -106.6 dBm. This means that it has not improved the measurements to higher RSSI values.

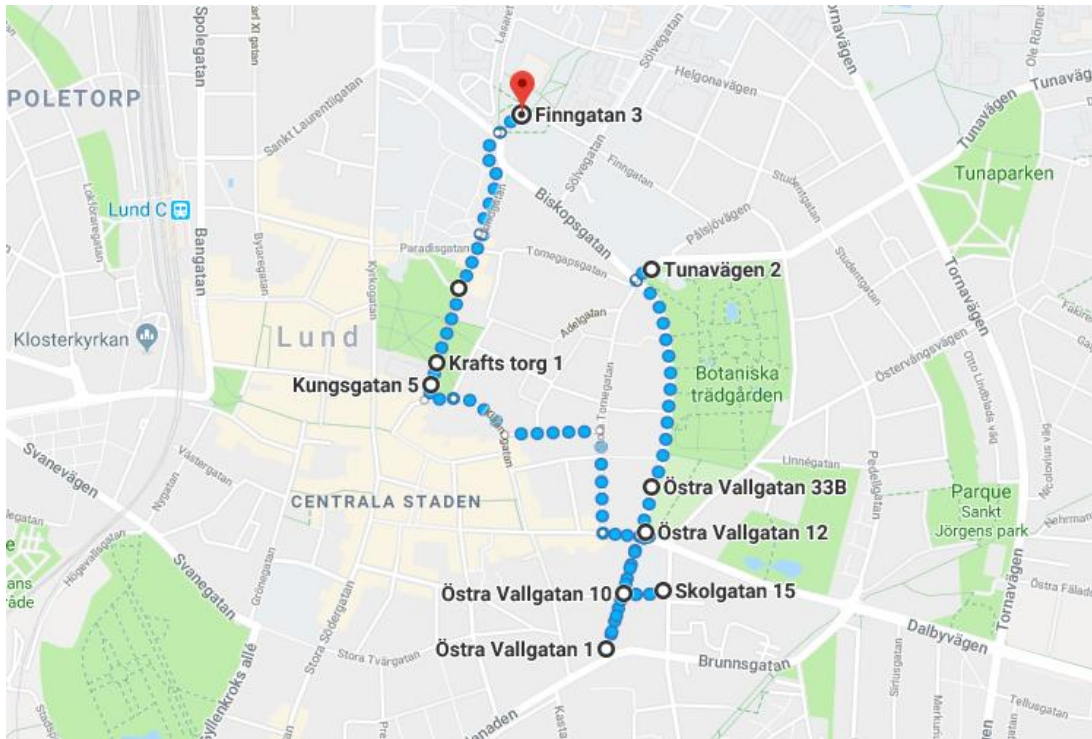


Figure 20: Test 1 locations

Table 18 shows the amount of green, yellow and red RSSI values in relation to the spreading factor, the majority of the values are using spreading factor 7.

	SF7	SF8	SF9	SF10	SF11	SF12
GREEN	38	1	1	3	2	3
YELLOW	22	4	0	6	3	2
RED	71	7	4	10	2	7

Table 18: Relation spreading factor and RSSI values

The worst red values with spreading factor 12 are located in the limiting areas shown in Figure 21.

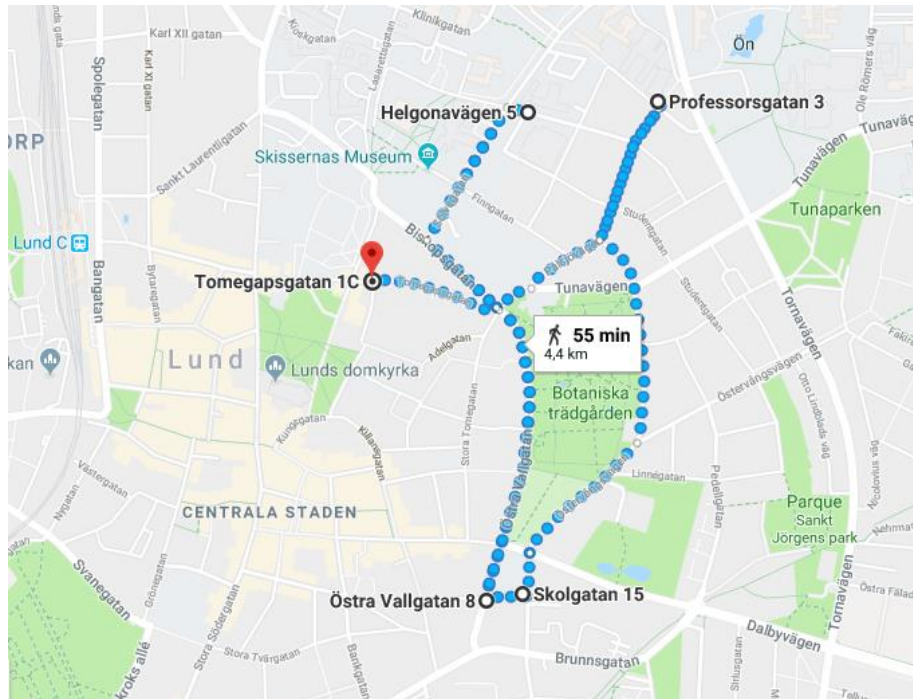


Figure 21: Red values – Spreading factor 12

Table 19 shows the minimum and maximum RSSI values for each spreading factor. It reflects that before reaching -120 dBm, the spreading factor is increased and for spreading factor 12, the measurement is not taken for lower RSSI values.

	SF7	SF8	SF9	SF10	SF11	SF12
Minimum RSSI	-118	-113	-115	-117	-108	-117
Maximum RSSI	-91	-99	-102	-93	-85	-99

Table 19: Minimum and maximum RSSI values

Placing a gateway at ground level can sometimes provide further coverage than expected but it is not a useful location as it cannot uniformly cover and improve the whole Lund's central area.

## 4.2. Test 2

The second test has been developed placing the gateway in the same location (Mårtenstorget), but at higher height. A drone was used to place the gateway at 25 m because there were no accessible buildings in that square. This procedure took longer due to the limiting factor of the drone batteries duration.

Table 20 shows the distribution of the 71 measurements taken. The results show that the majority of measurements are using SF7 (64.8% of measurements) and only 12 of the connections were not to the new gateway. The furthest point measured has been 340 m away to the south and it had spreading factor 7, which means that it may be possible to cover southern areas increasing in one or two units the spreading factor value. The coverage with spreading factor 7 allows to reduce the power consumed in the network.

	SF7	SF8	SF9	SF10	SF11	SF12
green	16	0	0	0	0	4
yellow	1	0	0	1	0	0

red | 29 | 4 | 0 | 11 | 2 | 3

Table 20: Spreading Factor distribution

Comparing the measurements from *Table 20* with the ones taken at the same area before adding the gateway, there were only five measurements in the same region: four of them with spreading factor 7, and one with spreading factor 9. Comparing the measurements only with five previous measurements cannot support or validate the algorithm.

In section 4.3, some more measurements have been taken considering different gateway locations and making possible to compare the results of Test 2 with those ones. It will allow to support the validity of the methodology.

### 4.3. New approach: list of locations

While evaluating the results, the biggest issue faced was the accessibility to the optimal location or to somewhere in the surroundings. The proposed solution to this problem is to find the optimal location among a list of possible locations. This list can be as long as desired and it should contain locations that are reachable.

*Table 21* shows the created list for Lund.

Location	Latitude	Longitude	Height
Mårtensstorget	55.701513	13.195974	2
LTH E-huset	55.711103	13.210414	23.5083333
Sensefarm	55.716515	13.224933	23.5083333
Mårtensstorget	55.701513	13.195974	25
Damgården parking	55.699239	13.199903	20.44
P-hus Parking	55.700877	13.191446	23.5083333

Table 21: List of possible locations in Lund

The heights have been estimated using the tool [39].

#### 4.3.1. Methodology

To apply the methodology used in this section over Lund, the steps to follow are:

1. Display the list of locations in an Excel file with the structure:

Location	Latitude	Longitude	Height
----------	----------	-----------	--------

2. Create a file with the measured network values with the structure:

eui	Latitude	Longitude	RSSI	SNR	Time	Gateway	Gateway connection	Gateway height (m)	Gateway latitude
-----	----------	-----------	------	-----	------	---------	--------------------	--------------------	------------------

Gateway longitude	Gateway gain	Power transmitted	Environment (urban, sub-urban, rural)	max lat	min lat	max long	min long
-------------------	--------------	-------------------	---------------------------------------	---------	---------	----------	----------

*eui* is an identifier for the measurement (it adds no information to the calculus) and *latitude* and *longitude* are the geographical coordinates where the measurement has been taken. *RSSI* and *SNR* are signal features and *Time* is the instant when the measurement was taken (it adds no information to the calculations). *Gateway* and

*Gateway connection* are the identifier and the gateway name; *Gateway height, latitude, longitude and gain* are the data relative to the gateway to which the measurement has been connected. The *Power transmitted* is the one that the measuring device sends and the *Type of environment* can be chosen from urban, sub-urban or rural depending on the scenario. *Max lat., min lat., max long and min long* are the geographical limits of the area that is going to be studied.

3. The R script calculates the optimal location applying the same methodology and algorithms used in chapter 3, for the new gateway among the list of options.

The last script will provide the result telling which the optimal location is among the list. This procedure can be applied over whichever place and not only in Lund. Section 4.3.2 show the optimization results of this procedure.

### 4.3.2. Results

After applying the methodology from chapter 3, which considers the one slope log-normal and the GPS algorithm, among previous options, the result of the optimization is that the best place to locate the gateway is Mårtenstorget at 25m, followed by P-hus Parking, LTH E-huset, Sensefarm, Damgården parking , and finally Mårtenstorget at 2m.

The height is the feature with higher impact to consider when placing a gateway as it provides more visibility. The optimal location is the highest one being also the one obtained at the previous simulations. Among P-hus Parking, LTH E-huset and Sensefarm, P-hus Parking is more centric and closer to the worse recorded measurements, which will provide a better coverage. Then, the second closer to the center is LTH E-huset, and it is the third best option followed by Sensefarm facilities. Damgården parking is not tall which explains why it is not providing better results; despite being nearer to where there is a higher concentration of bad measurements.

### 4.3.3. Methodology testing

#### 4.3.3.1 Mårtenstorget at 25 m

These results have been shown in section 4.2. The key factor is that 64.8% of the measurements are using spreading factor 7 in the central area of Lund where mostly all the bad measurements are. This location is the best, following the optimization criteria, to place a new gateway. However, as it does not provide enough measurements to validate the methodology, it cannot be chosen as a solution and the second solution, P-hus Parking, from the methodology explained in section 4.3.1 may be considered as the best result.

#### 4.3.3.2 P-hus Parking

In *Figure 22*, the gateway location is shown in red and, in blue are defined the points that are more in the north, south, east and west. The gateway has covered all the city centre and southern areas of Lund which explains why this is the second best option where to place a new gateway in the network.



Figure 22: Map representation of P-hus Parking

From *Table 22*, the 50.77 % of the measurements use spreading factor 7. The majority of the measurements with spreading factor 12 were taken at Södra Esplanaden, which is the furthest area covered at the south. Some other measurements with spreading factor 12 were taken at the northern covered area because the cathedral has a great shadowing effect.

	SF7	SF8	SF9	SF10	SF11	SF12
green	18	0	0	1	0	0
yellow	1	2	0	2	0	0
red	14	2	1	5	2	17

Table 22: Spreading factor distribution at P-hus Parking

*Table 23* shows the results from the measurements without the placement of the P-hus parking gateway. Of the collected measurement, 40% use spreading factor 7. Consequently, there has been an improvement of 10.77% in the use of spreading factor 7. As explained in the references [16] and [18], the use of a lower spreading factor reduces the necessary power to transmit information, and thereby, the overall power consumption is reduced.

	SF7	SF8	SF9	SF10	SF11	SF12
green	0	0	0	0	0	0
yellow	0	0	0	0	0	0
red	36	9	6	17	7	15

Table 23: Initial spreading factor distribution at the P-hus Parking region

#### 4.3.3.3 LTH E-huset

In *Figure 23*, the gateway location is in red. As it is far from the central area of Lund, it cannot fully cover the city center. In blue are shown the measurements obtained more to the west and

south. It covers a wide area considering how far it is located, however, it is not enough, especially because the highest accumulation of worse measurements is located in the southern areas.

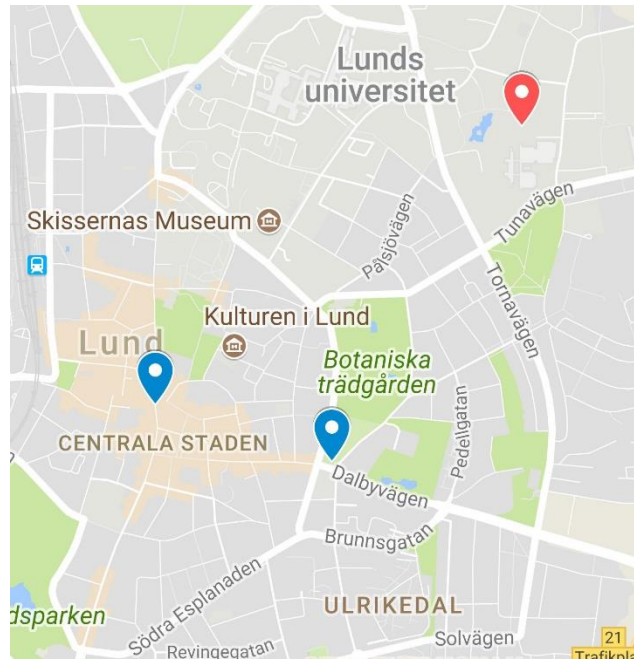


Figure 23: Map with the gateway at LTH E-huset

Table 24 shows that 40.49% of the total measurements are using spreading factor 7.

	SF7	SF8	SF9	SF10	SF11	SF12
green	5	0	0	1	0	0
yellow	10	0	1	3	0	2
red	34	3	6	17	5	34

Table 24: Spreading factor distribution LTH E-huset

Table 25 shows the results from the measurements without the placement of the LTH E-huset gateway. It shows that 36.67% of the total measurements are using spreading factor 7. There has been an improvement of 2.61% in the number of measurements applying spreading factor 7.

	SF7	SF8	SF9	SF10	SF11	SF12
green	0	0	0	0	0	0
yellow	0	0	0	0	0	0
red	33	12	9	15	6	15

Table 25: Initial spreading factor distribution at the LTH E-huset region

#### 4.3.3.4 Sensefarm

The gateway has been placed at the rooftop of Sensefarm's facilities (shown in red in Figure 24). The more southern point (shown in blue) is a bit up in the north compared to the interest area, and this gateway does not really cover the city centre, just northern areas. This topology can only cover a portion of the interest area.

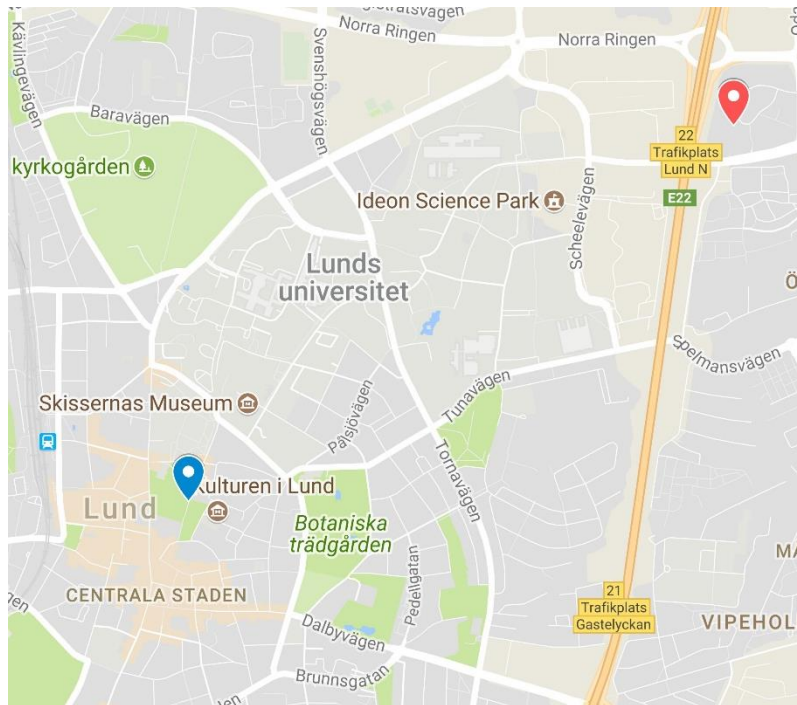


Figure 24: Sensefarm map

Table 26 shows the spreading factors' distribution in the interest area of central and southern Lund. Despite this gateway is placed at the same height as LTH E-huset and P-hus Parking, it is further from the interest area to improve, the results then are not better. In the surroundings of this location, the results can reach spreading factor 7, but this area is not the one to be improved. Here, 39.4 % of the measurements are using spreading factor 7.

	SF7	SF8	SF9	SF10	SF11	SF12
green	13	2	1	4	2	2
yellow	0	0	1	1	0	0
red	2	0	0	1	0	9

Table 26: Spreading factor distribution at Sensefarm facilities

Table 27 shows the results from the measurements without the placement of the Sensefarm gateway. It shows that 38% of the total measurements are using spreading factor 7. There has been an improvement of 1.47% in the number of measurements with spreading factor 7.

	SF7	SF8	SF9	SF10	SF11	SF12
green	0	0	0	0	0	0
yellow	0	0	0	0	0	0
red	80	43	29	41	7	10

Table 27: Initial spreading factor distribution at Sensefarm region

#### 4.3.3.5 Damgården parking

In Figure 25, the gateway location is marked in red. The lines in orange and the two blue points are the locations where this gateway uses spreading factor 7. The coverage is limited to the areas with line of sight. The green point shows the furthest point that this gateway covers. This gateway's location undercovers the city centre as it barely reaches it.



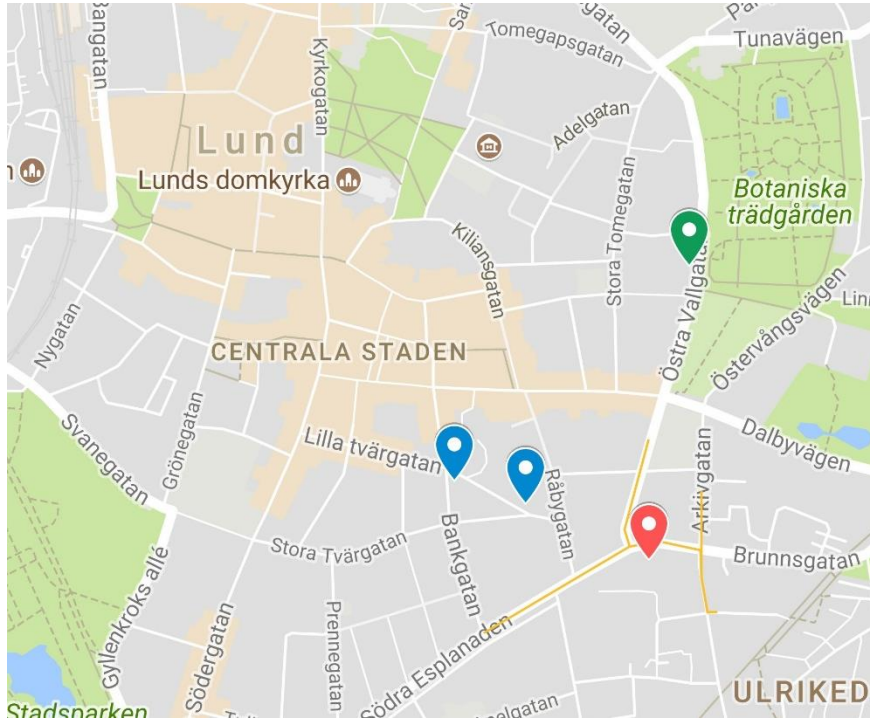


Figure 25: Damgarden parking coverage

Table 28 shows the spreading factors' distribution. The great majority of measurements at spreading factor 7 are at line of sight, only the two blue points and the measurements at Arkivgatan do not have line of sight. There is a total of 40.32% of spreading factor 7 measurements.

	SF7	SF8	SF9	SF10	SF11	SF12
green	17	0	1	0	1	0
yellow	3	0	1	1	1	2
red	5	5	3	10	1	11

Table 28: Damgarden parking spreading factor distribution

Table 29 shows the results from the measurements without the placement of the Damgarden parking gateway. 55.77% of the measurements use spreading factor 7. Consequently, there has been a 15.45% improvement in the use of spreading factor 7. Despite the improvement being high, the coverage is worse than the previous gateway locations coverage. It does not consist of the city center, hence this possibility is discarded.

	SF7	SF8	SF9	SF10	SF11	SF12
green	0	0	0	0	0	0
yellow	0	0	0	0	0	0
red	29	8	2	7	1	5

Table 29: Initial spreading factor distribution at Damgarden region

#### 4.3.3.6 Mårtenstorget at 2 m

These results have been shown in section 4.1. The key factor is that the measurements are irregular as there are more interfering elements (buildings, cars, trees, people, etc.) in the line of sight of the antenna's gateway. Thus, it is not a trustworthy solution.

## 5. CONCLUSIONS

This thesis has optimized the gateways' location in the LoRaWAN network in Lund. LoRaWAN is a LPWAN; hence, one of its main benefits is the low power consumption. The goal of this thesis has been to reduce its power consumption even more.

It has been possible to calculate an optimal location for a new possible gateway location in an existing network. Nevertheless, due to external causes, the accessibility to that exact location has not been attainable. The solution to overcome this issue has been selecting the best location to place that new gateway from a list of possible and accessible locations. Calculating the best location to place a new gateway in a network considering a list of possible locations allows this methodology to be applied over any scenario. It makes this solution a general way to approach the same problem over another network, it can be extrapolated by creating a list of possible locations. Nevertheless, the solution could be conditioned to the initial point set.

Further research could be done by introducing more data visualization, developing a tool to measure how the power consumption varies with the change of the spreading factor, increasing the number of gateways at street level, or testing if another channel model would get a more accurate environment estimation. The already developed code and the further research possibilities could be developed in a free-licensed software as it was suggested when I presented the previous work in the Low Power conference in Malmö. The most suitable options would be Python because it is generally integrated with web applications, or R because it provides a great variety of graphical sources. Both are state of art programming languages in statistics, data analysis and databases [41].

An analogous research could be done by analysing the feasibility of deploying the gateways indoor in LoRaWAN networks. Nevertheless, before carrying out the study, one should bear in mind that while indoor gateways provide better coverage, and seem to be cheaper (an outdoor gateway costs between 500 € and 1500 €, whereas an indoor gateway costs between 300 € and 500 €, according to Sensefarm's data), they require a higher number of devices in comparison with outdoor gateways. Finding a trade-off between the number of indoor gateways and its price could be a feasible solution. For the concerning analysis, the channel model is different than for outdoor scenarios. According to [3], the most suitable model to use for this study would be the four slopes log-normal model.

## 6. ANNEXES

Chapter 6 contains additional information that broadens the concepts explained during the thesis.

### 6.1. Related work on channel models

The Lee propagation model has been analysed in order to see if it fits better than the log-normal model as it has been tested over LoRaWAN networks. The Lee model results are valid for urban environments. As Lund is considered a sub-urban area, this model is not an option to feature the channel. [42]

Research in the cities of Oulu (Finland) and Dortmund (Germany) are similar to Lund's research. The results obtained from [5] and [6] of these cities at 868 MHz are in *Table 30*.

	Oulu	Dortmund
n	2.32	2.65
B	128.95	132.25

Table 30: Oulu and Dortmund measurements [6]

Lund's population is around 89,000 inhabitants [43], Oulu's population is 193,902 inhabitants [44], and Dortmund's population is 580,000 inhabitants [45]. Considering the population level and as both Lund and Oulu are flat cities, sub-urban areas, and are not far from the sea, the channel model that is going to be more similar to estimate the path losses in Lund is the one from Oulu. *Equation 15* shows the path loss expression for Oulu.

$$EPL(dB) = 128.95 + 10 \times 2.32 \times \log_{10}\left(\frac{d}{d_0}\right)$$

Equation 15: Expected path loss at Oulu

These last two examples are more closely related to Lund's study due to similar environment conditions. However, the majority of studies consider that the expression that models the path losses is *Equation 16*.

$$PL(dB) = PL(1m)(dB) + 10 \times n \times \log_{10}(d(m)) + X$$

Equation 16: Path loss

Where X is a zero-mean Gaussian random variable with a certain standard deviation that represents the shadowing effect and the  $PL(1m)$  value is the path loss at 1m.

*Equation 16* differs from *Equation 4* on the distance units and on the constant value B. Actually, this is just a different way of expressing the same because B includes the shadowing effect in its value. *Equation 17 and 18* show the Oulu and Dortmund values as in *Equation 16*.

$$\begin{aligned} PL(dB) &= PL(1m)(dB) + 10 \times n \times \log_{10}(d(m)) + X \\ &= 128.95 + 10 \times 2.32 \times \log_{10}\left(\frac{d(km)}{d_0}\right) \rightarrow PL(dB) \\ &= 59.35 + 10 \times 2.32 \times \log_{10}(d(m)) + X \end{aligned}$$

Equation 17: Path loss Oulu

$$\begin{aligned}
 PL(dB) &= PL(1m)(dB) + 10 \times n \times \log_{10}(d(m)) + X \\
 &= 132.25 + 10 \times 2.65 \times \log_{10}\left(\frac{d(km)}{d_0}\right) \rightarrow PL(dB) \\
 &= 52.75 + 10 \times 2.65 \times \log_{10}(d(m)) + X
 \end{aligned}$$

Equation 18: Path loss Dortmund

Other studies with one slope have been developed in different environment applying *Equation 16* and they are shown in *Table 31*.

	$PL(1m)(dB)$	$n$	$\sigma (dB)$
Flat open yard and sandy dunes with bushes, 2.4 GHz [46]	40.15	3.684	11.5
Ground plain (flat) [47]		3.12	1.83
University yard surrounded by buildings [47]		3.57	3.27
Curved grass park [47]		3.69	1.42
Snowy floor, antenna of 1m and 2.425 GHz [48]	66.76	1.26	2.97
Plaza, antenna of 1m and 2.4 GHz [49]	42.86	1.86	3.25
Sidewalk, antenna of 1m and 2.4 GHz [49]	40.36	1.99	2.45
Grassland, antenna of 1m and 2.4 GHz [49]	40.51	1.9	3.02

Table 31: Path loss values

*Equations 19 to 21* show the maximum distance calculation.

$$Sensitivity \leq Transmitted\ power - Path\ losses$$

Equation 19: Sensitivity upper limit

$$PL(dB) \leq P_{TX}(dBm) - S(dBm) \leftarrow Maximum\ path\ loss$$

Equation 20: Path loss upper limit

$$Maximum\ distance\ (km) = 10^{(maxPL(dB)-B)/(10*n)}$$

Equation 21: Maximum distance

Where  $B$  is 128.95 and  $n$  is 2.32 for Oulu. Conversely, if *Equation 4* is applied without considering the shadowing effect, the result would be the same, but in meters. *Table 32* calculates the maximum communication distance for each spreading factor in Oulu.

SF	Bandwidth (kHz)	Coding rate	Bit rate (bps)	Transmitted power (dBm)	Sensitivity (dBm)	Maximum path loss (dB)	Maximum distance (km)
12	125	4/6	244,14	14	-137	151	8,92135938
11	125	4/6	447,59	12	-136	148	6,62400558
10	125	4/5	976,56	10	-134	144	4,45355578
9	125	4/5	1757,81	8	-131	139	2,71137542
8	125	4/5	3125	6	-128	134	1,6507162
7	125	4/5	5468,75	4	-125	129	1,0049748
7	250	4/5	10937,5	2	-122	124	0,61184009

Table 32: Relation SF - bandwidth - coding rate - bit rate - transmitted power - sensitivity - maximum path loss - maximum distance

## 6.2. Optimization theory

There are mainly two types of optimization algorithms: deterministic and probabilistic algorithms. In deterministic algorithms, the output has a relation with the input; otherwise, if there is no actual relation between input and output, it is a probabilistic algorithm. [50]

Optimization has been used over networks to improve the congestion as it affects the general network's performance, the efficiency, and its delivery time. For these types of applications, genetic algorithms and particle swarm optimization have been used. [50]

To understand these optimization types, firstly, it is going to be described the optimization classification. Optimization algorithms can be classified as:

- Iterative: it repeats the algorithms several times until it reaches the solution.
- Stochastic: it follows a probabilistic rule.
- Deterministic.
- Population based: it works with a set of solutions and it looks for improving them.

The two population based algorithms used the most are: swarm intelligence algorithms and evolutionary algorithms, for example Genetic Algorithms. [51]

Genetic algorithms are search algorithms based on the natural genetics where the strongest population elements are the ones that survive over the others. These algorithms have been created to analyse the natural processes while expressing them through software. [52]

Particle swarm optimization is another optimization technique that adjust each point movement considering previous experiences. [53] It can be applied over continuous nonlinear functions. [54]

As the network under study does not have to optimize the network's congestion, population based algorithms are not applied to it, they can be exclusively applied over congestion's optimizations.

### 6.2.1. Graphical optimization

In order to optimize the gateway's location, as explained in Section 1.6, a number of optimization methods have been considered but none of them was applicable to this scenario: a LPWAN with LoRaWAN technology. In [55], a graphical analysis has been developed for an indoor environment using Building Information Models (BIM) that provides a way to exchange information from buildings and it is shared by The Industry Foundation Classes (IFC). Its way of representing a building is shown in Figure 26. Rendering a map model of a whole city in a software programme would be technically unfeasible, hence this option has been discarded.

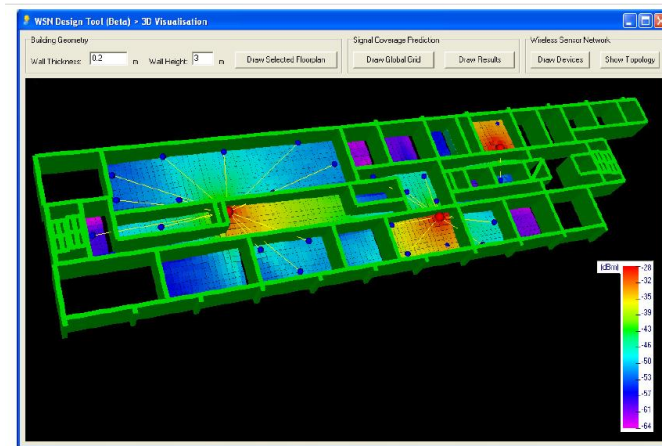


Figure 26: Building Information Models software [55]

## 6.3. Mathematical approach to optimization

### 6.3.1. Optimal points

An optimal point is one where the objective function has a minimum; there are two types of optimal points:

- Global optima: the function value in global optima is below or equal to any other point in the function.

- Local optima: the function value in local optima is below or equal to any other point in a limited region of the function. [26]

### 6.3.2. Optimization problems classification

Regarding the type of optimization, the problems can be classified as local optimization problems or global optimization problems. The difference is the type of optimal values that are necessary to achieve: local or global.

Regarding the existence of restrictions, the problems can be classified as with or without restrictions.

Regarding the nature of the objective function and the restriction functions, the problems can be classified as linear or not linear.

Regarding the nature of the optimization, the problems can be classified as deterministic when the problem parameters are fixed or as stochastic when the problem parameters are expressed with random variables. [26]

### 6.3.3. Convex optimization

The convex property can be applied over functions and sets. A set  $S$  is convex if for two  $x$  and  $y$  points of  $S$ , there is another point  $z$  that is from  $S$  too and that satisfies *Equation 22*.

$$z = \alpha x + (1 - \alpha)y \text{ for } 0 \leq \alpha \leq 1$$

Equation 22: convex set

A function is convex when its domain  $S$  is a convex set and when, for two points  $x$  and  $y$  from  $S$ , Equation 23 is satisfied.

$$f(\alpha x + (1 - \alpha)y) \leq \alpha f(x) + (1 - \alpha)f(y) \text{ for } 0 \leq \alpha \leq 1$$

Equation 23: convex set condition

A convex optimization problem has to have a convex objective function, inequality convex functions, and affine equality constraints. It is useful to consider a problem convex, as there are several optimization methodologies, and algorithms that allow solving these problems. [26]

### 6.3.4. Lagrangian

Considering the general structure of an optimization problem, there is a way to express all the functions that take part in the optimization ( $f(x)$ ,  $g_j(x)$  and  $h_k(x)$ ) in one through the Lagrangian expressed in Equation 24.

$$L(x, \lambda, v) = f(x) + \sum_{j=1}^m \lambda_j g_j(x) + \sum_{k=1}^p v_k h_k(x)$$

Equation 24: Lagrangian

The values  $\lambda_j$  and  $v_k$  are the Lagrange multipliers associated to  $g_j(x)$  and  $h_k(x)$  and  $\lambda$  and  $v$  are known as dual variables or Lagrange multipliers vectors associated to the optimization problem.

The dual Lagrange function is the minimum value of the Lagrange function in the  $x$  variable and it is shown in Equation 25.

$$d(\lambda, v) = \min_x L(x, \lambda, v)$$

Equation 25: Dual Lagrange function

If  $\lambda \geq 0$ , and  $p^*$  is the function value at the optimal point, the following condition is satisfied:  $d(\lambda, v) \leq p^*$

The dual Lagrange function provides an inferior level of the optimal value  $p^*$  as a function of  $\lambda$  and  $v$ . [26]

### 6.3.5. Simple heuristics

The application of a certain simple heuristic depends on the type of optimization problem considered: unconstrained optimization, optimization with equality constraints or optimization with inequality constraints.

#### 6.3.5.1. Unconstrained optimization

##### 6.3.5.1.1. Direct solution

For this heuristic, if the function has a local minimum or maximum at  $x_0$  and the function's gradient in this point exists, it satisfies:  $\nabla f(x_0) = 0$ . This is a necessary condition and the resulting values of  $x_0$  are the stationary points.

A sufficient condition is that  $x_0$  is a local minimum or maximum if the hessian of  $f(x)$  is positive definite for a strong local minimum and negative definite for a strong local maximum.

To solve an optimization problem using the direct solution, the necessary condition is applied to get the stationary points. Over the stationary points, the sufficient condition is also applied in order to get the local minimums, local maximums, and saddle points (the rest of the stationary points that are not local minimums or maximums).

#### **6.3.5.1.2. Direction search method**

This is an iterative process, a design vector is proposed and it is applied to an iterative process until it close enough to the local minimum or maximum. The steps to follow are:

- Selection of the initial vector design:  $x_0$ .
- Selection of the vector that indicates the search direction:  $d_i$
- Selection of the size of the step for the direction:  $\lambda_i$ . For that, the function  $f(x_i + \lambda_i d_i)$  is minimized, it only depends on  $\lambda_i$ .
- Update of the design vector:  $x_{i+1} = x_i + \lambda_i d_i$
- If the convergence condition is satisfied, the design vector is  $x_{i+1}$ .
- If the convergence condition is not satisfied,  $i=i+1$  and the process is repeated.

#### **6.3.5.1.3. Gradient descent method**

In this methodology, the search direction is  $d_i = -\nabla f(x_i)$ . It is a simple procedure, but the convergence speed is low. The process to follow is similar to the direction search method:

- Selection of the initial vector design:  $x_0$ .
- Calculation of the vector that indicates the search direction:  $d_i = -\nabla f(x_i)$ .
- Selection of the size of the step for the direction:  $\lambda_i$ . For that, the function  $f(x_i + \lambda_i d_i)$  is minimized, it only depends on  $\lambda_i$ .
- Update of the design vector:  $x_{i+1} = x_i + \lambda_i d_i$
- If the convergence condition is satisfied, the design vector is  $x_{i+1}$
- If the convergence condition is not satisfied,  $i=i+1$  and the process is repeated.

#### **6.3.5.1.4. Newton method**

As it has happened with the gradient descent method, it has the same basis as the direction search method but the search direction is  $d_i = -[\nabla^2 f(x_i)]^{-1} \nabla f(x_i)$ .

- Selection of the initial vector design:  $x_0$ .
- Calculation of the vector that indicates the search direction:  $d_i = -[\nabla^2 f(x_i)]^{-1} \nabla f(x_i)$ .
- Selection of the size of the step for the direction:  $\lambda_i$ . For that, the function  $f(x_i + \lambda_i d_i)$  is minimized, it only depends on  $\lambda_i$ .
- Update of the design vector:  $x_{i+1} = x_i + \lambda_i d_i$
- If the convergence condition is satisfied, the design vector is  $x_{i+1}$
- If the convergence condition is not satisfied,  $i=i+1$  and the process is repeated.

In all of these methods, the convergence condition is satisfied when the sufficient and necessary conditions of the direct solution are satisfied or at least, they are close enough.



### 6.3.5.2. Optimization with equality constraints

These methods are applied when the problem scenario looks like *Equation 26*.

$$\min_x f(x)$$

$$h_k(x) = 0 \quad k = 1, 2, \dots, p$$

Equation 26: Optimization with equality constraints

#### 6.3.5.2.1. Lagrange multipliers method

In this method, the lagrangian definition is shown in *Equation 27*.

$$L(x, \lambda) = f(x) + \sum_{k=1}^p \lambda_k h_k(x)$$

Equation 27: Lagrange multipliers method

The necessary condition is applied over the lagrangian as if it were an unconstrained problem. *Equation 28* is used to get the possible solutions.

$$\frac{\partial L(x, \lambda)}{\partial x_i} = \frac{\partial f(x)}{\partial x_i} + \sum_{j=1}^p \lambda_j \frac{\partial h_j(x)}{\partial x_i} = 0, \quad i = 1, 2, \dots, n$$

$$\frac{\partial L(x, \lambda)}{\partial x_i} = h_j(x) = 0, \quad j = 1, 2, \dots, p$$

Equation 28: Equations for Lagrange multipliers method

The sufficient condition is applied over  $\nabla^2 L(x^*, \lambda^*)$ . If it is positive definite, the points  $x^*$  and  $\lambda^*$  are the solution.

### 6.3.5.3. Optimization with inequality constraints

The scenario in this situation is represented in *Equation 29*.

$$\min_x f(x)$$

$$g_j(x) \leq 0 \quad j = 1, 2, \dots, m$$

Equation 29: Optimization with inequality constraints

#### 6.3.5.3.1. Kuhn-Tucker conditions

The main idea for facing these kind of problems consists on transforming the inequality problem in an equality problem and then apply the Lagrange multipliers method. To transform the inequality constraint, an auxiliary variable is added and it is represented in *Equation 30*.

$$g_j(x) + y_j^2 = 0, \quad j = 1, 2, \dots, m$$

Equation 30: Kuhn-Tucker conditions

The problem to be solved now is expressed in *Equation 31*.

$$\min_x f(x)$$

$$g_j(x) + y_j^2 = 0, j = 1, 2, \dots, m$$

Equation 31: Kuhn-Tucker problem

Equation 32 calculates the lagrangian considering the Equation 31.

$$L(x, y, \lambda) = f(x) + \sum_{k=1}^p \lambda_k (g_j(x) + y_j^2)$$

Equation 32: Lagrangian solution for Kuhn-Tucker problem

The necessary conditions are expressed in Equation 33.

$$\frac{\partial L(x, y, \lambda)}{\partial x_i} = \frac{\partial f(x)}{\partial x_i} + \sum_{j=1}^p \lambda_j \frac{\partial g_j(x)}{\partial x_i} = 0, i = 1, 2, \dots, n$$

$$\frac{\partial L(x, y, \lambda)}{\partial \lambda_j} = g_j(x) + y_j^2 = 0, j = 1, 2, \dots, m$$

$$\frac{\partial L(x, y, \lambda)}{\partial y_j} = 2\lambda_j y_j = 0, j = 1, 2, \dots, m$$

Equation 33: Kuhn-Tucker conditions

Equation 33 can also be expressed as Equation 34.

$$\frac{\partial f(x)}{\partial x_i} + \sum_{j=1}^p \lambda_j \frac{\partial g_j(x)}{\partial x_i} = 0, i = 1, 2, \dots, n$$

$$\lambda_j g_j(x) = 0, j = 1, 2, \dots, m$$

$$g_j(x) \leq 0, j = 1, 2, \dots, m$$

$$\lambda_j \geq 0, j = 1, 2, \dots, m$$

Equation 34: Kuhn-Tucker conditions

Solving these equations, the possible points for the solution are obtained. If it is a convex optimization problem, these equations' solutions provide the global minimum. If it is a maximization problem or  $g_j(x) \geq 0$ , the equation  $\lambda_j \geq 0, j = 1, 2, \dots, m$  becomes  $\lambda_j \leq 0, j = 1, 2, \dots, m$ .

### 6.3.5.3.2. Interior point method

The method adds the restrictions to the objective function; the new objective function can be optimized using whichever unconstrained method. The objective function is modified as:

$$\Phi(x, r_k) = f(x) + r_k \sum_{j=1}^m G_j(g_j(x))$$

Equation 35: Interior point method

The most common way to express  $G_j(g_j(x))$  is as in Equation 36.

$$G_j(g_j(x)) = -\frac{1}{g_j(x)}$$

Equation 36:  $G_j(g_j(x))$  definition using the interior point method

Equation 37 results from the combination of Equation 35 and Equation 36.

$$\Phi(x, r_k) = f(x) - r_k \sum_{j=1}^m \frac{1}{g_j(x)}$$

Equation 37: Interior point method including  $G_j(g_j(x))$

The process follow is:

- Selection of the initial  $x_0$  and  $r_0$ .
- Creation of the function  $\Phi(x, r_k) = f(x) - r_k \sum_{j=1}^m \frac{1}{g_j(x)}$
- Minimize  $\Phi(x, r_k)$
- If the convergence condition is satisfied over the solution of minimizing  $\Phi(x, r_k)$ , the iteration is finished.
- If the convergence condition is not satisfied,  $r_{k+1} = cr_k$  (where c is typically 0.5, 0.2 or 0.1),  $k=k+1$  and the process is repeated. [26]

## 6.4. Comparison with other optimization methodologies used in Matlab

Matlab provides more algorithms than *patternsearch*. In section 6.4.1 to 6.4.5, other algorithms have been analysed.

### 6.4.1. fminsearch

The function 'fminsearch' minimizes unconstrained functions, and therefore, is not applicable in this case. [56] It has been tested what the result of using fminsearch would be to find the optimal position. After 159 iterations, the procedure has been automatically stopped before it finishes because the maximum number of function evaluations has been exceeded, which means that the obtained value is not an optimal one (55.7013°, 13.1952°). The algorithm used in this type of optimization is Nelder-Mead simplex direct search.

### 6.4.2. fseminf

'fseminf' is focused on semi-infinitely constraints. [57]

$$\min_x f(x)$$

such that  $K(x, w) \leq 0$  for all  $w, c(x) \leq 0, ceq(x) = 0, Ax \leq b, Aeq * x = beq, lb \leq x \leq ub$

Equation 38: fseminf optimization problem formulation

It results in failure when trying to test this methodology because there is no semi-constraints in the problems treated in this thesis.

#### 6.4.3. fsolve

This function solves non-linear equations applying levenberg marquardt algorithm. [58] When it has been tested with the objective function, it has not found a solution for it. It has only reached a non-minimum solution with 12 iterations, 55.7012°, 13.1958°. It can be seen that the minimum value obtained from the optimization function is  $1.43002 \cdot 10^{79}$ , which is higher than with other methodologies.

#### 6.4.4. fmincon

This function is used for constrained optimizations considering the interior point optimization method. As the other methodologies, it does not allow to consider a large measurements' number. [59]

Table 33 shows all the techniques used and their results considering 40 measurements to compare the results.

Function	Latitude	Longitude	Function value	Observations
fmincon	55.7012°	13.1971°	$1.775713 \cdot 10^{98}$	Higher function value. It cannot consider all the measurements at the same time.
fminsearch	55.7013°	13.1952°	$2.24755 \cdot 10^{22}$	It only minimizes unconstrained problems. The maximum number of function evaluations has been exceeded: the solution is not a global optimum.
fsolve	55.7012°	13.1958°	$1.43002 \cdot 10^{79}$	Not a real optimum. Higher function value.
patternsearch	55.7018°	13.1952°	$9.5173 \cdot 10^{79}$	

Table 33: Comparison between optimization techniques

#### 6.4.5. Kuhn-Tucker equations

Previously, two methods for constrained optimization have been explained: Kuhn-Tucker and Interior Point. The second method is used in 'fmincon', but if Kuhn-Tucker is to be deployed, the equations have to be manually programmed to implement this procedure. Due to their complexity, this alternative has been discarded.

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