POLITECNICO DI TORINO

Collegio di Ingegneria Elettronica, delle Telecomunicazioni e Fisica
(ETF)
Corso di Laurea Magistrale in Ingegneria Elettronica

Tesi di Laurea Magistrale

Methodology for the dimensioning and development of an urban LoRaWAN network

Relatore
Prof. Roberto Garello

Consulente Aziendale
Eng. Simone Scarafia

Candidato
Marcio Johao Quinones Olaya

Aprile 2019

Acknowledgements

Firstly, I would like to dedicate this thesis to God, to my family and my grandmothers Rosa and Aurea. Thanks for all.

I want to thanks to God for having managed to finish this step of my life in which find satisfying. To my mother Betty and my father Jofre for always give me the support of go ahead, for teaching me to never surrender any adversity and for allowing me to feel his presence in spite to the distance. To my brothers Jenny, Angie and Leo, to my grandmother Rosa and all my relatives that are my engine to continue in every moment.

To my electronic colleagues and to all my friends that have somehow been part of this, for giving me support in difficult moments and never feeling alone, in special to my friends "Caleños", "Rolos", "Paisas", "Costeños", my Chilean female friend and my Mexican friend, and Italian people in Torino. All of them are considered my other family.

To my professor Roberto, to my advisor Simone and to all the CSP family to develop this thesis, for helping me in this project in all moment and for giving me always your trust in me.

Equally, I give thanks to my university Javeriana Cali and Politecnico di Torino for allow me to be part of this experience in which has been and will be important in my educational and professional development.

Simply, quoting to Gustavo Cerati, how would say: "Gracias Totales".

Abstract

As the world of information and communication technologies is evolving, we are looking to connect everything around us. One way to achieve this is through the Internet of Things (IoT) where mainly it's function is to reach the intercommunication of our environment through devices that collect the information needed to be delivered by users.

One way to implement this network is by using the Low Power Wireless Area Network (LP-WAN) technologies that enable communication of devices using low data rates and low power consumption. Consequently, the LoRaWAN technology is chosen to study, belonging to the LP-WAN group, because lately, it is taking great field of application and development in IoT.

Therefore, the objective of the thesis is the use of LoRaWAN as a technology to design and planning for the city of Torino, a city in which constantly seeks the development of Information and Communication Technologies (ICT), and finally show a possible final design of the IoT network.

Keywords: *LoRa, LoRaWAN, Cover Area, Simulation, dBm, RSSI.*

Contents

List of Figures

List of Tables

List of Abbreviations

ACK Acknowledgement Packet. 11

AWGN Addition White Gaussian Noise. 18

BER Bit Error Rate. 20

BPSK Binary Phase Shift Keying. 20

BW Bandwidth. 7

CSS Chirp Spread Spectrum. 8

Dn Downlink. 14

DTM Digital Terrain Model. 24

FFT Fast Fourier Transform. 19

IEEE Institute of Electrical and Electronic Engineers, Inc. 7

IoT Internet of Things. 1

ISM Industrial, Scientific, Medical Frequency Band. 10

ITS Institute for Telecommunication Science. 25

LAN Local Area Network. 42

LOS Line Of Sight. 54

RF Radio Frequency. 24

RMD Reflection Multiple Diffraction. 27

RSSI Received Signal Strength Indicator. 45

SF Spreading Factor. 8

SNR Signal/Noise Rate. 20

Up Uplink. 14

WAN Wide Area Network. 42

WLAN Wireless Local Area Network. 7

Chapter 1

Introduction

The IoT is taking a big boom in recent years, becoming a fundamental piece for global development at the technological level. It basically consists of the ability to communication devices and sensors over the Internet in order to be able to interact in the medium and, in turn, be an intelligent medium (Smart). The various applications are numerous, some of them are the industrial sector, agronomist, urban, domestic, among others.

There are many technologies to implement an IoT network, such as Wi-Fi, Zigbee, Bluetooth, Sigfox and others, but we will base and study the technology LoRaWAN (Long Range Wireless Area Network) which consists of a technology developed mainly by the company Semtech in conjunction with the entity "LoRa Alliance" with capacity of work at low power, rates of low speeds and high coverage in large areas. These features potentially make use to design an IoT network.

Knowing the previous points, we proceed to the thematic of the thesis that consists of the study of implementation and design of a network IoT in the city of Torino using the technology LoRaWAN. Where we will start in the theoretical knowledge of LoRa and LoRaWAN, then simulations will be made through programs of radio propagation calculations, then the simulated results will be verified through real tests and finally, a network will be designed in such a way that works best in the city.

The content of the thesis comprises of the following chapters, the chapter 2 consists of the theoretical framework of IoT Technologies emphasizing LoRa modulation and LoRaWAN protocol, the chapter 3 consists of LoRa operation study through a channel simulation with the tool MATLAB, the chapter 4 it comprises of the simulations of the coverage area with the help of different radio simulation programs using test point and LoRa parameters for compare and choose the best RF simulator, the chapter 5 presents the final simulations of our LoRaWAN network, the real field tests made based on the results of the previous simulations and the final network IoT in the urban area of the city of Torino, and finally the final chapter talks about the conclusions and future works.

1.1 Thesis Objective

The principle objective of the thesis is find a methodology for LoRaWAN network planning taking into account:

- LoRaWAN physical characteristics
- Urban Topology (i.e presence of building) that could be applied to any urban contest

1.2 State of the Art

For the investigation part, it was investigated several papers but only ten papers were taken into account. Then, overall characteristic of these papers are the general idea of IoT; principles of LP-WAN; description, different applications and functionally of LoRa and LoRa-WAN.

For understand the importance of IoT implementation, it's found in the investigation of [1] where principally it talk about general vision of IoT in terms of the growing of implementation over the years, the different technologies based of wireless sensor networks, some applications as Smart city, Smart agriculture, Smart transportation, among others, and the principle architecture for the different implementations of IoT with their respective characteristics. Furthermore, every time this concept of interconnection achieve great field in the world of telecommunications due to search of new applications and facilities of interactions of devices and final users.

Subsequently, according to [2], a way to implement to IoT network is through to Low Power Wide Area Network (LP-WAN) technologies and consist to communicate the devices using low power consumption where their system achieves be scalable, that is, the network is able to add other devices easily. It is worth noting that LP-WAN is important to use in industrial development. Of course, all the types of this technology presents similar conditions and objectives of functioning but your differences will depend of more detailed parameters.

The main causes of choosing LoRa like technology to study is due for the reasons and descriptions of [3]. Its highlighted general terms of LoRa and LoRa-WAN describing physic components, numerous applications, performance at the network level, functions, security and encryption messages, among others characteristics. Additionally, its talked some extensions for increase the functionality of LoRa-WAN standard with their respective advantages and disadvantages. And finally, it concludes that LoRa works optimally to requested requirements by different situations.

However, some difficulties are present in LoRa network in terms of scalability and capacity according to [4]. These drawbacks are due to limitations of data rate for send packages for support scability, and flaws of reliability and some delays for receive packages because of collisions found in the channel used. Also, taking in account [5], the real behaviour of a Wireless Sensor Network using LoRa and LoRa-WAN designs, it is evident a few problems in the network when the density of the buildings is higher. For this reason, it is proposed study the power consumption in LoRa for better results.

Now, for corroborate some inconveniences previously indicated, is necessary calculate the coverage area of LoRa-WAN using RF simulators. Exists numerous programs but take the correct simulator depend of the number of parameters that can be put in the calculation, for example in [6] its calculated the coverage area in four different simulators and a simulator estimated the coverage area very close to the expected results by including other parameters not witnessed in the rest of the simulators in spite of similar shape of coverage area in the other programs.

Despite of different disadvantages presents in LoRa-WAN network, exists numerous real applications demonstrating that it is a good choose for IoT implementation.

Some proof applications are Smart city pilot project at the Bologna city [7], coverage evaluation in urban and densely urban at the Buenos Aires and Cordoba cities [8], Smart waste collection system at the Salamanca city [9] and monitoring of public transport at the Torino city [10]. Overall, the results presented are satisfactory as long as the simulator is calibrated correctly and the receive device position is higher and put more than one if the city have much buildings. Nonetheless, LoRa-WAN report weakness if the device to transmit is moving quickly due to Doppler effect causing lost packages and the low range in the city compared with theoretical range.

Chapter 2

IoT Technologies and LoRaWAN

2.1 IoT Technologies

There are many technologies to implement a IoT system that can be used. Clearly, take the decision of which is the technology to implement depends on factors such as coverage distances, power levels, costs, among others.

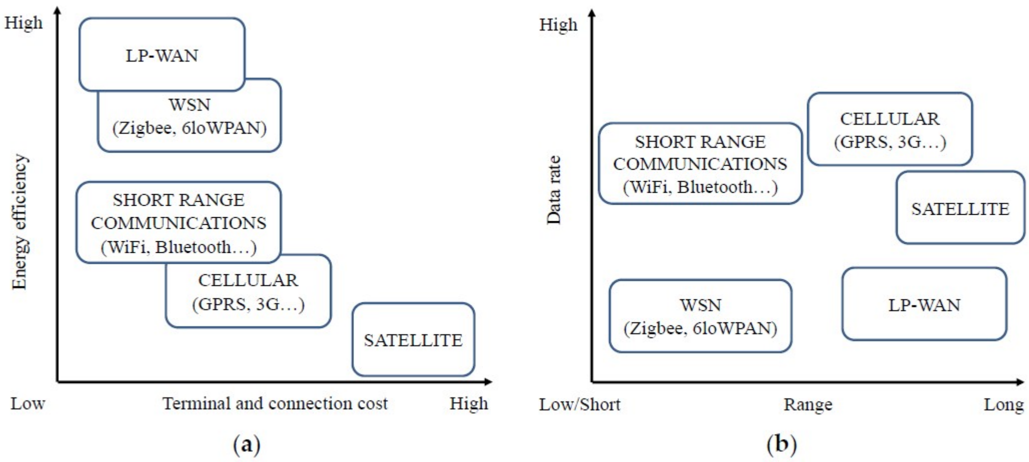


Figure 2.1: IoT Technologies Comparison - (a) Cost vs Energy Efficiency, (b) Range vs Data Rate[2]

Some of the most recognized technologies are:

- **Sigfox:** Is a technology known worldwide because it is the first LP-WAN technology. The operating mode in the physical layer is based on the Ultra Narrow Band modulation where consist to take very narrow parts of the spectrum in such a way that they are highly immune to noise and interference.

Its main features are low data rate below 100bps, low power consumption, coverage range above 50km and capacity of 140 message per device per day[11].

- **ZigBee:** Technology present in the Low Rate Wireless Area Network (LR-WAN). It is outstanding by its many types of topology that can work, whether it be star, mesh, tree or peer-peer as a type of networks.

  It is characterized like a low cost technology, secure into the transmission, low power consumption, data rate below of 250kbps, easy to develop and supports a large number of nodes and is used mostly in the industrial sector[11].

- **NB-IoT:** Narrow Band - IoT is based in the utilization of narrow band as a modulation system where it uses a BW of 200kHz for the data to be transmitted and received, and it is different from the others due to it uses licensed frequencies.

  It is characterized by data rate close to 150kbps, coverage area approximately to 11km and the power transmission of 20 dBm[11].

- **IEEE 802.11.ah:** Belongs to the IEEE 802.11 standard group corresponding to WLAN. This standard is specially designed to implement networks related to IoT but of local type, that is to say, the area of coverage is low[11].

In the next table, it shows the most important characteristics summarized of the IoT technologies previously talked:

	ZigBee	Wi-Fi	Bluetooth	Sigfox	NB-IoT	LoRa
Frequency	sub-GHz/2.4GHz	2.4/5GHz	2.4GHz	sub-GHz	Licensed GSM/LTE bands	sub-GHz
ISM(Freq)	Yes	Yes	Yes	Yes	No	Yes
Range	100m	50m	[100-400]m	50km	15km	15km
Data Rate	250kbps	600Mbps; ax: 10Gbps	<25Mbps	1kbps	250kbps	50kbps
Power	Low	Medium	Low	Low	Medium	Low
Cost	Medium	Medium	Low	Low	Medium	Medium

Table 2.1: Comparison of differents IoT Technologies[12]

Due to the design characteristics of the IoT network for the urban city and knowing the different technologies, it is show that the group of technologies LP-WAN are the most suitable because this have low consumption and the high range in the coverage area compared with other technologies. In other words, LoRa, Sigfox and NB-IoT technologies can be implemented, but in this case LoRa is chosen as a technology to study and develop.

2.2 LoRa Modulation

The Long Range (LoRa) use a type of modulation knowing as the Chirp Spread Spectrum (CSS) that comprises a modulated signal through to chirps, where they are signals that are increasing or decreasing in frequency, in which they are can be UpChirp or DownChirp respectively, as it can be see in the figure 2.2. Originally, these were used in the radar communications due to the low interference levels and the high security so as not be easily decoded.

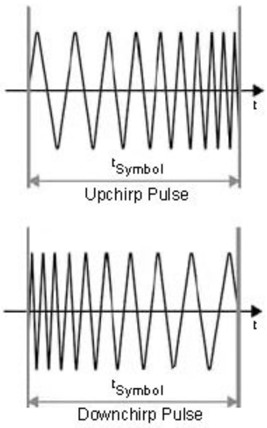


Figure 2.2: Up: UpChirp Signal, Down: DownChirp Signal[13]

Theoretically, the data bit rate, the symbol rate and the chirp rate for LoRa modulation have a relationship considerable[14]. For demonstrate this relation, first define the next equations:

The data bit rate is:

$$R_b = SF \cdot \frac{1}{2^{SF}/BW} \quad Bits/sec \tag{2.1}$$

Where SF is the spreading factor ($SF = 7, ..., 12$) and BW is the bandwidth of the signal in Hz

Now, the symbol rate is:

$$R_s = \frac{1}{T_s} = \frac{BW}{2^{SF}} \quad Symbols/sec \tag{2.2}$$

Where T_s correspond to the symbol period in seconds

And the chirp rate is

$$R_c = R_s \cdot 2^{SF} \quad Chirp/sec \tag{2.3}$$

As it's seen in the equations, the spreading factor and the bandwidth are the main parameters of the LoRa modulation. And replace the symbol rate, equation 2.2, to the chirp rate, equation 2.3, it's can say that the chirp rate is equal to the bandwidth of the signal.

$$R_c = R_s \cdot 2^{SF} = \frac{BW}{\cancel{2^{SF}}} \cdot \cancel{2^{SF}} = BW \tag{2.4}$$

If we want to know the robustness of the transmitted signal, the nominal bit rate can include this characteristic as:

$$R_b = SF \cdot \frac{Rate\,Code}{2^{SF}/BW} \quad Bits/sec \tag{2.5}$$

Where:

$$Rate\,Code = \frac{4}{4 + CR} \tag{2.6}$$

For $CR = 1, ..., 4$

Now, the frame of a LoRa signal comprises of 3 parts of CSS signals, the first is preamble, the second is synchronization and the last is data information. The preamble consists of eight UpChirp symbols and are used to indicate when the signal begins. Later, the synchronization are two DownChirp symbols in which it allows to synchronize the signal with the demodulator so that the data is correctly recognized. And the data comprises of discontinuous chirp symbols where the signal message is located. The amount of CSS signals are according to the LoRa specification provided by the LoRa Alliance Community.

In the next figure it's find the LoRa signal example.

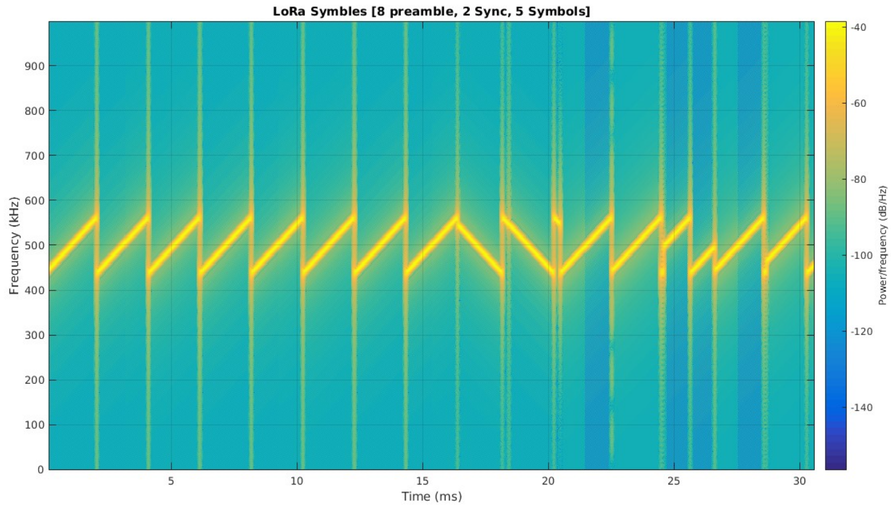


Figure 2.3: LoRa Signal Example[15]

Clearly, we can see defined the preamble, the sync and the symbols data parts. This signal only can be watch with spectrum devices due to the frequency response.

2.3 LoRaWAN Protocol

The Long Range Wireless Area Network (LoRaWAN) is a communication technology that it's found in the LP-WAN group where it work in the Industrial, Scientific, Medical frequency band (ISM band) which consist of those unlicensed frequencies used in the area of the industry, science and medical. They also work specifically for low-power devices.

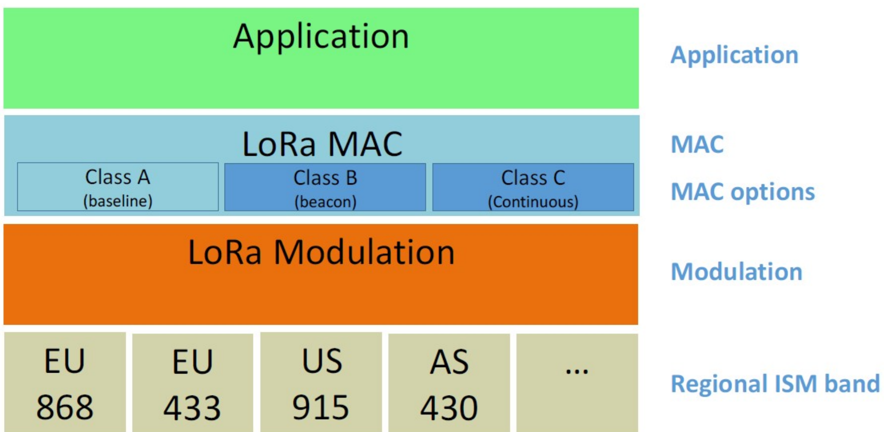


Figure 2.4: LoRaWAN Protocol Structure[16]

Mainly, the architecture of the IoT network comprises of end nodes that are responsible for the collection and processing of the sensors, a gateway that allow communicate the nodes through the LoRa technology and, in turn, connects to a central point using the internet, a central server allow the interpretation and storage of the data collected by the sensors and, subsequently, to be visualized towards the client.

The work topologies are star-type, mostly used due to high performance and low communication consumption, and mesh-type, used when all the nodes need the same message from the gateway. Clearly, the use decision depends on the application that it's want to implement.

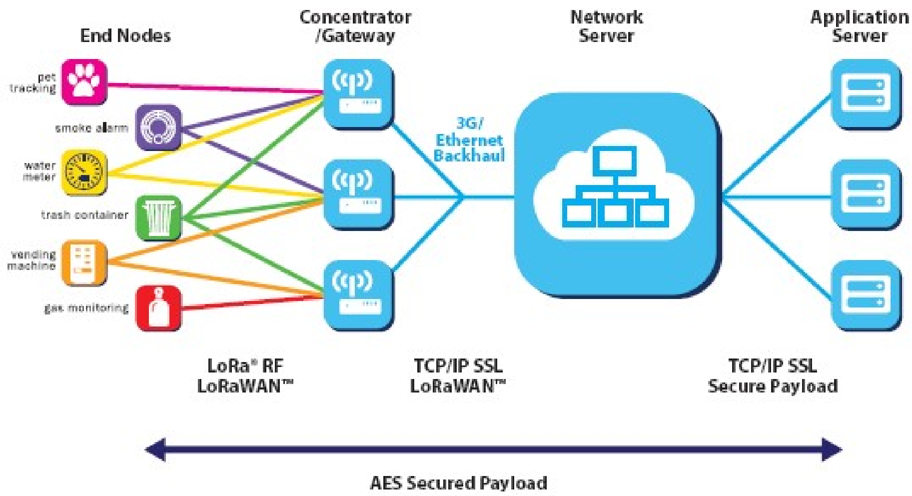


Figure 2.5: LoRaWAN Typical Topology[16]

LoRaWAN works in different classes and its use depend of the mode in which it want to communicate the base station with the end nodes, and they are known as:

- **Class A (Battery Powered):** This mode is the most used in LoRaWAN. It consists in the communication programmed through a MAC protocol known as ALOHA, which uses ACK for the confirmation of data transmission. The communications works in Uplink by the final device followed by two laps of time of Downlink transmitted by the base station and the power consumption is low and advisable to work in the downloading of data by the sensors[17].

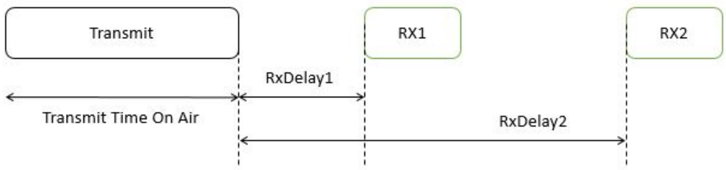


Figure 2.6: LoRaWAN Class A[16]

- **Class B (Low Latency):** It's operation is similar to Class A, but it differs in the extra time for the Downlink by the final device. Additionally, it need a package called beacon that allow open the data at the same time it was programmed[17].

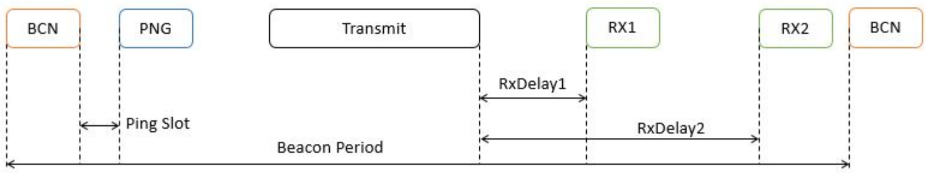


Figure 2.7: LoRaWAN Class B[16]

- **Class C (No Latency):** Allow a continuous time of Downlink in the final device allowing be always listening by the gateway. For it's working mode, the power consumption is higher and the latency y lower compared with Class A[17].

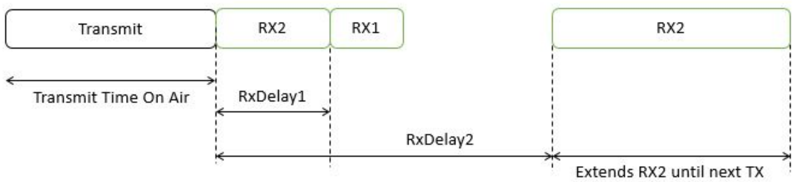


Figure 2.8: LoRaWAN Class C[16]

The max sensibility, max bit rate and SNR level for every SF and data rate in LoRaWAN is:

SF	Data Rate(DR)	Max. Bit Rate(kb/s)	Min. Sensibility(dBm)	Min. SNR(dB)
12	0	0.293	-137	-20
11	1	0.537	-134.5	-17.5
10	2	0.976	-132	-15
9	3	1.757	-129	-12.5
8	4	3.125	-126	-10
7	5	5.468	-123	-7.5

Table 2.2: Sensibility and Bit Rate for LoRaWAN[18]

As it's can see in the previous table, the min sensibility and SNR supported for LoRaWAN is close to -137dBm and -20dB respectively. The SF is inversely proportional to Bit Rate, since when LoRaWAN network works SF low, the bit rate is high. But, this effect into SF and Bit Rate produce significant delays known as "Time On Air", where according as increase the previous factors, the time also increase producing different times of occupancy channels. In the figure 2.9, it's appreciated this behaviour.

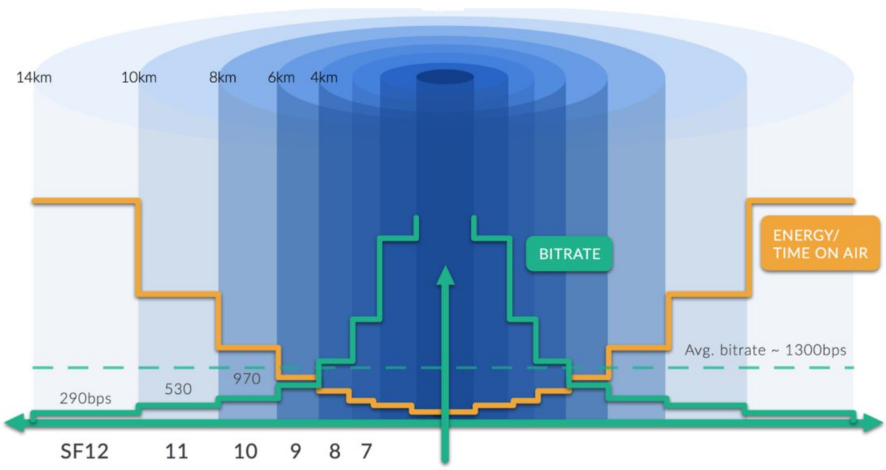


Figure 2.9: Behavior of LoRaWAN to SF, Time Over Air and Bit Rate[18]

And some important characteristic of LoRaWAN in Europe and North America are in the next table:

	Europe	North America
Frequency band	867-869MHz	902-928MHz
Channels	10	64 + 8 +8
Channel BW Up	125/250kHz	125/500kHz
Channel BW Dn	125kHz	500kHz
TX Power Up	+14dBm	+20dBm typ (+30dBm allowed)
TX Power Dn	+14dBm	+27dBm
SF Up	7-12	7-10
Data rate	250bps- 50kbps	980bps-21.9kpbs
Link Budget Up	155dB	154dB
Link Budget Dn	155dB	157dB

Figure 2.10: LoRa Characteristics[16]

Comparing the previous table, in North America use more channels, more channel bandwidth and more power transmission for Up and Dn. This characterizes produce a little more power consumption for the devices but in this case, only take in account the LoRa parameters in Europe because the network to design is for Europe city.

2.4 LoRaWAN Specifications Updates

The LoRaWAN protocol has suffered much developments over the years, of which its seen in four important versions. Some description of these are:

- **Specification v1.0:** Present the first version of LoRaWAN launched in January 2015 where this provides all the characteristics of communication through different classes very detailed[17].

- **Specification v1.0.1:** Is the second version of LoRaWAN launched in February 2016 where its clarified, removed and corrected some features as encryption, payload sizes, types of channels and duty cycle limitations in MAC layer.

In addition, its added frequency plans to Chinese 470-510MHz and Australian 915-928MHz[19].

- **Specification v1.0.2:** Is the third version of LoRaWAN launched in July 2016, the same year of the version v1.0.1, where its added the control power transmission parameter, its cleared the functions of device identifications and its improved the performance of the class B[19].

- **Specification v1.1:** Correspond to the last version of LoRaWAN most used for LoRa devices launched in October 2017. In this version, its produces significant changes of re-transmission, key access, MAC commands, activation modes, class B and C where produce better understanding and development in LoRaWAN systems[19].

Chapter 3

Simulation of Communication System LoRa

3.1 Block Diagram System

Knowing a little about the LoRa technology, it is important to know how is the procedure of the transmission and receiving of a communication system using LoRa as transmission technique. Briefly, the simulation communication system consist to generate bits randomly, this bits pass to LoRa modulation (CSS signals) going through to noise channel and demodulate this signal to bits again. The following figure shows the block diagram of the system to simulate[15].

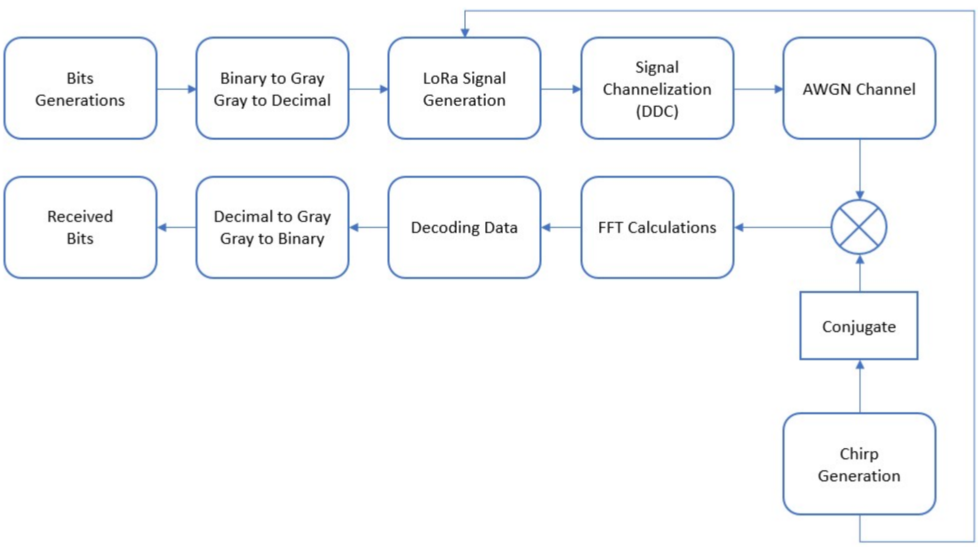


Figure 3.1: Communication System Block of LoRa

The operation of each block consist of:

1. **Bits Generation:** Randomly it generates the bits to transmit.

2. **Binary to Gray, Gray to Decimal:** It group the bits depending on SF, then they become in Gray codification system and, finally, they become to decimal numbers.

3. **LoRa Signal Generation:** It produces the LoRa signal with its respective preamble, synchronization and data information. For example, the next figure show LoRa signal with basic parameters.

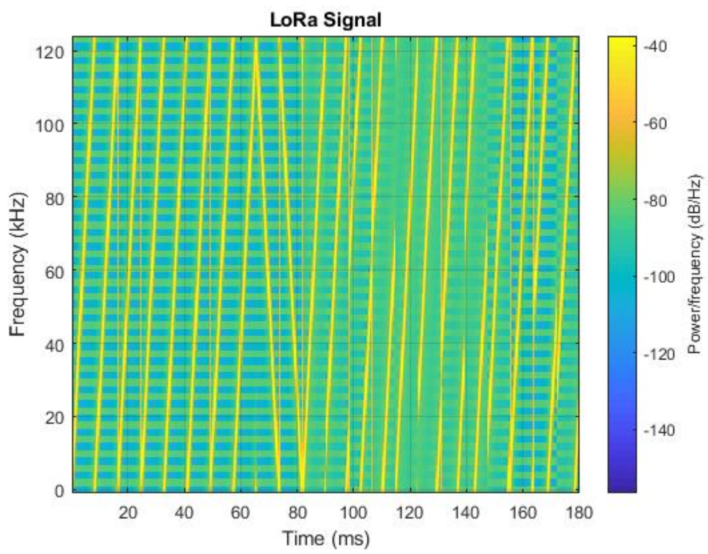


Figure 3.2: LoRa Signal with 8 Preamble, 2 Synch and 12 Symbols

4. **Signal Channelization:** Converts the LoRa signal into a band-base signal to be processed easily and efficiently.

5. **AWGN Channel:** The signal coming through a channel Addition White Gaussian Noise (AWGN).

6. **Multiplication Step:** Consist to the multiplication between the transmitted signal and the purely DownChirp signal, which is the conjugate of a signal UpChirp. The figure 3.3 show the multiplication result.

   As it's can see, the discontinuous lines correspond to constant frequencies where indicate the data and, later, is the information to extract.

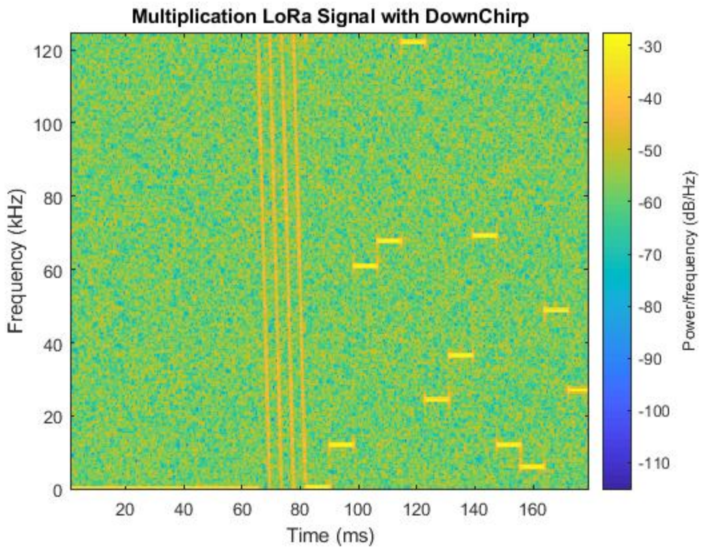


Figure 3.3: Multiplication Result

7. **FFT Calculation:** To extract information from the data, its necessary FFT that allows detect the information from the amount of energy. The figure 3.4 is the FFT process for the LoRa signal.

   Clearly, the different peaks are the constant frequencies extracted and it is noted the noise level present in the transmission system in which, for this case, is very low.

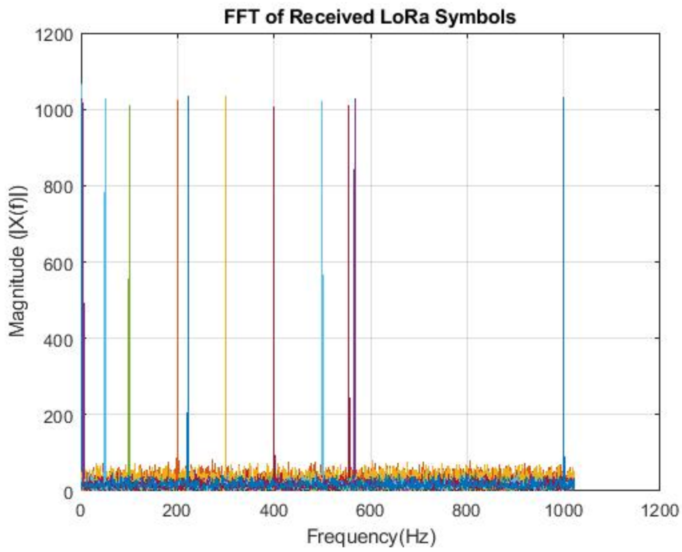


Figure 3.4: FFT of Multiplication Result

8. **Decoding Data:** Detect every peaks presents in the FFT signal and later extract the correspond values.

9. **Decimal to Gray, Gray to Binary:** Is the reverse process of the 2nd block of the system

10. **Received Bits:** Correspond to the received bits.

3.2 Efficiency of the LoRa System (BER Calculations)

To know the efficiency that LoRa system, it is necessary to make use of the BER estimation and basically is the calculation of the reason of the bits that were found erroneous and the total of bits that were transmitted. This allow to know until a certain level of SNR the type of modulation is tolerable to transmit the data without presenting considerable losses of information.

Therefore, the previous system will be taken in account to calculate the BER in front of each SF, but first its show the BER compassion between the BPSK signal and LoRa signal for observe if the BER behaviour is the expected [20] and, thus, compare the performance with Sigfox due to that this technology uses BPSK modulation.

Now, for this calculation, it was used the LoRa modulation system and the BPSK modulation theoretical formula, known as:

$$BER_{BPSK} = \frac{1}{2} \cdot erfc\left(\sqrt{\frac{Eb}{No}}\right) \tag{3.1}$$

Where Eb/No is the energy per bit to noise ratio.

The LoRa parameters for the simulation are:

- SF = 7
- BW = 125kHz
- Preamble Length = 8
- Sync Length = 2
- Preamble Length = 27720 bits = 3465 bytes

- Sampling Frequency (F_s) = 125kHz
- Number of samples, the next equation:

$$F_s \cdot \frac{2^{SF}}{BW} = 128 \quad Samples \tag{3.2}$$

The BER efficiency calculation for LoRa and BPSK modulations result is:

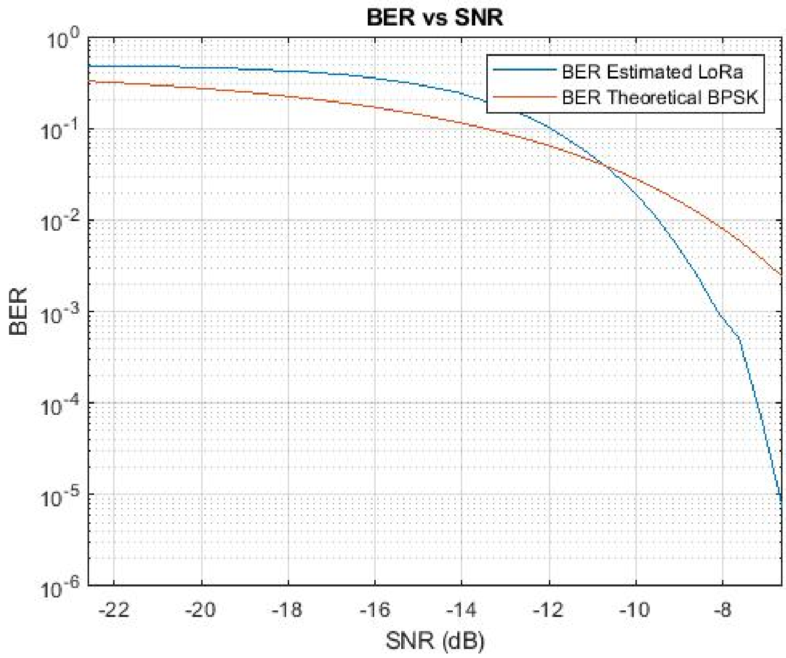


Figure 3.5: BER Estimation LoRa System with SF=7 and BPSK

The behaviour of the LoRa signal under BER calculations is the expected because to higher SNR values, lower BER values. This means that the probability of the loss information in the transmission channel is low when the signal is more powerful that the channel noise. Also, comparing the LoRa and BPSK it turns out that for highly noisy channels, BPSK have better BER and for little noisy channel, LoRa have better BER. The figure 3.5 show this result.

Knowing the LoRa system behaviour in the BER calculation, now showing the BER for each SF for LoRa signals.

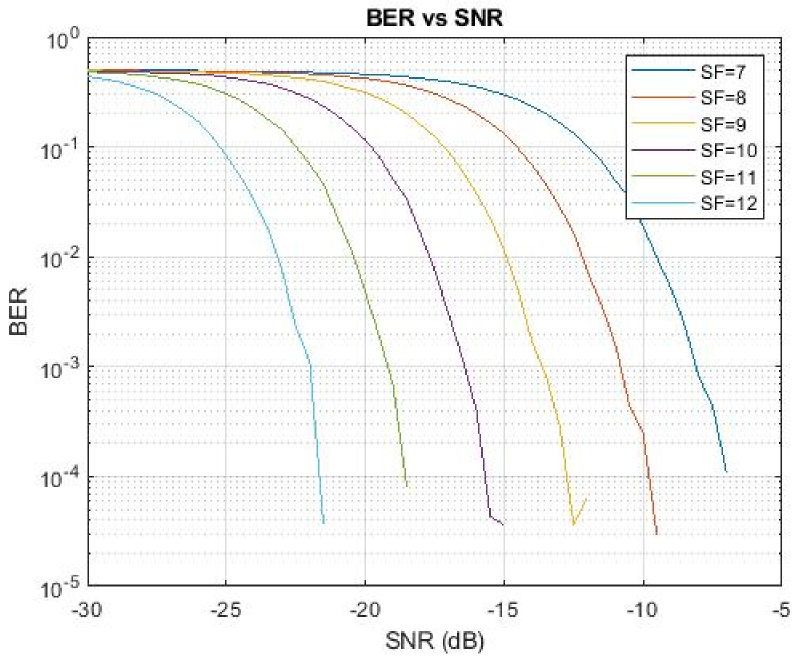


Figure 3.6: BER Estimation for LoRa System

And as shown in the figure 3.6, it can be say that for SF higher is better the BER and the signals are more resistant to noise. For this reason the LoRa signals with SF equal to 10, 11 or 12 can be stay more time in the channel, in this case, in the air. The BER curves are not well defined due to the amount of bits and the number of interactions used, since the computational resources are limited and doing a good simulation, the time calculation is very high.

Chapter 4

Simulation of Coverage Area LoRaWAN

The programs selected for study the simulations are Radio Mobile, EMLAB Aldena and CloudRF because of to availability.

4.1 Radio Mobile Software

Radio Mobile is a software created by Roger Coudé VE2DBE where allow calculate RF propagation. This program use the terrain information and the mathematical model for calculate the coverage area from radiation point fixed taking like mobile reference point[6].

Also, the coverage area can be estimate just with DTM, is the representation of the terrain surface, or take the DTM and the Land Cover information, where correspond to the characteristic of different obstacles of terrain as buildings, forests, rivers, etc.

For example, the figure 4.2 show the land cover of the Torino City and we can see that much of the city consists to buildings higher(red color representation) and lower(blue color representation), letting us understand that the buildings can have considerable interference's in this city, for this reason, the height of the antenna will be key for the coverage area calculation. In Radio Mobile, the land cover information can be changed in the interface showing in the figure 4.3.

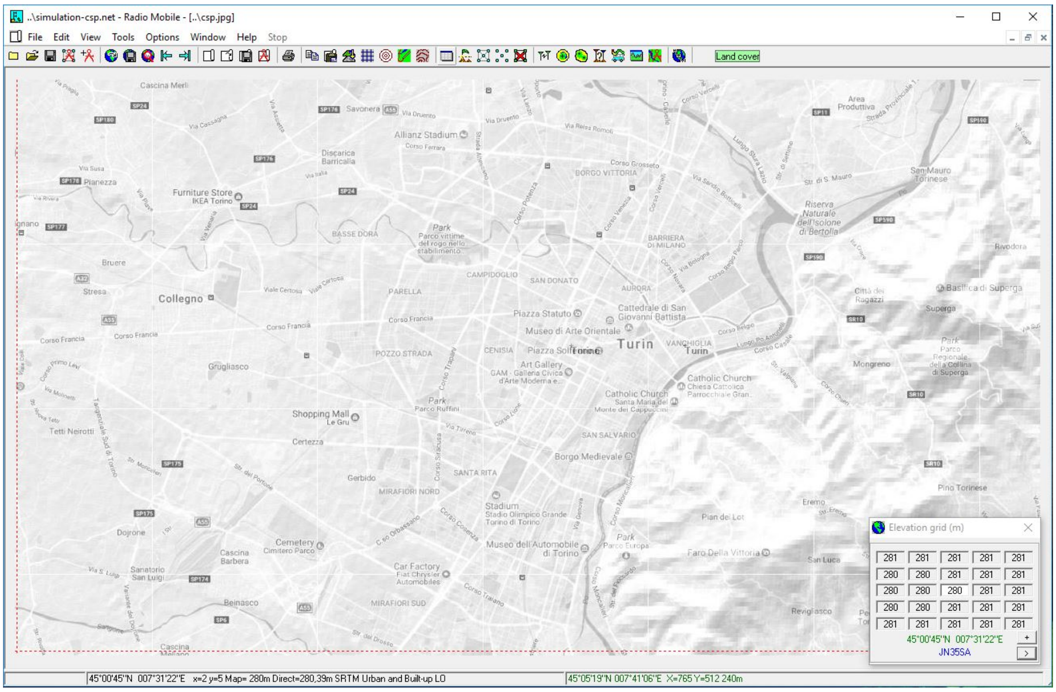


Figure 4.1: Radio Mobile Interface

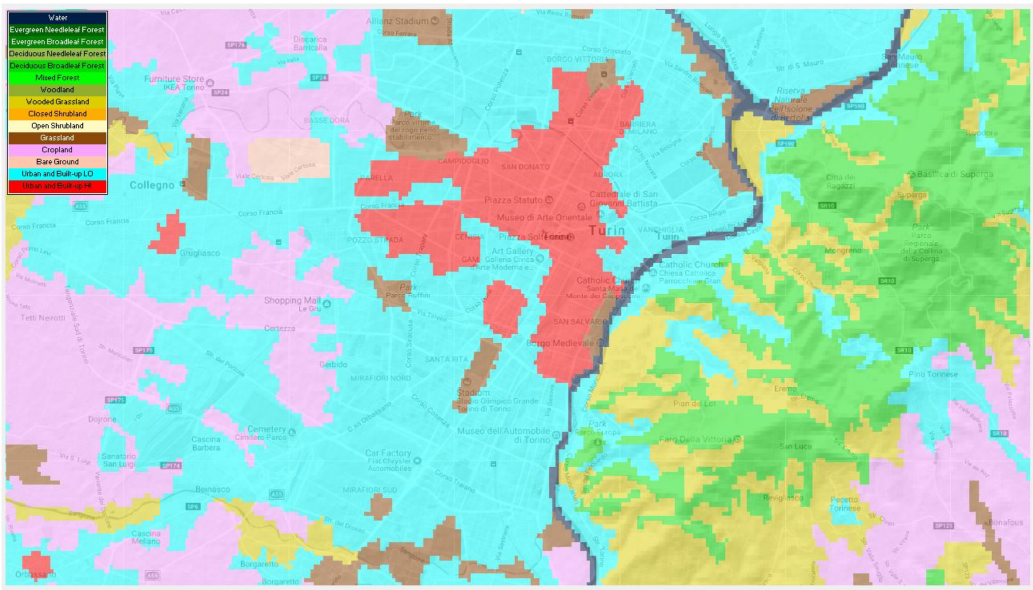


Figure 4.2: Land Cover Torino City

The propagation model which use Radio Mobile is ITS Irregular Terrain Model and consist to radio propagation model for frequencies between 20MHz to 20GHz based to the Longley-Rice model where can estimate the median attenuation of a radio signal as a function of distance and the variability of the signal in space and in time[21].

This model take in account the next parameters[22]:

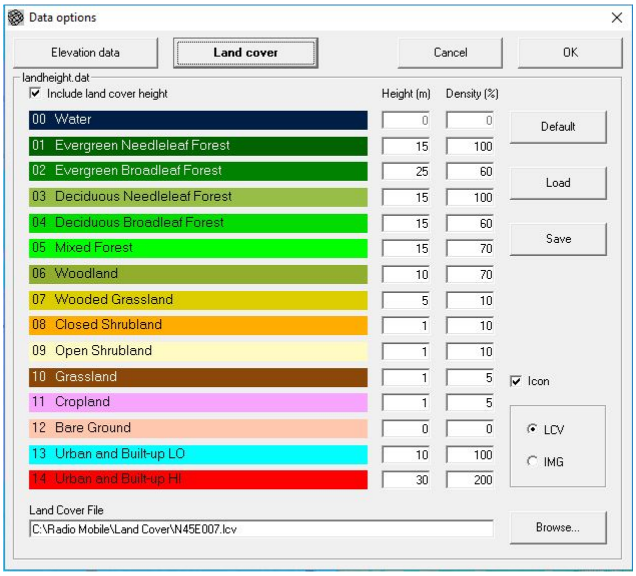


Figure 4.3: Land Cover Configuration Interface

- **Polarization:** Type of polarization of the antenna either vertical or horizontal.
- **Refractivity:** Depend of the atmosphere conditions and the earth curvature.
- **Permittivity and Conductivity:** Is the permittivity, or dielectric constant, and conductivity of the ground to calculate.
- **Climate:** Correspond to the weather of the terrain. For example, Equatorial, Desert, Continental Temperate, among others.
- **Variability:** Determinate the reliability and confidence of the values used in the model.

4.2 EMLAB Aldena Software

EMLAB is the sofware created by Telecomunicazioni Aldena S.r.l. where allow evaluate either the final irradiation solid, the environmental impact for health purposes, and radioelectric coverage on orographic basis in broadcast telecommunication systems[23]. The coverage area is calculated by the SQL Data Base where is it located the terrain information of the city.

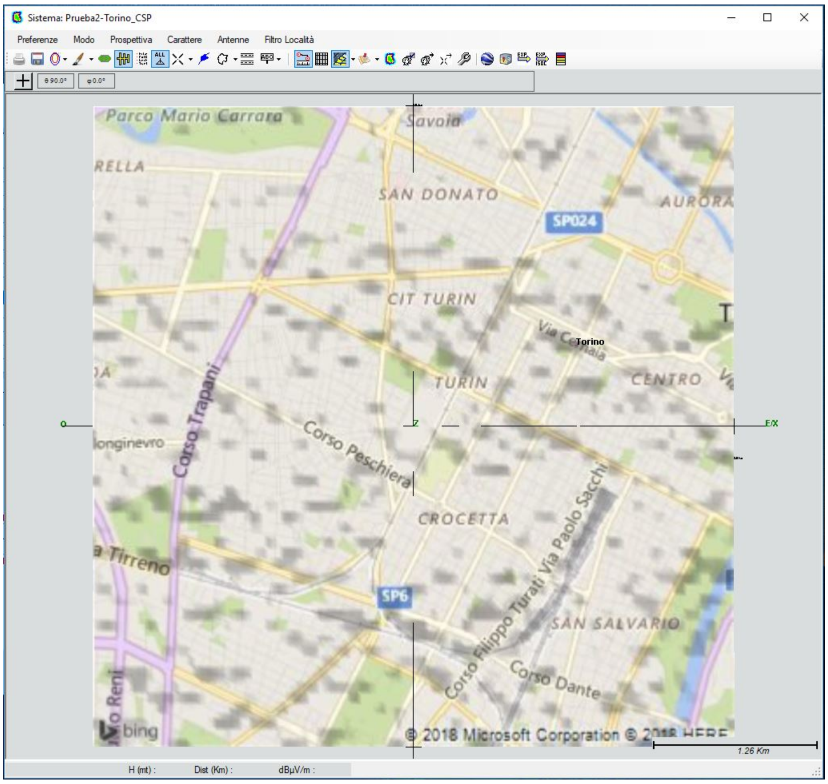


Figure 4.4: EMLAB Aldena Interface

This software have 7 different propagations models, where are Free Space+RMD, Okumura-Hata ITU 529, Okumura-Hata Davidson, COST 231, ITU-R 1546-2, ITU-R 1546-2 + RMD and Line-Of-Sight (LOS). In this case, it will be explained in detail the Free Space+RMD.

The Free Space+RMD is the propagation model for frequencies between 30MHz to 40GHz which use the terrain obstacle, variability and the urban loss factors for calculate the excess path loss in the coverage area calculations. It should be clarified that the receive site are not mobile locations but this points are designed for appropriate calculations using directional antennas[24].

The functionality of this propagation model comprise of calculations of Free-space propagation for LOS path, single reflection for LOS path and multiple reflection for NLOS path. Mainly, the LOS calculation is estimate the Free-space field strength using one ray propagation energy directly and other ray propagation energy reflectively. And, the NLOS calculation is estimate the propagation when the transmission present multiple obstacles where the ray propagation have diffraction [25].

4.3 CloudRF Software

CloudRF is online RF software created by Farrant Consulting Ltd where allow calculate coverage area for TV broadcasters, meshes for WISP, IoT networks and cellular propagation systems between 20MHz to 100GHz[26]. In addition, CloudRF is available to Android, Linux, Mac/OSX and Windows.

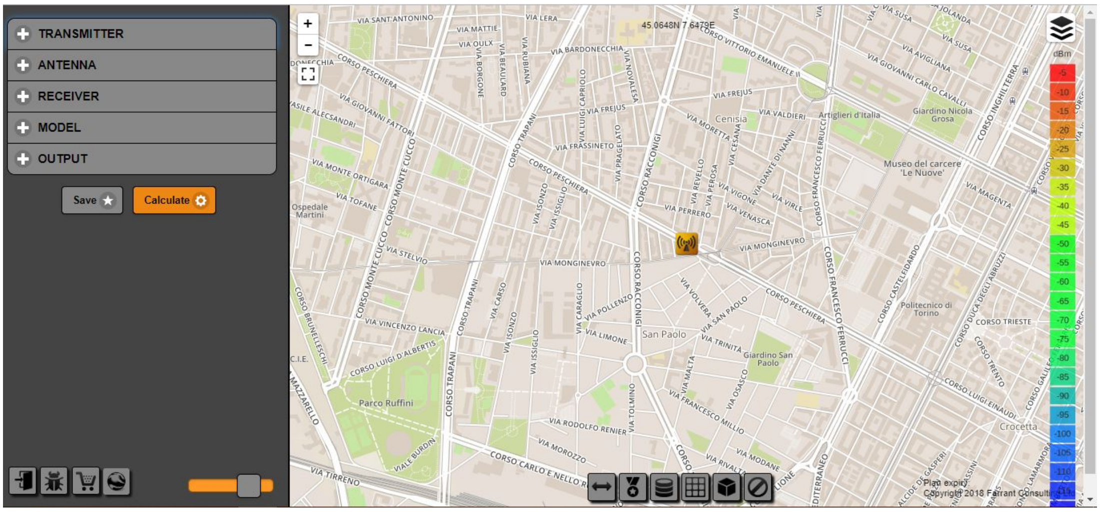


Figure 4.5: CloudRF Interface

This program use the empirical and deterministic models such as Irregular Terrain Model (ITM), Okumura-Hata, COST231-Hata, Egli VHF/UHF, among others. But, the Irregular Terrain Model is also used to simulate and it facilitates comparison between RF simulators proposed.

4.4 Simulations Results

The simulation of the coverage area of LoRaWAN, it's used the next parameters showing in the tables 4.1, 4.2 and 4.3 for the Radio Mobile, EMLAB and CloudRF simulation respectively.

For this simulation, we take the parameters of the CSP LoRaWAN Antenna as test point for watch the behaviour of the different simulators, in the figure 4.6 is present the position.

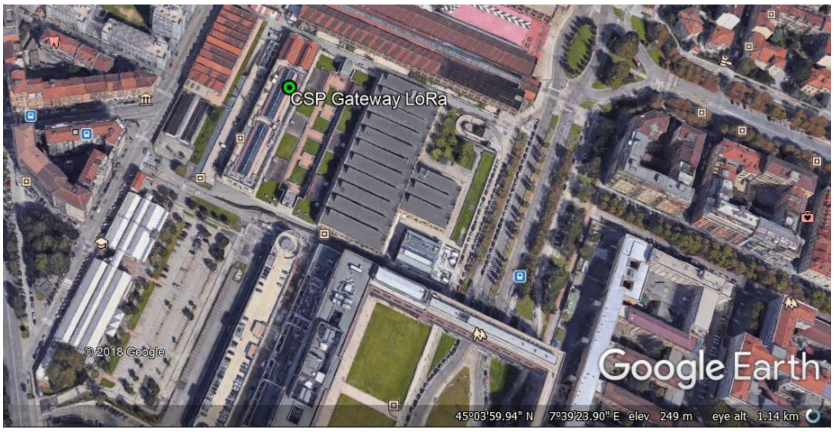


Figure 4.6: Location CSP Gateway LoRa

Parameter	Configuration
Type of Antenna Tx, Rx	Omnidirectional
Type of Polarization	Vertical
Antenna Gain Tx	14dBm
Antenna Height Tx	16m
Antenna Gain Rx	0dBm
Antenna Height Rx	2m
Sensivity Tx, Rx	-137dBm
Line Loss Tx, Rx	0.5dB
Frequency Range	(863 - 870)MHz
Propagation Model	ITS Irregular Terrain Model
Climate	Continental Temperate
Type of Topology Network	Data Net, Cluster(Node/Terminal)
Latitude and Longitude	45.0658118° and 7.6582894°

Table 4.1: Radio Mobile Simulation Parameters

Parameter	Configuration
Type of Antenna Tx, Rx	Omnidirectional
Type of Polarization	Vertical
Antenna Gain Tx	14dBm
Antenna Height Tx	16m
Antenna Gain Rx	0dBm
Antenna Height Rx	2m
Line Loss Tx, Rx	0.5dB
Frequency	868MHz
Propagation Model	Free Space+RMD
Climate	Average Dry Ground
Latitude and Longitude	45.0658118° and 7.6582894°

Table 4.2: EMLAB Simulation Parameters

Parameter	Configuration
Type of Antenna Tx, Rx	Omnidirectional
Type of Polarization	Vertical
Antenna Gain Tx	14dBm
Antenna Height Tx	16m
Antenna Gain Rx	0dBm
Antenna Height Rx	2m
Line Loss Tx, Rx	0.5dB
Frequency	868MHz
Propagation Model	ITS Irregular Terrain Model
Climate	City
Latitude and Longitude	45.0658118° and 7.6582894°

Table 4.3: CloudRF Simulation Parameters

The results are show in the next figures. It must take in account that the measurement unit choice is the Field Strength ($dB\mu V/m$) due to is the only unit for measure the RF propagation in EMLAB software.

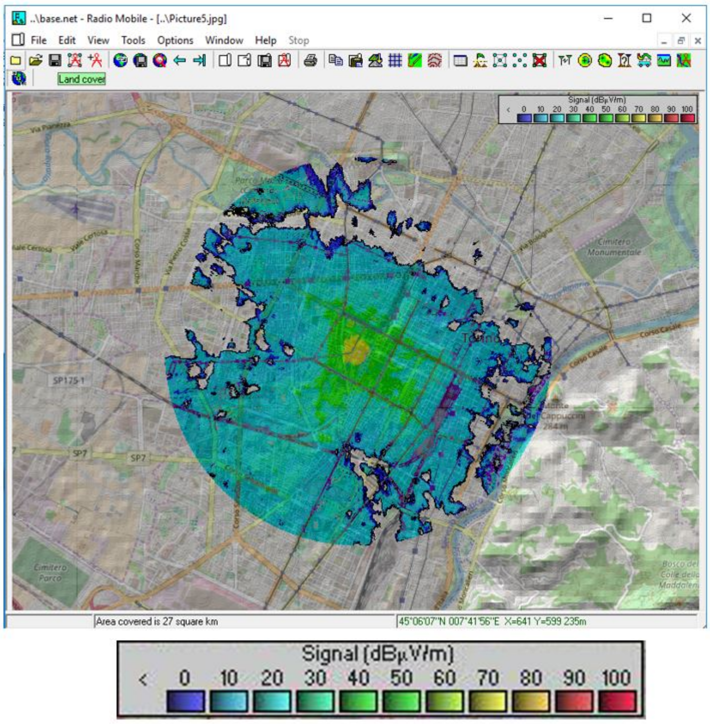


Figure 4.7: Coverage Area in Radio Mobile

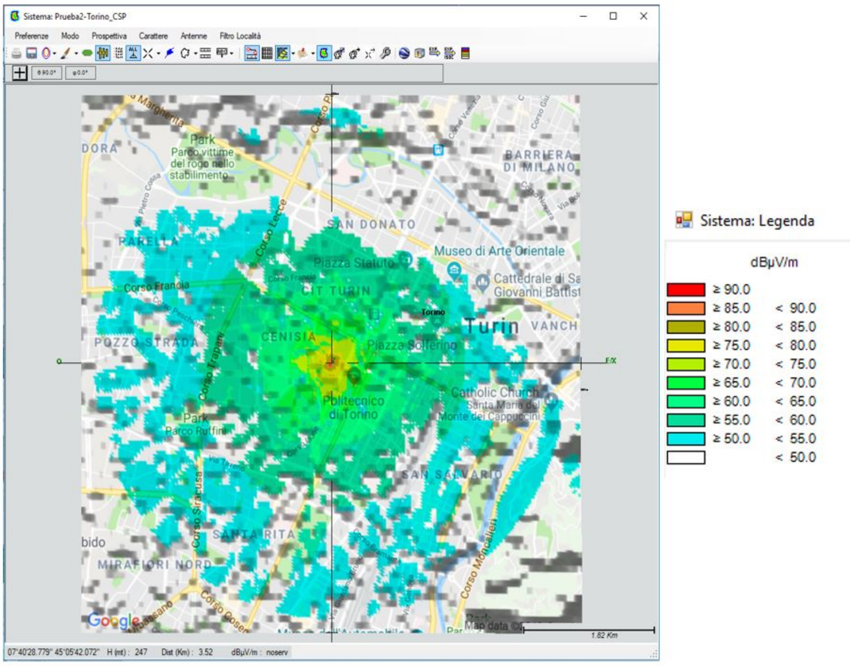


Figure 4.8: Coverage Area in EMLAB Aldena

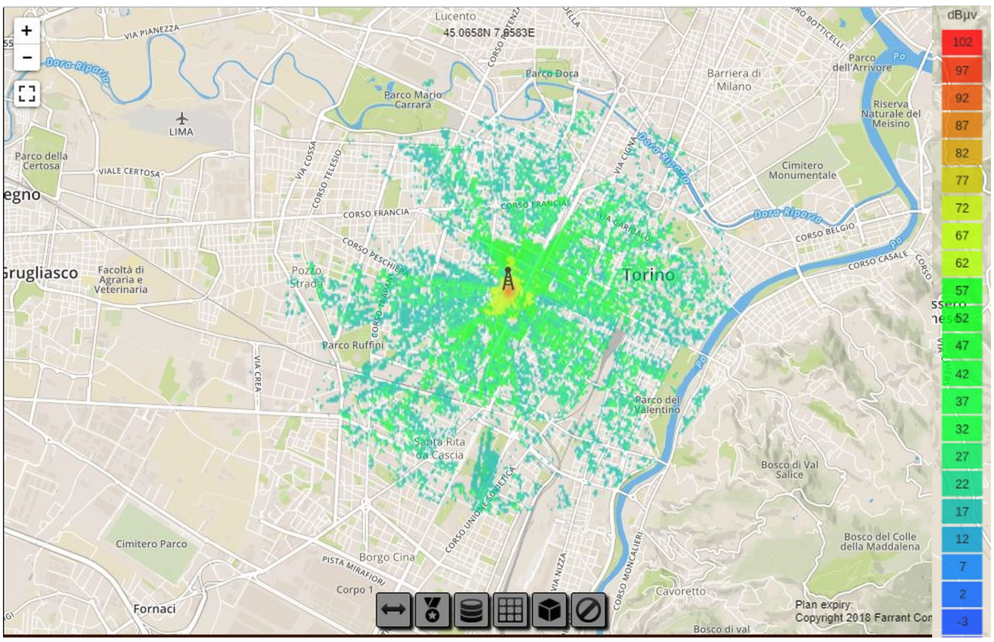


Figure 4.9: Coverage Area in CloudRF

We can see that both simulations are a little similar, but the differences are very considerable. For example, the north-west area coverage in Radio Mobile and CloudRF not received receive power but in EMLAB present receive power in some zones. For this reason, we study the terrain profile with random receive point located the north-west in Radio Mobile and EMLAB programs. In the case of CloudRF, not is possible compare through the terrain profile due to randomly representation of clutters and others obstacles.

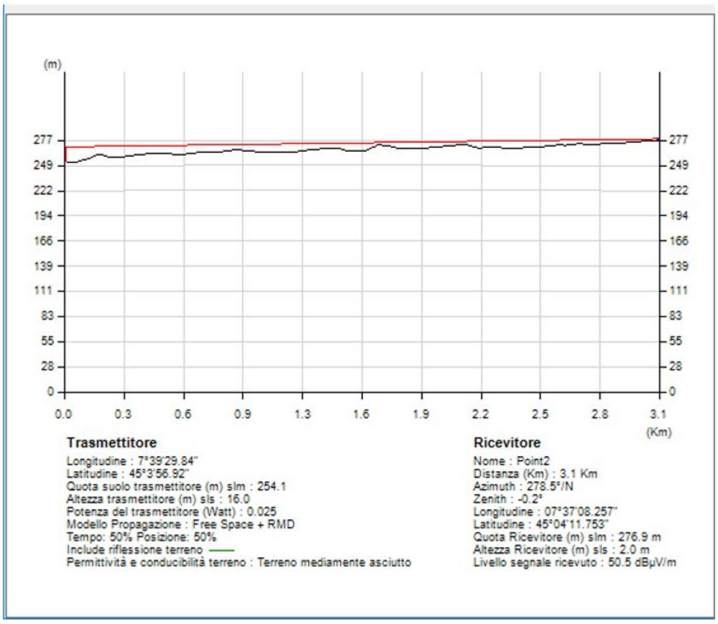


Figure 4.10: Terrain Profile in EMLAB Aldena

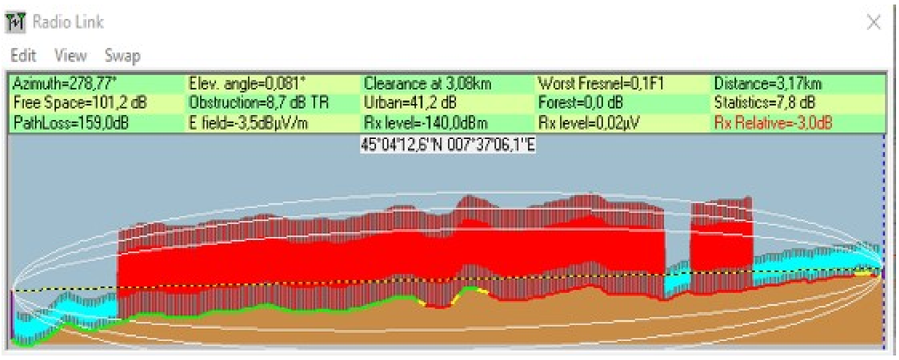


Figure 4.11: Terrain Profile in Radio Mobile

Later, in the figures 4.10 and 4.11, both simulation present same terrain conditions, but Radio Mobile takes in account the Land Cover properties (Red and blue zones in Path Profile of Radio Mobile) in the terrain. And it's important because is closer of the real conditions. Clearly EMLAB not have the Land Cover in spite of have behaviour similar in the coverage area with Radio Mobile, and this is a key difference in the RF propagation results. For this reason, some points receive Rx signal in EMLAB software.

Owing to the previous results on the simulations, for the final simulation in the network Torino is chosen Radio Mobile because this software allow calculate the coverage area like receive point Tx and the gateway LoRa Rx, measure the receive power to dBm and, as we see in the previous results, have the Land Cover properties. EMLAB is a limited software because only have one measure RF unit and the gateway LoRa can be only configured as Tx but this program is adequate for celluar or TV communications.

Chapter 5

LoRaWAN Network Planning in Torino

5.1 Introduction and Methodology

The CSP project consist of the reach of design and implementation of a LoRa network searching the resolution of complex task from the urban context. Where it is reached the total coverage of the metropolitan area at Torino city.

The main objectives which must be compliments are the proportion of a IoT network with total coverage and consolidate a method of planning in such a way that it can be replicated for any city.

The methodology of the design and implementation consist to make simulation of coverage area in strategic points. Then of study and installations of the gateway device in those points, its begins to do measurements around of the points. And finally, take the simulation and measure information for make optimization step to simulation tool.

5.2 Radio Mobile Simulations

For simulate the coverage area in Radio Mobile, it's used the next parameters:

Parameter	Configuration
Type of Antenna Tx, Rx	Omnidirectional
Type of Polarization	Vertical
Antenna Gain Tx	14dBm
Antenna Gain Rx	0dBm
Antenna Height Tx	2m
Sensivity Tx, Rx	-137dBm
Line Loss Tx, Rx	0.5dB
Frequency Range	(863 - 870)MHz
Coverage Area Range	3km
Propagation Model	ITS Irregular Terrain Model
Climate	Continental Temperate
Type of Topology Network	Data Net, Cluster(Node/Terminal)

Table 5.1: Radio Mobile Parameters for Coverage Area Calculation

In the next table, it's show the gateway points to simulate with their respect coordinates:

Point Name	**Height(m)**	**Address**	**Latitude/Longitude**
IREN-ISI	30	Via Alassio	45,03946° and 7,668239°
IREN-ARBE	12	Via Arbe	45,05459° and 7,630889°
IREN-GBRUNO	25	Corso Bramante	45,04448° and 7,665085°
IREN-MARTINETTO	21	Corso Appio Claudio	45,08556° and 7,651389°
IREN-TORRE_BERT	15	Strada Comunale da San Vito	45,04248° and 7,703796°

Table 5.2: Localization of the Gateways LoRa in Torino City

The results are shown below:

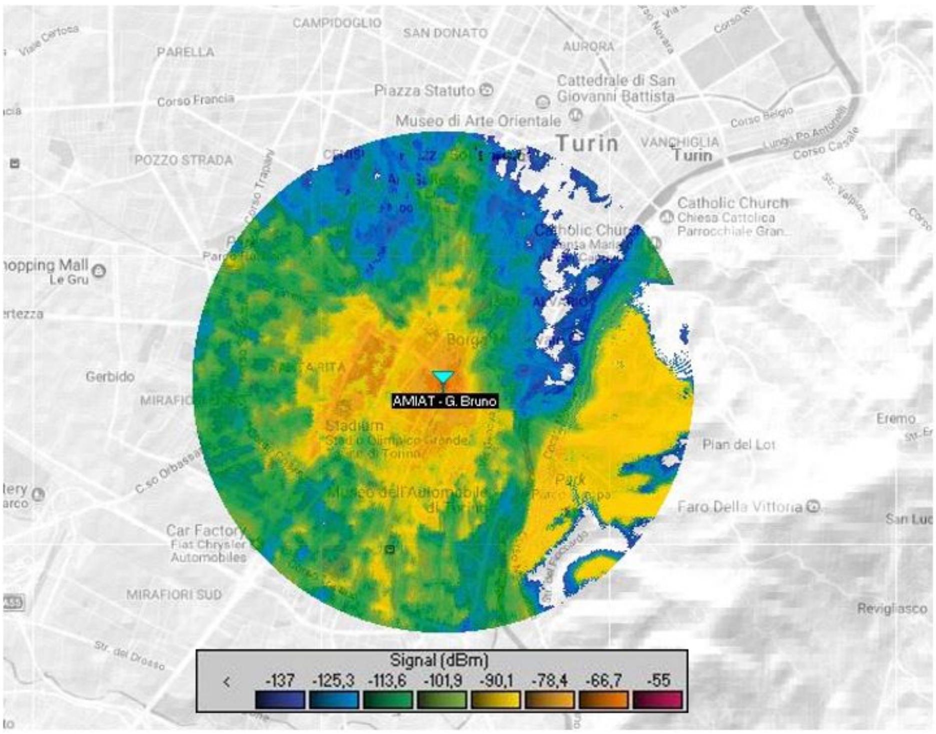


Figure 5.1: Coverage Area of Gateway AMIAT-G.Bruno

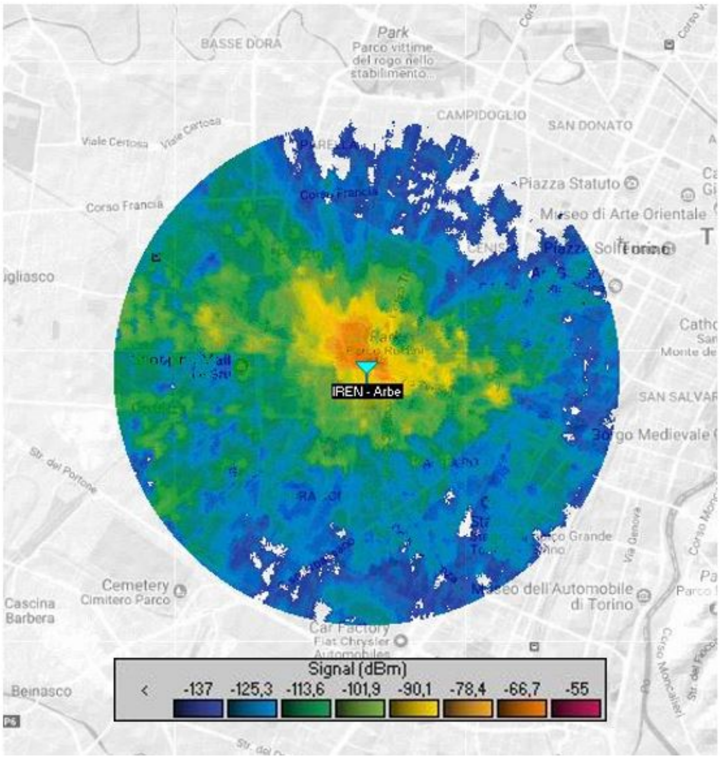


Figure 5.2: Coverage Area of Gateway Arbe

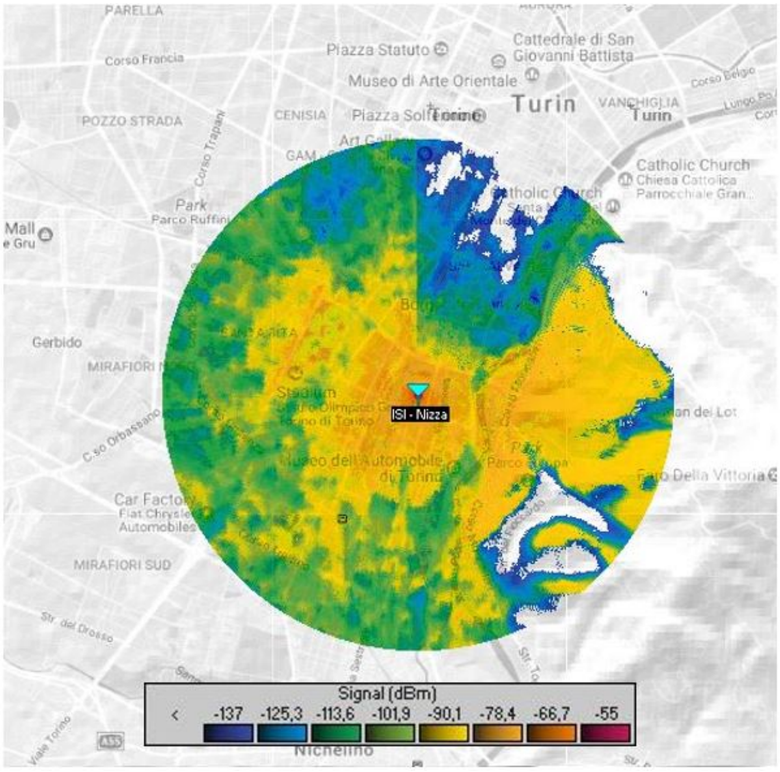


Figure 5.3: Coverage Area of Gateway ISI

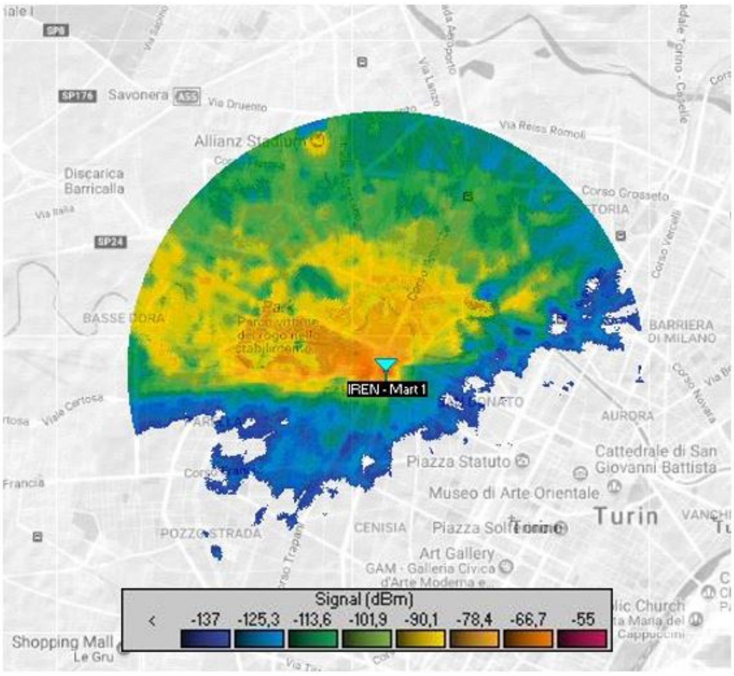


Figure 5.4: Coverage Area of Gateway Martinetto

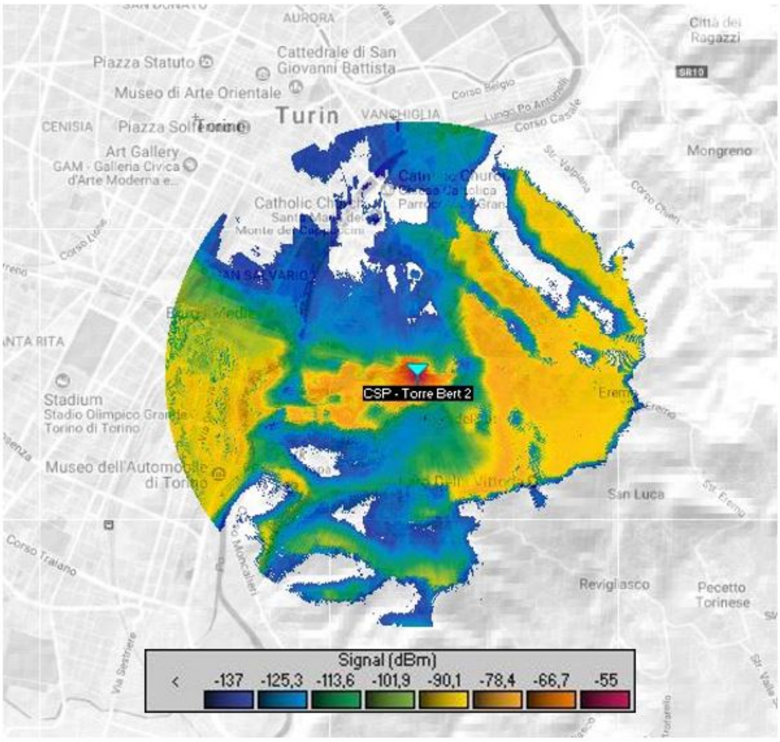


Figure 5.5: Coverage Area of Gateway Torre-Bert

According to the simulations of the points G.Bruno and ISI, figures 5.1 and 5.3, the coverage area pattern is similar due to the position of the gateways is close but the power receive signal is more better in the case of the gateway ISI because the height of the gateway is more higher that the gateway G.Bruno.

The position where present more lower power receive signal is the gateway Arbe despite the zone around of the gateway not have much buildings and others obstacles high. But the height of this gateway is low and this characteristic it is reflected in the simulation result of the figure 5.2.

On the other hand, in the figures 5.1, 5.4 and 5.5 it can be seen similarities where not have the power receive signal in the center zone of the Torino. Clearly, this zone is concentrate by many buildings high. In general terms, the simulation results are expected but is important corroborate with real experiments.

5.3 Devices and Configurations

Basically, for the activation of the communication LoRaWAN device, we have two modes of activation:

- **Over-The-Air Activation (OTAA):** Consist to communicate with the network server through to a join procedure prior. When the communication is finished or lost, the end-device must begin again the join procedure. For configure the join OTAA, is necessary a unique end-device identifier for all the devices (DevEUI-64-bit), the application identifier (AppEUI-64-bit) and authentication with Application key (AppKey-128 bits AES encryption key)[27].
- **Activation By Personalization (ABP):** Allow the communication to a specific network passing the join request- join accept procedure. For this, each device have a unique network session key (NwkSKey-128 bits AES encryption key), application session key(AppSKey-128 bits AES encryption key) and device address (DevAddr-32 bits identifier)[27]. This information is stored in the devices and always the devices are ready to communicate without any additional procedure[16].

For simplicity, we configure the devices as ABP for avoid the join procedure every time when access the LoRa network server.

Now, the measure of the coverage area is necessary use the device with coordinates, RSSI, SNR and data rate information. The device used is Adeunis Tester LoRa.

Figure 5.6: Adeunis Tester LoRa

Some technical specifications of the device are:

Communication	LoRaWAN protocol & LoRa Modulation
LoRaWan Specification compliant	V1.0.1
Radio Rate	Variable (SF12/125kHz (∼183 bps) to FSK (∼50kbps)
Frequency	ISM band 865-870MHz
RF Power	14dBm (25mW)
Sensitivity	Down to -140 dBm in SF12/CR4
Range (Open)	Up to 15km
Standards met	EN 300-220, EN 301-489, EN 60950
Network area	EU863-870

Table 5.3: Technical Specifications of Adeunis Tester LoRa[28]

The configuration of the device Adeunis is across to serial terminal communication in which using AT commands where begin with 2 characters "AT" followed by other characters which correspond to certain command. For example, for storage all the configurations the command correspond is AT&W[28]. Some configurations allowed are GPS activation, transmission period, Adaptive Data Rate (ADR) activation and, of course, the LoRa activation of communication either ABP or OTAA.

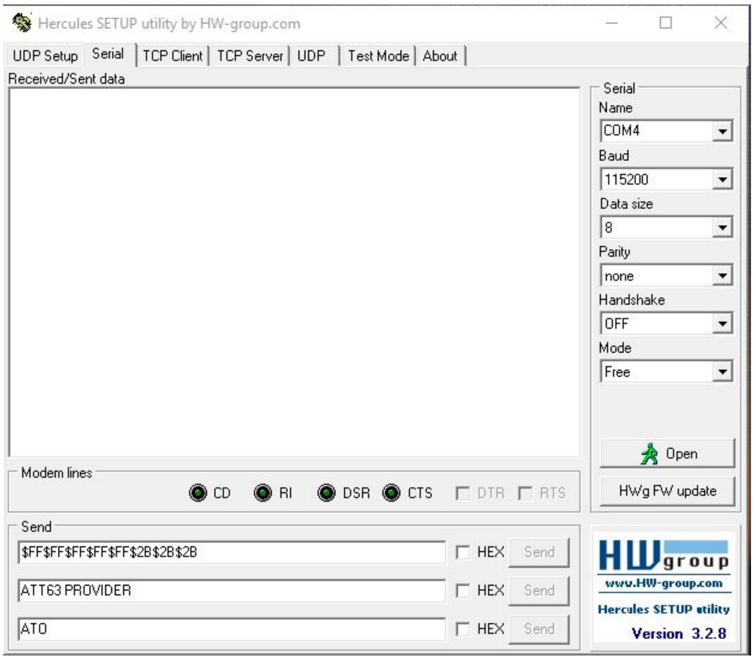


Figure 5.7: Serial Terminal Interface of Hercules

For the gateways LoRaWAN, it was configured and it was used the device Gateway Multitech Conduit IP67 Base Station.

Figure 5.8: Gateway Multitech Conduit IP67 Base Station

Some technical specifications of the device are:

Processor	ARM9 processor with 32-Bit ARM & 16-Bit Thumb instruction sets
Packet Data	Up to 100 Mbps downlink, Up to 50 Mbps uplink
Radio Frequency LoRa	LoRa 868 or 915 MHz – a proprietary Digital Spread Spectrum technique
Input Voltage	Power over Ethernet (PoE) 48Vdc 25W compliant to IEEE802.3at
Connector Ethernet	1 RJ-45 Ethernet 10/100 port (PoE)
Connector Antenna	Cell 3dBi (Qty2), LoRa 3dBi (Qty1), GPS (Qty 1)
Radio Compliance	FCC 15.247, IC RSS-210, EU EN 300 220
Operating Temperature	-30° C to +70° C
Weight	2.75 kg

Table 5.4: Technical Specifications of Gateway Multitech Conduit IP67 Base Station[29]

The configuration of the gateway Multitech, is necessary use the interface stored in the device like we can see in the figure 5.9, where is set the LAN(Ethernet connection), WAN(Cellular connection), Tunnels properties and other configurations. In our case, just we need configure the LAN option for access and connect through to internet.

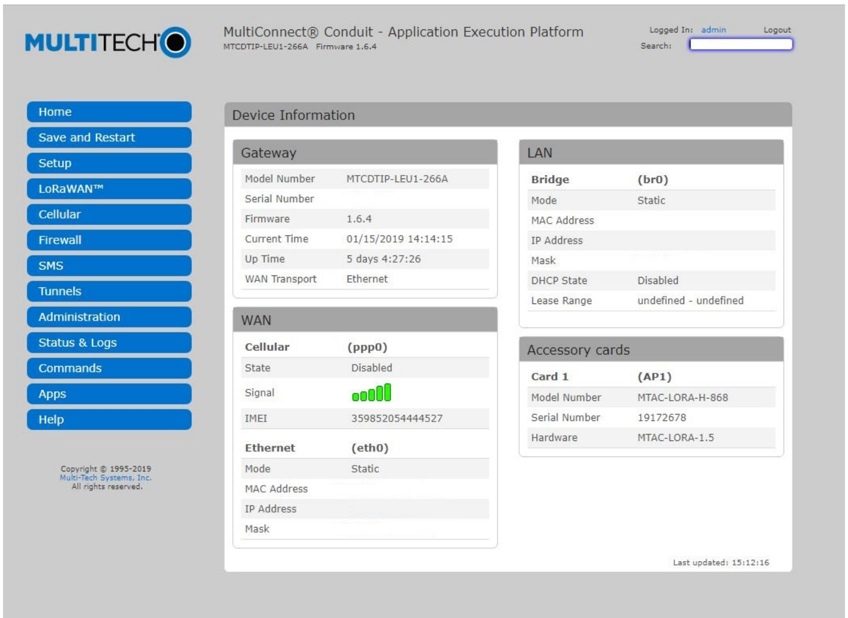


Figure 5.9: Gateway Multitech Interface Configuration

Later in the LoRaWAN option, the figure 5.10, we find all the parameters required for activate LoRaWAN and connect our gateways in the server in which allow provide the gateway activities.

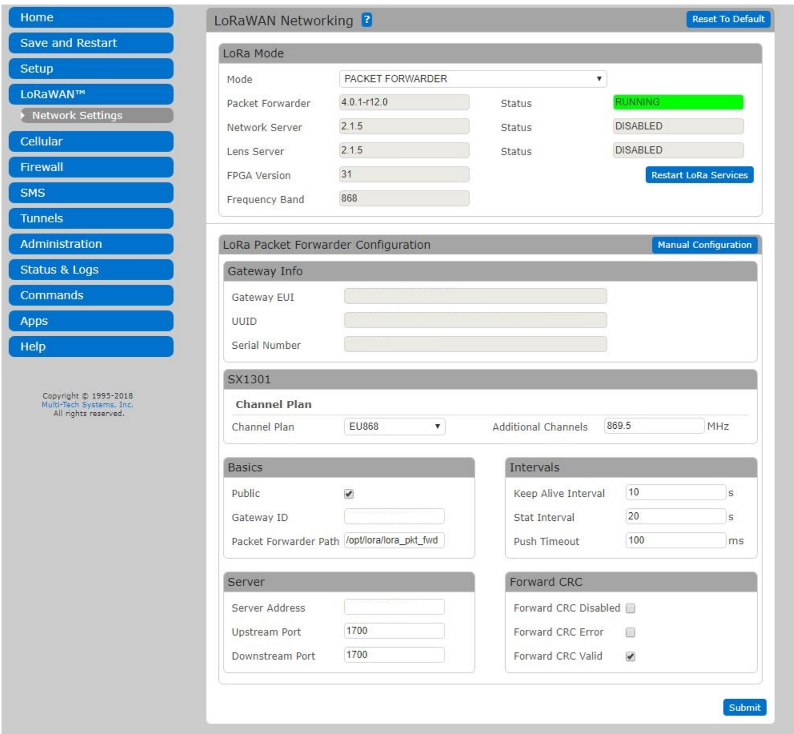


Figure 5.10: LoRaWAN Configuration of Gateway Multitech

5.4 Field-test Results

When all the devices are configure, we can proceed to do the coverage area measurement. But first, is necessary clarify the server to use, how to decode the information and what is the experiment for collect the power receive signal.

The Adeunis device information necessary for obtain good measure is present in the table 5.5 where these data is stored in the server know as LoraServer. This server allow see the activities and configure all the devices and gateways presents in the LoRa networks and, also, create applications for decode and encode LoRa message. For obtain the information, it was required create a code to decode all the payload presented in the Adeunis device.

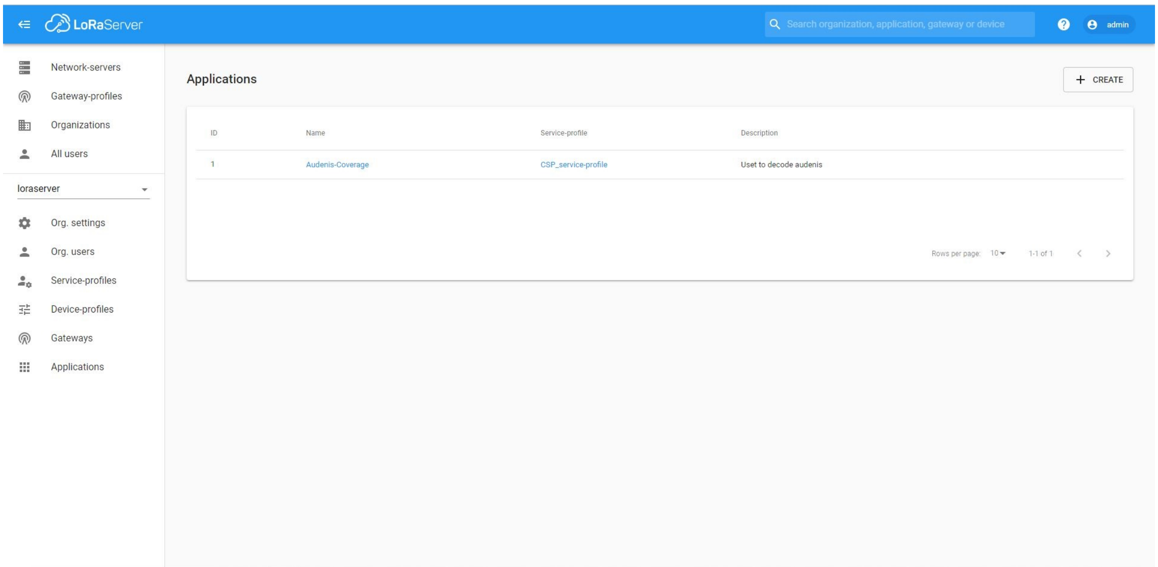


Figure 5.11: LoraServer Interface

Time (Date)	Name	Device Name	Latitude(°)	Longitude(°)	Battery(mV)	RSSI(dBm)	SNR(dB)	DR	Total(dBm)
a	b	c	d	e	f	g	h	i	j

Table 5.5: Data Collection from Adeunis Rf Device

Just the decode code of the Adeunis device provide the Latitude, Longitude and Battery information, the rest information it's found in gateway respond where is present in the server. Now, for concatenate all the information is through to other code stored in the server memory where not is possible access to him.

a. **Time:** Correspond to the date and the hour when the message is receive for the gateway.

b. **Name Gateway Rx:** Is the gateway name which receive the message.

c. **Device Name:** Is the device name which send the message. For obtain the coverage map, the device always is Adeunis.

d. **Latitude:** Correspond to the latitude position of the device Tx in °degrees format.

e. **Longitude:** Correspond to the longitude position of the device Tx in °degrees format.

f. **Battery Level:** Indicate the battery of the device Tx in mV(millivolts).

g. **RSSI:** The Received Signal Strength Indicator is the measure of the message transmission between the gateway and the device Tx in dBm.

h. **SNR:** Is the relation signal/noise of the message transmission between the gateway and the device Tx in dB.

i. **DR:** Indicate the data rate used for send the message.

j. **Total:** The Total or Sensitivity correspond to the addition between the RSSI and the SNR in dBm. For make this addition, is important that they only add up when the SNR is negative, on the contrary the Total is only RSSI.

For example, this is the data measure for Adeunis Tester stored in .csv format:

```
time,name,deviceName,lat,lon,bat,rssi,loRaSNR,dr,total
2019-01-11T14:40:29.399418,IREN_GBRUNO,Adeunis_Tester,
45.0536,7.654667,4099,-94,6,5,-94
2019-01-11T14:40:44.403535,IREN_TORRE_BERT,Adeunis_Tester,
45.0536,7.654667,4098,-112,-5.8,5,-117.8
2019-01-11T14:40:47.401569,IREN_ISI,Adeunis_Tester,
45.0536,7.654667,4098,-114,1.8,5,-114
2019-01-11T14:40:59.393039,IREN_GBRUNO,Adeunis_Tester,
45.053633,7.654667,4097,-108,5.8,5,-108
2019-01-11T14:41:14.401122,IREN_TORRE_BERT,Adeunis_Tester,
45.053583,7.654833,4097,-116,0.5,5,-116
2019-01-11T14:41:17.422311,IREN_TORRE_BERT,Adeunis_Tester,
45.053583,7.654833,4097,-111,4,5,-111
2019-01-11T14:41:29.388582,IREN_TORRE_BERT,Adeunis_Tester,
45.053033,7.655167,4099,-110,4.2,5,-110
2019-01-11T14:41:32.394032,IREN_TORRE_BERT,Adeunis_Tester,
45.053033,7.655167,4099,-111,2.8,5,-111
...
```

Cleared up previously how obtain the parameters necessary to calculate the coverage area of each gateway point, the field-test that was done consist of travel by the streets of Torino using a car and send message, each 15 seconds, to the gateways localized at the city using the Adeunis Tester. Finished the travel by Torino, it's extracted the file .cvs and it's separated the information by gateway and, later, it's imported the files in "Google Earth" program taking as "total" parameter a color criterion for see the coverage area similar to the simulation results.

For example, this is the coverage area of Torino respect to the field-test measurements:

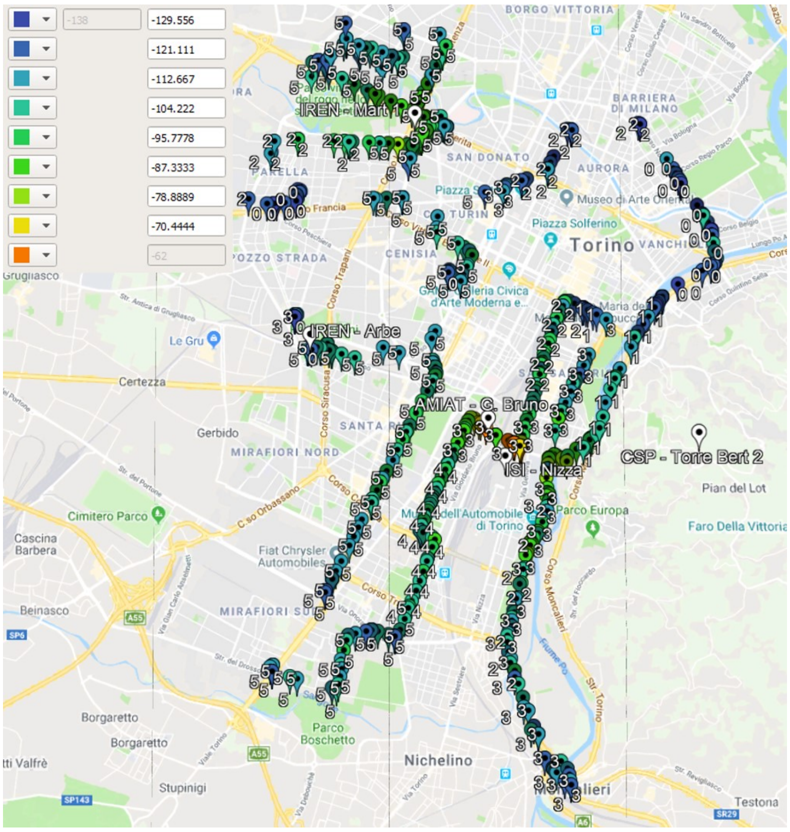


Figure 5.12: Coverage Area of Torino taking "Total" parameter as color criterion

It is important to mention that Adeunis Tester device is configured in mode ADR not to have limitations in terms of coverage distances. Also, the numbers designated of every power receive measured, seen in the figure 5.12, corresponding to DR used by the transmission device for send the package message. The decision of select DR for send the message consist to begin to send with DR more high, that is, equal to 5. When the gateway not receive the message, the Tx device change DR and try again to send until the gateway receive the message.

5.5 Optimization of Simulation Radio Mobile

The optimization process in Radio Mobile consist to change the parameters "Urban and Built-Up LO" (low buildings) and "Urban and Built-Up HI" (high buildings) based to the results of field-test realized. The procedure is modify the height and density of the buildings of the city presented in Land Cover information.

Taking in account the data information, the new parameters for the next simulations are:

a. Previously parameters:

- Urban and Built-Up LO: $Height = 10m, Density = 100\%$
- Urban and Built-Up HI: $Height = 30m, Density = 200\%$

b. New parameters:

- Urban and Built-Up LO: $Height = 20m, Density = 110\%$
- Urban and Built-Up HI: $Height = 30m, Density = 160\%$

The other parameters are not necessary to change them due to the low presence in the city and the low causative of interference in the coverage area simulations. The final Land Cover configuration optimized is showed in the next figure:

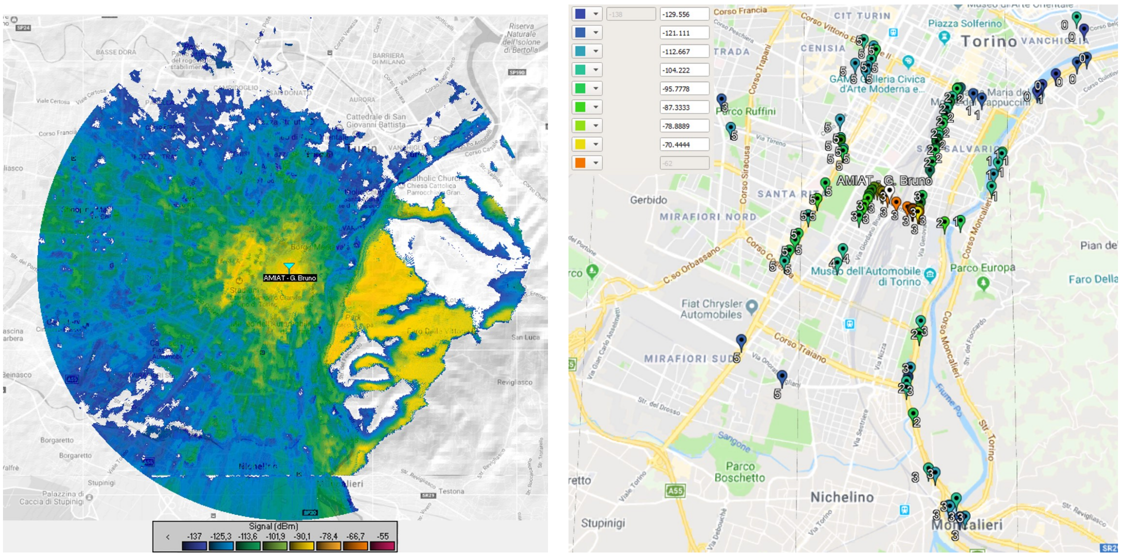

landheight.dat

☑ Include land cover height

	Height (m)	Density (%)
00 Water	0	0
01 Evergreen Needleleaf Forest	15	100
02 Evergreen Broadleaf Forest	25	60
03 Deciduous Needleleaf Forest	15	100
04 Deciduous Broadleaf Forest	15	60
05 Mixed Forest	15	70
06 Woodland	10	70
07 Wooded Grassland	5	10
08 Closed Shrubland	1	10
09 Open Shrubland	1	10
10 Grassland	1	5
11 Cropland	1	0
12 Bare Ground	0	0
13 Urban and Built-up LO	20	110
14 Urban and Built-up HI	30	160

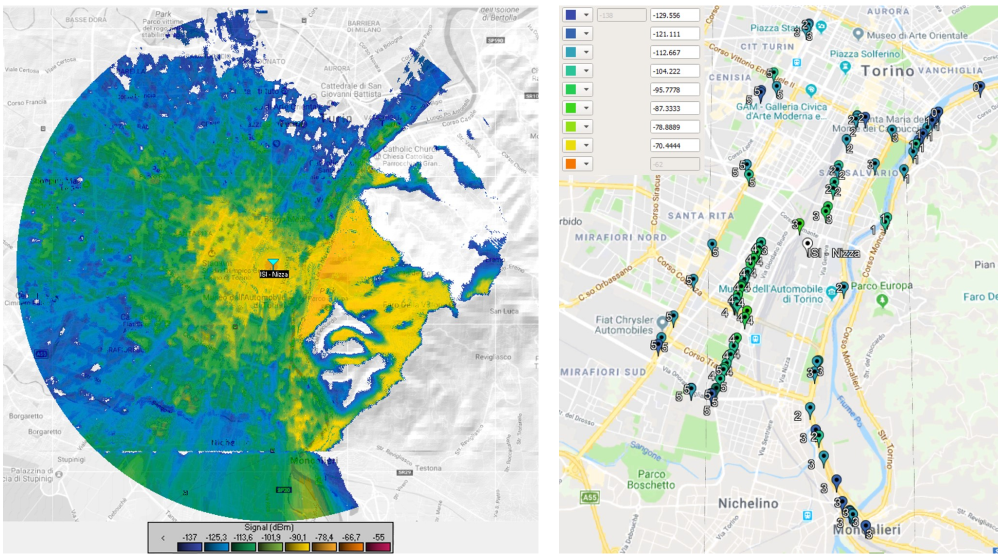
Figure 5.13: Land Cover Parameters Optimization

Now, the simulation results with respective field-test for each gateway point are:



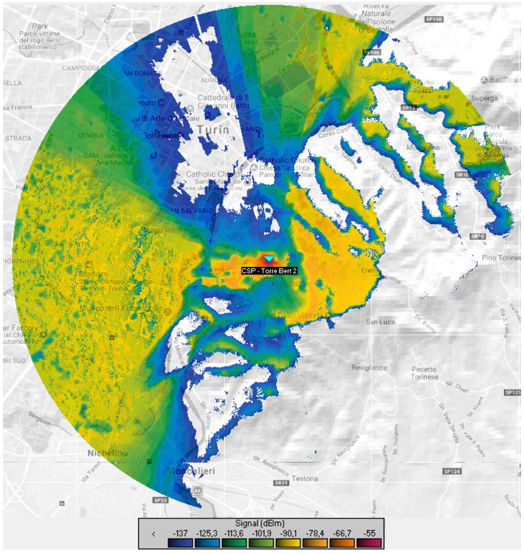
(a) Optimization Simulation (b) Field-Test

Figure 5.14: AMIAT G.Bruno

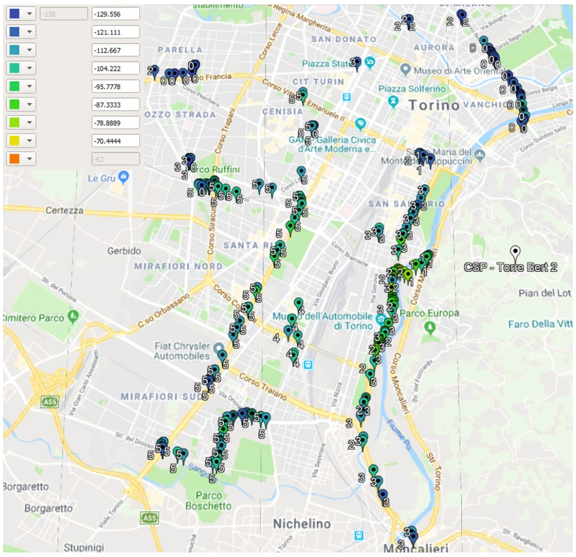


(a) Optimization Simulation (b) Field-Test

Figure 5.15: ISI

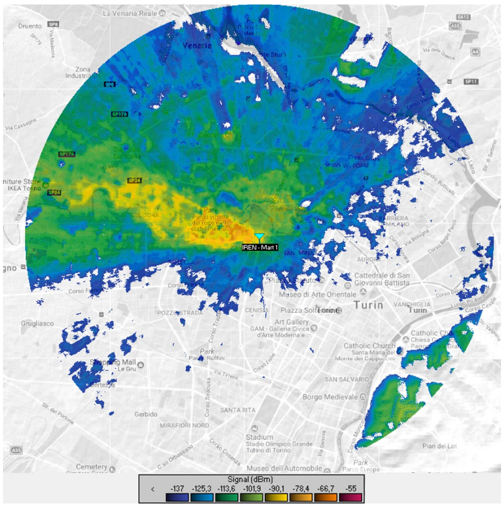


(a) Optimization Simulation

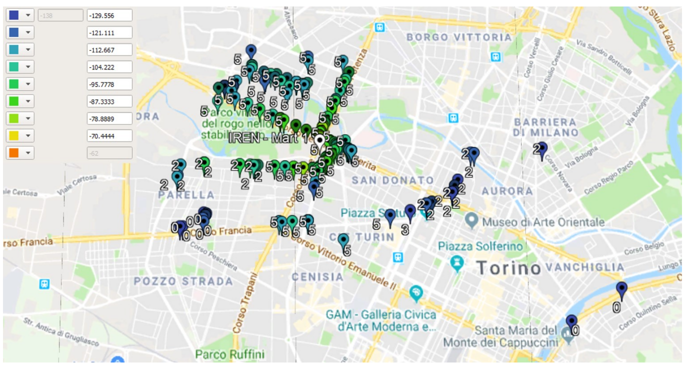


(b) Field-Test

Figure 5.16: Torre Bert



(a) Optimization Simulation



(b) Field-Test

Figure 5.17: Martinetto

It can be shown that the simulations optimized are very similar to the field-test results in pattern characteristic, in the figure 5.17 show great similarities. Just in some zones the power receive level is different, exactly close to Po river, because in the figures 5.14, 5.15 and 5.16 reflect the low power receive when the simulation show high power receive in that zone. In general terms, it can rely in the simulations with those optimization configurations resorting field-test just for check the results.

5.6 Final LoRaWAN Network

Taking all the previous study and results, it gets to the next LoRaWAN network with four gateway points with its respective topology.

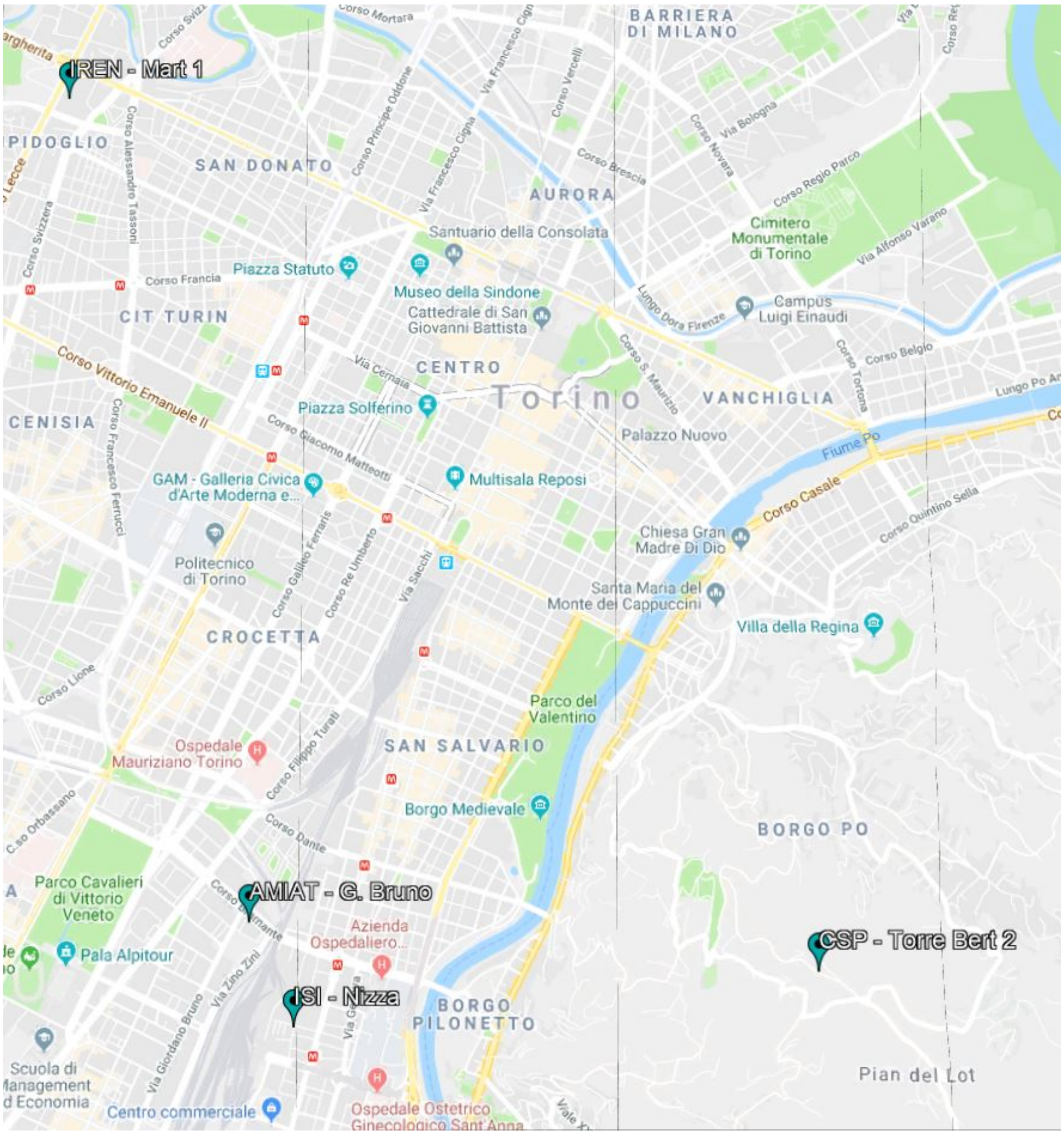


Figure 5.18: Gateway Positions LoRaWAN Torino

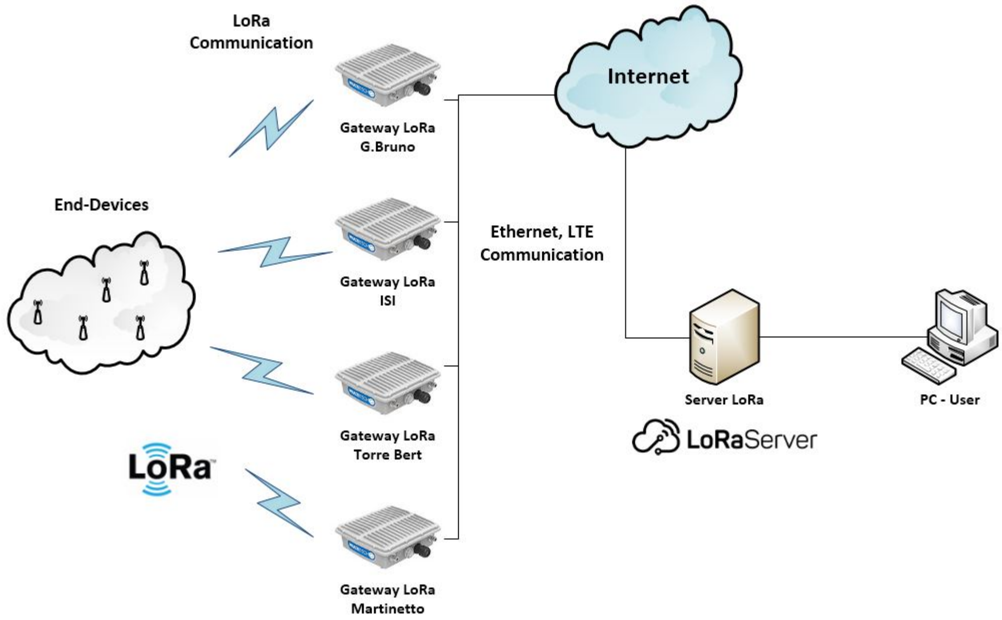


Figure 5.19: Topology LoRaWAN Torino

The total coverage area simulating radial area 5km for each one of them is:

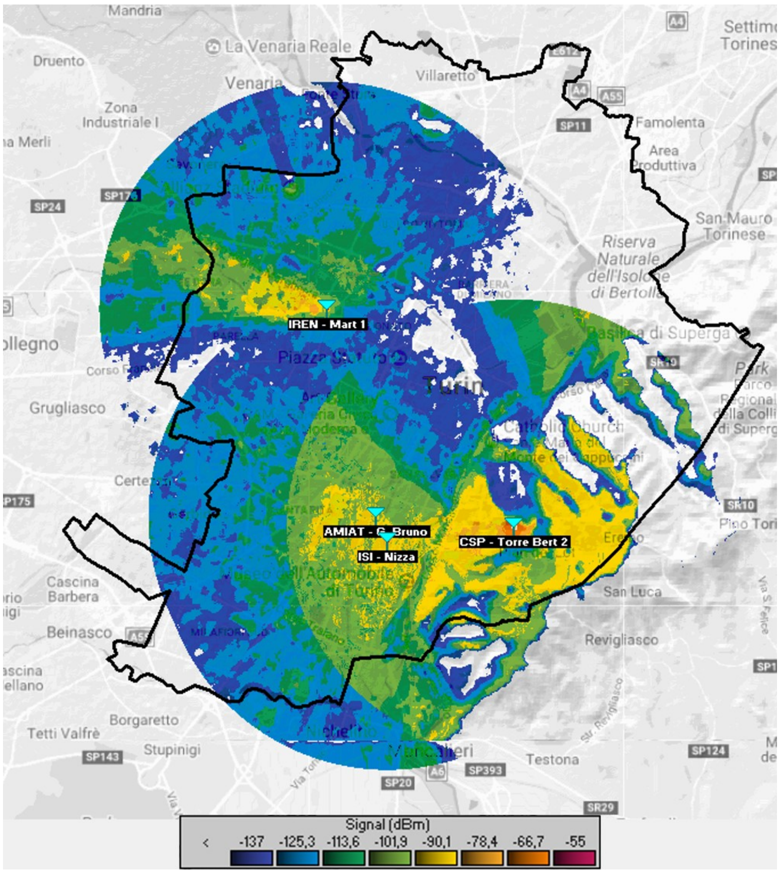


Figure 5.20: Coverage Area of LoRaWAN Torino

Gateway Points	Coverage Zone	Coverage Signal
Martinetto	North and West	Medium
G.Bruno	South, Center and West	Medium
ISI	South, Center and West	Medium
Torre Bert	East, Center, South and North	High

Table 5.6: Coverage Characteristics of Gateway Points LoRaWAN

If desired have a better coverage, it could be replaced some point, either G.Bruno or ISI, and put it in the north-east zone because the previous points are very close and the coverage is enough for one point.

Chapter 6

Conclusions and Future Works

The LoRaWAN technology turns out to be a platform very adequate for implement IoT networks in urban cities due to the good coverage, high range and high immunity to noise. But this present some contradictions with the theoretical specification because the theoretical range for LoRa is close to 15km[12] when in the montage real range is close to 7km in the city based to the field-test results. For this reason is important the practice tests for rectify the LoRa specifications. Also, along the configuration of different devices for measure the power receive and for allocate the gateway points, its found that configure those devices are very intuitive and little complex. Achieving thus, they loRaWAN a technology manageable and understandable when implementing an IoT network.

The height of the antenna in LoRaWAN gateways plays a very important role for the network design because of the cover area for any system depends of the LOS characteristic where if the transmitter can be viewed by the receive, the power receive is higher. Then, the height of the gateways must be higher with little obstruction so that all the end-devices located around the city can transmit without any problem to the gateways.

Radio Mobile software achieves to be a adequate simulator according to the cover area simulation at LoRaWAN technology because the parameters of the network properties and the Land Cover properties are enough for make a decent and realistic simulation. The only observation is the limitation of the propagation model, since having different propagation models allow take into account like another optimization parameter getting better the simulation. For this reason, it's recommended for future simulations try with other simulator with different propagation models, obstacles properties and other parameters to declare a LoRaWAN network.

The behaviour of the data collection of the received power presents different measurements not only if the tester-device is still but also if the device is moving. This effect its observed due to a time delay considered of the receive packages which arise when the transmitter is in motion and a time delay negligible when the transmitter is still. Possible causes are the Doppler effect when the message occupy a channel in the frequency domain[10].

Finally, as first step of planning of LoRaWAN network at Torino city we found that it reaches a very good coverage, almost entirely of the city, allowing the possibility of implementation of diverse IoT systems. Now, to get a total coverage is necessary a better distribution of the gateways and locate in missing areas of Torino, as explained in the chapter 5. It is clarified that the elimination of IREN-Arbe point of the final design of the network it has been due to present failures in Field-test and little time to repair and test again the device, but it would be interesting add and measure that point in the future.

Some future works to develop are:

a. *Behavior of LoRaWAN network with end-devices in distribute fixed points.*

b. *Evaluation of LoRaWAN network in indoor environments.*

c. *Optimization process for minimize the number of the gateway devices for urban LoRaWAN network.*

d. *Analysis of localization techniques using LoRaWAN network*

Appendix A

Appendix

A.1 MATLAB Code Simulation

This codes are based to the references[15][30].

A.1.1 LoRa Simulation System

```
clear all; close all; clc;

%% Parameters of LoRa Channel Simulation

SF = 7;                       % Spreading Factor
BW = 125e3;                   % 125kHz
Fs = 125e3;                   % Sampling Frequency
preamble_len = 8;             % Preamble Length
sync_len = 2;                 % Sync Length
total_bits = 27720;           % Total bits to be transmitted in ...
    LoRa message
Total_iterations = 5;         % Number of iteration of simulation
EbNo_db = -10:0.5:6;          % Eb/No (Energy bits/Noise) rate in dB
EbNo = 10.^(EbNo_db/10);      % Eb/No (Energy bits/Noise) rate
num_samples = Fs*(2^SF)/BW;   % Number of Samples
% SNR Calculation
snr_db = EbNo_db + 10*log10(BW/(2^SF)) + 10*log10(SF) - ...
    10*log10(BW);
BER = zeros(Total_iterations,length(snr_db));
```

```

%% Random Number Generation
[Input_sample_Bi, input_len] = ...
    LoRa_random_number_generation(total_bits,SF);

rand_num_matrix = reshape(Input_sample_Bi, SF, input_len);

% Binary to Gray Conversion
Input_sample_gray = binary2gray(rand_num_matrix);

% Binary to Decimal conversion
Input_sample = bi2de(Input_sample_gray','left-msb')';

% Total transmitted symbols
lora_total_sym = preamble_len + sync_len + input_len;

%% Preamble Generation
inverse = 0;
for i = 1:preamble_len
    [out_preamble] = ...
        LoRa_Modulation(SF,BW,Fs,num_samples,0,inverse);
    outp((i-1)*num_samples+1 : i*num_samples) = out_preamble;
end

%% Sync Symbols Generation
inverse = 1;
for i = 1:sync_len
    [out_sync] = LoRa_Modulation(SF,BW,Fs,num_samples,32,inverse);
    outp = [outp out_sync];
end

%% Symbols Generation
inverse = 0;
for i = 1:input_len
    [out_sym] = LoRa_Modulation(SF,BW,Fs, ...
    num_samples,Input_sample(i),inverse);
    outp = [outp out_sym];
end

```

```
for ite = 1:1:Total_iterations
    for y=1:length(snr_db)

        %% Signal channelization (DDC)
        % Bring signal to baseband
        t = 0:1/Fs:length(outp)/Fs-1/Fs;
        outp = outp.*cos(2*pi*Fs*t);

        %% Transmission Channel
        SignalRx=awgn(outp,snr_db(y),'measured');

        %% Reverse chirp generation for receiver
        inverse = 1;

        [out_reverse] = ...
            LoRa_Modulation(SF,BW,Fs,num_samples,0,inverse);

        %% Multiplying with the reverse chirp
        for n = 1:1:lora_total_sym
            decoded_out((n-1)*num_samples + 1 : n*num_samples) = ...
                (SignalRx((n-1)*num_samples + 1 : ...
                n*num_samples).*out_reverse);
        end

        %% Calculating FFT
        for m = 1:1:lora_total_sym
            FFT_out(m,:) = ...
                abs((fft(decoded_out((m-1)*num_samples + 1 : ...
                m*num_samples))));
        end

        %% Decoding the received data
        k=1;
        for m = preamble_len+sync_len+1:1:lora_total_sym
            [r,c] = max(FFT_out(m,:));
            data_received(k) = c-1;
            k = k+1;
        end

```

```
        % Decimal to Binary Conversion
        data_received_bin = de2bi(data_received,SF,'left-msb')';
        % Gray to Binary Conversion
        data_received_gray = gray2binary(data_received_bin);
        % Matrix to array conversion
        data_received_De = reshape(data_received_gray,total_bits,1);

        %% BER Counter

        BER(ite,y) = sum(abs(data_received_De - ...
            Input_sample_Bi))/total_bits;
    end
end

Avg_BER(1,:) = mean(BER);    % Average BER over all the iterations
BER_T = 1/2*erfc(sqrt(EbNo));  % BER calculation for BPSK

%Plot BER Calculation
semilogy(snr_db,Avg_BER);
hold on
semilogy(snr_db,BER_T);
title('BER vs SNR');
xlabel('SNR (dB)');
ylabel('BER');
xlim([min(snr_db) max(snr_db)]);
legend('BER Estimated LoRa','BER Theoretical BPSK');
grid on;
```

A.1.2 LoRa Modulation Function

```
% Matlab function to Modulate LoRa symbols

function out_preamble = ...
    LoRa_Modulation(SF,BW,Fs,num_samples,symbol,inverse)

    %initialization
    phase = 0;
    Frequency_Offset = (Fs/2) - (BW/2);

    shift = symbol;
    out_preamble = zeros(1,num_samples);

    for k=1:num_samples

        %output the complex signal
        out_preamble(k) = cos(phase) + 1i*sin(phase);

        % Frequency from cyclic shift
        f = BW*shift/(2^SF);
        if(inverse == 1)
               f = BW - f;
        end

        %apply Frequency offset away from DC
        f = f + Frequency_Offset;

        % Increase the phase according to frequency
        phase = phase + 2*pi*f/Fs;
        if phase > pi
            phase = phase - 2*pi;
        end

        %update cyclic shift
        shift = shift + BW/Fs;
        if shift >= (2^SF)
            shift = shift - 2^SF;
```

```
        end
    end
end
```

A.1.3 Generate Random Numbers for LoRa System Function

```
% Matlab function to Generate random numbers
function [random_number_input, columns] = ...
    LoRa_random_number_generation(total_sym, SF)

rows = SF;
columns = ceil(total_sym/SF);
random_number_input = round(0.75*rand(1,rows*columns))';
```

A.1.4 Binary to Codification Gray Function

```
%% Matlab function to Binary to Gray Conversion

function [Input_sample_gray] =  binary2gray(Input_sample_Bi)

[r,c] = size(Input_sample_Bi);
Input_sample_gray = zeros(r,c);

Input_sample_gray(1,:) = Input_sample_Bi(1,:);   % Copying First bit

for m = 1:1:c
    for g = 2:1:r       % Xor of input bit with last input bit
        Input_sample_gray(g,m) = xor(Input_sample_Bi(g,m), ...
            Input_sample_Bi(g-1,m));
    end
end
```

A.1.5 Codification Gray to Binary Function

```
%% Matlab function to Gray to Binary Conversion

function [data_received_bin] = gray2binary(data_received_gray)

[r,c] = size(data_received_gray);
data_received_bin = zeros(r,c);

data_received_bin(1,:) = data_received_gray(1,:);   % Copying ...
    First bit

for m = 1:1:c
    for g = 2:1:r       % Xor of input bit with last output bit
        data_received_bin(g,m) = xor(data_received_bin(g-1,m), ...
            data_received_gray(g,m));
    end
end
```

A.2 Adeunis device decode information

This code is based to JavaScript.

```
function Decode(fPort, bytes) {
  var index = [1,2,6,13];
  var status = bytes[0];
  var gap = 0;
  var latlon = [];
  var latitudine = [];
  var longitudine = [];
  var battery = [];
  var bat = [];
  if (status&0x80){

  }
  else{
```

```
    gap=gap-1;
  }
  if (status&0x10){
    latitudine = bytes.slice(index[1]+gap,index[1]+gap+4);
    longitudine = bytes.slice(index[2]+gap,index[2]+gap+4);
    var lat = (latitudine[0]>>4)*10+(latitudine[0]&0xF)+
                ((latitudine[1]>>4)*10+(latitudine[1]&0xF)+
                (latitudine[2]>>4)*0.1+
                (latitudine[2]&0xF)*0.01+
                (latitudine[3]>>4)*0.001)/60;
    var lon = (longitudine[1]>>4)+((longitudine[1]&0xF)*10+
              (longitudine[2]>>4)+(longitudine[2]&0xF)*0.1+
              (longitudine[3]>>4)*0.01)/60;
  }
  else{
    gap=gap-9;
    latitudine = 0;
    longitudine = 0;
    lat = latitudine;
    lon = longitudine;
  }
  if (status&0x08){

  }
  else{
    gap=gap-1;
  }
  if (status&0x04){

  }
  else{
    gap=gap-1;
  }
  battery = bytes.slice(index[3]+gap,index[3]+gap+2);
  bat = (battery[0])*256+(battery[1]);
  lat=parseFloat(Math.round(lat * 1000000) / 1000000).toFixed(6);
  lon=parseFloat(Math.round(lon * 1000000) / 1000000).toFixed(6);
  latlon = ...
      lat.toString()+'\u0020'+lon.toString()+'\u0020'+bat.toString();
```

```
  return {"lat":lat.toString(), "lon":lon.toString(), ...
      "bat":bat.toString()}
}
```

Bibliography

[1] Jayavardhana Gubbi et al. "Internet of Things (IoT): A vision, architectural elements, and future directions". In: *Future generation computer systems* 29.7 (2013), pp. 1645–1660.

[2] Ramon Sanchez-Iborra and Maria-Dolores Cano. "State of the art in LP-WAN solutions for industrial IoT services". In: *Sensors* 16.5 (2016), p. 708.

[3] Jetmir Haxhibeqiri et al. "A survey of lorawan for iot: From technology to application". In: *Sensors* 18.11 (2018), p. 3995.

[4] Konstantin Mikhaylov, Juha Petaejaejaervi, and Tuomo Haenninen. "Analysis of capacity and scalability of the LoRa low power wide area network technology". In: *European Wireless 2016; 22th European Wireless Conference; Proceedings of.* VDE. 2016, pp. 1–6.

[5] Andrew J Wixted et al. "Evaluation of LoRa and LoRaWAN for wireless sensor networks". In: *SENSORS, 2016 IEEE.* IEEE. 2016, pp. 1–3.

[6] Radek Fuidiak et al. "Simulated Coverage Estimation of Single Gateway LoRaWAN Network". In: *2018 25th International Conference on Systems, Signals and Image Processing (IWSSIP).* IEEE. 2018, pp. 1–4.

[7] Gianni Pasolini et al. "Smart City Pilot Projects Using LoRa and IEEE802. 15.4 Technologies". In: *Sensors* 18.4 (2018), p. 1118.

[8] Fabrizio J Grión et al. "LoRa network coverage evaluation in urban and densely urban enviroment simulation and validation tests in Autonomous City of Buenos Aires". In: *Information Processing and Control (RPIC), 2017 XVII Workshop on.* IEEE. 2017, pp. 1–5.

[9] Álvaro Lozano et al. "Smart Waste Collection System with Low Consumption LoRaWAN Nodes and Route Optimization". In: *Sensors* 18.5 (2018), p. 1465.

[10] Silvano Bertoldo et al. "A LoRa-based distributed network for environmental monitoring using public transport". In: (2018).

[11] Tabbane Sami. "Developing the ICT ecosystem to harness IoTs". In: *IoT Network Planning*. ITU ASP COE TRAINING ON. 2016.

[12] Chua Jefferson Yang Daniel. *An Examination of LPWAN Technology in IoT*. Oct. 2018. URL: `https://www.electronicdesign.com/industrial-automation/examination-lpwan-technology-iot`.

[13] nanotron Technology. *Chirp Spread Spectrum (CSS)*. URL: `https://nanotron.com/EN/co_techn-css-php/`.

[14] AN Semtech. "120022". In: *LoRa Modulation Basics* (2015).

[15] Ghoslya. *All About LoRa and LoRaWAN*. 2017. URL: `http://www.sghoslya.com/`.

[16] LoRa Alliance. "A technical overview of LoRa and LoRaWAN". In: *White Paper* (2015).

[17] N Sornin et al. "LoRaWAN™ Specification v1.0". In: *LoRa alliance* (2015).

[18] Thomas Telkamp. *Building A Global Internet Of Things Network Together*. 2016. URL: `https://www.thethingsnetwork.org/forum/t/lora-crash-course-by-thomas-telkamp/3981`.

[19] Sornin. N and Yegin. A. "LoRaWAN™ Specification v1.1". In: *LoRa alliance* (2017).

[20] Brecht Reynders, Wannes Meert, and Sofie Pollin. "Range and coexistence analysis of long range unlicensed communication". In: *Telecommunications (ICT), 2016 23rd International Conference on*. IEEE. 2016, pp. 1–6.

[21] George Allen Hufford, Anita G Longley, William A Kissick, et al. *A guide to the use of the ITS irregular terrain model in the area prediction mode*. US Department of Commerce, National Telecommunications and Information Administration, 1982.

[22] SoftWright LLC. *Notes on Longley-Rice Propagation*. 2000. URL: `https://www.softwright.com/faq/engineering/prop_longley_rice.html`.

[23] Telecomunicazioni Aldena S.r.l. *EMLAB*. URL: `https://www.aldena.it/index.php/softaware-uk/emlab-uk.html`.

[24] Kiran Ahuja Manoj Kumar. "Significance of Empirical and Physical Propagation Models to Calculate the Excess Path Loss". In: *Journal of Engineering Research and Studies E-ISSN* 976 (2011), p. 7916.

[25] Harry R Anderson. *Fixed broadband wireless system design*. John Wiley & Sons, 2003.

[26] Farrant Consulting Ltd. *CloudRF About Us*. 2018. URL: `https://cloudrf.com/about`.

[27] M. Luis N. Sornin. *LoRaWAN™ Specification*. 2400 Camino Ramon, Suite 375: LoRa Alliance, Inc, 2015.

[28] *FIELD TEST DEVICE LoRaWAN Europe EU863-870*. Version V1.2.2. Adeunis Wireless Products and Soluctions. 2016.

[29] *MultiConnect® Conduit™ IP67 Base Station*. Multi-Tech Systems, Inc. Mar. 2018.

[30] Navneet Kumar Ortas Guillermo Hamad Abdul Aziz. "LoRa receiver SDR implementation in MATLAB using the RTL-SDR dongle". In: (2017).