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LoRa Applications and Validations in Complex Urban Environment

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Abstract

Low Power Wide Area Network(LPWAN), is a new technology that is so popular these days due to some crucial features that are fundamental of the Internet of Things(IoT) such as low power consumption, a massive number of connections, and long-range. Sectors that mostly benefit from the LPWAN are agriculture, health care, manufacturing and etc. As cities are going to be smart in the 4th industrial era, it is essential to move toward automation and data exchanges which include IoT, cloud computing and and so on. LPWAN technologies used widely in industry to connect machines and sensors. Sensors in LPWAN technologies and manufacturing facilities may broadcast important data in long ranges to a network, where it can be processed.
This thesis has the objective to investigate coverage and performance outcomes of one of the LPWAN technologies called LoRaWAN in a harsh urban environment. This has been achieved through experimental and system-level evaluation of the LoRaWAN technology which is followed by some simulations and data analysis of extracted test results. We have set up a basic LoRaWAN network that includes a sensor node, a gateway and a network server in order to study the communication, based on Lora modulation. The research has been done in indoor and outdoor environment with the main focus on outdoor experiments. The measured results illustrate that for Non-Line-of-Sight(NLOS) LoRa communication in urban areas the maximum reach is less than 2km. Further investigations have been done to check the packet delivery ratio in different ranges and different spreading factors which demonstrate that increasing the spreading factor in long ranges results in less packet loss and higher performance on Lora link. Besides, it is worth noting that based on extracted results and data analysis, by increasing the packet size, the time on air for each sent packet increases which degrades the communication performance.

Acknowledgments

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Chapter 1

Introduction

The technology of the Internet of Things(IoT) enables any device to connect to the Internet and communicate with other objects, such as automobiles, animals, and plants. [1] [2]. IoT applications [3] [1], such as smart homes and smart cities, are becoming increasingly common, resulting in an increase in the density and volume of networked sensor deployments[5] [6]. The majority of IoT end devices are powered by batteries. They will last for almost 10 years without requiring any maintenance. Wireless networks must provide stable operations, larger coverage, and great energy efficiency in order to link to IoT devices [3]. The devices communicate across a long distance in a multi-hop fashion to send useful data like humidity, temperature, and other factors. Because traditional IoT networking technologies like Zigbee and Bluetooth can only give a limited range [1], [10], [15]. As a result of these requirements, Low Power Wide Area Networking (LPWAN) has emerged as a new branch of IoT networking technology to achieve great energy economy. LPWAN technologies solve one of the biggest issues of the sensor networks, which is the communication range.Radio communications mostly affected by the communication path and distance from the gateway. Transmitted messages may not be received successfully because of signal blockage by obstacles or due to interference with other radio waves. As a result,LPWAN emerged to facilitate radio communication in long ranges with more robustness to the interference.

One of the LPWAN technologies [7] is LoRa, which provides a number of advantages. Unlike ZigBee, which has a small coverage area and is better ideal for indoor usage [12], LoRa offers a large coverage range to remote regions and requires less power [4][16]. LoRa is also a solution for IoT and M2M communication since it uses a spectrum that does not require a license [7] [8]. Because LoRa networking [11] is an open-source technology that allows for low-cost autonomous network setup, it is commonly employed for LPWAN applications.

1.1 Thesis Contribution

In the framework outlined above, the objective of the thesis is to evaluate the performance of LoRa together with the presence of a point to multi-point networking protocol called LoRaWAN in terms of received signal strength Indicator(RSSI) in different outdoor locations in a harsh urban environment as well as indoor areas. Besides, further evaluations of packet delivery ratio and payload size effect, on the overall performance are discussed. Moreover, this research points to the maximum range in which the LoRaWAN gateway would be able to receive the LoRa packets.

This dissertation is carried out to connect a sensor node which is defined as a temperature and humidity sensor along with an RFM95W LoRa module to a LoRaWAN gateway. During the experiment, the gateway is fixed at a height of 12m above the ground. In LoRa system evaluations, choosing the right spreading factor is one of the most important keys in achieving maximum coverage. In this thesis, by activating adaptive data rate(ADR), intelligently the best data rate for sending information as well as spreading factor is determined. In a harsh urban environment, with the gradual increase of the spreading factor(lowering data rate), the gateway is able to receive LoRa packets up to a distance of less than 2km, which is a relatively long distance in a lossy environment. In all telecommunication systems, by moving away from the gateway, the received power by the base station and signal quality decreases. LoRa is no exception and according to the test results, in places far from the gateway, the amount of power received exceeds -100dBm. Thanks to high sensitivity LoRaWAN gateways which are able to receive down to -139dBm at spreading factor 12.

The originality of the work is mainly related to the testing environment that was surrounded by high buildings which degrade the communication performance a lot. However, experiments illustrate that LoRa would be a good choice even in harsh urban environments.

LoRaWAN networks are best suited for outdoor IoT applications such as smart cities, agriculture, farming, and airports, among others. There has always been a gap in indoor deployment that causes signal propagation and network issues in inside scenarios and applications for various indoor users.Therefore, more research regarding indoor developments needed in the future.

1.2 Thesis Outline

The remainder of the thesis work is structured as follows: Chapter 2 is the demonstration of the new LPWAN technologies and their unique features. In Chapter 3, we describe the concept of LoRa, the general architecture of LoRaWAN and reviewing the main parameters of physical and MAC layers. Chapter 4 introduces the system model and components which will be used in this research. Measurement results and evaluation are described in Chapter 5 and the analysis and simulation of the extracted results will be argued in chapter 6. The conclusion of the research work is provided in Chapter 7.

Chapter 2

Low Power Wide Area Network(LPWAN)

LPWAN uses a basic network architecture and long-distance communication with low data rates [9], and it was built specifically for applications that require only a few messages per day to be transmitted across a long radio range. SigFox, LoRaWAN, and NB-IoT are the most popular technologies. The three typical important challenges for LPWAN are: [13]

1. Nodes should be cheap (chip price 1-2).
2. Nodes should have a lifetime of up to ten years when they are battery-powered (2500 mAh) and
3. The distance between the base station and a node may exceed 10 km.

Long Range, Ultra-Low Power Operations, Low Cost and low data rate are the primary characteristics of LPWAN, which will be discussed.

1. Long Range: LPWAN technologies help to provide wide-area coverage with good signal transmission, even in challenging and harsh environments. End devices can communicate with the base station across long distances. Using the sub-GHz band allows for reliable communication while maintaining a low power budget. Low-frequency signals have the benefit of being more robust to multipath fading and attenuation due to obstructions or thick surfaces. Furthermore, because most popular wireless technologies such as Wi-Fi, Bluetooth, and ZigBee use the 2.4 GHz band, these frequencies are less overcrowded.
2. Low Power: To enter into the business of IoT devices that run on batteries, a solution must have extremely low power consumption. The following is the key LPWAN design strategies for achieving it:
   Duty Cycle: Only by turning off power-hungry components of IoT devices power-efficient operation can be achieved. The duty cycle of

a component, device, or system is the percentage of time it is used. The duty cycle can be stated as a percentage or a ratio Depending on the channel, there is a 0.1 percent to 1.0 percent duty cycle every day in Europe. Duty cycle limiting allows LPWAN systems to broadcast and receive data only when they are needed. As a result, power-hungry components, such as transceivers, are often turned off during the network's lifetime. The end device only wakes up for transmission if the application requires data to be sent through an uplink connection. Furthermore, the end device only listens when the data is transmitted in downlink mode by the base station. For a transmitter to establish the time limit to occupy the channel, regional norms are in effect. The European Telecommunication Standard Institute [9] and the Institute of Electrical and Electronics Engineering [10] are two famous standard-setting organizations.

3. Cost Effectiveness: One of the reasons for the commercial success of LPWAN technologies are their cost effectiveness, with hardware prices as low as a few dollars [33]. This allows technology to compete with cellular networks by providing services to numerous applications.

4. Low Data Rate Using a low data rate with small packet data sizes is one of the characteristics of LPWAN systems that differs for different LPWAN technologies such as SigFox, LoRa ...

2.1 Famous LPWAN Technologies

In this section, different proprietary technologies e.g. SigFox, LoRaWAN, and NB-IoT is highlighted.

2.1.1 SigFox

SigFox provides LPWAN solutions in unlicensed sub-GHz bands that are implemented across many geographies. Sigfox uses 868 MHz, 902 MHz, and 433 MHz across Europe, North America, and Asia, respectively. End-devices connect with the base station using Binary Shift Keying (BPSK) modulation in a narrow band of 100 Hz with a data rate of 100 bits per second in uplink transmission. As a result, using UNB in the sub-GHz spectrum leads to improved frequency band utilization with lower noise levels [37]. Therefore, receiver sensitivity is increased while power consumption is reduced. Furthermore, Sigfox was originally designed for uplink communication, but it eventually evolved into bidirectional communication. Regional restrictions limit the number of messages sent by uplink transmission to 140 with 12-byte message size [35]. Despite this, downlink communications are limited to four per day, preventing the base station from acknowledging every uplink message. Downlink messages have an 8-byte payload.

2.1.2 NarrowBand IoT (NB-IoT)

Narrowband IoT is a technology that coexists in LTE and GSM under licensed frequency bands. Main capabilities of NB-IoT include: Main capabilities of NB-IoT include:

1. Deployment in a very small bandwidth
2. Extended coverage compared with existing cellular
3. Optimized for very long terminal battery life (10 years)
4. Support for massive connections (50K devices)
5. Optimized for ultra-low terminal cost

NB-IoT should support 3 different modes of operation which are shown in figure 2.1.

1. Stand-alone: using for example the spectrum currently being used by other systems a replacement of one or more GSM carriers, as well as scattered spectrum.
2. Guard-band: utilizing the resource blocks that are unused within a LTE carriers guard band.
3. In-band: utilizing resource blocks within a normal LTE carrier[36].

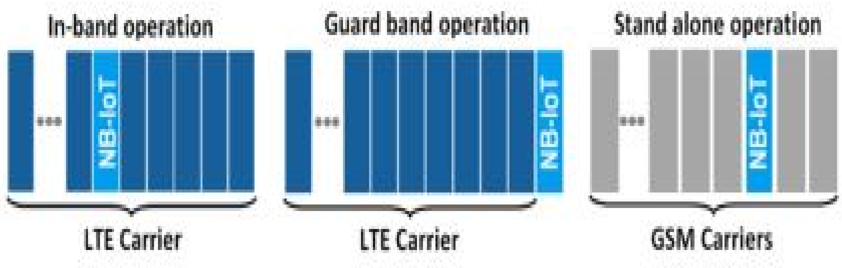


Figure 2.1: Operation Modes of NB-IoT

2.1.3 LoRaWAN

The architecture of a LoRa network, as well as the medium access control (MAC) and network layers, are defined in the LoRaWAN standard [31]. The LoRa Alliance, a non-profit organization, maintains the LoRaWAN specification and offers a certification procedure to ensure compatibility. Devices communicate directly to one or more gateways in LoRaWAN, which transfer messages to a network server over an Internet backbone. The network server removes duplicate messages (data from devices might come in through many gateways) and sends them to the appropriate application server. The end-user typically provides only the devices and application server, while a network provider provides the gateways and network server. All MAC choices, such as data rate and ACK processing, are made at the servers. To handle collisions, the LoRaWAN utilizes The ALOHA MAC mode, which permits end-devices to transmit as soon as they wake up and apply exponential back-off in the event of a collision [29]. The major goal of its development is to give sensors the ability to exchange data frames with a server at a low data rate and with a comparably short time between transmissions. The network architecture is set up in a star-of-stars topology, with end-devices connecting to network servers via the gateway. The bit rate of LoRaWAN is adjusted in line with the available channel quality. It makes use of the SF characteristic to adjust between modulated signal robustness and bit rate. When a sensor node has poor network quality, LoRaWAN boosts the SF to allow the modulated signal to be sent over a long distance. In this case, the bit rate would be low. This variation in data rate is controlled by the LoRaWAN parameter (DR), which in the EU ranges from DR0 (SF12, lowest bit rate) to DR5 (SF7, highest bit rate).

2.2 LPWAN Comparison

In order to be able to choose the best technology for industry usage, a comparison between different LPWAN technologies must be considered which is argued in table 2.1. Both LoRaWAN and SigFox use license-free sub-GHz band which is less cost for these two technologies. Interference and multipath fading are reduced as a result of this. NB-IoT makes use of licensed bands to deliver QoS at a high cost. NB-IoT devices have a shorter working lifetime with respect to SigFox and LoRaWAN [38]. In general, all LPWAN technologies have a well-established deployment paradigm, and among them LoRaWAN technology being implemented in over 100 countries [39].

Table 2.1: Technical Specification of LPWAN Technologies

	SigFox	LoRa	NB-IoT
Modulation	BPSK	CSS	QPSK
Frequency	Sub-GHz ISM EU 868 MHz US 902 MHz	Unlicensed ISM EU 868 MHz US 915 MHz	Licensed LTE Frequency Band
Data Rate	100 bps [UL] 600 bps [DL]	0.3-50 kbps	200 kbps
Range	10 km [Urban] 50 km [Rural]	5 km [Urban] 15 km [Rural]	1 km [Urban] 10 km [Rural]

Chapter 3

LoRa and LoRaWAN Overview

3.1 LoRa Technology

Long Range (LoRa) is a WSN technology that supports IoT by sending long-range signals with minimal power consumption. The goal of LoRa is to provide secure bidirectional communication[32]. Semtech [7] introduced LoRa in 2012. LoRa technology uses sub-GHz frequencies in the 433 (Asia), 868 (Europe), and 915 (North America) MHz bands in the Physical Layer Protocol. Each nation regulates the frequency of LoRa, which has various frequencies [8] [23]. In the European area, the LoRa standard frequency is 863–870 MHz (EU863) [14]. Using frequency bands of (863 MHz - 870 MHz) in Europe, requires to follow the below guidelines:

1. The maximum transmission power for uplink is restricted to 25mW. (14 dBm).
2. The maximum transmission power for downlink is restricted to 0.5W. (27 dBm).

The network operator (for example, The Things Network) might impose extra limits in addition to the ISM band requirements. LoRa is generally divided between two layers:

1. Physical Layer: The Chirp Spread Spectrum (CSS) radio modulation technique is utilized to communicate between end devices and gateways.
2. MAC Layer: LoRaWAN is a multicast networking technology that employs the LoRa MAC layer protocol. It specifies the set of rules that radio waves must follow in order to get access to the LoRaWAN gateway and execute channel operations.

The LoRa physical layer is a Semtech-developed private technology, whereas LoRaWAN is a LoRa-Alliance-developed open standard.

3.1.1 LoRa Physical Layer

The physical layer of LoRa uses LoRa modulation. A chirp spread spectrum modulation employs wide-band linear frequency modulated pulses whose frequency changes over time. As a result of this modulation technique, LoRa technology is robust to multipath fading and the Doppler effect.
The chip rate (chip-per-second-per-Hertz) is equal to the programmed bandwidth and can be 125, 250, or 500 kHz. To boost noise resistance, the LoRa physical layer includes forward error-correcting codes. Different data speeds are available, ranging from 300 bps to 50 kbps, according to reports. The choice of data rate is based on a trade-off between transmission length (the amount of time the message is sent over the air) and range [21]. Furthermore, depending on the communication distance and required on-air duration, the spreading factor (SF) for a LoRa link may be adjusted. Using forward error-correcting code along with frequency hopping spread spectrum(FHSS) reduces interferences with other radio waves. Traffic is considerably imbalanced in LoRa communication, with uplink dominating over the downlink. End devices send at any moment on any supported channel without utilizing listen before talk. In practice, the channel should be chosen pseudo-randomly while respecting the duty cycle limits imposed by frequency rules. The European standards [22] imposes a maximum 1% duty cycle to each LoRa end device.

3.1.2 LoRa Characteristics

LoRa technology has various characteristics that make it a popular technology. The distinguishing characteristics are as below:

1. Ultra-long distance: According to the previous researches in [17], [25], the longest SF12 can reach a distance of up to 5Km and the smallest SF7 can accomplish a distance of 2Km in Line-of-Sight (LOS) communications. The longest distance reached in Non-Line-of-Sight (NLOS) circumstances with structures are less than 2Km [26]. It is also worth noting that the factors Bandwidth, SF, transmission power, and coding rate all have an effect on communication distance [18].

2. Low cost and complexity: The LoRa devices are manufactured in such a way that they are not complicated. As a result of this, we can face low-cost end nodes. By reducing the complexity the overhead reduces during the communication as well. The end devices operate in such a way that they do not use the complicated listen before talk(LBT), instead the nodes start transmission when they need, Therefore the

pure ALOHA system is using. Pure ALOHA system is a random access protocol in which the end device transmits whenever it has data to be sent toward the gateway at any time. In this system the frames that are collided will be destroyed. In LoRa, The chance of collision is low due to the 1% duty cycle restrictions.

3. Extended lifetime: Depending on the radios and boards utilized, LoRa uses 120-150 mW for transmission. This can be extended to a total life period of 2-5 years.

4. Concurrent reception of LoRaWAN gateway: LoRa gateways can receive data on up to eight channels at the same time. The same SF can be received on many channels. All of the spreading factors from SF7 to SF12 are orthogonal, therefore broadcasts with various SFs can be received on the same channel at the same time.

5. Resilience to Doppler effect: LoRa transmissions are highly resistant to the Doppler effect because of the CSS modulation technique. moving LoRa end-devices operating at a constant speed and in LOS can achieve packet delivery ratio(PDR) more than 85%[30].

3.1.3 LoRa Parameters

To customize connection performance and energy usage, a LoRa device uses different transmission parameters such as Transmission Power (TP), Carrier Frequency (CF), Spreading Factor (SF), Bandwidth (BW), and Coding Rate (CR).

1. Transmission Power: TP on a LoRa radio may be modified from 4 dBm to 20 dBm, however, due to hardware implementation restrictions, the range is limited from 2 dBm to 20 dBm. Furthermore, due to hardware restrictions, power levels greater than 17 dBm may only be used on a 1% duty cycle.

2. Carrier Frequency: The carrier frequency is the central frequency that may be set in stages of 61 Hz between 137MHz and 1020MHz and is used to transmit data. This range may be restricted to 860MHz to 1020MHz depending on the LoRa chip.

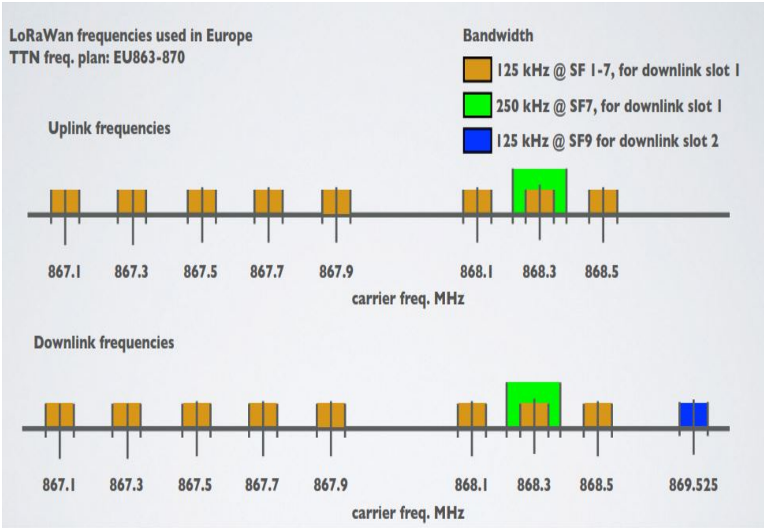


Figure 3.1: EU863-870 ISM band channel frequencies

3. Spreading Factor: The symbol rate to chip rate ratio is defined by SF. A greater spreading factor improves the signal-to-noise ratio (SNR), sensitivity and range, but it results in increasing the packet transmission duration. The number of chips per symbol is equal to 2^{SF}. For instance, 4096 chips/symbol are used with an SF of 12 (SF12). The spreading factor can be set between 7 and 12. Different SF radio communications are orthogonal to each other, and network separation using different SF is possible [19][7][4]. If we increase the SF by 1:

    (a) The symbol duration time almost doubles with respect to the previous SF.

    (b) It cuts the bit rate in half as compared to the previous SF.

    (c) The Time on Air (ToA) increases.

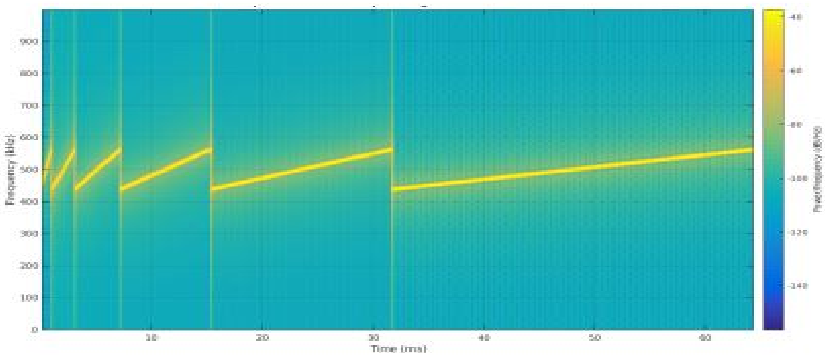


Figure 3.2: LoRa chirps with different spreading factor

Figure 3.2 depicts a summary of symbol durations in relation to various Spreading Factors.The symbol duration doubles when the SF rises by one.

4. Bandwidth: The width of the transmission band is defined by BW. Larger BW results in a higher data rate (and consequently less time on-air), but results in decreasing the sensitivity (because of integration of additional noise). A lower BW results in greater sensitivity but a lower data rate. 125 kHz bandwidth corresponds to a chip rate of 125 kbps. Although bandwidth may be chosen from 7.8 kHz to 500 kHz, a typical LoRa network works at 500 kHz, 250 kHz, or 125 kHz.

5. Coding Rate: CR is the LoRa modem's FEC rate that protects against bursts of interference and may be adjusted to 4/5, 4/6, 4/7, or 4/8. A greater CR provides better protection, but increases the amount of time spent in the air.

3.1.4 LoRa Packet Format

The physical layer frame format is defined in Semtech manufactured transceivers. A message frame's bandwidth and spreading factor stay constant. LoRa message includes a preamble, physical header, physical header Cyclic redundancy check, physical payload and cyclic redundancy check for error detection.

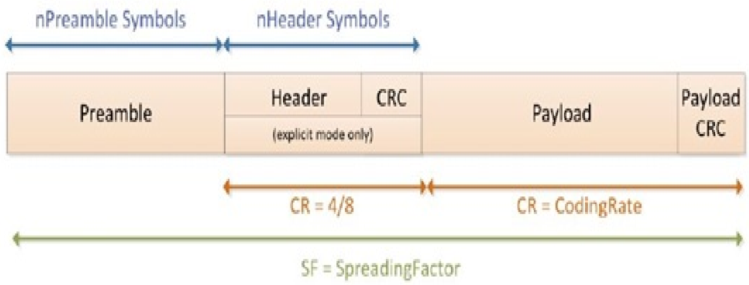


Figure 3.3: Physical Layer Message Format [34]

The preamble is utilized by the receiver to determine the start of the packet. The default mode of operation is the header. It contains payload information such as payload length in bytes, forward error-correcting code rate, and the presence of a 16-bit CRC for the payload The payload is a variable-length field containing the actual data encoded at the forward error-correcting coding rate set in the header in explicit mode or fixed in implicit mode. A payload CRC is optionally added. A LoRa frame starts with a preamble. The preamble initializes with a sequence of constant up chirps. The last two up chirps encode the sync word which is shown in figure 3.4. The sync word is a one-byte value used to distinguish LoRa networks that operate in the same frequency ranges. If the decoded sync word does not match the device's settings, the device will stop listening to the message. Two and a quarter down chirps come after the sync word, for a duration of 2.25 symbols.

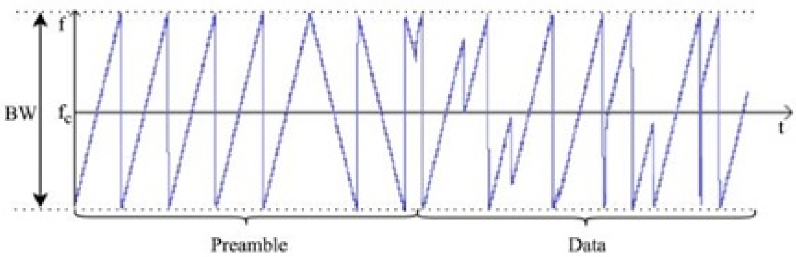


Figure 3.4: Frequency changes over time of a sample signal emitted by a LoRa transmitter [40]

The preamble length is adjustable. Furthermore, only uplink communication has 2 bytes of PHDR, 4 bits of PHDR CRC, a variable length of Payload, and 2 bytes of CRC.

3.1.5 LoRa End Device Activation Methods

LoRaWAN End-Device activations are classified into two types: Activation-by-Personalization (ABP) and Over-the-Air (OTA) activated End-Devices.

Over the Air Activation (OTAA)

To be activated on a certain network, OTA End-Devices go through the Join Procedure, during which a dynamic device address (DevAddr) is issued to an end device and root keys are used to generate session keys. As a result, DevAddr and session keys change with each new session [44]. Over-the-Air (OTA) activation is employed in this study. With respect to ABP activation method, OTAA is the preferred because it provides the most secure way to connect end devices to a network server. Before activation:

1. End devices must know and save its DevEUI, AppEUI and AppKey.
2. The network server must know and save the same AppKey.

EUI stands for Extended Unique Identifier which is 64-bits long and is generally used for the identification of network components. The DevEUI, which is comparable to a MAC address, uniquely identifies the end device. The AppEUI, which is comparable to a port number, uniquely identifies the Application Server. The AppKey is a 128-bit AES (Advanced Encryption Standard) symmetric key (also known as the root key) that is used to produce the Message Integrity Code (MIC) to verify the message's integrity. The identical AppKey must be stored on both the end device and the network server. To prevent malicious devices from replaying the Join-Request, the end device creates the DevNonce, which is a randomly generated number. The end device creates a message that includes the DevNonce, AppEUI, and DevEUI. The AppKey generates the Message Integrity Code (MIC) for this message.

The LoRa end device activates itself by transmitting a Join-Request message including the DevNonce, AppEUI, DevEUI, and MIC to the network server. When the network server gets the Join-Request message, it checks to see if the DevNonce has never been used before. The network server uses the MIC value to authenticate the end device. If approved, the network server generates the following values: DevAddress (Device Address) In order to decrease protocol overhead in transmitted frames, the DevAddr translates the DevEUI to a shorter address (32 bits). The network server creates a message that includes the DevAddr, AppNonce, NetID, and certain network parameters. The AppKey generates the Message Integrity Code (MIC) for this message. The AppKey is utilized to encrypt the message itself. The network server then delivers a Join-Accept response to the end device, which includes the encrypted communication and the MIC. The AppNonce and DevNonce are now shared by both the end device and the network server.

The AppNonce and DevNonce are used by the end device and network server to produce two session keys: the Network Session Key (NwkSKey) and the Application Session Key (AppSKey). The AppSKey and DevAddr are sent to the application server by the network server. To maintain data integrity, the end device and network server utilize the NwkSKey to calculate and validate the Message Integrity Code (MIC) of all data messages. The NwkSKey is also employed in the encryption and decryption of the payload. The AppSKey protects end-to-end communications between the end device and the application server. The application server and end device employ the shared symmetric key to encrypt and decode the payload. End-to-end encryption is used between the end device and the application server.

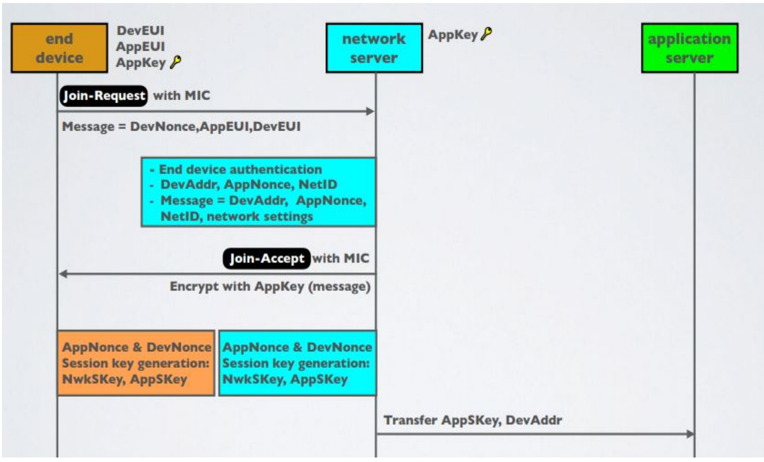


Figure 3.5: OTAA procedure

Activation by Personalization (ABP)

In the Activation-By-Personalisation (ABP) mode no Join-Request or JoinAccept messages is sent. By passing the Join Procedure, ABP End-Devices are immediately linked to a specific network.

3.2 LoRaWAN Technology

LoRa has the network characteristics of "a star-of-star topology" [4] [12] [24], as shown in figure 3.6. A LoRa network includes several elements:

1. Endpoints: Endpoints are low-cost, battery-powered. They are parts of the LoRa network that perform sensing or control. They are usually situated in a distant location.

2. LoRa gateway : The gateway accepts messages from LoRa endpoints and routes them to the backhaul infrastructure. This component of the LoRa network would be Cellular, Ethernet, or any other telecommunications links. Standard IP connections are used to link the gateways to the network server.

3. LoRa Network Server (NS): It is in the center of the star topology. Network servers in LoRaWAN ensure the security of the data which is routed toward the network and are responsible for management and connectivity of LoRa end devices, gateways and end-user applications. Generic features of NS are:

   (a) End-Device address check

   (b) Data rate adaptation

   (c) Responding to MAC layer requests sent by the end device

   (d) Forwarding uplink application payloads to the specific Application Servers

   (e) Queuing of downlink payloads coming from any Application Server to any End Device connected to the network

   (f) Forwarding Join-request and Join-accept messages between the End-Devices and the Join Servers.

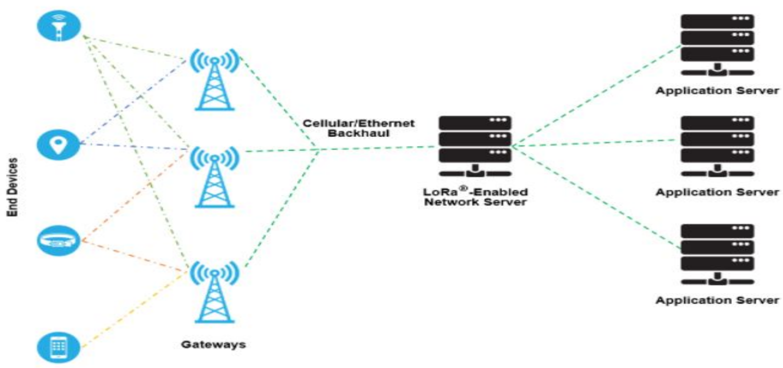
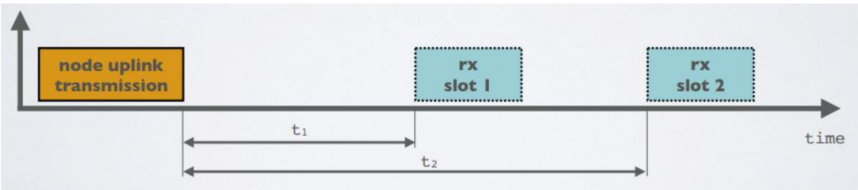


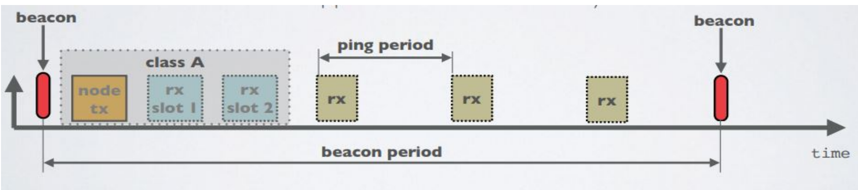
Figure 3.6: LoRaWAN Network

3.2.1 LoRaWAN Classes

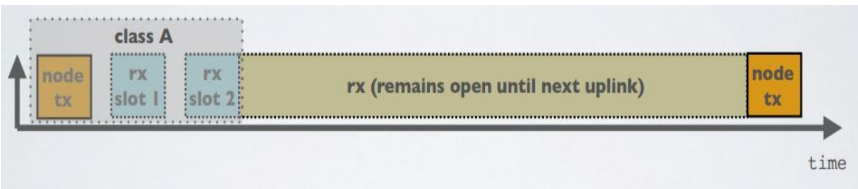
There are three types of devices in LoRaWAN: class A, class B, and class C. End devices that operate in Class A and Class B modes are often battery-powered, whereas end devices that operate in Class C are often mains powered. Class A consumes less energy than Class B and Class C. End devices in Class A anticipate an acknowledgment (ACK) from the Network server after transmitting confirmed messages during two pre-agreed-upon time-slots known as "receive windows (RW)". Figure 3.7 depicts the RWs of Class A, B and C operating modes. The first RW's frequency and data rate are the same as the uplink transmission characteristics, while the second slot operates on pre-agreed specifications. Unconfirmed communications do not provide responses from end devices. Class B operating mode allows gateways to plan extra receive windows through beacon packets. As a result, a periodic beacon from the gateway is required for synchronization. Class C mode has no downlink constraints and can receive downlink messages at any time it is not broadcasting so this type of classes consumes much more energy with respect to others[41]. The study provided in this work mainly focuses on Class A end-devices.



Class A



Class B



Class C

Figure 3.7: LoRaWAN Classes

LoRaWAN does not provide inter-device communication. Packets can only be sent from an end device to a gateway or vice versa. Figure 3.8 depicts the LoRaWAN protocol stack. The physical layer defines the ISM bands, while the LoRa modulation layer is appropriate for long-distance communication with low power consumption. Semtech has used CSS modulation to do this [42].

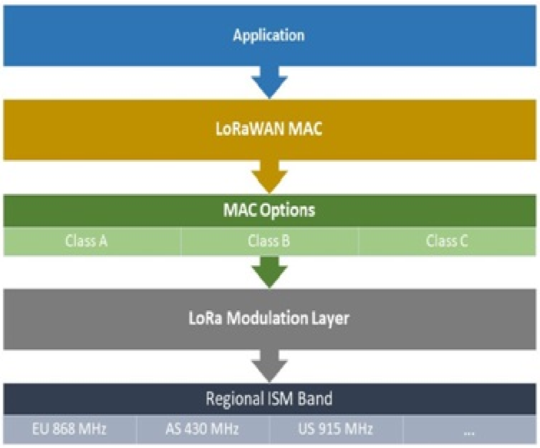


Figure 3.8: LoRaWAN Protocol Stack

Chapter 4

System Design and Implementation

4.1 Proposed System Model

In this chapter, we are going to introduce the system model and the components that are used for this approach.

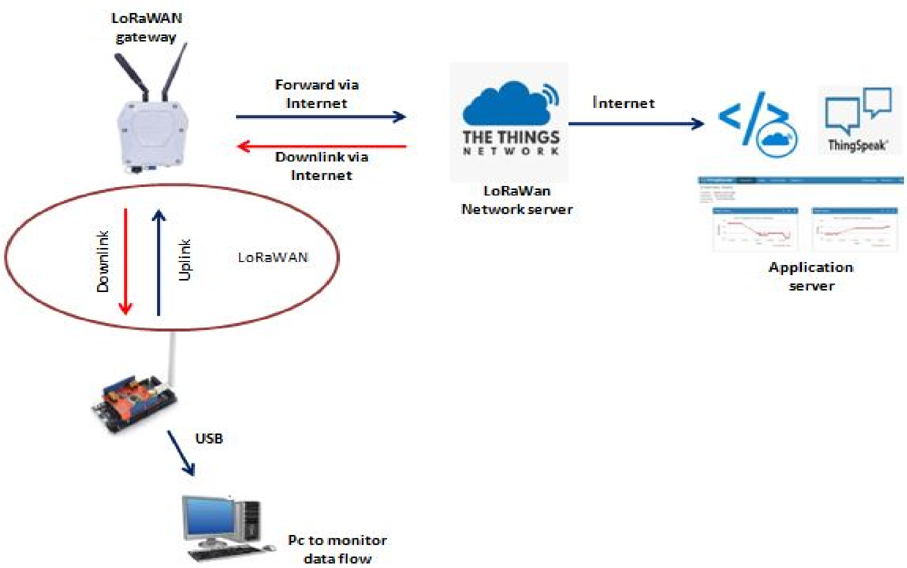


Figure 4.1: System Model

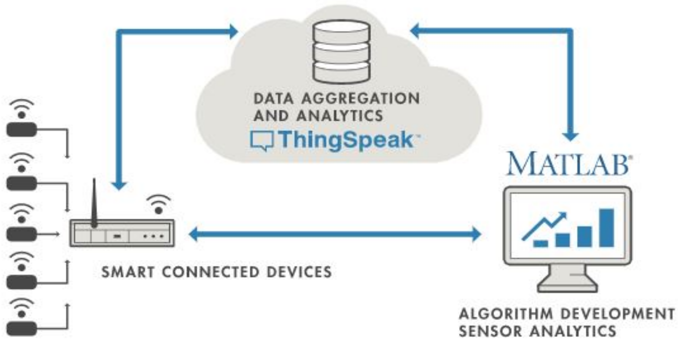


Figure 4.2: ThingSpeak mechanism

The goal is to build a LoRaWAN network for sending sensor node data to the gateway and then transferring info to the network server in order to be processed. In the other direction, due to bidirectional communication in LoRaWAN the end device will receive downlink packets that are sent by the gateway. Graphic above depicts the overall relationship of components. Sensor data will be delivered over a LoRaWAN gateway to a Thing Network server, and when the packet arrives, it allows us to collect, display, and analyze live data streams in the cloud. Our data is saved in channels with ThingSpeak integration. Each channel may hold up to eight fields of data. Pc in this architecture is used to see the data flow on the application side and it is not necessary to connect the end device to the Pc in order to be run. There are many end devices in the market which are battery powered without any need to the Pc connection.

4.2 System Architecture and Components

4.2.1 Gateway

Every LoRa gateway has two components listed below:

1. A processor to demodulate the signal.

2. One or two TX/RX radios.

The gateway utilized in this experiment is SenseCap, a ready-made gateway that uses the RAK2247(SX1301) LoRa concentrator module at 868MHz frequency. The gateway connects to the Internet via numerous means, including 4G and Ethernet, and It offers super long-distance communication of up to 10 kilometers of line-of-sight (LOS) and almost 2 km of non LOS in urban areas. Sensecap gateway can receive on 8 channels in parallel in sub-bands 868 MHz and 867 MHz and with all spreading factors. Because spreading factors are orthogonal to each other, two packets with different

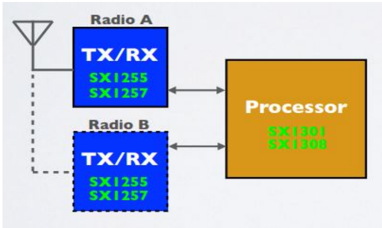


Figure 4.3: LoRa gateway Architecture

SF can be delivered on the same channel at the same time. This gateway is able to receive up to -139dBm at spreading factor 12. As can be seen from the picture below, two antennas are connected to the gateway which are LoRa and 4G antennas.

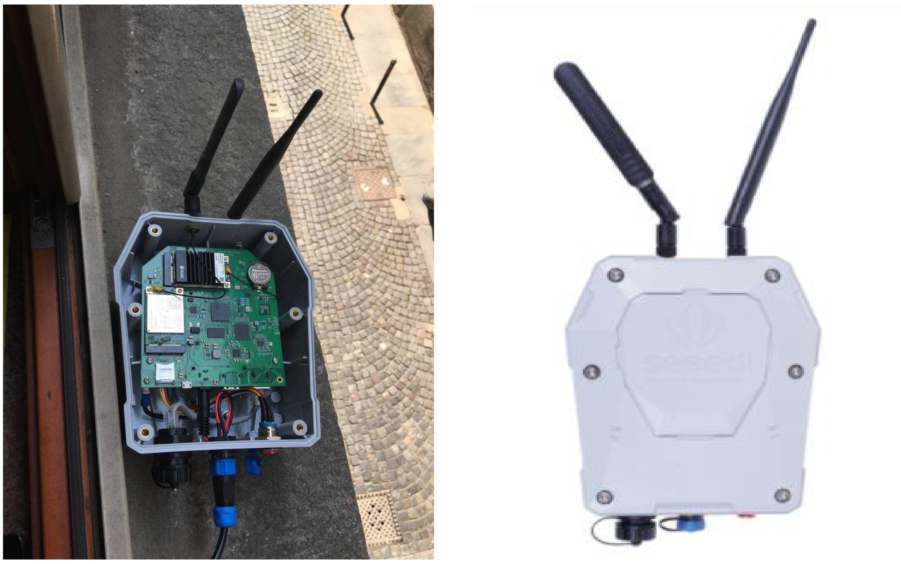


Figure 4.4: LoRaWAN gateway

4.2.2 LoRaWAN Network Server

The Network Server (NS) is the entity at the heart of the star architecture that is responsible for receiving and sending packets via the gateways. It is in charge of the data rate adaption algorithm as well as any MAC layer requests from end devices. The Join requests are sent to the Join Server (JS), which handles network device authentication and controls the Over-the-Air (OTA) End-Device activation procedure. Finally, the Application Server (AS) manages the network's applications; precisely, all traffic related to a certain application and group of devices is forwarded through a single interface. The Application Server manages all application layer payloads from the related End-Devices and provides the end-user with application-level service. It also creates all application layer downlink payloads for associated End-Devices [43].

In this thesis, the things network (TTN) server is employed. TTN offers a set of open tools and a global, open network to help us develop our next IoT application at a cheap cost, with optimum security and scalability. A safe and collaborative Internet of Things network that covers several nations across the world is developed using strong end-to-end encryption. It is possible to construct programs and register devices to them using their DevEUI, a unique address assigned to the transceiver during the manufacturing process. The device data may be accessed using the Message Queue Telemetry Transport (MQTT) and Hyper Text Transfer Protocol (HTTP) protocols. The network server saved all the received packets together with information from the physical layer such as RSSI and SNR values, channel on which it was received and the code rate.

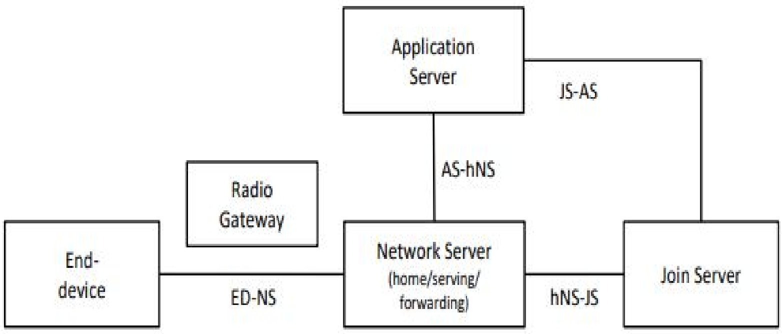


Figure 4.5: LoRaWAN network reference model

Various integrations enabled by The Things Network server were utilized throughout the test to pass messages to some webhook or other messaging endpoints (uplink messages), such as HTTP and ThingsSpeak. Integrations are the most convenient way for us to link our gadgets to apps. An integration makes use of the same APIs as a standalone program Together with the platform's private or public APIs, it connects the platform's application to The Things Network. Integrations serve as a link between the Handler Data API and any endpoint you specify. It also serves as an endpoint for us to deliver messages back to devices (downlink messages).

TTN Limitations

The Things Network imposes some limitations and rules when using TTN server which is called Fair Access Policy. Fair Access Policy limits the data each end-device can send, by allowing:

1. An average of 30 seconds uplink time on-air, per 24 hours, per device.
2. At most 10 downlink messages per 24 hours, including the ACKs for confirmed uplinks.

ThingsSpeak Integration

ThingSpeak is an IoT analytics platform service provided by Math Works, the company behind MATLAB and Simulink. We can use ThingSpeak to collect, visualize, and analyze live data streams on the cloud. ThingSpeak generates real-time visualizations of data sent by devices or equipment. We execute MATLAB code in ThingSpeak and do real-time data analysis and processing.

HTTP Integration

HTTP integration for uplink and downlink data is made easier by the Things Network. This feature allows one to send data from the TTN console to an HTTP endpoint and receive and pass data from the endpoint to a LoRa node.

4.2.3 LoRa End Device

All LoRa end devices must have a micro-controller (e.g. ATMega32), a LoRa radio module (e.g. SX1276) and, an antenna.

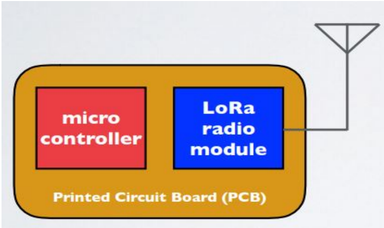


Figure 4.6: Lora node

Dragino LoRa Shield v95 is selected to use as LoRa end device which is connected to a dipole antenna with 2.15 dbi gain. The Dragino LoRa Shield is a long-range transceiver on an Arduino. The LoRa Shield enables users to communicate data over long distances at low data rates. It offers ultra-long range spread spectrum communication and great interference immunity while consuming the least amount of power.
The SX1276/SX1278-based LoRa Shield is intended for professional wireless sensor network applications such as smart cities, building automation, and so on. Using Semtech's unique LoRa modulation method, the LoRa Shield can reach a sensitivity of more than -148dBm while utilizing a low-cost crystal and bill of materials. The combination of high sensitivity and an included +20 dBm power amplifier results in an industry-leading link budget, making it ideal for any application needing range or durability.

Figure 4.7: Dragino lora shield v95

Besides the SX1276 transceiver, the node included a set of sensors such as temperature and humidity digital sensor (DHT11).
The DHT11 is a basic digital temperature and humidity sensor that is extremely inexpensive. It measures the humidity and temperature and outputs a digital signal on the data pin. In these sensor types, there is no need for

analog pins.

Figure 4.8: DHT11 digital sensor

In order to extract the sensor measurements, we must add DHT library in the beginning, below a piece of code that is used for initializing sensor data is given:

```
#include <DHT.h>

#define DHTPIN 4
#define DHTTYPE DHT11
DHT dht(DHTPIN, DHTTYPE);
```

Based on the above code data pin of the DHT sensor connected to digital pin 4 of Arduino Uno.
To read the value of temperature which returns the value in Celsius the code below is used:

```
dht.temperature
```

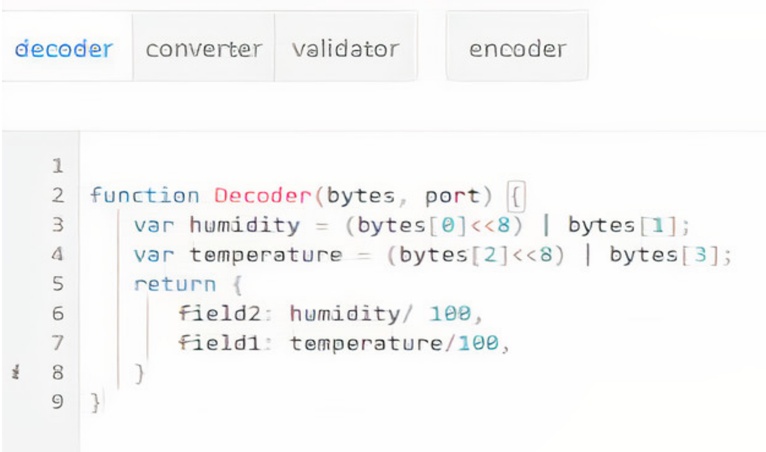
Figure 4.9: Temperature

And for humidity we have:

```
dht.humidity
```

Figure 4.10: Humidity

To make the payload data of the sensor more human-readable in TTN, payload changed with the code below:



decoder | converter | validator | encoder

```
function Decoder(bytes, port) {
    var humidity = (bytes[0]<<8) | bytes[1];
    var temperature = (bytes[2]<<8) | bytes[3];
    return {
        field2: humidity/ 100,
        field1: temperature/100,
    }
}
```

Figure 4.11: Payload decoder function

Which filed 1 shows temperature and field 2 is humidity. Along with the LoRa module and sensors, a micro-controller must be used in the end device. The microcontroller is a piece of hardware that collects data from linked sensors and transmits it to the gateway through LoRa packets. In this test, the micro-controller that used is Arduino Uno. The Arduino Uno is a free and open-source microcontroller board based on the Microchip ATmega328P. The board features 14 digital I/O pins, 6 analog I/O pins, and is programmable through a USB cable using the Arduino IDE. The microcontroller is linked to the LoRa module, which is in charge of performing LoRa modulation through a high-speed SPI connection.

Figure 4.12: Arduino uno

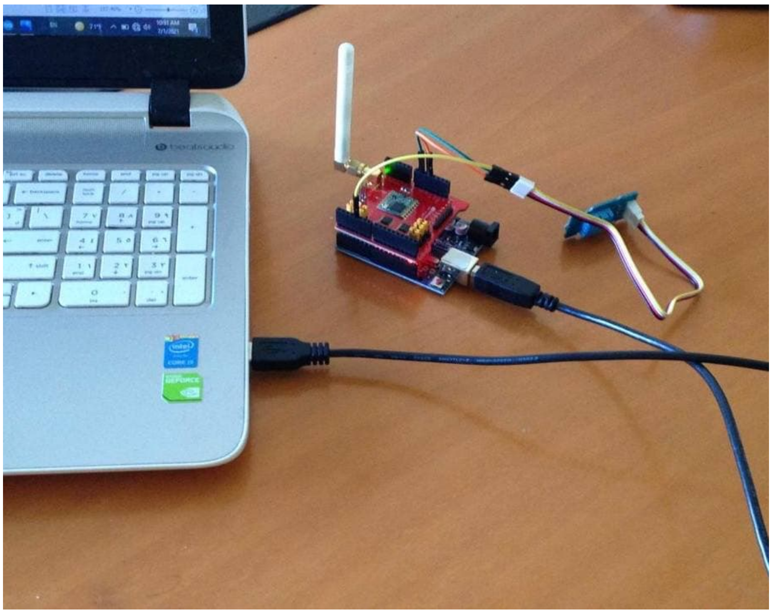


Figure 4.13: LoRa end Node

To make a LoRa end device an interface must be built between the LoRa module and Arduino uno. The special library which is used for this approach is called LMIC library. The LMIC library has a rather full LoRaWAN Class A and Class B implementation that supports the EU-868 and US-915 frequencies. Changes must be done to suit the library with thesis requirements such as adding sensor codes along with enabling the adaptive data rate mechanism and etc.

Adaptive Data Rate (ADR)

Thanks to TTN which made the ADR algorithm publicly available to optimize the data rates, ToA, and energy consumption. The LoRaWAN protocol describes the Adaptive Data Rate (ADR) strategy for controlling the uplink transmission parameters of LoRa devices (spreading factor, bandwidth, and transmission power). End nodes request that the ADR feature be used by setting the ADR flag in the uplink message. If the ADR flag is set, the network server can control the transmission settings of the end node.

```
#define ADR_MODE 1
LMIC_setAdrMode(ADR_MODE);
```

ADR is a relatively basic technique that alters the data rate based on a set of rules:

1. If the link budget is high, the data rate must be increased (decrease in SF)

2. If the link budget is low, the data rate must be decreased (increase in SF)

The end device sends a message up through the gateway, which just forwards the message without acting on the data. The gateway in a LoRaWAN network is a basic, low-cost device that translates LoRaWAN messages into IP packets that may be forwarded to the network server through a secure backhaul. These IP packets provide some metadata regarding the reception time and signal strength. The network server determines the best node data rate based on the strength of the received signal (that is, the spreading factor). The network server's Media Access Controller, commonly known as the MAC layer, communicates with the same layer in the end-LoRaWAN node's stack. The server then issues a MAC command based on its global perspective of the strength of the signals received from all gateways. After collecting numerous results, the network server computes the median of those values to establish both the available link budget and the maximum data throughput that can be maintained, as well as a margin for error to account for fluctuations in channel characteristics. Following the next uplink, a MAC instruction is sent down to the end device to modify the data rate, if necessary. The data rate that the node should utilize is returned to the device from the server via the gateway with the strongest signal strength. ADR should only be utilized in circumstances with stable Radio Frequency (RF) and end nodes that do not move. Mobile end nodes that are immobile for an extended period of time can allow ADR during that time.

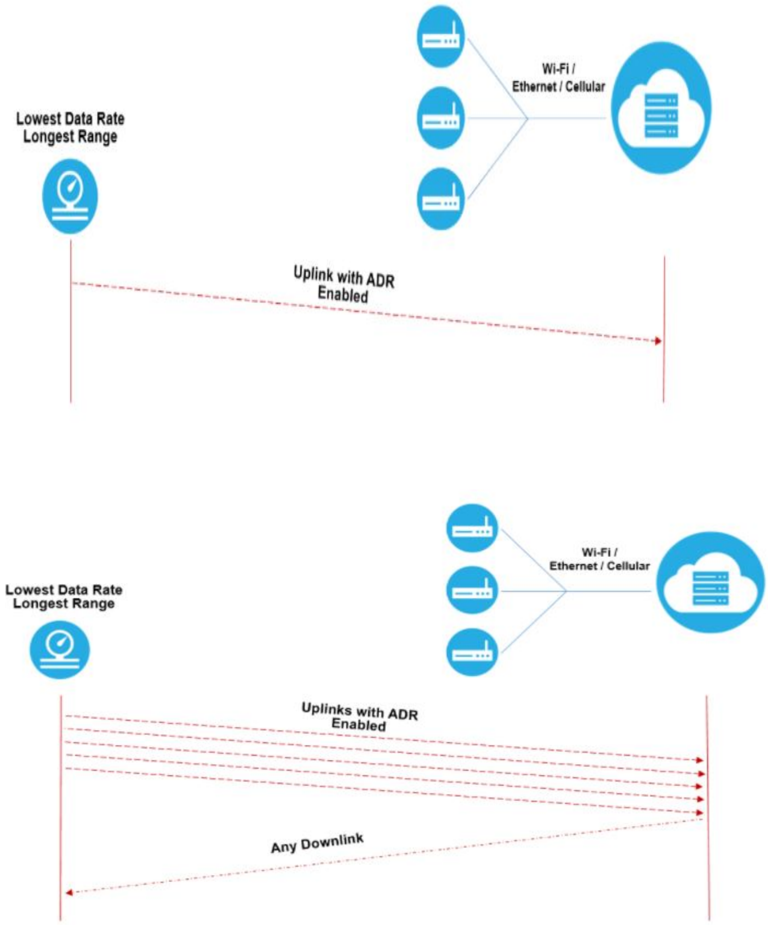


Figure 4.14: ADR mechanism

pictures below were taken from the gateway traffic in TTN server after enabling the ADR. Outcomes illustrate that the network server starts evaluating the link quality in order to adjust the best data rate for the LoRa communication.

0ms	bridge-v3 **forward to Packet Broker**	
3.7ms	router ttn-router-eu **receive**	*gateway:* eui-2cf7f110:
3.86ms	router ttn-router-eu **build downlink**	*options:* 2
3.88ms	router ttn-router-eu **forward**	*brokers:* 1
4.27ms	broker ttn-broker-eu **receive**	
204.32ms	broker ttn-broker-eu **deduplicate**	*duplicates:* 1
206.88ms	broker ttn-broker-eu **got devices from networkserver**	*devices:* 5
206.9ms	broker ttn-broker-eu **check mic**	*mic checks:* 2

208.68ms	networkserver ttn-networkserver-eu **update state**	
209.28ms	networkserver ttn-networkserver-eu **schedule mac command**	*cmd:* link-adr *reason:* adr-ack-req
215.63ms	broker ttn-broker-eu **forward**	*handler:* ttn-handler-eu
216.1ms	handler ttn-handler-eu **receive**	
217.01ms	handler ttn-handler-eu **process uplink**	
217.02ms	handler ttn-handler-eu **check mic**	
599.4ms	handler ttn-handler-eu **prepare downlink**	

600.74ms	handler ttn-handler-eu **process downlink**	
601.01ms	handler ttn-handler-eu **set empty payload**	
601.05ms	handler ttn-handler-eu **forward**	*broker:* ttn-broker-eu
605.54ms	broker ttn-broker-eu **receive**	
624.76ms	networkserver ttn-networkserver-eu **update state**	
627.06ms	broker ttn-broker-eu **forward**	*router:* ttn-router-eu
628.74ms	router ttn-router-eu **receive**	
629.38ms	router ttn-router-eu **send**	

Figure 4.15: Mac commands

Chapter 5

Measurements and Results

After describing the system components and the methodology which is used to evaluate the system performance, in this chapter, we will discuss some test results done by implementing the system structure mentioned in the previous chapter. This test was performed to assess the degree to which LoRa can deliver and receive data. The goal of this test is to analyze the performance of LoRaWAN in a harsh environment to determine the maximum range over which a LoRa gateway can receive LoRa packets.

5.1 Initial Test Parameters

During the measurements, each node sent a packet including temperature and humidity information to the base station on a regular basis. As stated in the preceding chapter, adaptive data rate (ADR) is enabled to manage the data rate. The period of sending the packets was set to 60 seconds. During the experiments, the node was randomly choosing between one of six channels to send each packet. Because Italy uses the EU863-870 band, then according to the LoRaWAN Regional document every end device working in EU868MHz must implement the following channels:

1. 868.10 MHz, bandwidth = 125 kHz
2. 868.30 MHz, bandwidth = 125 kHz
3. 868.50 MHz, bandwidth = 125 kHz

and additional 5 frequencies. The other 5 frequencies can be freely adjusted by the network operator. For example, The Things Network implemented 867.1, 867.3, 867.5, 867.7 and 867.9 frequencies. Note, that node automatically counts own on-air time for each radio channel and follows the imposed duty cycle restrictions. The transmission power for the end node was set to 14 dBm (25 mW).

5.1.1 Received Signal Strength Indicator(RSSI)

The Received Signal Strength Indicator (RSSI) is the measured received signal power in milliwatts (dBm). This number is used to discover how effectively a receiver can "hear" a signal sent by a sender.

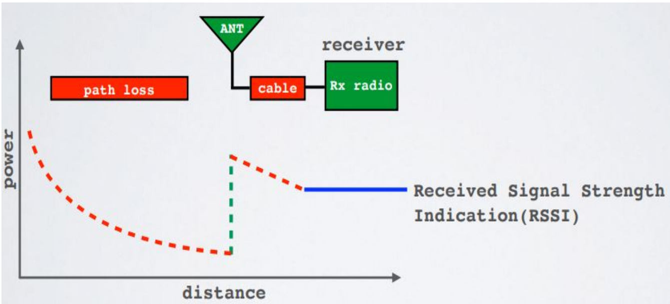


Figure 5.1: Received Signal Strength Indicator

The RSSI unit is dBm and it is a negative value. RSSI value close to zero shows better signal strength. Typical LoRa RSSI values are:
RSSI minimum = -120 dBm.
If RSSI=-30dBm: signal is strong.
If RSSI=-120dBm: signal is weak.

5.1.2 Signal to Noise Ratio(SNR)

Signal-to-Noise Ratio (SNR) is the ratio between received signal power and the noise power level. The noise floor is a region that contains all undesired interfering signal sources that might distort the transmitted signal and cause re-transmissions. Normally, the physical limit of sensitivity is the noise floor; however, LoRa operates below the noise level.

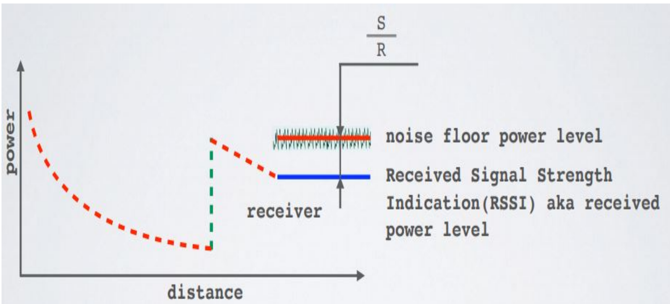


Figure 5.2: Signal to Noise Ratio

Typical LoRa SNR values are between: -20dB and +10dB A value closer to +10dB means the received signal is less corrupted. LoRa has the ability to demodulate signals which are -7.5 dB to -20 dB under the noise floor.

5.2 Measurement Scenarios

The purpose of this section is to find the maximum communication range in which the gateway is able to receive LoRa packets. The measurement is done in two different scenarios: indoor and outdoor.

5.2.1 Indoor Measurements

In indoor tests, the end node was positioned in two different rooms in 10 and 20m distances from the gateway. Every room of this building features a very thick concrete core. The transmitter was placed adjacent to the concrete core of the building with mixed materials that affect RF propagation. During all the measurements the location of the base station is fixed and it is located inside the house window 3m above the ground. This location was chosen specifically because radio waves must propagate through the core of the building to reach this receiver. In this scenario, ADR is enabled by considering 4/5 coding rate at 125kHz bandwidth.

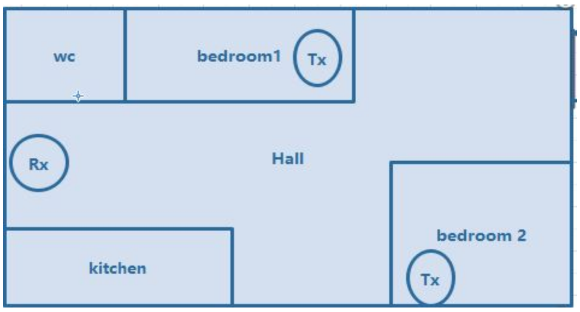


Figure 5.3: Indoor map

Room1

From now on we discuss the results that are extracted from different tests by evaluating RSSI and SNR of received packets. All the pictures are taken from TTN network server.

In order to establish uplink and downlink communications, firstly, the end device must be registered on the network server. Devices in TTN are added within the Application and they can communicate with applications that they have been registered to. Furthermore, it is important to note that, Gateways do not have decoder functions. There is nothing that can be decided at that point. Only at the application level the data is decrypted and can be decoded. Below the data at the application level is shown which includes transmission time, counter, port number, and the transmitted payload. Field1 and field2 illustrate temperature and humidity values respectively.

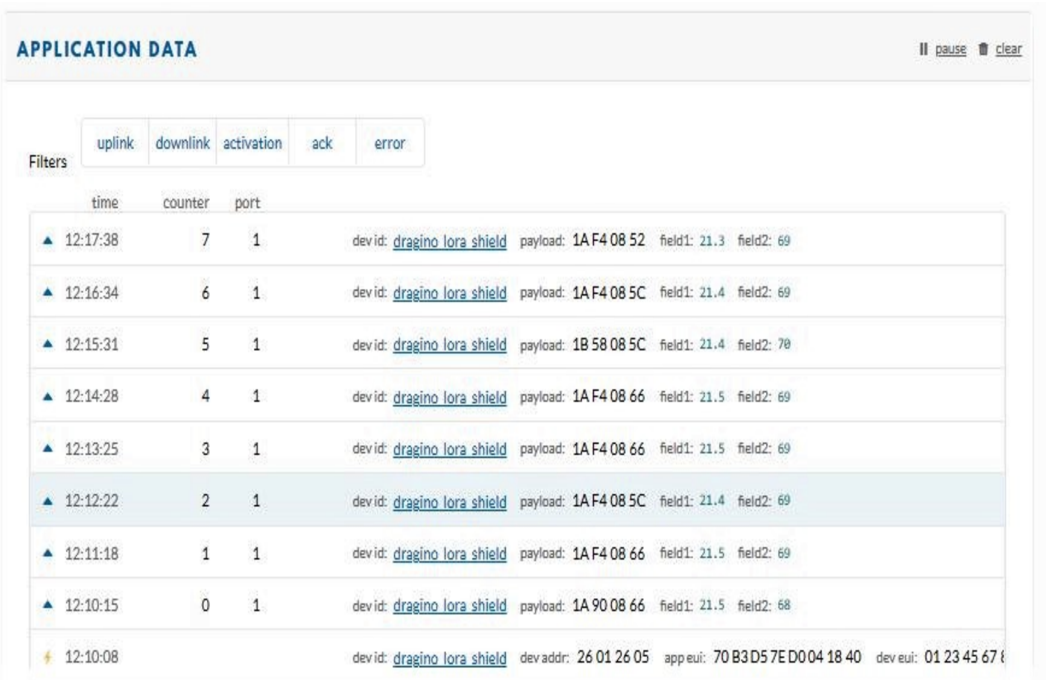


Figure 5.4: Application data

The pictures below illustrate the received packets info by the gateway with id:eui-2cf7f11024400045. Mentioned gateway is a trusted gateway which is registered by me on TTN server which was demonstrated in chapter 4.

Gateway traffic shows some useful info about the received packets such as the reception time and frequency, coding rate, bandwidth, time on-air and the payload size.

By paying attention to the RSSI and SNR values, it can be concluded that the quality of communication is almost good, because by considering the short distance between the transmitter and receiver, it was expected to have higher RSSI value. So, it is worth noting that the concrete wall and the windows have an inevitable influence on the performance in indoor scenario.

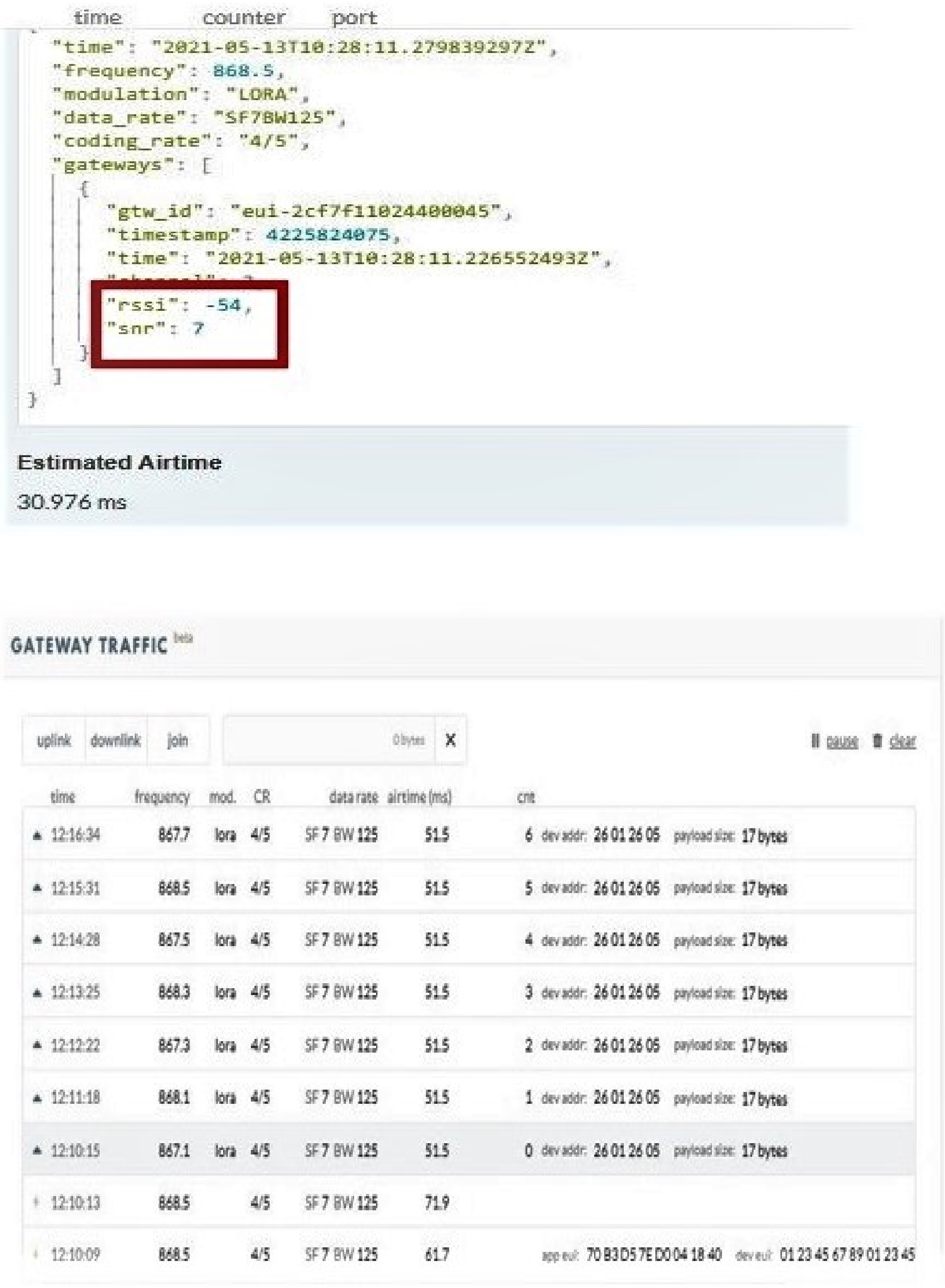


Figure 5.5: Gateway traffic

Room2

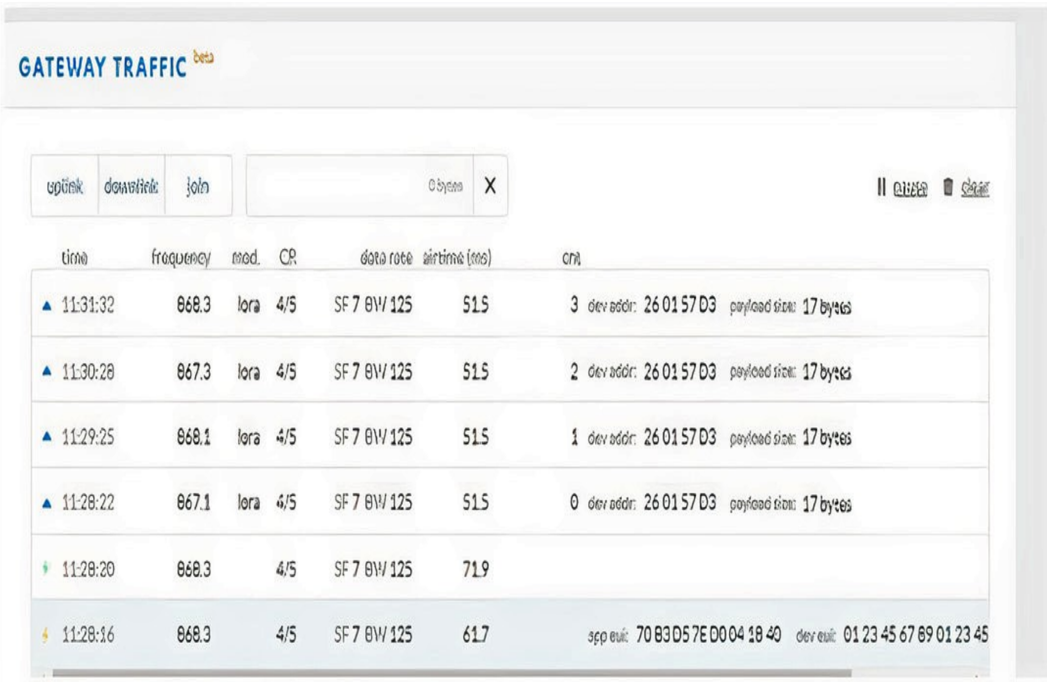


Figure 5.6: Gateway traffic

Based on the gateway traffics for two rooms, the end node was able to join the server with the highest data rate(SF7) and almost high amount of SNR value, which means the quality of communication is almost good. By paying attention to the reception frequencies, as mentioned before we have frequency changing in every packet transmission which makes the communication more robust to any interference.

The results taken from two rooms demonstrate that by increasing the range in LoRa, RSSI decreases. In room two due to increasing the walls and windows that were between the receiver and transmitter the amount of RSSI and SNR decreased significantly.
In the following, some live values of temperature and humidity took from two test points that were analyzed by the ThingSpeak integration which was mentioned in the previous chapter are shown. The gap between is due to movement from one room to another one.

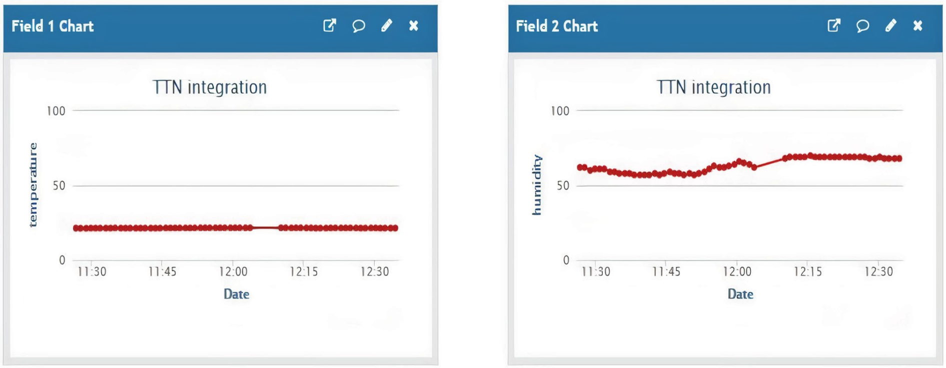


Figure 5.7: Live temperature and humidity values

5.2.2 Outdoor Measurements

The outdoor measurement took place in the city of Turin, Italia. The Turin metropolitan area is estimated to have a population of 2.2 million and the highest residential buildings are 12 floors high, which makes communication much more challenging.
The gateway is located on the 4th floors balcony in an area surrounded by lots of high buildings, 12m above the ground and, the LoRa end node location is varied from100 meters to 2km. The measurement points are shown in figure, Where the black location in figure 5.8 illustrates the gateway location and 1, 2, 3, 4, 5, 6 and, 7 demonstrate the position of the LoRa end device. Test carried out in non-line-of-sight (NLOS) locations. Each node is configured at LoRa and then 50 data packets are sent with a maximum payload of 17 bytes. The gateway info can be seen by the two value indicators. The first value is RSSI (Received Signal Strength Indicator) and the second value is SNR (Signal to Noise Ratio).
In all experiments, to determine the optimal data rate, the network needs some measurements (uplink messages). Currently, TTN considers the 20 most recent uplinks, starting from the moment when the ADR bit is set. These measurements consist of the frame counter, signal-to-noise ratio (SNR) and number of gateways that received each uplink. For each of these measurements, TTN takes the SNR of the best gateway, and then calculates the margin, which is the SNR minus the required SNR to demodulate a message given the data rate. This margin is utilized to determine how much data rate must be increased or how much transmitted power must be lowered.

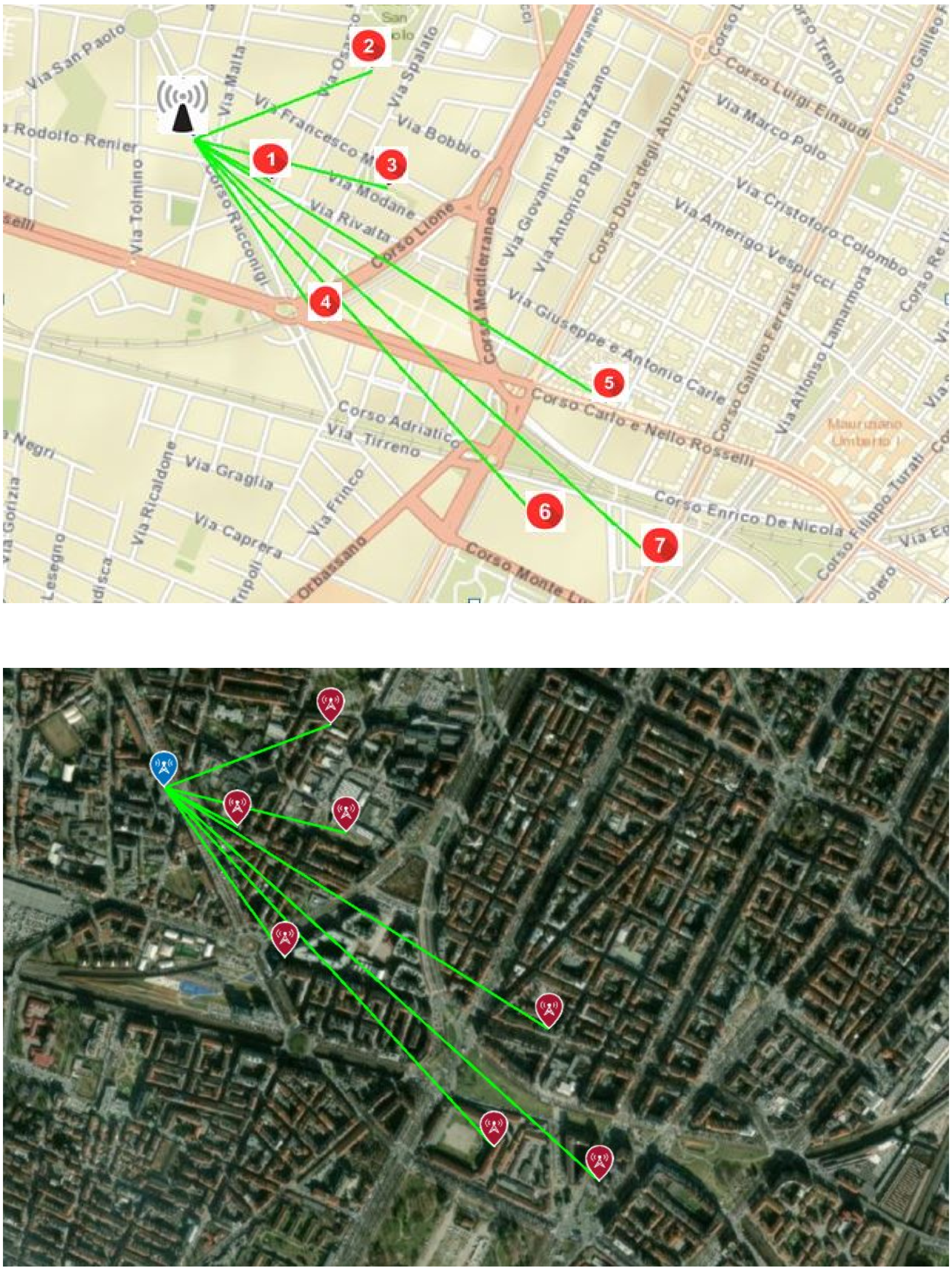


Figure 5.8: Outdoor map

location 1(300m)

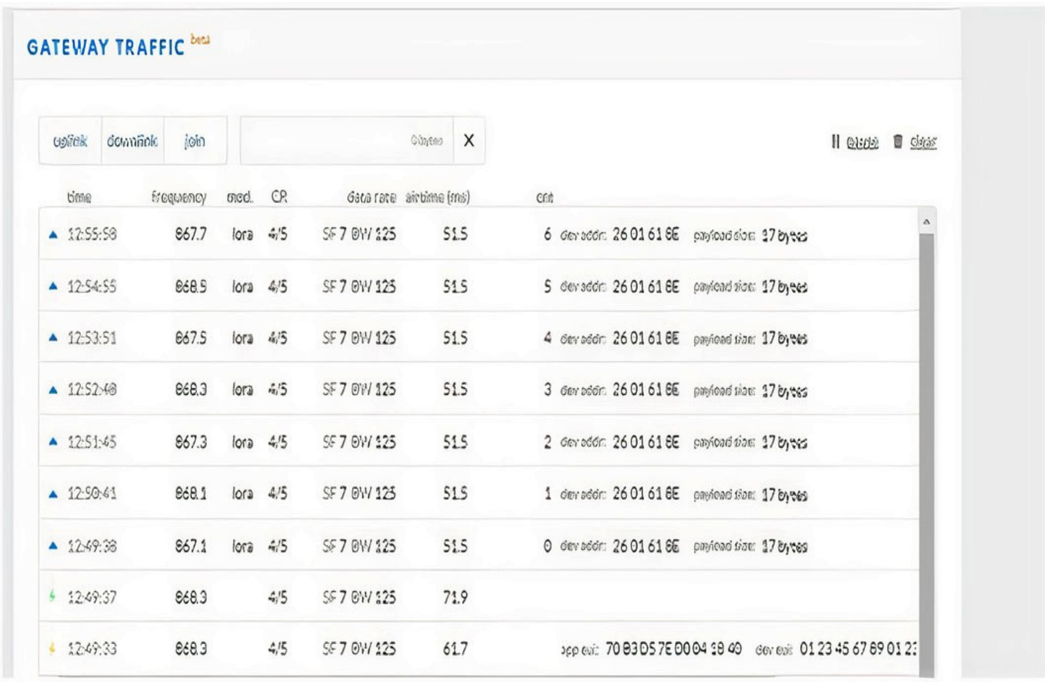
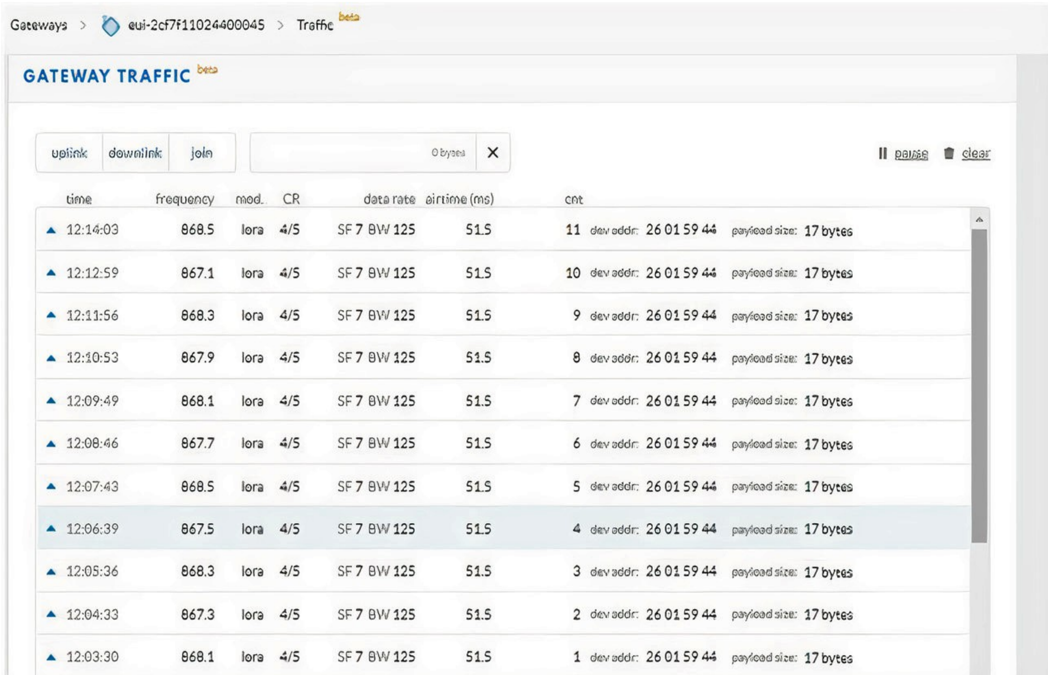


Figure 5.9: Gateway traffic

location 2(450m)

```
"f_cnt": 27,
"lora": {
  "spreading_factor": 7,
  "bandwidth": 125,
  "air_time": 51456000
},
"coding_rate": "4/5",
"timestamp": "2021-05-14T10:30:56.019Z",
"rssi": -101,
"snr": 8.8,
"dev_addr": "26015944",
"frequency": 868300000
```

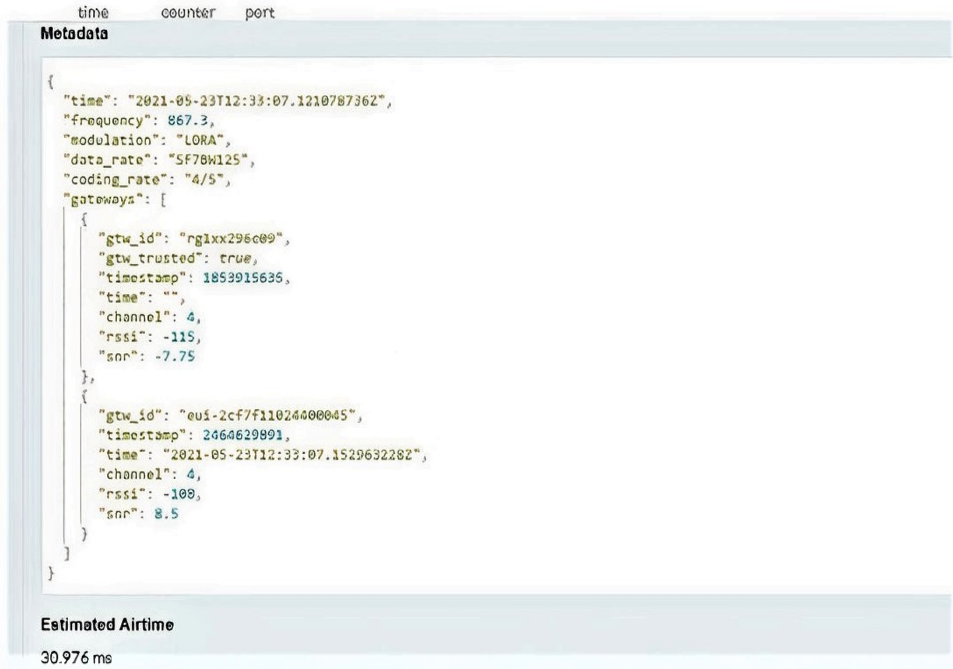
time	frequency	mod.	CR	data rate	airtime (ms)	cnt		
12:14:03	868.5	lora	4/5	SF 7 BW 125	51.5	11	dev addr: 26 01 59 44	payload size: 17 bytes
12:12:59	867.1	lora	4/5	SF 7 BW 125	51.5	10	dev addr: 26 01 59 44	payload size: 17 bytes
12:11:56	868.3	lora	4/5	SF 7 BW 125	51.5	9	dev addr: 26 01 59 44	payload size: 17 bytes
12:10:53	867.9	lora	4/5	SF 7 BW 125	51.5	8	dev addr: 26 01 59 44	payload size: 17 bytes
12:09:49	868.1	lora	4/5	SF 7 BW 125	51.5	7	dev addr: 26 01 59 44	payload size: 17 bytes
12:08:46	867.7	lora	4/5	SF 7 BW 125	51.5	6	dev addr: 26 01 59 44	payload size: 17 bytes
12:07:43	868.5	lora	4/5	SF 7 BW 125	51.5	5	dev addr: 26 01 59 44	payload size: 17 bytes
12:06:39	867.5	lora	4/5	SF 7 BW 125	51.5	4	dev addr: 26 01 59 44	payload size: 17 bytes
12:05:36	868.3	lora	4/5	SF 7 BW 125	51.5	3	dev addr: 26 01 59 44	payload size: 17 bytes
12:04:33	867.3	lora	4/5	SF 7 BW 125	51.5	2	dev addr: 26 01 59 44	payload size: 17 bytes
12:03:30	868.1	lora	4/5	SF 7 BW 125	51.5	1	dev addr: 26 01 59 44	payload size: 17 bytes

Figure 5.10: Gateway traffic

Pictures above are some results that were taken from the gateway traffic: In these locations node is less blockade by some obstacles and the interferences from other radio systems.

In **Point1**, the end node was located in a park surrounded by lots of trees exactly behind the gateway location which does not allow the Line of Sight communication along the route and there was no building in between. At this point, 100% of the transmitted packets were received.
In **Point2** signal passed through two buildings. In this scenario, there were a little group of low-rise buildings. 98% of the transmitted signals were received correctly by the gateway. The presented results reveal that due to low range, fewer buildings and obstacles between LoRa end device and the gateway in these two points, RSSI and SNR amounts are high and we have good communication performance.

location 3(700m)



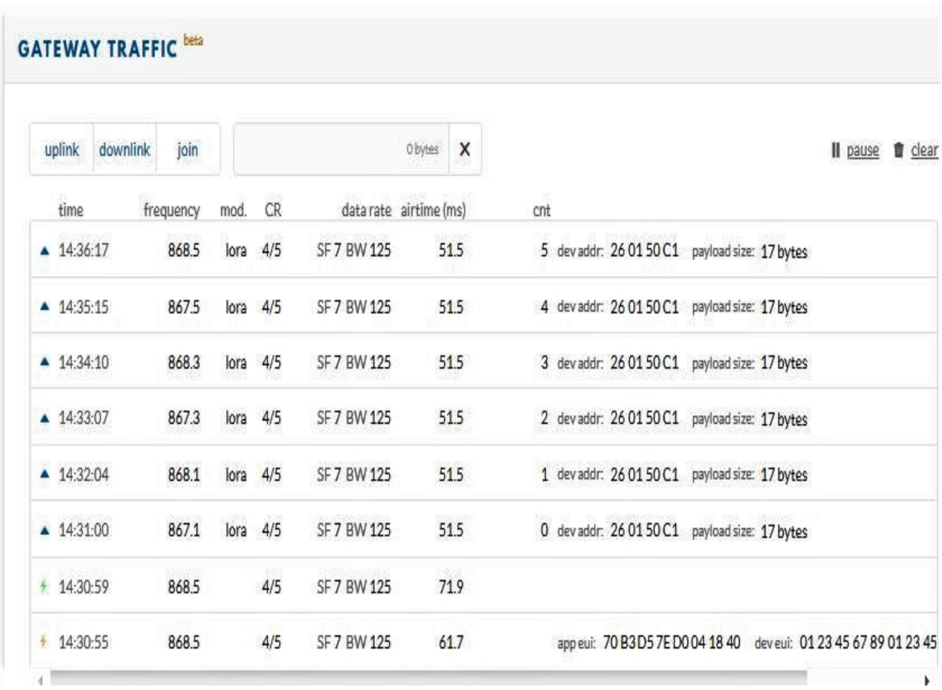


Figure 5.11: Gateway traffic

location 4(950m)

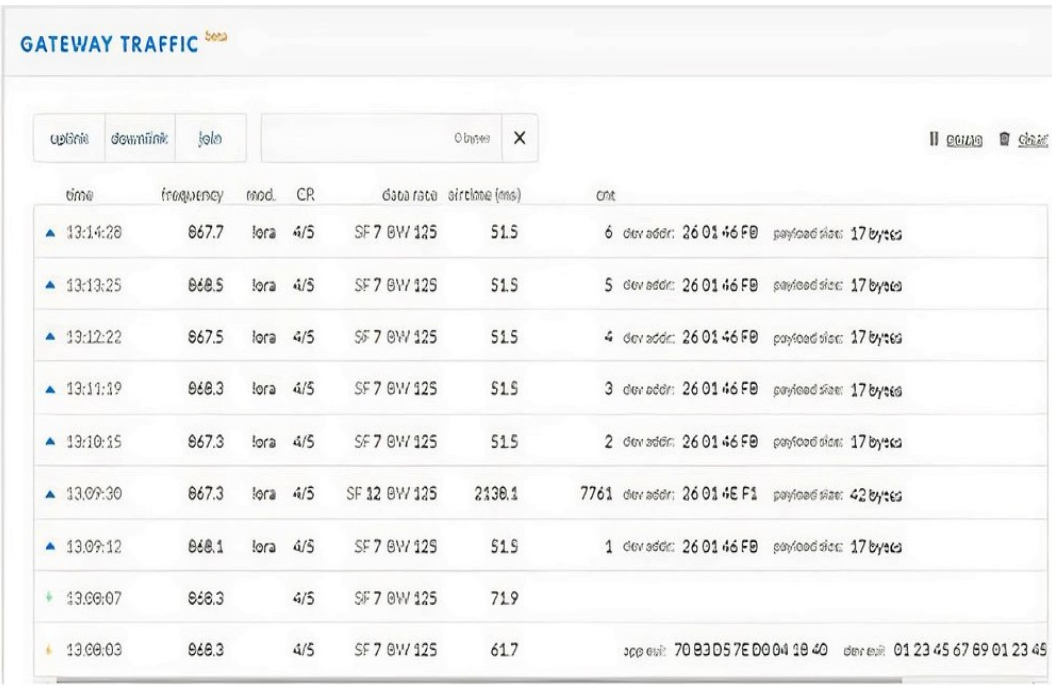


Figure 5.12: Gateway traffic

Figures illustrate the packets were received by more than one gateway. As mentioned before LoRaWAN architecture is the star of star topology which means many gateways are able to receive the same packet. The one that is highlighted is the gateway used in this test.
In **Point3** end device was positioned in an area in which the number of buildings between the transmitter and the receiver exceeded five apartments. In this location 98% of the packets received.
In **Point4**, the signal passed through more than 10 buildings which were not so high that is why the received signal quality degraded significantly. 74% of packets received successfully. Here in this location we have negative SNR. This is due to the non-LOS communication and increased number of buildings between the LoRa node and the gateway. Even for negative SNR values (up to -20 dB) the gateway will still be able to receive the packet due to the robustness of the modulation scheme.

location 5(1200m)

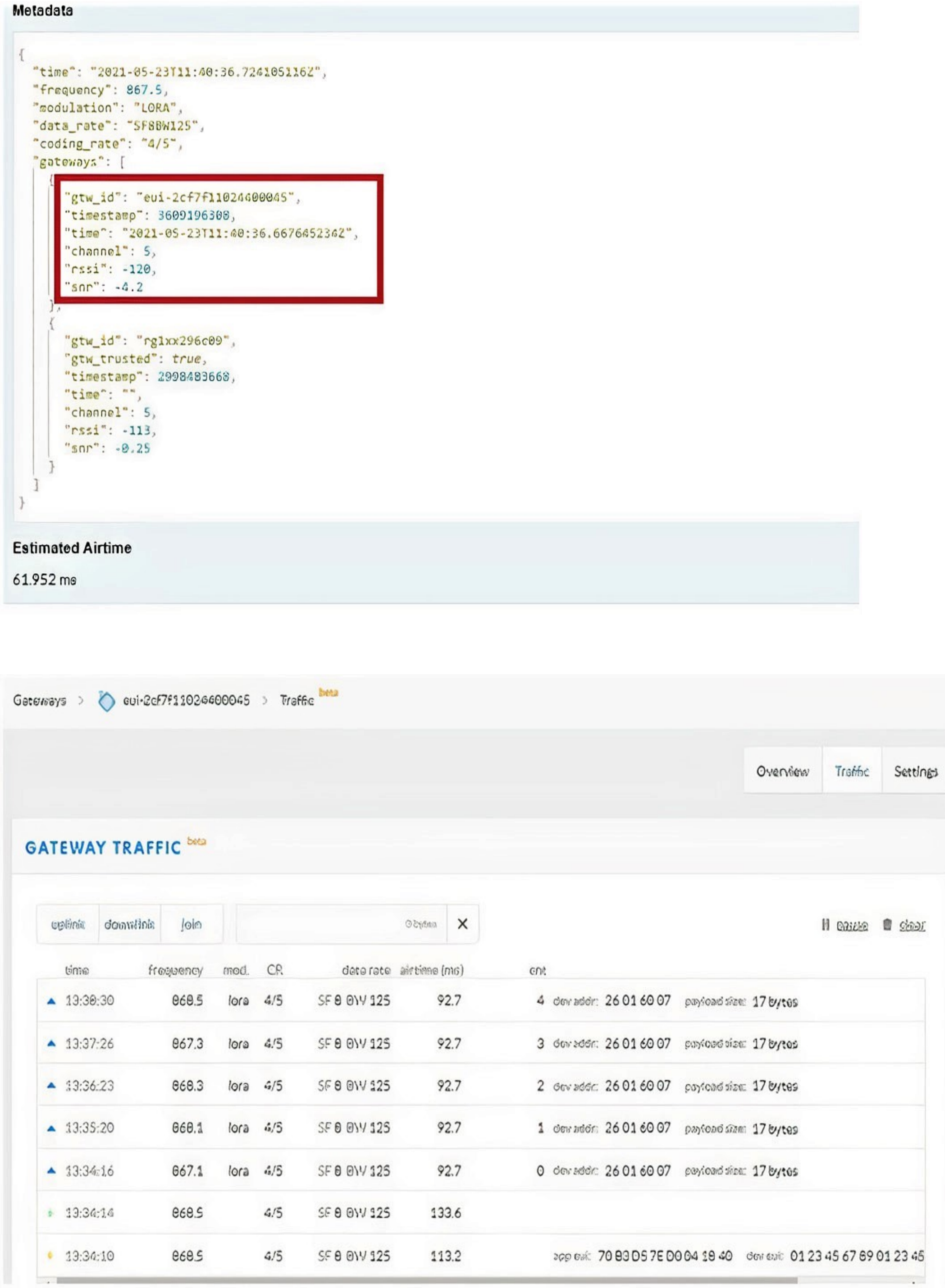


Figure 5.13: Gateway traffic

location 6(1450)


```
    "spreading_factor": 10,
    "bandwidth": 125,
    "air_time": 329728000
  },
  "coding_rate": "4/5",
  "timestamp": "2021-05-23T13:11:37.478Z",
  "rssi": -121,
  "snr": -7.5,
  "dev_addr": "260164A2",
  "frequency": 868100000
}
```


Gateways > eui-2cf7f11024400045 > Traffic beta

uplink | downlink | join   0 bytes ×   ⏸ pause 🗑 cl

	time	frequency	mod.	CR	data rate	airtime (ms)	cnt		
▲	15:10:33	868.5	lora	4/5	SF 10 BW 125	329.7	3	dev addr: 26 01 64 A2	payload size: 17 bytes
▲	15:09:30	868.3	lora	4/5	SF 10 BW 125	329.7	2	dev addr: 26 01 64 A2	payload size: 17 bytes
▲	15:09:29	868.1	lora	4/5	SF 12 BW 125	2138.1	7773	dev addr: 26 01 4E F1	payload size: 42 bytes
▲	15:08:26	868.1	lora	4/5	SF 10 BW 125	329.7	1	dev addr: 26 01 64 A2	payload size: 17 bytes
▲	15:07:23	867.1	lora	4/5	SF 10 BW 125	329.7	0	dev addr: 26 01 64 A2	payload size: 17 bytes
⚡	15:07:20	868.1		4/5	SF 10 BW 125	452.6			
⚡	15:07:16	868.1		4/5	SF 10 BW 125	370.7		app eui: 70 B3 D5 7E D0 04 18 40	dev eui: 01 23 45 67 89 01 23
⚡	15:00:35	868.5		4/5	SF 10 BW 125	452.6			
⚡	15:00:31	868.5		4/5	SF 10 BW 125	370.7		app eui: 70 B3 D5 7E D0 04 18 40	dev eui: 01 23 45 67 89 01 23
▲	14:59:29	867.1	lora	4/5	SF 12 BW 125	2138.1	7772	dev addr: 26 01 4E F1	payload size: 42 bytes
⚡	14:56:33	868.3		4/5	SF 9 BW 125	246.8			
⚡	14:56:29	868.3		4/5	SF 9 BW 125	205.8		app eui: 70 B3 D5 7E D0 04 18 40	dev eui: 01 23 45 67 89 01 23

Figure 5.14: Gateway traffic

In both **Point5** and **Point6**, the signal passed through many high buildings in order to reach the receiver. As a result, less than 70% and 52% of transmitted packets received respectively. Moving far from the gateway can be translated into increasing high buildings in the harsh urban environment which results in more reflections and refractions. This is the reason why the LoRa nodes in locations 5 and 6 could not join the server with lower spreading factors.

As mentioned before, the ADR mechanism helps to adjust the best data rate for communication. This procedure is achieved by increasing transmission power and spreading factor step by step to regain the connectivity which can be seen in gateway traffics. When the communication link is very bad, nodes are still required to transmit and lose a huge amount of packets to increase their spreading factor and transmission power gradually to have a reliable communication setting.
By looking more closely at the reception time on gateway traffic, it is clear that the convergence time in the ADR mechanism is fairly slow, more significantly when the link quality starts decreasing, which introduces higher energy consumption and packet losses.

location 7(1700m)

Location7 was about 2km away from the gateway and it could not join the gateway with any spreading factors.

Table 5.1: Results from the outdoor environment

Test Point	SF	RSSI[dBm]	SNR[dB]
1(300m)	7	-83	9
2(450m)	7	-101	8.8
3(700m)	7	-106	8.2
4(950m)	7	-117	-2
5(1200m)	8	-120	-4.2
6(1450m)	10	-121	-7.5
7(1700m)			

The table above is a comparison between all 7 test points in this experiment. From the test results that have been carried out on the range and quality, it can be concluded that not only distance and spreading factor affect RSSI and SNR values, but also obstacles have an inevitable impact on the proficiency level. Extracted results reveal that the maximum range which LoRa packets received by the gateway in lossy and harsh environments is less than 2km. Besides, after the 450m range the amount of RSSI degrades significantly and exceeds -100dBm.

Downlink Communication

As previously stated, one important aspect of LoRaWAN is its ability to provide bidirectional communication. This means that an end device (sensor node) may both transmit and receive messages from the network. LoRa devices can be programmed or built to send status indications to faraway places as a result of this. A further test has been done to see if the LoRa node is able to receive scheduled downlink messages organized by the network server. For this approach Curl programming language is used. Curl is an object-oriented programming language for interactive web applications whose aim is to provide a smoother transition between formatting and programming. In chapter 4 we mentioned the HTTP integration which is used for sending downlink and uplink messages, here we used this integration for downlink. My application can schedule a downlink message to a URL form application in a region, process name and app access key. This mentioned URL is also provided for each uplink message. However, we can call this URL any time to schedule a downlink. The data will be delivered in the following format by the integration:


```
"app_id": "polito_lora"
"dev_id": "dragino_lora_shield"
"hardware_serial": "0123456789012345"
"port": 1
"counter": 9
"payload_raw": "CigJzg=="
"payload_fields":
"field1": 25.1
"field2": 26
"metadata":
"time": "2021-05-23T13:35:17.115070012Z"
"frequency": 867.7
"modulation": "LORA"
"data_rate": "SF8BW125"
"coding_rate": "4/5"
"gateways":
"gtw_id": "eui-60c5a8fffe7664c3"
"timestamp": 605066500
"time": ""
"channel": 3
"rssi": -121
"snr": -5.8
"rf_chain": 0
"latitude": 45.01531
"longitude": 7.70266
"altitude": 490
"downlink_url": "https://integrations.thethingsnetwork.org/ttn-
eu/api/v2/down/polito_lora/test_lora?key=ttn-account-
v2.wNxcQHlBaqhDQr-WRaEGHSHXGBA9F-GLuARy4IuoqbM"
```


Figure 5.15: JSON data format

```
C:\Users\Mahyar>curl -v -X POST --data "{\"dev_id\":\"dragino_lora_shield\",\"payload_raw\":\"AQE=\"}" https://integrations.thethingsnetwork.org/ttn-eu/api/v2/down/poli
to_lora/test_lora?key=ttn-account-v2.wNxcQH1BaqhDQr-WRaEGHSHXGBA9F-GLuARy4IuoqbM
Note: Unnecessary use of -X or --request, POST is already inferred.
*   Trying 13.69.184.129...
* TCP_NODELAY set
* Connected to integrations.thethingsnetwork.org (13.69.184.129) port 443 (#0)
* schannel: SSL/TLS connection with integrations.thethingsnetwork.org port 443 (step 1/3)
* schannel: checking server certificate revocation
* schannel: sending initial handshake data: sending 204 bytes...
* schannel: sent initial handshake data: sent 204 bytes
* schannel: SSL/TLS connection with integrations.thethingsnetwork.org port 443 (step 2/3)
* schannel: failed to receive handshake, need more data
* schannel: SSL/TLS connection with integrations.thethingsnetwork.org port 443 (step 2/3)
* schannel: encrypted data got 2892
* schannel: encrypted data buffer: offset 2892 length 4096
* schannel: sending next handshake data: sending 93 bytes...
* schannel: SSL/TLS connection with integrations.thethingsnetwork.org port 443 (step 2/3)
* schannel: encrypted data got 290
* schannel: encrypted data buffer: offset 290 length 4096
* schannel: SSL/TLS handshake complete
* schannel: SSL/TLS connection with integrations.thethingsnetwork.org port 443 (step 3/3)
* schannel: stored credential handle in session cache
> POST /ttn-eu/api/v2/down/polito_lora/test_lora?key=ttn-account-v2.wNxcQH1BaqhDQr-WRaEGHSHXGBA9F-GLuARy4IuoqbM HTTP/1.1
> Host: integrations.thethingsnetwork.org
> User-Agent: curl/7.55.1
> Accept: */*
> Content-Length: 53
> Content-Type: application/x-www-form-urlencoded
>
* upload completely sent off: 53 out of 53 bytes
* schannel: client wants to read 102400 bytes
* schannel: encdata_buffer resized 103424
* schannel: encrypted data buffer: offset 0 length 103424
* schannel: encrypted data got 190
* schannel: encrypted data buffer: offset 190 length 103424
* schannel: decrypted data length: 161
* schannel: decrypted data added: 161
* schannel: decrypted data cached: offset 161 length 102400
* schannel: encrypted data buffer: offset 0 length 103424
* schannel: decrypted data buffer: offset 161 length 102400
* schannel: schannel_recv cleanup
* schannel: decrypted data returned 161
* schannel: decrypted data buffer: offset 0 length 102400
< HTTP/1.1 202 Accepted
```

```
* schannel: encrypted data got 290
* schannel: encrypted data buffer: offset 290 length 4096
* schannel: SSL/TLS handshake complete
* schannel: SSL/TLS connection with integrations.thethingsnetwork.org port 443 (step 3/3)
* schannel: stored credential handle in session cache
> POST /ttn-eu/api/v2/down/polito_lora/test_lora?key=ttn-account-v2.wNxcQH1BaqhDQr-WRaEGHSHXGBA9F-GLuARy4IuoqbM HTTP/1.1
> Host: integrations.thethingsnetwork.org
> User-Agent: curl/7.55.1
> Accept: */*
> Content-Length: 53
> Content-Type: application/x-www-form-urlencoded
>
* upload completely sent off: 53 out of 53 bytes
* schannel: client wants to read 102400 bytes
* schannel: encdata_buffer resized 103424
* schannel: encrypted data buffer: offset 0 length 103424
* schannel: encrypted data got 190
* schannel: encrypted data buffer: offset 190 length 103424
* schannel: decrypted data length: 161
* schannel: decrypted data added: 161
* schannel: decrypted data cached: offset 161 length 102400
* schannel: encrypted data buffer: offset 0 length 103424
* schannel: decrypted data buffer: offset 161 length 102400
* schannel: schannel_recv cleanup
* schannel: decrypted data returned 161
* schannel: decrypted data buffer: offset 0 length 102400
< HTTP/1.1 202 Accepted
< Server: nginx
< Date: Thu, 06 May 2021 11:55:01 GMT
< Content-Type: text/plain; charset=utf-8
< Content-Length: 0
< Connection: keep-alive
```

Figure 5.16: Curl result

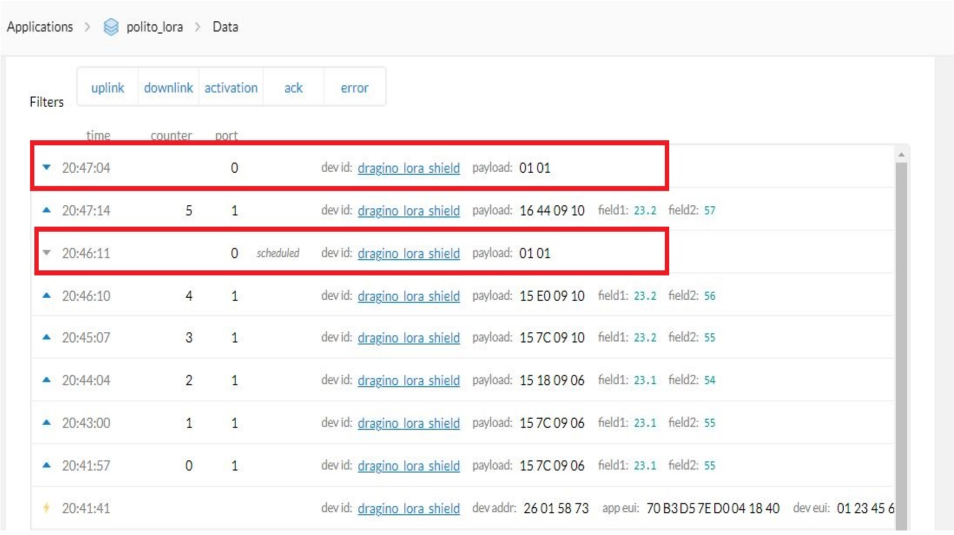


Figure 5.17: received downlink message

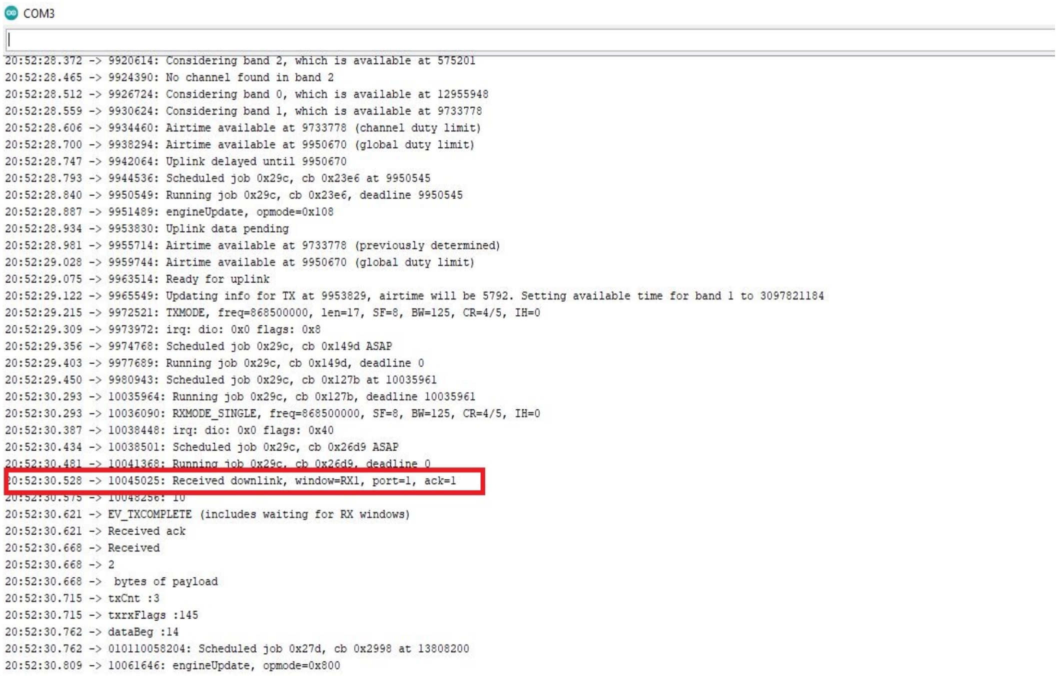


Figure 5.18: Arduino log

From the pictures above it is clear that the downlink message received correctly by the end device.

Chapter 6

Simulation and Data Analysis

This chapter contains a detailed discussion of data analysis and simulation of the results taken from the measurements introduced in the previous chapter.
The analysis will be presented under the following major headings:
Packet delivery ratio, RSSI and throughput analysis, and packet length interpretation.

6.1 Packet Delivery ratio

The PDR (Packet Delivery Ratio) used to determine the quality of LoRa communication. Based on the packet received at the gateway, PDR values can be determined. The following PDR formula:

$$\text{packet delivery ratio} = \frac{\sum(\text{number of packets received})}{\sum(\text{number of packets sent})} \tag{6.1}$$

Where:

1. Number of packets received is equal to the total packets received by the gateway.

2. The number of packets sent is equal to the total packet that has been sent by the transmitter.

Table 6.1 shows the total number of transmitted and received packets and the packet delivery ratio for the node in its join spreading factor. Note that The total number of packets transmitted during the test was in the order of 50. Definitely, this amount is not enough to have reliable results, but due to some limitations on the duty cycle and TTN server this number must be reduced.

Table 6.1: Results of PDR

Range[m]	SF	Number of Transmitted Packets	Number of Received Packets	Packet Delivery Ratio
300	7	50	50	100%
450	7	50	49	98%
700	7	50	49	98%
950	7	50	37	74%
1200	8	50	35	70%
1450	10	50	26	52%

The extracted results illustrate within the 700m range only 2% of the sent packets were lost, which is the indication of good spreading factor selection. However, by moving far from the gateway the number of packets that were lost started increasing. The reasons why this happens are signal blockade by some obstacles such as trees, cars, buildings... and interferences with other radio systems.
By adjusting higher spreading factors to have better performance and to decrease the packet loss for the last three test points, the results change significantly and PDR improves to more than 75% for long test ranges as shown in table 6.2.

Table 6.2: Results of PDR

Range[m]	SF	Number of Transmitted Packets	Number of Received Packets	Packet Delivery Ratio
950	8	50	45	90%
1200	9	50	46	92%
1450	11	50	43	86%

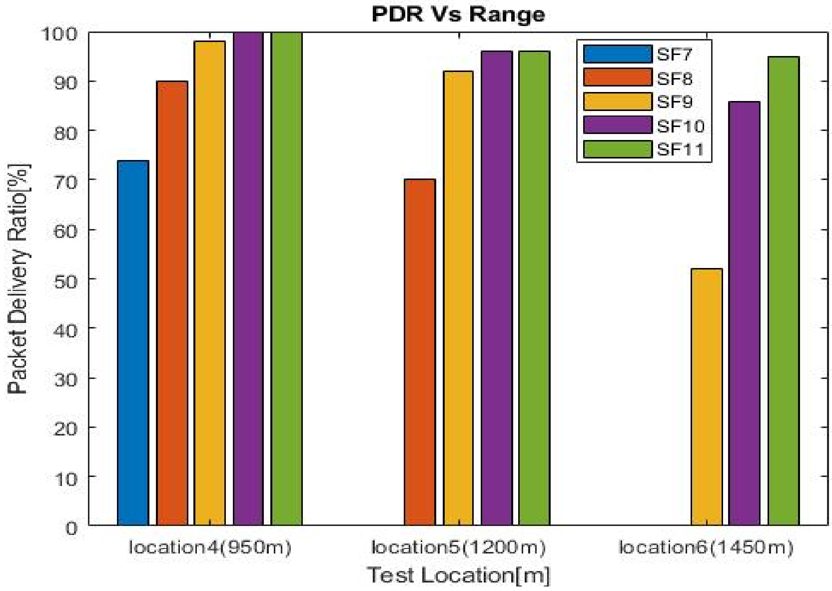


Figure 6.1: PDR for different test locations

6.2 System Performance Analysis

6.2.1 Path Loss Models

In this part we will discuss some path loss models and compare them to the experiment results in LoRa communications. Previous researches have presented various mathematical models for calculation of path loss. Different urban environment path loss models have been tested to see which one can well describe the loss that is achieved in real harsh urban environment. However, because of the complexity of signal propagation, it is hard to adjust a single model that accurately describes all path loss properties in different communication environments.

Free-Space Path Loss

Free-space path loss model(Friis equation), is a baseline of all proposed propagation models so far. This is the simplest model to define the radio signal propagation. The formula is as below:

$$PL_{f_s} = 20 \times \log f + 20 \times \log d + 32.45 \tag{6.2}$$

where, d is distance in km, and f is the frequency in MHz[47].

HATA-OKUMURA Model

This model is an empirical path loss model and is limited to the input parameters. The formula for calculating path loss model in urban area is as below:

$$L(urban) = 69.55 + 26.16 \log f - 13.82 \log h_{te} - a h_{re} + (44.9 - 6.55 \log h_{te}) \log d \quad (6.3)$$

where

$$a(h_{re}) = (1.1 \log f - 0.7) h_{re} - (1.56 \log f - 0.8) \quad (6.4)$$

In this equation, f is the frequency in MHz, h_{te} and h_{re} are antenna effective height for the base station and the device in meter respectively, and d is the distance between transmitter and receiver[48].

Ericsson Model

Ericsson model is a modified version of the HATA-OKUMURA model in which we can change parameters according to the environment that we are doing experiment.

$$L = a_0 + a_1 \log(d) + a_2 \log(h_b) + a_3 \log(h_b) \log(d) - 3.2(\log(11.75 h_r)^2) + g(f) \quad (6.5)$$

$$g(f) = 44.49 \log(f) - 4.78(\log(f))^2 \quad (6.6)$$

where f is the frequency in MHz, h_b and h_r are the height of transmitter and receiver antenna in meter. The values of a_0, a_1, a_2, and a_3 for urban areas are 36.2, 30.2, 12 and 0.1 respectively[49].

Proposed Model

It is better to derive a simple model that captures the heart of signal propagation for general analysis of different systems than developing a model which approximates real world channel status[45]. Among many models the following model can better define the urban environment path loss model. The formula below defined for this purpose:

$$P_r[dBm] = P_t[dBm] + K - 10\gamma log[\frac{d}{d_0}][46] \quad (6.7)$$

where P_t and P_r are transmission and reception powers, respectively. d_0 is a reference to the far-field of an antenna which is in 10-100m range in outdoor environment. K is a constant with no unit set to free space path loss at distance d_0 which is mentioned. γ is called path loss exponent. The value is in the 2-4 range for the normal environment but it increases to almost 4-6 for a harsh and lossy environment. Results suggest that when there is LOS communication in an urban environment the amount of γ should be set to almost 2.6 but this amount must be increased for NLOS scenarios.

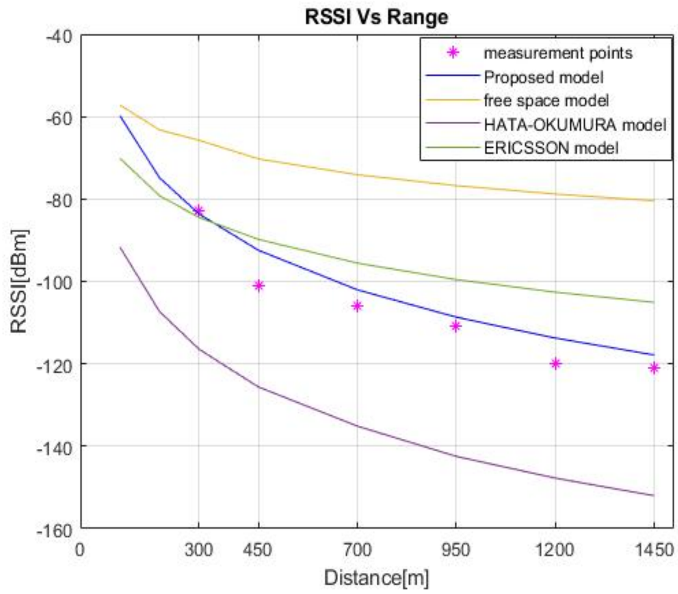


Figure 6.2: Received signal power in outdoor environment for different path loss models

By looking more closely at the extracted results, it can be seen that by carefully selecting the parameters in the proposed model, it is possible to well overlap the tested points and the theoretical model which demonstrates the accuracy and efficiency of the proposed model. furthermore, the graph illustrates, moving away from the gateway results in a degradation in system performance.

6.2.2 Throughput

In this section, we will do LoRaWAN performance evaluation in terms of maximum data rate with which the LoRa packets can be transmitted. Each spreading factor demonstrates a special bit rate which can be calculated by the formula below:

$$\mathrm{R}_b = SF \times \frac{BW}{2^{SF}} \times CR \tag{6.8}$$

Where:

1. SF means the Spreading Factor used
2. BW means the Bandwidth used
3. CR means the Code Rate used

Table 6.3: Semtech SX1276, Sensitivity of LoRa Receiver (dBm)[4][20]

Data Rate	Spreading Factor	Bit Rate [kbps]	Rx Sensitivity [dBm]
DR0	12	0.25	-136
DR1	11	0.44	-133
DR2	10	0.98	-132
DR3	9	1.7	-129
DR4	8	3.1	-126
DR5	7	5.4	-123

Table 6.3 summarizes the relationship between BW, SF, and Receiver Sensitivity. Although the spreading factor has a proportionate connection with receiver sensitivity, increasing the bandwidth reduces decoder sensitivity. The reduction in coding rate will aid in lowering the Packet Error Rate (PER) due to interference.

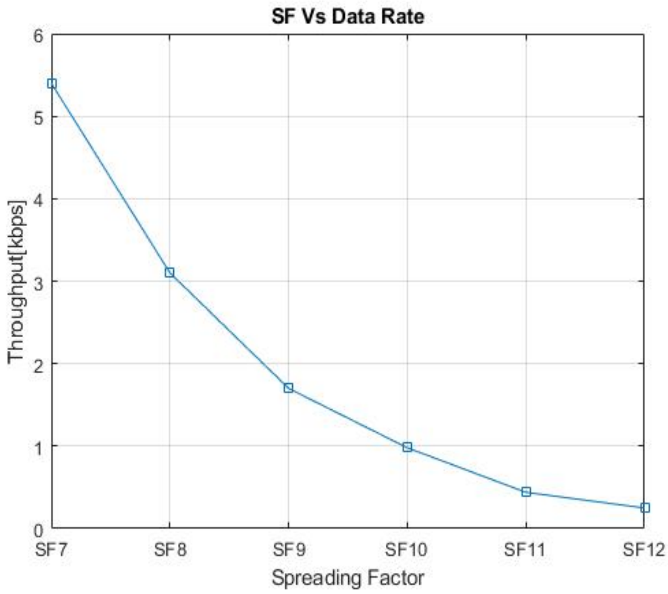


Figure 6.3: Data rate evaluation with different SF(125kHz bandwidth)

6.3 Packet Length Analysis

LoRaWAN supports data rates in 0.3 to 50 kbps ranges depends on which SF, BW and CR are using for the measurements. However, as the frame includes actual data plus a 13 byte preamble(LoRaWAN protocol) the time on-air varies.
The simulation below shows the transmission time for two different packet sizes (excluding preamble). The higher is the payload size the more is the time on air for LoRa packets. From the results, it is clear that the spreading factor has a crucial impact on LoRa communication performance. A large spreading factor will increase time on air of the transmitted packet which results in an increase in energy consumption, data rate reduction, and improving communication range.

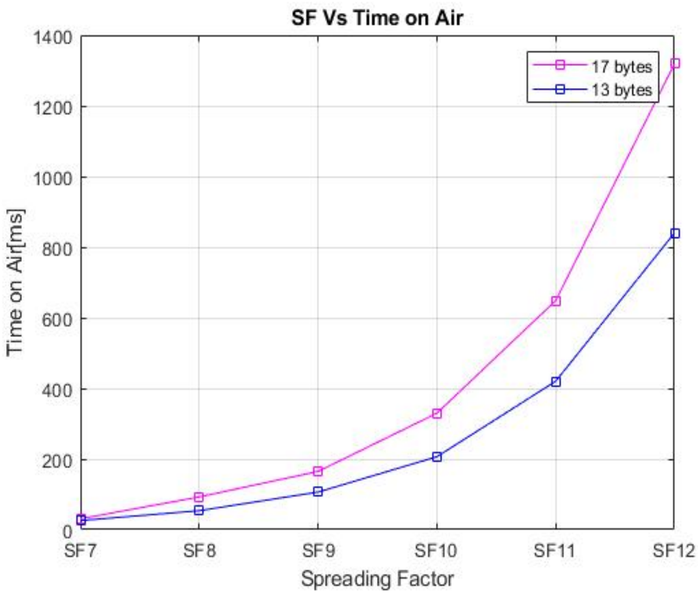


Figure 6.4: Time on air vs SF with BW=125 kHz, CR=4/5

Chapter 7

Conclusion and Future Works

7.1 Conclusion

This research has tried to show the performance of LoRa technology in a harsh urban environment in case of the maximum distance in which packets received successfully by the gateway.
Thesis defined a detailed description of different Low Power Wide Area technologies which are so famous these days due to some precious characteristics that are inevitable in the 4th industrial era. Furthermore, some comparisons between LoRa and LoRaWAN technologies along with the transmission parameters of LoRa and their selection in order to have a good communication performance on LoRa link have been outlined. In the end, we have set up a LoRaWAN network that includes a sensor node, a gateway and, a network server in order to build a communication based on Lora modulation to send packets toward the gateway.
Two scenarios have been analyzed in this research: indoor and outdoor with the main focus on outdoor environmental experiments. In indoor scenarios as might be expected, despite the close distance between transmitter and receiver, the values of SNR and RSSI indicate a not very high quality communication in an indoor environment. Due to the presence of glasses and concrete walls with high thickness between the LoRa end device and gateway, signals are blocked while passing obstacles.
In the outdoor scenario, the area of the test was full of high buildings which resulted in many reflections and refractions. As a result, the gateway was able to receive LoRa packets which were sent at a distance of less than 2km with the highest spreading factor. Besides, we introduced that LoRaWAN can be assessed by defining the packet delivery ratio for each transmission. Based on the results, less than 5% of the transmitted packets were lost in low ranges and we have mentioned that for long-range communications because

of low PDR values(less than 60%), this amount can be increased by increasing the spreading factor which results in a decrease in data rate. The results reveal that, the performance of LoRaWAN networks extremely depends on the selected parameters such as spreading factor, coding rate, bandwidth, and also the environment in which they are implemented.
Moreover, further investigations have been done to illustrate how an increase in packet size degrades the LoRaWAN communication performance and triggers more time on air for each sent packet. In this dissertation, the gateway has been located on the 4th floor almost 12m distance from the ground which again has an effect on communication range. It is very important to note that the height of the gateway from the ground is a factor that hugely affects communication range and locating the gateway at a high distance would give better performance on LoRa link.

7.2 Future works

We introduced the LoRaWAN in previous sections, and relevant work has been completed up until today. When compared to other communication technologies, LoRaWAN offers the benefits of being an open standard, having built-in security, long-range communication, low energy consumption, and the opportunity to have private installations. Aside from its benefits, low data rate and duty cycle limits, limit the use of LoRaWAN networks for real-time applications. LoRaWAN is best suited to circumstances in which data transfers are infrequent (a few packets per day) and the payload size is between 10 and 50 bytes. All these mentioned challenging issues should be handled and studied in the near future.

In earlier parts, we discussed the LoRaWAN protocol. The protocol is based on Aloha, which is very simple to construct, but it has certain limitations when a growing number of network devices are involved. When the size of the network grows, packet transmission attempts will increase and successful packet delivery ratios will extremely decrease. So, having a more complicated system like listen before talk mechanism would be needed to achieve less packet losses in LoRaWAN.

Another future work could be promoting network servers to have less restrictions on the number of packets that can be sent in one day.

In the end, LoRaWAN networks are best suited for outdoor IoT applications such as smart cities, agriculture, farming, and airports. There has always been a gap in indoor deployment that causes signal propagation and network issues in inside scenarios and applications for various indoor users.

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