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BSc THESIS

Performance analysis of LoRa / LoRaWAN communications

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ΠΤΥΧΙΑΚΗ ΕΡΓΑΣΙΑ

Ανάλυση επίδοσης LoRa / LoRaWAN επικοινωνιών

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ΑΘΗΝΑ

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ABSTRACT

In a rapidly developing technological world, where many devices need to be connected to the network to offer multiple services to the end user, the need for high connectivity and low power consumption is vital. Internet of Things (IoT), as well as the user's will to be always online and interact with the physical and the virtual world, are the crucial factors that create this necessity. The technological and practical requirements are many and imperative, given that a very large amount of data has to be exchanged wirelessly fast while keeping the communication secure.

Low Power Wide Area Networks (LPWANs) is an emerging networking paradigm in the area of IoT communications. Its main purpose is to enable sensor-like devices to successfully send data to a receiver in a periodic-based or event-driven scheme, by using as little power as possible to reach the distant concentrator. These goals are achievable, among others, with the use of LoRa and LoRaWAN technologies. LoRa modulation technique is applied on messages that follow the LoRaWAN protocol and promises wide coverage, low energy consumption and highly reliable data transmission. This technology stack has contributed to the realization of many IoT applications, spanning in a plethora of use cases, like energy management, protection from natural disasters, environmental pollution check, and hazardous event detection.

This thesis is focused on evaluating the LoRa modulation technique, which resides in the Physical layer (PHY), as well as the Medium Access Control layer (MAC) protocol LoRaWAN, that sits on top of LoRa. Initially, we lay the theoretical background on the two technologies. With the theoretical background established, we continue to the definition and implementation of two experimental scenarios, in order to highlight the real capabilities of this networking stack. specifically, we execute a series of measurements with commercial off-the-shelf LoRaWAN equipment, in an effort to comprehend the relationship between some parameters of LoRa links (e.g., SF) with some common network performance metrics (e.g., RSSI). Afterwards, we process the results of these experiments and we present the outcome in a tangible and understandable way, using a custom-made web application.

SUBJECT AREA: Wireless Networks

KEYWORDS: LPWAN, LoRa, LoRaWAN, IoT, Measurement Scenarios, ReactJS

ΠΕΡΙΛΗΨΗ

Σε ένα ταχύτατα μεταβαλλόμενο τεχνολογικά κόσμο, όπου πολλές συσκευές χρειάζεται να είναι συνδεδεμένες στο δίκτυο προσφέροντας πολλαπλές υπηρεσίες στον τελικό χρήστη, η ανάγκη για υψηλή συνδεσιμότητα και χαμηλή κατανάλωση ισχύος είναι απαραίτητη. Τόσο το Διαδίκτυο των Πραγμάτων (IoT), όσο και η επιθυμία του χρήστη να είναι πάντα συνδεδεμένος και να αλληλεπιδρά με το φυσικό και εικονικό περιβάλλον, είναι οι καθοριστικοί παράγοντες οι οποίοι δημιουργούν αυτή την ανάγκη. Οι απατήσεις σε πρακτικό και τεχνικό επίπεδο είναι αρκετές και επιτακτικές, δεδομένου ότι ένας πολύ μεγάλος όγκος δεδομένων πρέπει να ανταλλάσσεται ασύρματα, με υψηλή ταχύτητα, διατηρώντας ταυτόχρονα την επικοινωνία ασφαλή.

Τα δίκτυα χαμηλής κατανάλωσης ισχύος και ευρείας εμβέλειας (LPWAN) αποτελούν ένα ανερχόμενο δικτυακό υπόδειγμα στον τομέα των επικοινωνιών IoT. Κύριος στόχος τους είναι οι συσκευές τύπου αισθητήρα να μπορούν να στέλνουν αποτελεσματικά τα δεδομένα τους σε ένα συγκεντρωτή βάσει ενός περιοδικού διαστήματος ή ενός σχήματος εντοπισμού συμβάντων, χρησιμοποιώντας όσο λιγότερη ενέργεια γίνεται για να φτάσουν τον απομακρυσμένο συλλέκτη. Η πραγματοποίηση αυτού του στόχου είναι εφικτή, μεταξύ άλλων, μέσω των τεχνολογιών LoRa και LoRaWAN. Η τεχνική διαμόρφωσης LoRa εφαρμόζεται σε σήματα που ακολουθούν το πρωτόκολλο LoRaWAN και υπόσχεται μεγάλη εμβέλεια, χαμηλή κατανάλωση ενέργειας και αξιόπιστη μεταφορά δεδομένων. Η τεχνολογία αυτή έχει συμβάλλει στην ανάπτυξη πολλών εφαρμογών IoT που εφαρμόζονται σε μία πληθώρα από καθημερινά ζητήματα όπως η διαχείριση ενέργειας, η προστασία από φυσικές καταστροφές, ο έλεγχος της περιβαλλοντολογικής μόλυνσης και η ανίχνευση πιθανών καταστροφών.

Η παρούσα εργασία αναλύει τόσο την τεχνική διαμόρφωσης LoRa – η οποία ανήκει στο φυσικό επίπεδο – όσο και το πρωτόκολλο επιπέδου ελέγχου πρόσβασης μέσου (MAC) LoRaWAN, το οποίο εφαρμόζεται πάνω στο LoRa. Σε πρώτη φάση, χτίζουμε το θεωρητικό υπόβαθρο για αυτές τις δύο τεχνολογίες. Έχοντας καθορίσει αυτό, προχωράμε στον ορισμό και στην υλοποίηση δύο πειραματικών σεναρίων με σκοπό την ανάδειξη των πραγματικών δυνατοτήτων αυτής της στοίβας δικτύου. Συγκεκριμένα, με τον γενικής χρήσης εμπορικό εξοπλισμό LoRaWAN που διαθέτουμε, εκτελούμε μία σειρά μετρήσεων προκειμένου να κατανοήσουμε τη συσχέτιση μεταξύ ορισμένων παραμέτρων των ζεύξεων LoRa (π.χ., SF) και κάποιων κοινών μετρικών απόδοσης στα δίκτυα (π.χ., RSSI). Τέλος, επεξεργαζόμαστε τα αποτελέσματα που προκύπτουν από αυτά τα πειράματα και τα αναπαριστούμε με απτό και κατανοητό τρόπο σε μία ειδικά προσαρμοσμένη εφαρμογή παγκοσμίου ιστού.

ΘΕΜΑΤΙΚΗ ΠΕΡΙΟΧΗ: Ασύρματα Δίκτυα

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: LPWAN, LoRa, LoRaWAN, IoT, Σενάρια μετρήσεων, ReactJS

To our families

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First of all, we would like to thank our families for the understanding and the support they gave us during our academic path. Next, we would like to thank each supervisor separately for the opportunity, the help and for all the useful advice they provided us while we were implementing and writing this thesis. Their active and effective help in each stage contributed to the successful elaboration of our thesis.

ΕΥΧΑΡΙΣΤΙΕΣ

Αρχικά, θα θέλαμε να ευχαριστήσουμε τις οικογένειες μας για την κατανόηση και στήριξη που μας παρείχαν σε όλη την ακαδημαϊκής μας πορεία ως τώρα. Εν συνεχεία, θα θέλαμε να ευχαριστήσουμε κάθε επιβλέπων ξεχωριστά για την ευκαιρία, τη βοήθεια και τις χρήσιμες συμβουλές που μας έδωσαν κατά την εκπόνηση αυτής της εργασίας. Η ενεργή παρουσία και βοήθειά τους σε κάθε στάδιο συντέλεσε στην επιτυχή ολοκλήρωσή της.

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1. INTRODUCTION

1.1 What is LoRa?

LoRa is a Physical layer (PHY) or bit-layer implementation intended for low throughput, low data rate, and high link budget [1] wireless communications. Developed by Cycleo, a company later acquired by Semtech, it is considered as a long-range RF[1] technology, which belongs to the LPWAN [2] family of networks. Its main characteristic is the low power consumption it takes to operate in distances comparable to the cellular networks [3].

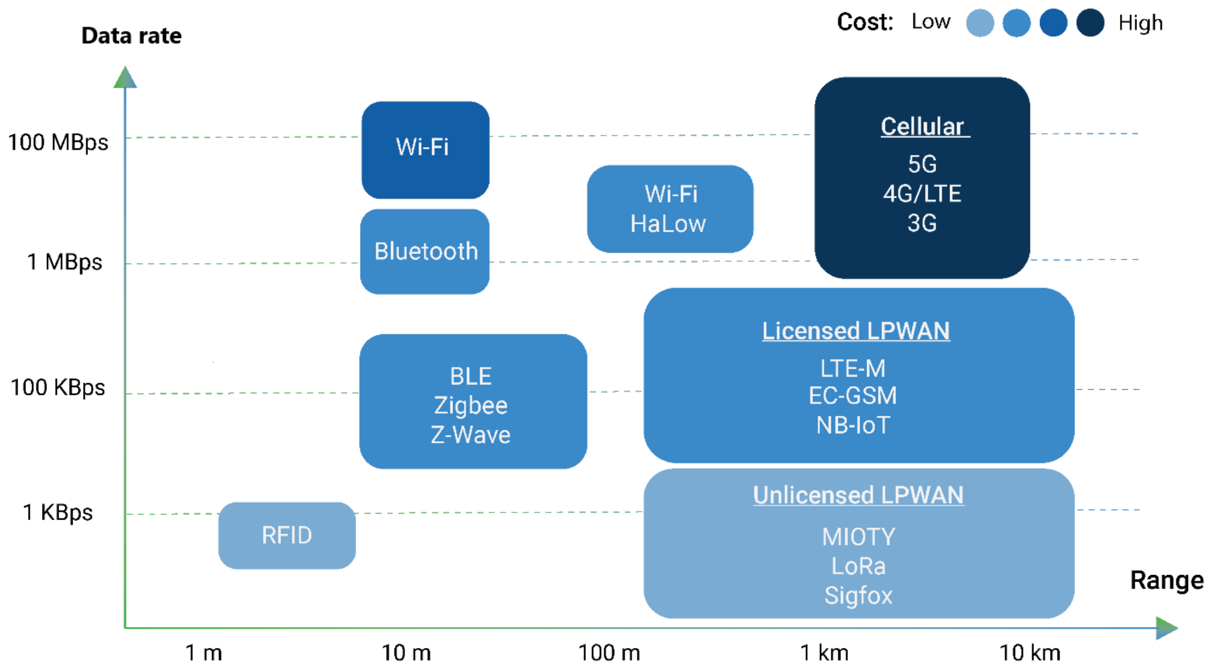

Figure 1: LoRa frequency scope

1.1.1 Modulation technique

LoRa is an RF modulation technology that uses the Chirp Spread Spectrum (CSS) technique for the transmission. This technique offers low-cost and low-power modulation while trading off the high data rate. LoRa operates with fixed bandwidth channels of either 125 kHz, 250 kHz, or 500 kHz, depending on the area and the type of the channel. CSS uses wideband linear frequency modulated chirp pulses to encode information and utilizes the entire allocated bandwidth. This makes the signal resistant to multi-path fading, even when the transmission power is very low. Thanks to this modulation technique, LoRa is considered a very robust communication protocol, as this technique is also used in nature by animals like dolphins and bats, and has also been used for military purposes. Furthermore, CSS relies on the linear

[1] Radio Frequency (RF) is a measurement representing the oscillation rate of electromagnetic radiation spectrum, or electromagnetic radio waves, from frequencies ranging from 300 GHz to as low as 9 kHz.

nature of the chirp pulse which creates pseudo-orthogonal spreading codes that contribute to the durability against channel noise [4]. Lastly, this modulation also includes a variable error correction scheme that improves the endurance of the transmitted signal, but it doesn't provide any security mechanism other than Cyclic Redundancy Check (CRC). Thus, LoRa messages are only integrity protected. If the integrity is not intact, which means that CRC is incorrect, the message will be dropped by the receiver.

1.1.2 Characteristics and parameters

LoRa's field of application is the unlicensed radio spectrum frequencies of the Industrial, Scientific, Medical (ISM) band, like in most other LPWAN technologies. Depending on the country, the available frequencies are different, but are generally sub-GHz, which means an overall low bandwidth for LoRa links. However, the use of low frequencies compensates for this drawback, as it allows the signal to remain intact even at negative Signal to Noise (SNR) ratio values. In other words, the demodulation of the signal on the receiver side is possible even when the received power is lower than the noise level.

The LoRa radio has different configuration parameters which affect energy values and transmission ranges.

More specifically:

- Spreading Factor (SF): The SF is the number of modulated data bits per unit of time (usually seconds). It could also be described as the amount of spreading code applied to the original data signal. Its value is an integer number between 7 and 12 (SF7, SF8, ..., SF12). The greater value of SF means higher Time on Air (ToA) to transmit data, higher power consumption, and lower bit rate, but greater PHY robustness [3].
- Coding Rate (CR): The coding rate expression is $CR = 4/(4+n)$, where $1 \leq n \leq 4$. This means, that every 4 bits, additional n bits are used for redundancy in case of bit loss or bit flipping. The smaller the coding rate fraction is, the higher the ToA [3].
- Transition Power (TP): The TP is the power that a device uses to transmit a LoRa signal. Typical value is 20mW [5].
- Bandwidth (BW): The BW represents the range of frequencies in the transmission band. It can only be chosen among three options: 125 kHz, 250 kHz, or 500 kHz.
- Duty Cycle (EU) / Dwell Time (US): The Duty Cycle and the Dwell Time refer to the time that the end-device is busy with transmitting data. When time runs out the end-device will remain "silent" waiting to transmit again. In Europe, the regulated quantity is the Duty Cycle, and its value range is 0.1% - 10% [6].
- Carrier Frequency (CF): The CF is the center frequency used for the transmission band. CF is in the range of 863 MHz to 870 MHz in Europe and 902MHz to 925MHz in the United States.

There are also some performance indicator parameters which are used to evaluate the status of the link and are directly affected by the configuration parameters. The most important of them is ToA. ToA represents the time that a message takes to be sent through the air, starting when the transmitter sends the message and ending when the receiver gets all the payload. The higher the CR or, evenly, the lower the SF, the smallest time will be needed for the signal to be transmitted in the air.

Some of the configuration parameters, like CF, Duty Cycle, and Dwell Time are regional [7] and their values are based on local restrictions. Changing these values affects the performance of the link. Hence, LoRa provides a mechanism to adapt and control the values of SF, bandwidth, and transmission power. It uses an algorithm that is called Adaptive Data Rate (ADR) and is focused on optimizing data rates, ToA, and power consumption [8]. For example, if we increase the SF in the modulation process, then the receiver's sensitivity will improve, but transmission time will be longer. This is necessary when the link has a low SNR value due to distance or obstacle parameters. In general, if the receiver is placed close to the transmitter, then the selected SF will be low, thus using a high rate of modulation. Having obstacles added in-between, or increasing their distance will lead the mechanism to choose a higher SF to restore the desired Link-Budget value. In general, the use of orthogonal spreading factors helps in multiple packet transmission. Additionally, more than one entity can transmit in a channel with the same Frequency and Spreading Factor as long as one of the above parameters is different. This vastly improves the capacity and throughput of the link.

1.2 What is LoRaWAN?

LoRaWAN is a Data-Link protocol, designed by the LoRa Alliance. It is implemented in the Medium Access Control (MAC) sublayer and built on top of the LoRa modulation. The key aspect is to enable communication between end devices in a power-efficient way, in order to prolong their battery sustainability.

These end devices can be either geographically static or mobile and are usually organized in star-of-stars topologies. A network server is placed in the center of this topology and multiple gateways[2] are responsible for the transmission of the information in both directions between these two entities. The backend of the network consists of these gateways along with the network and the application servers. The links between these nodes are standard IP connections. On the other side, the end devices communicate with one or more gateways at once, using single-hop broadcast links, according to the LoRa regulations specified above.

The data flow from the end devices to the network server will be referred as uplink traffic, while the opposite will be referred as downlink traffic. Uplink messages are only restricted by duty cycle or dwell time, based on the region, but can otherwise be sent

[2] Gateways are also known as concentrators, routers, access points or base stations.

by the devices at any time. Downlink messages, though, can only be sent to a device under specific circumstances, as it will be explained below.

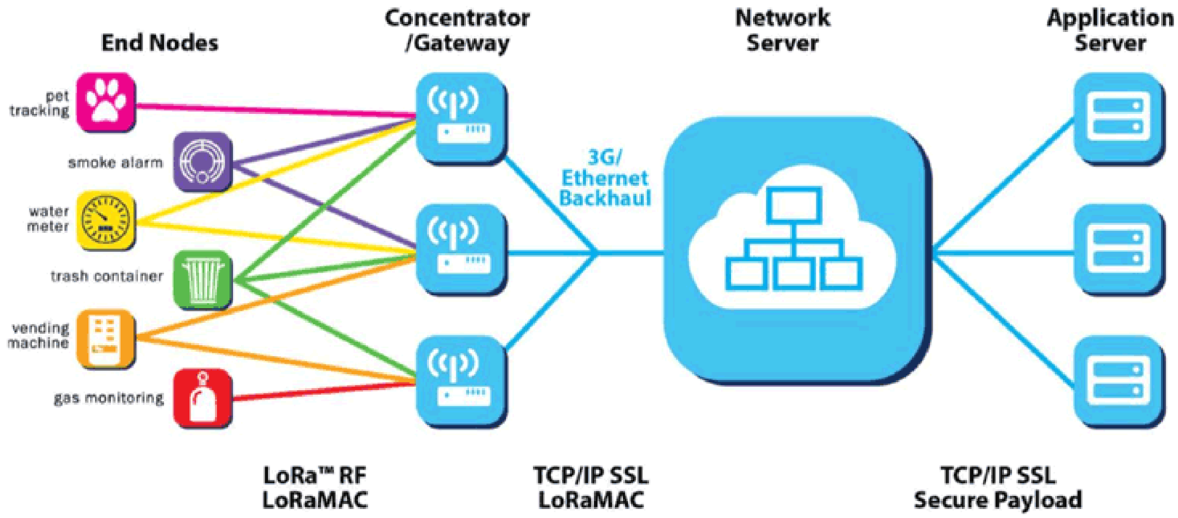

Figure 2: Typical LoRaWAN topology

1.2.1 First look into LoRaWAN Classes

LoRaWAN networks include end nodes with limited power resources and processing capabilities such as sensors, so special attention is required to ensure their networking activity is very lightweight. For this reason, the end devices are differentiated in three classes A, B, and C, which indicate their power consumption profile.

Class A-capable devices can receive a downlink response in one of the two time slots they initiate shortly after their uplink message was transmitted completely. These slots are timely spaced at approximately 1 second from each other and only one of them can be used by the server.

Class B-capable devices act like A devices, but additionally listen for a response periodically after the two first time slots. This approach gives the server more chances to reply to a device which might otherwise be missed or delayed. However, it's not as battery friendly as the first class.

Finally, class C-capable devices implement class A functionality too, but also listen for a pending reply continuously after the first two slots if they are both missed. This behavior can either be applied forever or, in some cases, until a specific time after which the response would not be useful for the device. Class C behavior is the most power consuming and is usually chosen for devices that are hard-wired and not on battery supply. Yet, it is the most efficient when it comes to a need for fast responses from the server.

All devices in a LoRaWAN network have to implement one or more of these three profiles, with Class-A being mandatory. The general purpose behind having these classes is to point out the ability of the end device to remain “silent” when there is no need to receive or transmit any data. This ability contributes to low energy consumption which is one of the most important goals of the LoRaWAN protocol.

1.2.2 End device activation

LoRaWAN packets consist of an 8-byte LoRa header and a minimum of 11 bytes for MAC payload. There are a number of MAC commands which are used for radio channel configuration, link and device status checking, duty cycle negotiation, RX window management, and data rate adjustment. There is also a definition of ports to discriminate between different applications behind the network server. By default, port 0 is used only for MAC commands.

There are two ways to register a device in a LoRaWAN network, Over the Air Activation (OTAA) and Activation by Personalization (ABP).

In the first method the device initiates its integration into the network by sending a Join-Request to the server. This request must contain a device-exclusive application key (AppKey), a device unique identifier (DevEUI), and the application unique key (AppEUI) of the application server it wants to connect to. This message is not encrypted, but its integrity is ensured by the use of the AppKey. The network server checks the AppKey validity in order to allow the device into the network. If the Join-Response by the server is a Join-Accept message then the device receives a message with a 24-bit Join Server Nonce (Join Nonce), a 24-bit NetID, a 32-bit DevArr (which is like the IP address in IP networks), downlink configuration settings (DLSettings), a delay between Tx and Rx, and an optional list of network parameters (CFList) for the Network the end device joining [9]. The device uses this information to generate a 128-bit Network-Session-Key (NwkSKey) and a 128-bit Application-Session-Key (AppSKey), which are used to encrypt messages with AES 128-bit. This method is thus a secure way of adding new devices to the network and also supports mobile clients, because all the information is provided by the server.

On the other hand, the ABP method is a more static approach to accomplish this task. In this case, each end device has already preinstalled the DevAddr, NwkSKey and AppSKey values by its manufacturer and they cannot be modified. No Join-Procedure takes place, and all the information is handed directly to the targeted network server. For this reason, this method is less secure, because the keys are stored locally in the device and it is additionally not mobile-friendly, as the hopping of networks is harder when the activation information is not dynamic.

Overall, OTAA is almost always preferred over the ABP method unless there is a good reason to do otherwise.

1.2.3 Security & Performance

LoRaWAN adds a lot of security features to the LoRa communication to achieve authenticity, integrity, and confidentiality in every session. Except for using simple frame counters, all message payloads, following the Join procedure, are end-to-end encrypted with the use of different keys for the network and the application servers. In addition, the topology usually contains a join server [10] entity, which stores all the AppKeys away from the network server and makes the activation procedure safer by acting like a registry for the sessions. Moreover, AppNonces are there to protect the message exchange from replay attacks[3].

LoRaWAN protocol also enhances the performance of the LoRa communication with mechanisms like link status and availability checking with specific MAC commands. Finally, it offers an acknowledgement option for received messages in both uplink and downlink.

1.3 Use of LoRa and LoRaWAN technologies

Combining all the above, we conclude that LoRa and LoRaWAN protocols together, can provide a competitive solution for IoT infrastructures. The need for great power autonomy is taken care of by multiple mechanisms. On top of that, a very long range and high-capacity communication can be achieved at a relatively low cost. Although its bandwidth is low and not capable of supporting continuous flow like videos or voice calls, it is ideal when handling small data signals which is the type of communication that is met in IoT devices. Lastly, these protocols make the transmission of the signal durable to collisions, Doppler effect, and can be applied on mobile end devices (installed on cars, trains, etc.) that face more intense interference and multipath phenomena than the static ones.

The presence of this technology provides a good alternative to popular types of wireless networks such as WiFi or Bluetooth, when there is a necessity for long distance links. Typical scenarios in IoT, where this feature would be important, are large scale procedures that can be automated or supervised by sensors. Namely, they can be smart agricultural environments, natural disaster prediction, remote healthcare monitoring, logistics, business chain control applications, and even more.

[3] In case someone tries to resent a message, known as replay attack, it will be detected and blocked because of frame counters. More specifically, there are two types FCntUp and FCntDown which are set to zero when the end device is activated. When the end device needs to transmit a message (uplink process) the frame counter FCntUp will be increased and when it needs to receive a message from Gateway the frame counter FCntDown will be increased. When the end device or the network receives a message with a frame counter with lower value than the previous one, it will ignore this message.

2. PHY Scenarios

2.1 Range measurements for static wireless nodes in relation to anaglyph of terrain

The purpose of this scenario is to study the quality of a connection among static end devices and a gateway. First of all, we consider three concentric circles, with their center being the gateway coordinates. These circles have a radius of 100 meters, 150 meters, and 200 meters respectively. We take several measurements on 12 - evenly spaced - points on each circle's perimeter. For these measurements, the end devices are static and the process of sending data is accomplished by pressing the button of the node. This scenario takes place in a suburban environment with plantation. This experiment is repeated for three different SFs. The goal of this study is to find out how the different parameters - other than distance - affect the connection between the gateway and the node. Ideally, we would expect all the points on the perimeter of one circle to have the same signal strength. However, we try to realize how signal strength is reinforced or weakened by the anaglyph of terrain, the existence of obstacles and other parameters such as temperature and humidity of the environment and the height between the two devices.

2.1.1 Metrics to study

We calculate RSSI, SNR and PDR of end devices which are located on the perimeter of a circle.

2.1.2 Hardware and software required

Hardware:

1. Two end devices, of type **The Things Node** [11].
2. A **LORIX One** gateway [12].
3. One Android device for each node.

Software:

1. A Map application (e.g., Google Earth Pro), for analyzing elevation profiles and drawing the circles.
2. A map API which you can find here to visualize the results.
3. Use of Arduino IDE and the sketch Basic from examples of library **TheThingsNode.h**
4. An Android application: TTN Mapper app to record and upload coverage information.
5. A Python script to validate the logged data and calculate statistics about RSSI, SNR and PDR values for each circle and SF.

Figure 3: The LORIX One gateway

Figure 4: Gateway's installation site

Figure 5: The Things Node

2.1.3 Parametrization

First, we take for granted that the gateway and the end devices are properly parametrized to send and receive Join-Requests. Then, we connect the end devices to the computer which already has Arduino IDE installed. Also, we need to include the library *TheThingsNode.h* in the Arduino IDE, by selecting *Sketch > IncludeLibrary > ManageLibraries*. The sketch we use to program the node is located in *File > Examples > TheThingsNode > Basic.* We modified this specific sketch, in order to deactivate some of the node's transmissions, caused by motion detection or a short periodic interval, thus leaving only the option to send data on the button press, ensuring full control over the time the measurements will be taken. Finally, we made the SF parameter constant, to choose only the one we want for each experiment.

```
  // Config Node
  node = TheThingsNode::setup();
  node->configLight(true);
  node->configInterval(true, 86400000);
  node->configTemperature(true);
  node->onWake(wake);
  node->onInterval(interval);
  node->onSleep(sleep);
//  node->onMotionStart(onMotionStart);
  node->onButtonRelease(onButtonRelease);
```

Figure 6: Deactivation of Uplinks based on periodic intervals and motion detection events

```
#include <TheThingsNode.h>

// Set your AppEUI [redacted]
const char *appEui = [redacted]
const char *appKey = [redacted]

#define loraSerial Serial1
#define debugSerial Serial

// Replace REPLACE_ME with TTN_FP_EU868 or TTN_FP_US915
#define freqPlan TTN_FP_EU868
uint8_t spreadingFactor = 9;

TheThingsNetwork ttn(loraSerial, debugSerial, freqPlan, spreadingFactor);
TheThingsNode *node;

#define PORT_SETUP 1
#define PORT_INTERVAL 2
#define PORT_MOTION 3
#define PORT_BUTTON 4
```

Figure 7: Static definition of SF parameter

2.1.4 Experimental process

First, the end device has to get a power load. In this case, we use batteries as an energy source. The next step is to draw a circle using Google Earth Pro with center the gateway and to find the points of measurements. These points differ by 30 degrees from each other and are on the perimeter of the circle. We draw 3 similar circles, one for each radius we want to test. Before each experiment, we make sure to load the sketch with the desired SF option (SF7, SF8 or SF9) on the node. We approach the points using the GPS on our phone. If there are physical obstacles or buildings on the site, we try to be as close as possible to the draw area. At these points, we will have the nodes send at least 10 measurements to the gateway, while remaining static at 1 meter above the ground during this process. The interval between 2 consecutive measurements at a site is approximately 20 seconds.

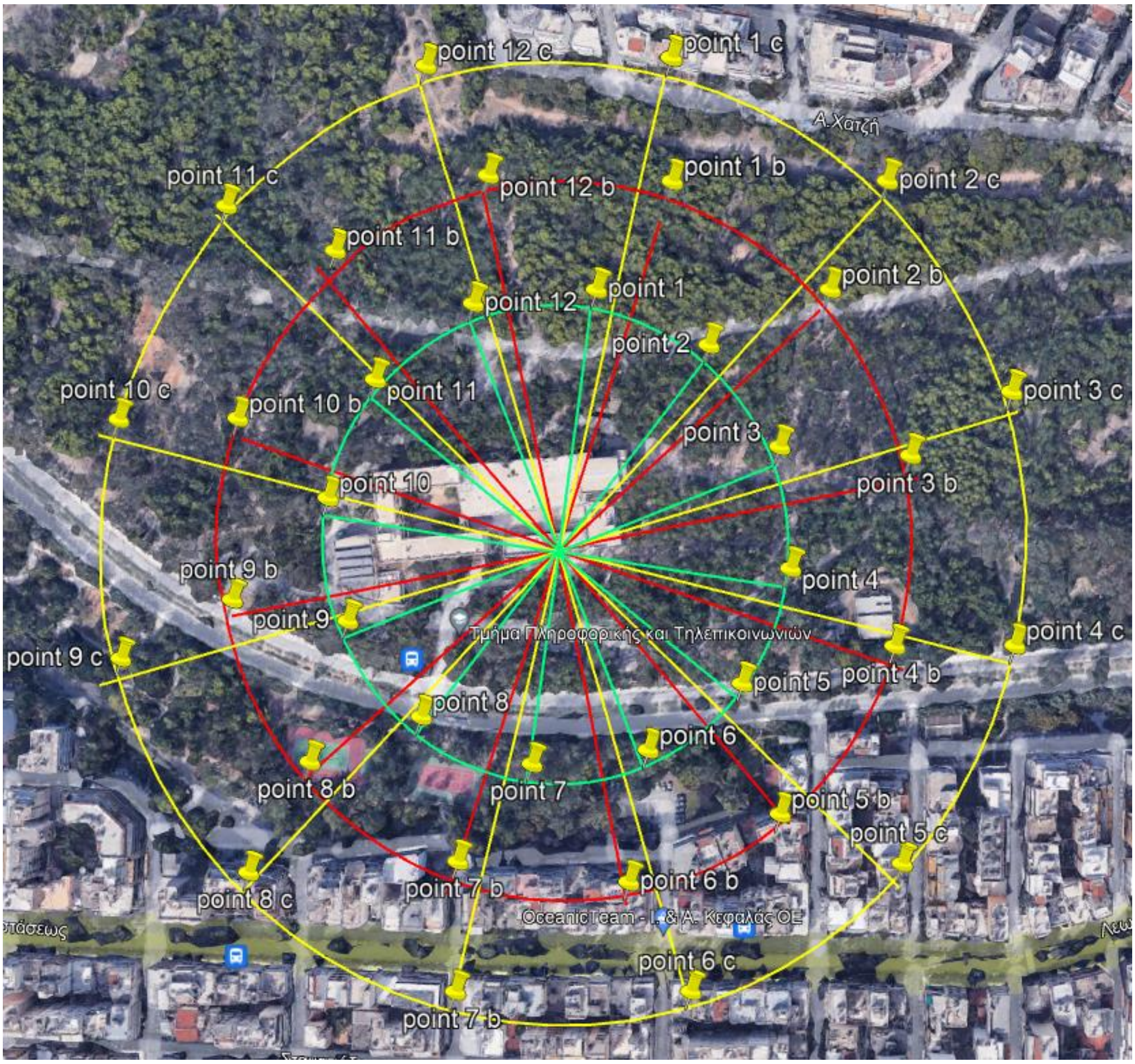

Figure 8: Circles and points of measurements

Figure 9: Antenna location

Table 1: Points tested at 100-meter radius

Radius 100 meters - Points	Latitude	Longitude
P1	37.9692	23.7675
P2	37.9689	23.768
P3	37.9685	23.7683
P4	37.968	23.7682
P5	37.9677	23.7678
P6	37.9675	23.7673
P7	37.9676	23.7668
P8	37.9689	23.768
P9	37.9682	23.766
P10	37.9687	23.766
P11	37.969	23.7664
P12	37.9692	23.7668

Table 2: Points tested at 150-meter radius

Radius 150 meters - Points	Latitude	Longitude
P1	37.9695	23.7679
P2	37.969	23.7686
P3	37.9682	23.7688

P4	37.9677	23.7686
P5	37.9673	23.7679
P6	37.9671	23.7672
P7	37.9672	23.7663
P8	37.9677	23.7656
P9	37.9684	23.7653
P10	37.969	23.7656
P11	37.9695	23.7663
P12	37.9697	23.7671

Table 3: Points tested at 200-meter radius

Radius 200 meters - Points	Latitude	Longitude
P1	37.9699	23.768
P2	37.9693	23.769
P3	37.9684	23.7692
P4	37.9676	23.7691
P5	37.9668	23.7686
P6	37.9666	23.7671
P7	37.9667	23.7662
P8	37.9674	23.7654
P9	37.9683	23.765
P10	37.9691	23.765
P11	37.9699	23.7658
P12	37.9701	23.7669

2.1.5 Quantitative and qualitative results

We organized the results in nine pairs of tables, one for each SF and radius combination. These results are extracted from the log-files of the TTNMapper app. They could be also extracted from The Things Network Console. For this scenario, we wrote a Python script, to validate and sum-up the original data into the following tables.

2.1.6 Conclusions

Table 4: Spreading Factor 7 – Radius 100m

ADR	CR	Channel	BW	TP	Number of devices in proximity	Number of other devices	SF
Off	4/5	EU668	125 kHz	14mW	0	68	7

Points	MAX RSSI	MIN RSSI	Aver. RSSI	Med. RSSI	MAX SNR	MIN SNR	Aver. SNR	Med. SNR	Aver. Accuracy	PDR (%)
P1	-71	-95	-82.18	-82	10.75	7.25	9.182	9.25	4	73.3
P2	-75	-93	-80.8	-79.5	10.25	6.75	8.6	8.75	4	100
P3	-82	-94	-85.26	-85	10.25	7.25	9.224	9.5	4.2	100
P4	-85	-89	-87.1	-87.5	10	7.25	8.75	9.125	4	100
P5	-85	-92	-87.24	-87	10.5	7.25	8.699	8.625	4.2	100
P6	-79	-97	-88	-87.5	10.5	7	9.1	9.25	4	100
P7	-79	-89	-81.71	-83	10.25	6.75	8.588	9.5	9.393	100
P8	-81	-97	-87.06	-87	10.25	6.75	8.503	8.625	4.2	100
P9	-92	-107	-97.24	-98	10	5.5	8.176	8.625	4.4	100.
P10	-88	-109	-92.34	-92.5	10	6	8.4	9	8.966	100
P11	-73	-83	-76.73	-77	10.75	7.75	9.126	9.25	4.2	90.9
P12	-64	-85	-71.38	-71.5	10.25	5.75	8.165	8.625	6.396	90.9

Table 5: Spreading Factor 8 – Radius 100m

ADR	CR	Channel	BW	TP	Number of devices in proximity	Number of other devices	SF
Off	4/5	EU668	125 kHz	14mW	1	72	8

Points	MAX RSSI	MIN RSSI	Aver. RSSI	Med. RSSI	MAX SNR	MIN SNR	Aver. SNR	Med. SNR	Aver. Accuracy	PDR (%)
P1	-71	-86	-79.07	-81	11.25	7.5	9.188	9.25	4.405	90.9
P2	-81	-94	-84.27	-90	12	7.25	9.555	11	15.665	100

P3	-82	-95	-86.5	-90	11	7.5	9.08	9.25	7.346	100
P4	-81	-94	-80.9	-84	12	8.25	9.835	10.75	6.863	100
P5	-83	-106	-91.1	-90	11.75	8.5	10.4	10.5	3.79	100
P6	-86	-106	-87.85	-90	11.75	5.75	9.555	10.25	6.248	100
P7	-82	-94	-81.91	-85	11.75	8	9.838	11.25	6.863	100
P8	-77	-87	-83.2	-85	12	8	10.225	10.5	3.79	100
P9	-85	-99	-85.44	-88	9.75	7.25	8.108	8.5	6.248	100
P10	-88	-106	-92.5	-90	9.75	5.25	7.75	7.375	3.79	100.
P11	-68	-79	-74.34	-76	10.5	6.75	9.408	9.75	4.405	100
P12	-64	-82	-65.48	-68	10.25	6.75	8.26	8.75	6.863	90.9

Table 6: Spreading Factor 9 – Radius 100m

ADR	CR	Channel	BW	TP	Number of devices in proximity	Number of other devices	SF
Off	4/5	EU668	125 kHz	14mW	1	72	9

Points	MAX RSSI	MIN RSSI	Aver. RSSI	Med. RSSI	MAX SNR	MIN SNR	Aver. SNR	Med. SNR	Aver. Accuracy	PDR (%)
P1	-76	-91	-84.2	-83.5	12.75	7	9.85	9.375	4	100
P2	-80	-88	-81.52	-82.5	13.5	8	10.831	11.625	9.142	100
P3	-89	-99	-93.73	-94	12.5	8	10.508	11	4.2	90.9
P4	-80	-95	-86.2	-86	13	9	11.025	11.5	4	100
P5	-89	-109	-94.95	-94.5	13	5.75	10.279	11.125	4.2	100
P6	-82	-94	-86.8	-86	12.75	8.25	11.05	11.5	4	100
P7	-81	-93	-86.23	-87	13.75	8.5	11.16	11.125	4.2	100
P8	-79	-93	-83.69	-89	12.75	8.25	10.592	11.25	6	100
P9	-85	-95	-90.9	-91	10.25	7.25	8.8	9	4	100
P10	-87	-104	-95.24	-97	10.5	5.5	7.93	8.125	4.6	100
P11	-75	-88	-79	-78	11	7.75	9.2	9.125	4	100
P12	-69	-88	-71.84	-75.5	10.75	7.75	8.446	8.875	9.178	100

Table 7: Spreading Factor 7 – Radius 150m

ADR	CR	Channel	BW	TP	Number of devices in proximity	Number of other devices	SF
Off	4/5	EU668	125 kHz	14mW	0	39	7

Points	MAX RSSI	MIN RSSI	Aver. RSSI	Med. RSSI	MAX SNR	MIN SNR	Aver. SNR	Med. SNR	Aver. Accuracy	PDR (%)
P1	-79	-95	-86.744	-89	9.75	7	8.144	8	4.473	75
P2	-81	-99	-89.323	-91	10	6.75	8.642	8.75	3.847	91.7
P3	-91	-107	-97	-95	9.5	-1.25	6.806	8	3.79	100
P4	-94	-106	-100.35	-101	9.25	-0.75	6.036	6.75	3.839	100
P5	-89	-110	-87.43	-99	9.5	2.25	6.48	8.125	9.88	100
P6	-83	-101	-83.425	-90	10	7.25	7.746	8.625	8.781	100
P7	-86	-101	-88.21	-92.5	10	6.25	7.842	8.75	6.301	100
P8	-83	-97	-90.4	-92.5	9.5	4.25	7.878	8.5	5.019	100
P9	-93	-105	-99.667	-100	8.75	1.5	6.417	8	3.79	100
P10	-91	-107	-97.091	-98	8.75	4.5	7.318	8	3.79	100
P11	-85	-95	-89.3	-88.5	9.25	7.25	8.375	8.5	3.79	100
P12	-85	-99	-88.356	-88	10	6.75	8.058	8.75	4.473	64.3

Table 8: Spreading Factor 8 – Radius 150m

ADR	CR	Channel	BW	TP	Number of devices in proximity	Number of other devices	SF
Off	4/5	EU668	125 kHz	14mW	1	72	8

Points	MAX RSSI	MIN RSSI	Aver. RSSI	Med. RSSI	MAX SNR	MIN SNR	Aver. SNR	Med. SNR	Aver. Accuracy	PDR (%)
P1	-81	-95	-81.7	-88.5	12	8.25	9.54	10.375	8.092	90.9
P2	-88	-100	-92.111	-89	11.25	7.5	9.444	10	3.79	90
P3	-92	-106	-98.6	-99	10.75	-1	8.375	9.625	3.79	100

P4	-97	-106	-89.91	-100.5	10.5	-0.75	6.39	8.125	9.935	100
P5	-89	-101	-83.35	-94.5	11.75	7.75	8.893	10.75	11.603	100
P6	-81	-95	-87.82	-92.5	11.25	6.75	9.535	10.125	5.019	100
P7	-82	-106	-84.04	-89	12	2.25	9.408	11	7.477	100
P8	-88	-101	-87.27	-94	11.75	8.5	9.865	10.5	8.092	100
P9	-89	-111	-97.818	-95	11.25	5	9.091	9.75	3.79	91.7
P10	-87	-100	-91.9	-91	11.25	8.25	10.425	10.5	3.79	100
P11	-81	-91	-87.8	-88	12.5	8.25	10.725	11.25	3.79	71.4
P12	-75	-105	-81.392	-85	12	8.25	9.694	10.75	6.35	85.7

Table 9: Spreading Factor 9 – Radius 150m

ADR	CR	Channel	BW	TP	Number of devices in proximity	Number of other devices	SF
Off	4/5	EU668	125 kHz	14mW	1	72	9

Points	MAX RSSI	MIN RSSI	Aver. RSSI	Med. RSSI	MAX SNR	MIN SNR	Aver. SNR	Med. SNR	Aver. Accuracy	PDR (%)
P1	-79	-100	-87.205	-87	13.25	8.75	10.855	11	4.2	83.3
P2	-91	-99	-92.115	-94	13.25	8.75	11.132	11.75	5	90.9
P3	-91	-108	-96.975	-100	13	3.25	9.281	9.875	4.8	100
P4	-88	-110	-95.88	-99	13.25	6.25	10.072	11	6.754	100
P5	-91	-103	-91.97	-94	13	7.5	9.85	10.875	5.6	100
P6	-89	-103	-90.345	-93	12.5	4.75	9.262	10.625	7	100
P7	-87	-106	-90.265	-93	12.75	6.75	10.448	11.5	5.4	100
P8	-78	-101	-90.975	-96	12.5	7.25	10.631	11.5	4.6	100
P9	-95	-115	-100.27	-100	12	-1	8.714	9.75	17.236	78.6
P10	-90	-111	-98.1	-99	12.75	3.75	9.6	10.375	4	83.3
P11	-87	-97	-88.475	-90	13.25	8.25	11.074	12.25	5.2	66.7
P12	-83	-97	-88.35	-89.5	13.75	8.75	11.806	12	4.333	75

Table 10: Spreading Factor 7 – Radius 200m

ADR	CR	Channel	BW	TP	Number of devices in proximity	Number of other devices	SF
Off	4/5	EU668	125 kHz	14mW	0	68	7

Points	MAX RSSI	MIN RSSI	Aver. RSSI	Med. RSSI	MAX SNR	MIN SNR	Aver. SNR	Med. SNR	Aver. Accuracy	PDR (%)
P1	-92	-107	-94.23	-97	10.25	4.25	7.333	8	6.154	76.5
P2	-91	-111	-95.79	-96	10	2.5	5.895	6.25	23.123	100
P3	-98	-113	-103.1	-104	7.75	-2	4.987	5.75	5.019	90.9
P4	-89	-104	-98.5	-98.5	10.25	6.5	8.6	8.625	3.79	100
P5	-107	-115	-100.1	-111.5	4	-7.25	-0.225	0.875	9.978	100
P6	-93	-110	-87.82	-99	8.75	5	6.43	7.375	10.812	100
P7	-89	-101	-87.33	-97	9.75	7.25	7.643	8.5	9.596	100
P8	-78	-87	-75	-81.5	10.25	7	8.228	9.375	8.706	100
P9	-95	-112	-94.94	-103.5	8	-2.25	5.678	6.75	8.926	100
P10	-101	-112	-105	-107	7.25	-0.5	3.57	4	15.651	100
P11	-91	-97	-94.6	-94.5	10	6.75	8.65	8.625	3.79	100
P12	-88	-107	-100.6	-102	9.75	4	7.219	7.25	3.79	61.5

Table 11: Spreading Factor 8 – Radius 200m

ADR	CR	Channel	BW	TP	Number of devices in proximity	Number of other devices	SF
Off	4/5	EU668	125 kHz	14mW	1	68	8

Points	MAX RSSI	MIN RSSI	Aver. RSSI	Med. RSSI	MAX SNR	MIN SNR	Aver. SNR	Med. SNR	Aver. Accuracy	PDR (%)
P1	-98	-110	-103.3	-102.5	10	-0.25	6.4	8	3.79	90.9
P2	-98	-109	-94.14	-104	10.25	2	6.165	6.875	9.321	100
P3	-92	-100	-98.1	-99	10.75	7.25	9.425	9.625	3.79	100

P4	-96	-113	-102.7	-102	10	1.25	7.2	7.5	3.79	100
P5	-106	-117	-100.08	-111.5	7	-7.25	-0.675	0.5	10.118	100
P6	-103	-112	-98.84	-109.5	7.5	-4.75	2.567	3.875	9.57	100
P7	-93	-104	-90.2	-98.5	11.25	6.5	8.553	9.625	8.706	100
P8	-93	-107	-86.23	-97	11	3.75	8.213	10.25	14.334	100
P9	-94	-111	-97.73	-104	9	-1.75	4.845	7	7.758	100
P10	-101	-116	-107.79	-110.5	7.75	-8.75	0.973	2.5	4.405	100
P11	-88	-107	-92	-95	10.75	4.75	7.855	8.5	6.863	100
P12	-98	-105	-100.54	-101	9.75	-3.5	7.114	9	3.79	55

Table 12: Spreading Factor 9 – Radius 200m

ADR	CR	Channel	BW	TP	Number of devices in proximity	Number of other devices	SF
Off	4/5	EU668	125 kHz	14mW	1	68	9

Points	MAX RSSI	MIN RSSI	Aver. RSSI	Med. RSSI	MAX SNR	MIN SNR	Aver. SNR	Med. SNR	Aver. Accuracy	PDR (%)
P1	-97	-115	-100.9	-100	13	-2.25	8.377	10	4.462	52
P2	-97	-106	-99.75	-101	12	4	8.028	8	4.714	66.7
P3	-99	-115	-104.5	-106	9.75	-5.25	5.682	7.375	4.6	100
P4	-91	-103	-94.69	-99.5	12.25	5.75	9.776	10.75	5.6	100
P5	-109	-116	-111.33	-113	3.75	-12.5	-3.98	-3.375	4.6	100
P6	-93	-101	-91.08	-95.5	12	7.75	9.539	10.5	6.6	100
P7	-93	-101	-91.57	-96	11.75	6.5	9.254	10.375	6.947	100
P8	-87	-103	-86.18	-92.5	12.5	8.5	9.694	10.625	10	100
P9	-97	-112	-103.2	-106	11	-0.75	5.799	6.875	4.8	100
P10	-98	-109	-100.6	-105	11	4.5	7.812	7.75	5.385	100
P11	-91	-112	-94.64	-97	12.75	3.75	9.909	11	5.455	100
P12	-97	-107	-98.47	-99	11.5	5.5	9.462	10.25	57.538	65

The above results lead us to a number of conclusions. First of all, we can clearly see that the signal strength on the perimeter of each circle differs a lot from point to point. To examine why this happens, we will use a set of tools, which help us study the terrain levels, and the buildings and obstacles within the circle areas. This will explain the difference between the points results, and generally how the signal is affected by the SF in every distance we chose to test. More specifically, we are going to use the Google Earth Pro API and the elevation profiling tool for this purpose. We decided to check which are the points where we noticed the best and the worst values of RSSI.

<u>100m radius circle notes:</u>

We notice that in all three SF tests, the area where the worst and the best signal is received is the same, with SF8 and SF9 agreeing that point 10 and point 12 bring these results respectively. The difference in SF7 is that the weakest signal is met at point 9 instead of 10 which is, however, a neighboring point of the previous. To find out why all three experiments have indicated the same areas, we use the elevation profiling tool for the path between the gateway and each one of the points 9, 10, and 12.

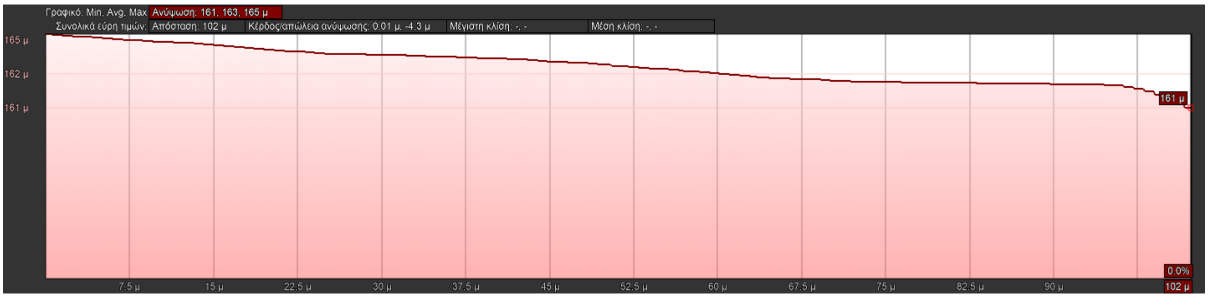

Figure 10: Elevation Profile – Radius 100 – Point 9

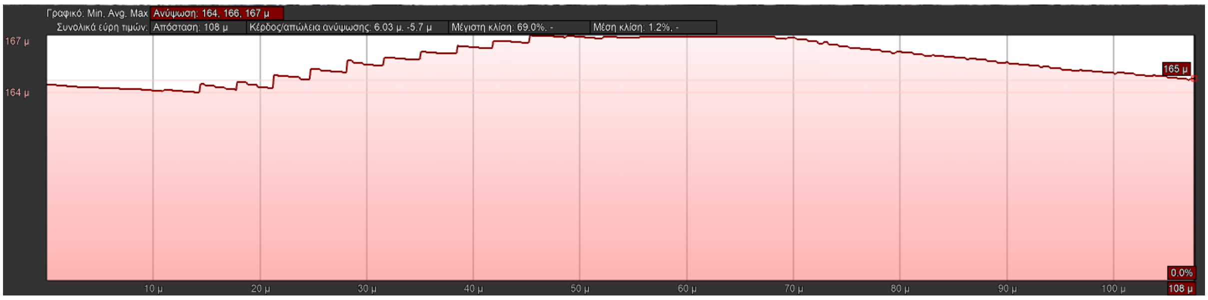

Figure 11: Elevation Profile – Radius 100 – Point 10

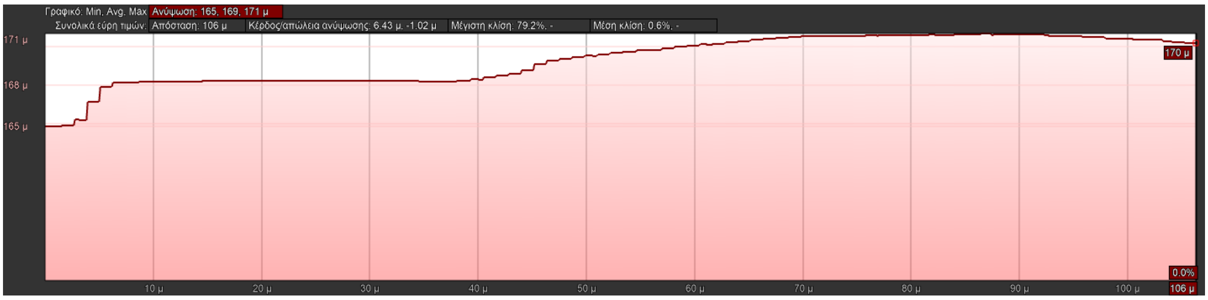

Figure 12: Elevation Profile – Radius 100 – Point 12

To examine the relation between SF and SNR, we calculate the average values of average SNR of each table (each table has a different value of SF).

These images show the terrain elevation. The gateway is on the left end while the node is placed on the right end. We figure out that in the first two points, the receiver is at the same or a bit lower ground level. The first point is lower, but the second one shows that there is a hill between the two devices. These two factors decrease the quality of the connection link. However, this alone, does not explain such a poor performance compared to the other points, since we happen to have more points in even lower altitude. We need to take a look at figure 8 to realize that there is another serious reason that causes this behavior. The university building is placed in a way that blocks more than half of the direct path. Because of the size of the obstacle, the line-of-sight connection is not possible, as it lies well within the Fresnel zone [13], and hence the signal is weakened significantly. This is clearly presented in figure 13.

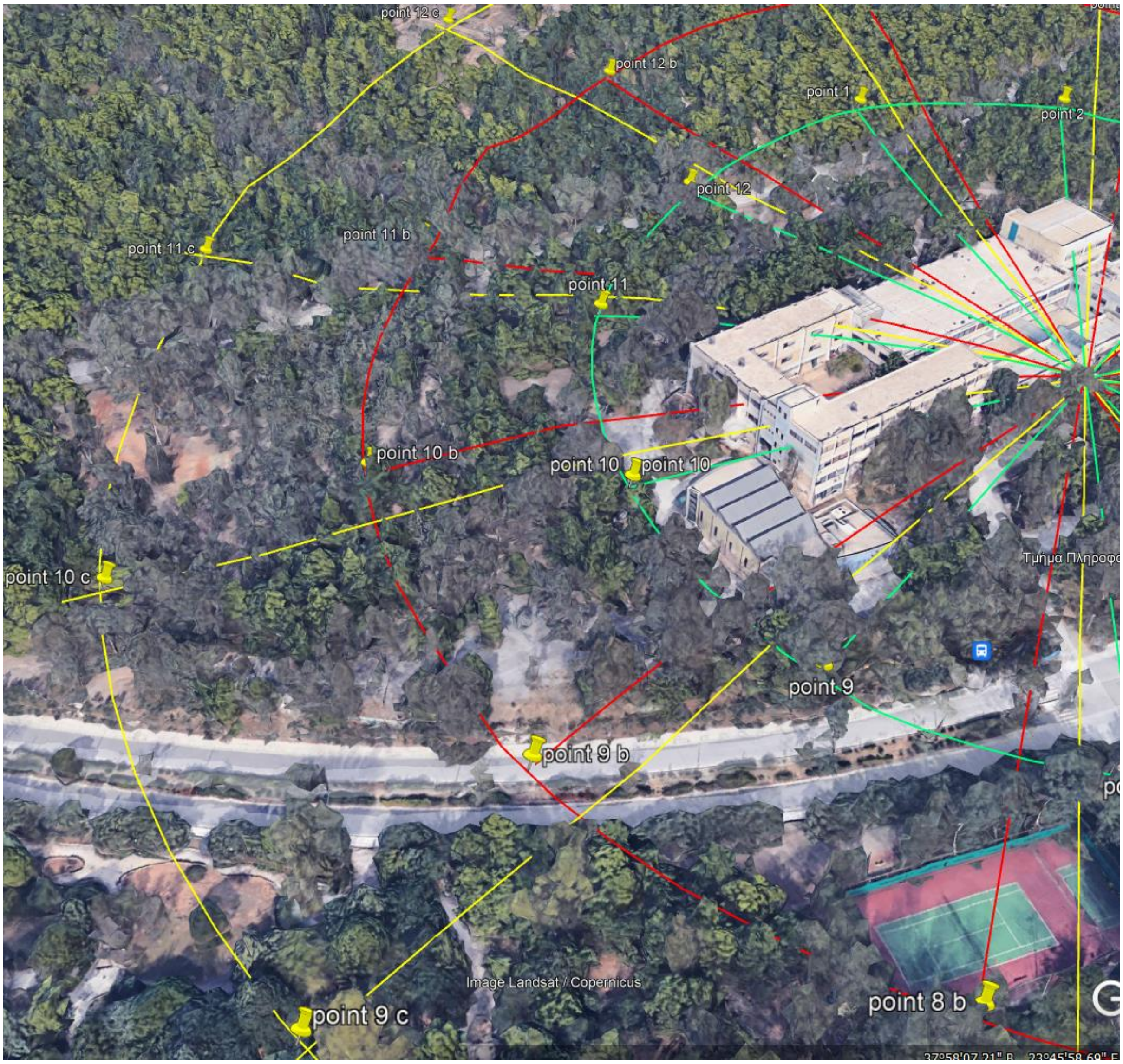

Figure 13: A closer look to the links 9, 10, 11 and 12

<u>150m radius circle notes:</u>

For this circle, we see that the points of interest are not always the same for every SF choice like before. A reason for this, is that as the transmitter-receiver distance increases, specific obstacles that remain static, affect the connection less. In cases where an obstacle is decreasing the signal a lot in short distances, we might get better results by moving away from the antenna, even though the propagation losses due to the distance will increase. This appears to be the case here, thus giving multiple points as candidates for minimum and maximum RSSI. In our case, this means the university building has a less effective role in propagating the signal, and other parameters decide where the final points will be. Similarly, to before though, point 9 seems to be again one of the worst places to put the node. When using SF7, this changes to point 4, yet it is very slightly better than point 9 once again. Regarding the better options we have, these appear to be point 6 – for SF7, point 12 – for SF8 and point 1 – for SF9.

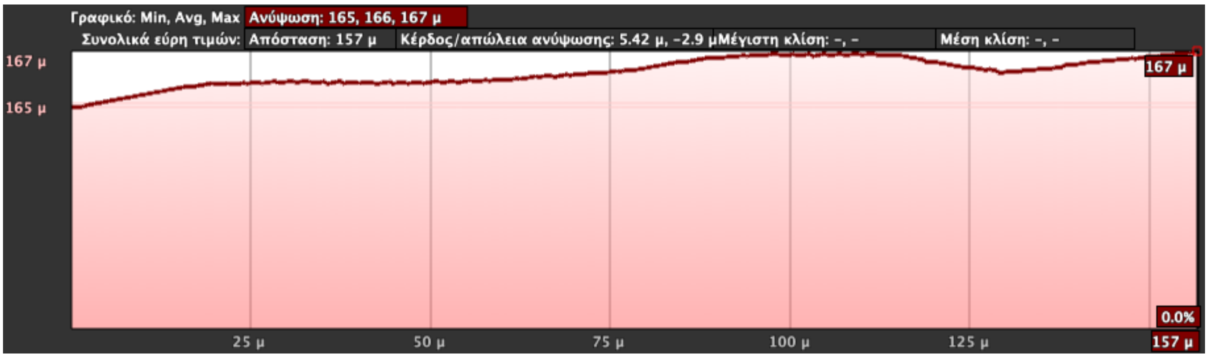

Figure 14: Elevation Profile – Radius 150 – Point 4

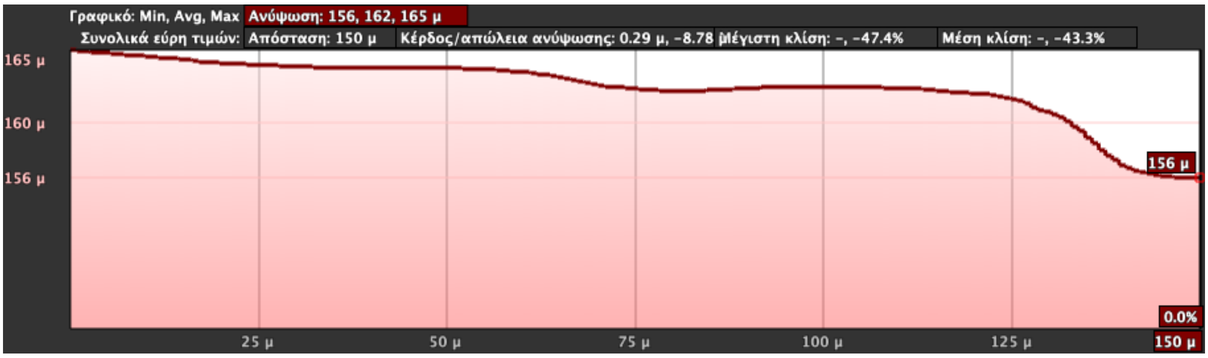

Figure 15: Elevation Profile – Radius 150 – Point 9

Point 4 seems to be at the same ground level as the gateway, but there is a very dense forestry area in the middle, as well as another university facility right next to the point. Both of these factors, affect the signal strength negatively. At point 9 however, the explanation is similar to before, with the addition that as we got further from the center of the circle, the altitude decreased even more, leaving a 10-meter height difference. At the same time, this location is exactly at the start of a small but steep hillside.

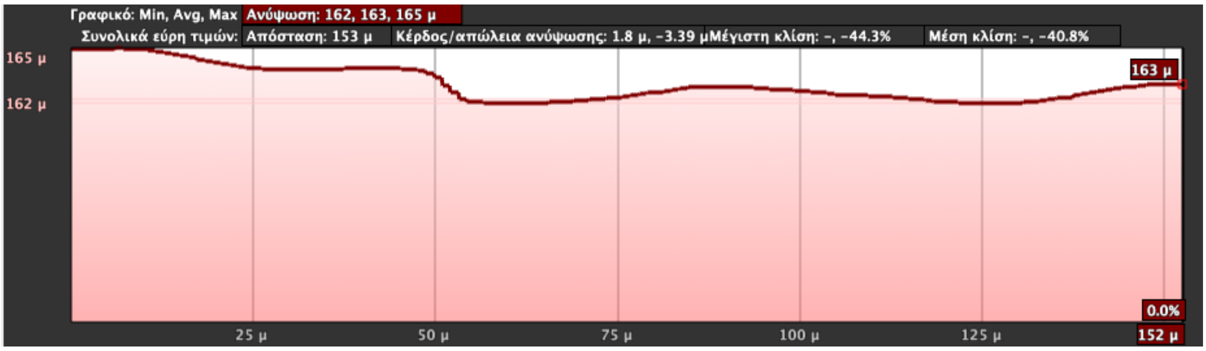

Figure 16: Elevation Profile – Radius 150 – Point 6

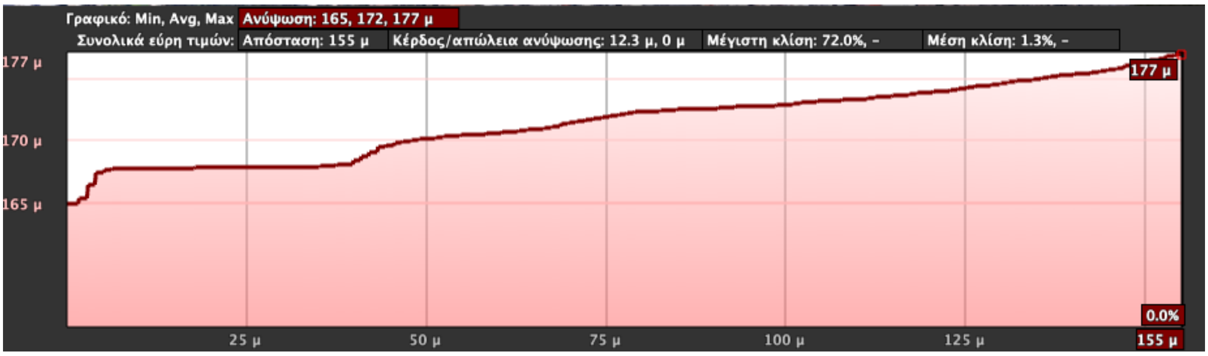

Figure 17: Elevation Profile – Radius 150 – Point 12

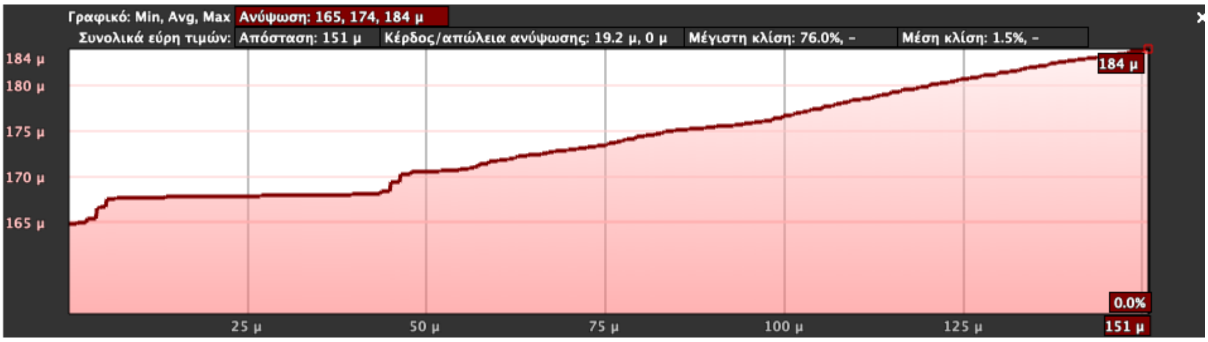

Figure 18: Elevation Profile – Radius 150 – Point 1

Judging purely from elevation profiling, point 6 is not expected to be one of the best sights, because its altitude is similar to the gateway and it lies at the start of the urban area. There are two main reasons why this happened. On the one hand, the path to the center of the circle from this point is clear from most obstacles and has very few trees. On the other hand, the exact coordinates of the sight, are on top of a high building, which was not accessible. Keeping in mind though, that having the node on a high altitude would too, give a major advantage to the connection link, we chose to place the node in front of the building. This way, the altitude was lower than it should be, but the distance from the gateway was also decreased by approximately 6 meters, resulting in less losses and balancing the final values of our measurements. Lastly, points 12 and 1 are also good options, because of their great height advantage over the gateway placement area, as shown in the above 2 images.

<u>200m radius circle notes:</u>

In this circle, we observe again the pattern where point 10 is one of the worst options, even though it seemed that point 9 was overtaking as we get away from the university infrastructure, without that meaning that point 9 is still performing very poorly compared to the average as well. In addition, we see that point 5 has also given some very low results too. On the other side, point 8 is where the best RSSI values are found in all three SF experiments.

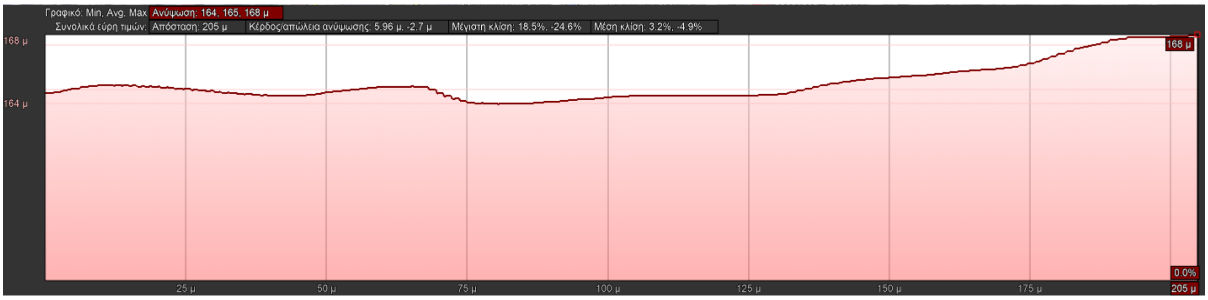

Figure 19: Elevation Profile – Radius 200 – Point 5

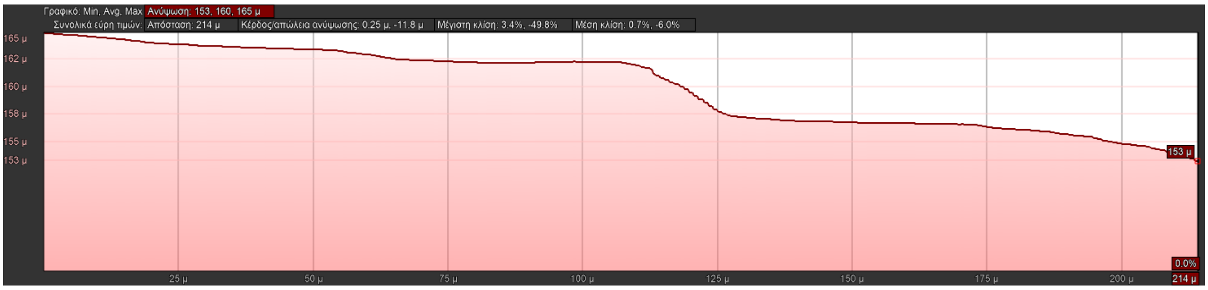

Figure 20: Elevation Profile – Radius 200 – Point 9

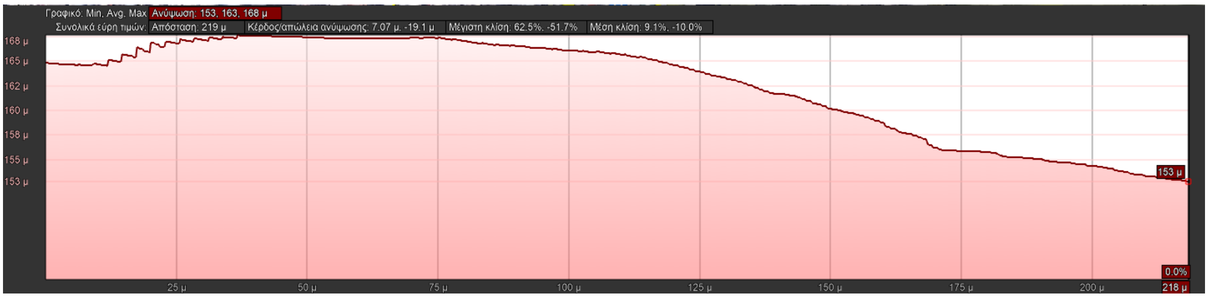

Figure 21: Elevation Profile – Radius 200 – Point 10

While point 5 seems to be at a decent altitude, the results over there are very low, because there is a big block of buildings right in front of the path we want to communicate over (figure 22). Having such an obstacle, so close to the node, affects the signal drastically, in the same way we explained that the university building does at point 10 of the smallest circle. The reason why other points in the urban area did not perform as bad as this one, is because we chose most of them to be on roads that have a small angle with the circle radius, so the path is not blocked so suffocatingly. This, obviously was not an option with all sights when we needed to keep the angle of the consecutive points stable at 30 degrees.

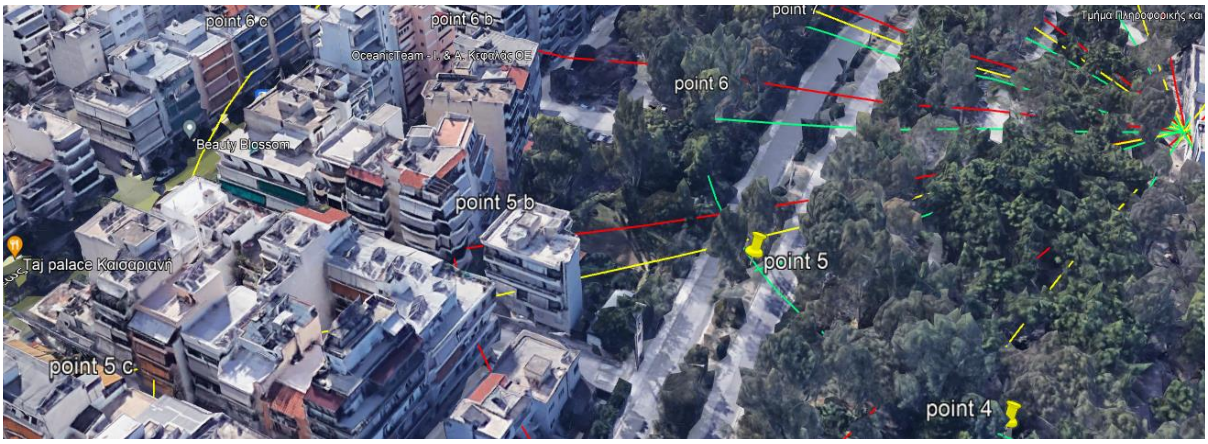

Figure 22: A closer look to point 5

Comparing points 9 and 10 to find out why the second performed worse, we notice that their altitude is the same. However, there is a long hill on the way to point 10 which expands up to 115 meters from the gateway. Because of this, the slide to reach the same height where point 9 is, has to be steeper. This, along with the fact that the gateway is hidden in the opposite direction of the roof than the one we are facing, causes the results we see. Again, this can be viewed in figure 13 and it must be noted that the height of the roof where the antenna is established is lower than the across side and the signal has to go over the whole length of the building.

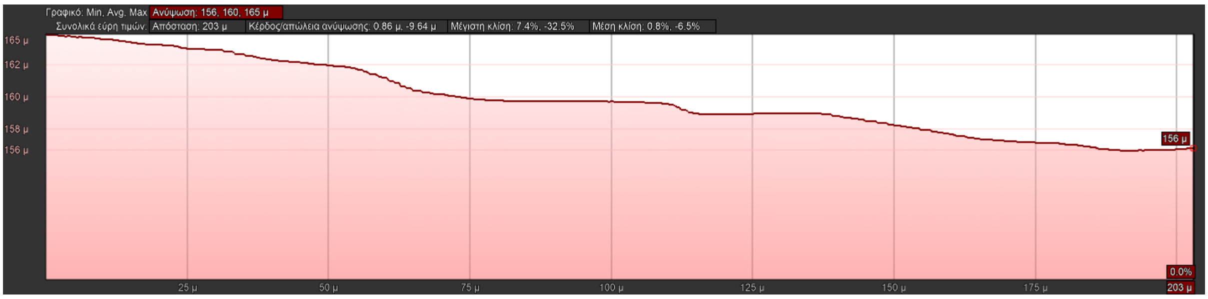

Figure 23: Elevation Profile – Radius 200 – Point 8

The altitude of point 8 doesn't reveal much about the reason why all the tests gave better results at this point, other than the slope of the hillside being very gentle. To understand why this happened we need to, once again, look at the map. We can see that point 8 lies on top of a high building and as we know, increasing the height of our end device leads to better signal strength overall, as there are less to none obstacles in the way. Despite this, not being able to reach the top of the building once again, we decided that the most reasonable solution is to stand exactly at the end of the building in the center side, thus placing the node in less distance than it is supposed to be from the gateway. In this case, we had to stand at approximately 190 meters, which reduced the signal losses due to the distance parameter once again and balancing the lost gain we would have if we could place it onto the building.

2.1.7 General comparison

Received Signal Strength Indicator:

After the examination of each individual experiment, we decided to study the connection status among all the circles.

As we know, RSSI is the signal power delivered to the receiver and shows us how well the Gateway can "hear" a signal from our node. The RSSI is represented in dBm, which means that an RSSI value of -60dBm is preferred over a -120dBm measurement.

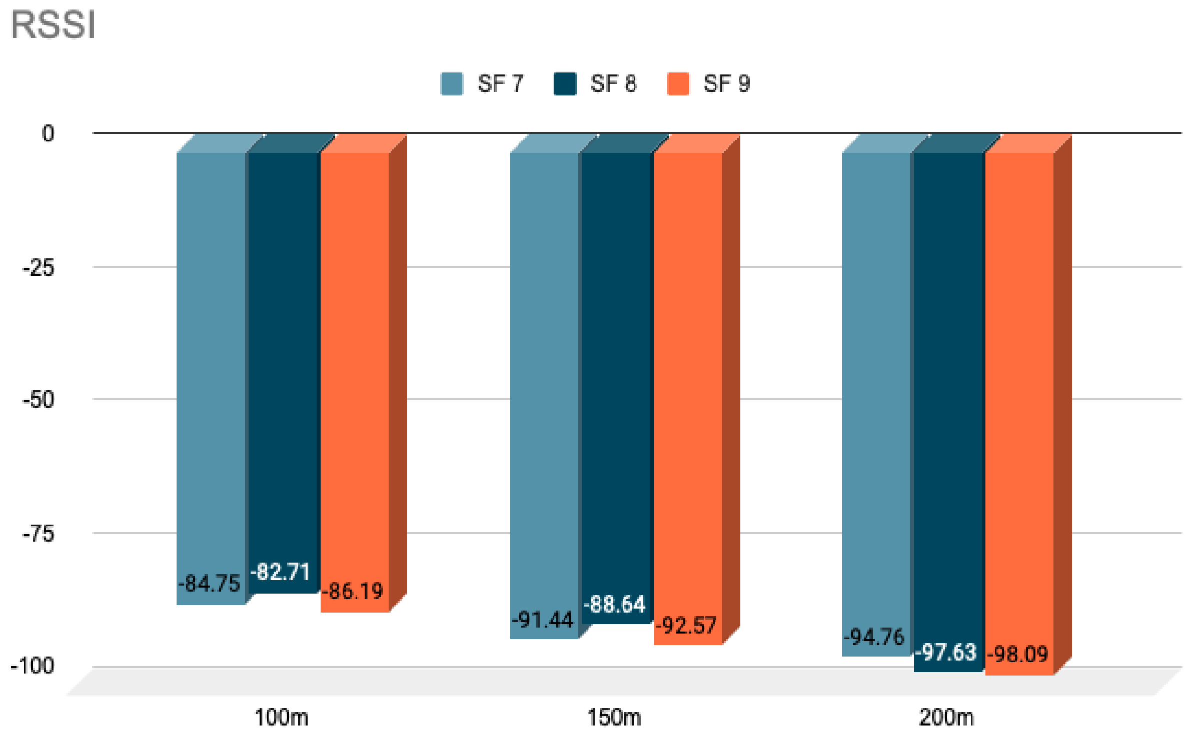

Figure 24: RSSI average values for all three circles and SFs

Generally, the distance between the two devices is a primary parameter to signal propagation. In addition, an increase of bandwidth lowers the receiver sensitivity[4] [14], whereas an increase of the SF decreases the sensitivity threshold which results too, to the increase of the sensitivity. The first hypothesis can be validated from the graphs in figure 24. As we see, moving forward from the circle of 100 meters to the one of 150 and finally the 200-meter radius, the RSSI drops gradually. However, things are less clear when we compare different SFs for one particular circle. If this parameter was to have a serious impact on our metric, we would expect the RSSI of SF9 to be better than the one of SF8 and both of them better than the one of SF7. In practice, we see this is not the case here, and our average values are too close to determine surely if the final order of the results is decided by the SF selection. In the first two circles, SF7 and SF8 do appear to have the expected behavior, but in the rest cases this is not true. This leads us to the conclusion that the distance from the gateway has probably the heaviest impact among the parameters, while the SF affects less or equally to

[4] The minimum power level at which the end node is able to decode the received frames.

other parameters like having buildings, hills, or trees on the link path. Hence, the results for each circle are sometimes judged from the data rate we have chosen and sometimes from the landscape. Yet, the results remain quite stable in each case and the values we see are too close to each other to let us order these parameters by significance without further investigation.

Signal to Noise Ratio:

Moving on, to examine the relation between SF and SNR, we create a chart with the average values of SNR of each circle. The measure of SNR shows us the ratio of signal power to the noise power and is represented in dB. A higher value of SNR indicates a better signal power to noise ratio which is translated into an enhanced capability of the receiver to tell data apart from noise. Also, the receiver's sensitivity requires a minimum SNR value so the information could be decoded correctly. In LoRa communications though, unlike other protocols, we can work even with negative SNR values, meaning below the noise level, due to the CSS technique.

In theory, we know that higher SFs provide higher receiver sensitivity [15]. Also, the performance of the LoRa modulation itself allows significant SNR improvements. So, it is clear that the SNR value depends upon the SF. Despite this, we need to remember that distance between the two devices applies here too as a parameter, like in RSSI measurements. And once again, the closer the node is to the gateway, the stronger the signal level we expect to have over the noise.

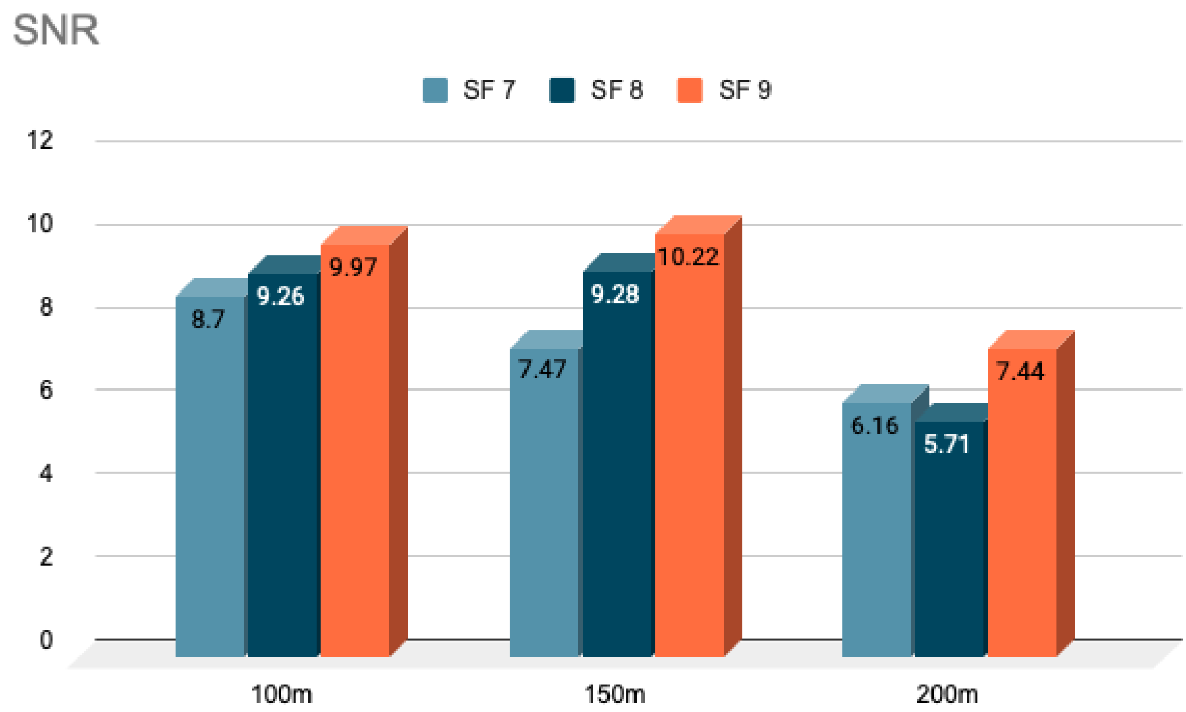

Figure 25: SNR average values for all three circles and SFs

In figure 25, we can see that when we change the value of SF to a higher one, SNR value is increased. This is obvious for the circles with a radius of 100 and 150 meters. The only abnormal result appears in the third circle, where we notice that by increasing the Spreading factor value from 7 to 8 the SNR value drops slightly instead of improving. Things come back to normal with the selection of SF9 where the desired value is improved substantially. In addition, when comparing the 3 circles to find out how distance affects SNR, it comes out that there are no significant changes other than in SF7 when moving from the first circle to the second one. But when moving even further to 200 meters, SNR drops quite rapidly, leading us to the hypothesis that the distance parameter weakens our link in an exponential manner rather than linear. The only SF that drops in every circle is 7, which is something to expect, as we stated in our previous assumption. The other two, seem to be more robust when it comes to dealing with the noise.

Packet Delivery Ratio (PDR):

A final metric we wanted to consider is PDR. This can indicate the quality of the connection as well as the previous two metrics. Overall, we expect to get high PDR values in areas with high coverage. There is one more parameter to take into consideration in this case though, and this is the existence of other Gateways in the area. In our case, there was a second gateway nearby, in the direction of points 1, 12 and 11. In total, the PDR values should be high, as promised by the LoRa modulation.

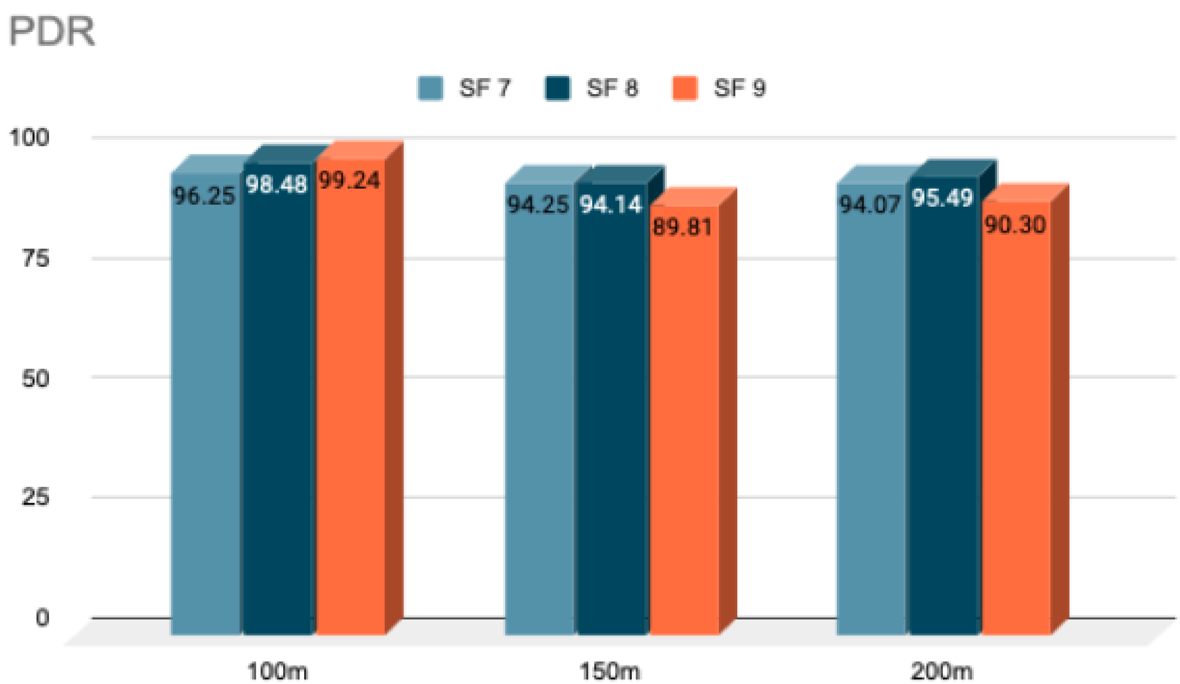

Figure 26: PDR average values for all three circles and SFs

First of all, it is to be noted that in all cases we got PDR values over 90%, which proves the claim of the robust modulation technique in LoRa communications. Moreover, we observe higher values when we are close to the gateway, and ideally, the higher the SF we select, the better delivery rate we should get. Both of the distance and SF parameters are showcased in the smallest circle, which has exceptional PDR values overall and gets even better as we increase the SF. It is also important to note that when we are so close to the gateway the interference from the other gateway is very low. For this reason, in the other two circles, we get lower values and the SF does not seem to improve the situation significantly, because as we move away from our gateway, the node is more vulnerable to interference. However, this does not happen randomly as we might think by looking just at figure 26. Instead, we need to see the tables of our results and we will understand that the lowest PDR values are usually found in neighboring points, implying that there is a high interference source in this area. And quite surely these points are usually in the arc that is drawn by point 9 to point 2 in every circle. This fact along with the SNR dropping as we fend off our gateway show us that the values we see are reasonable.

2.2 Measurements for maximum achievable range with the wireless interface

The purpose of this scenario is to find out the maximum distance among end devices and gateway. This distance is defined as the furthest point from the gateway that the end devices can successfully send messages to the gateway through a stable connection. The connection will be characterized as poor when more than half of the transmissions fail to reach the receiver. For this experiment, the end nodes remain static and all traffic is produced by pressing the button of the node. The environment in which the scenario takes place is considered as suburban with plantation. The goal of this study is to figure out the longest distance at which we can place the node and in which direction this is. For this reason, we will analyze the terrain topology and different parameters such as hills, plantation, buildings and other obstacles in the area to determine the points we should test.

2.2.1 Metrics to study

We conclude which is the longest distance at which the node has a stable connection with the gateway.

2.2.2 Hardware and software required

Hardware:

1. Two end devices type of **The Things Node**.
2. A **LORIX One** gateway.
3. An Android device for each node.

Software:

1. A Map application (e.g., Google Earth Pro) for analyzing elevation profiles and drawing the circles.
2. Map API which you can find here to visualize the results.
3. The Arduino IDE and sketch Basic from examples of library **TheThingsNode.h**
4. The Android application TTN Mapper app to keep and upload coverage information.
5. A Python script to calculate the distance between the Gateway and the logged data points.

2.2.3 Parametrization

For this scenario, we assume that the devices are properly configured and part of the same network as our gateway. We also use the same script as in the first scenario to program them. This means, allowing only controlled transmission of messages by the node and setting the SF parameter hardcoded each time.

2.2.4 Experimental process

First, the end device has to get a power load. In this case, we use batteries as an energy source. Then we study the map of the area around the gateway, to find out candidate points that we believe the node will successfully establish a connection at. Additionally, we will run this experiment using four different SFs to see how this parameter affects the maximum range of the link. We chose SF7, SF8, SF9 and SF10 in order to highlight the difference in the achieved range based purely on this option as much as possible. We will move in four main directions as seen in figure 27.

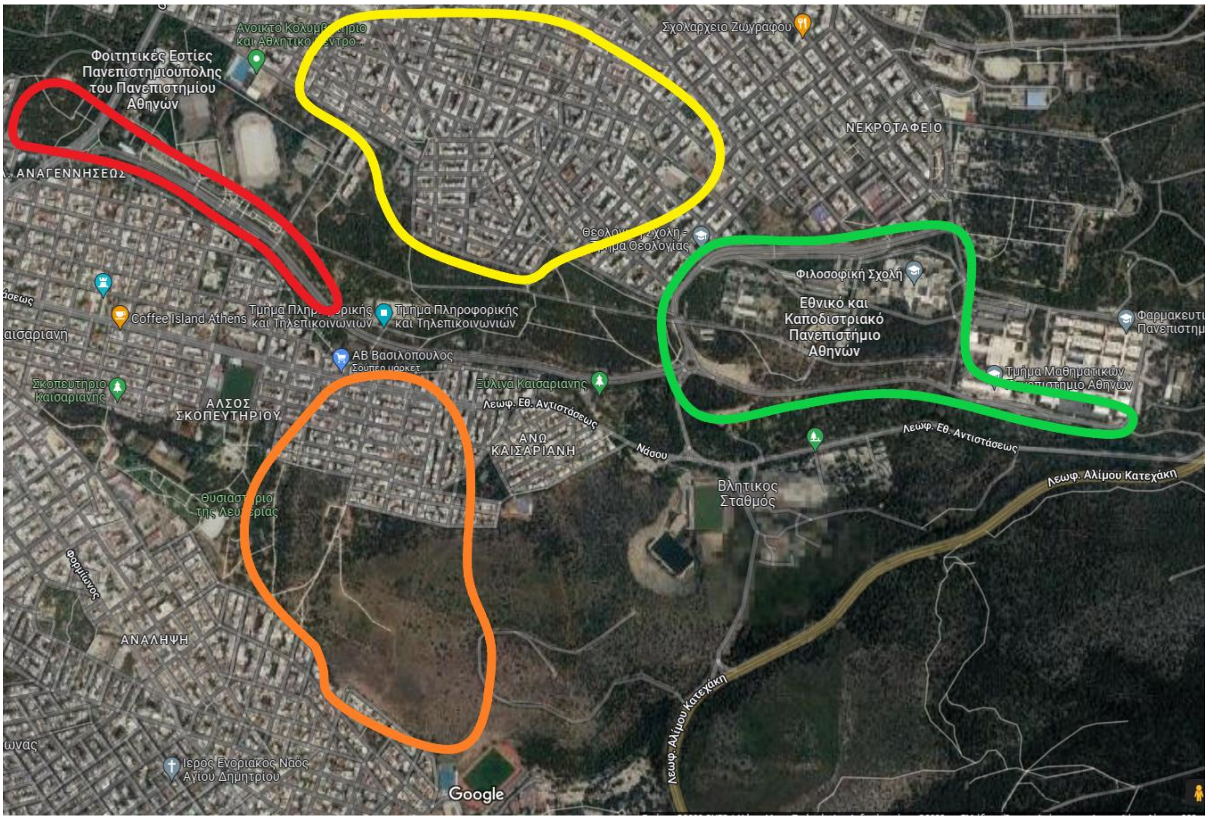

Figure 27: Areas to test maximum coverage

Based on the previous scenario, the north side had the best signal coverage overall. However, we see that just after 200 meters from the gateway, we get into a very dense urban area. So, we will examine if the good results we got before will lead us to the furthest point in this case.

On the east side, we might have average signal strength in our last test, but we notice that the terrain height increases as we get away from the gateway and there are very little obstacles in the path other than trees and few buildings. For this reason, we assume that the signal will be weakened gradually, based mostly on the distance parameter, which might let us reach our goal.

Heading south, we meet another urban area soon after we pass 150 meters, so we will only test points which are on main roads, aligned to the path between them and the gateway.

Lastly, we will check the west side, even though this proved to bring poor results in scenario A1. The reason behind this is that the road we have highlighted is totally aligned with our gateway and there are no obstacles, buildings or plantations in this path after the first 100 meters. Despite the fact that there is a steep hill near the gateway which caused problems before, we believe that as we move away the signal will not be affected that much from this factor. In this area, we are going to verify the conclusion from the first scenario, which indicated that moving away from a static obstacle located onto the link path brings better results.

2.2.5 Quantitatively and quality results

The final results are categorized in four tables, each one representing one of the four areas we examined. The results are extracted from the log-files of the TTNMapper app but they could be also extracted from The Things Network Console. Additionally, we develop a Python script to validate, short out the metrics and calculate the maximum distance.

2.2.6 Conclusions

Table 13: Maximum range scenario – LoRa settings

ADR	CR	Channel	BW	TP	Number of devices in proximity	SF
Off	4/5	EU668	125 kHz	14mW	1	7, 8, 9, 10

North Area:
This area is mainly urban with high buildings and a lot of hills. In addition, the field of tests, which is 200 meters away from the gateway, lies on a steep negative slope, while the terrain up to this distance was upward and led us to good signal measurements so far. Lastly, the buildings will weaken the signal a lot, so we will be taking measurements mostly on road junctions to avoid blocking the Fresnel zone as much as we can.

Table 14: North area maximum distance results per SF

SF	RSSI (dBm)	SNR (dB)	Distance (meters)
7	-116	-7.75	558
8	-117	-8.75	577
9	-117	-13.75	619
10	-117	-15.5	652

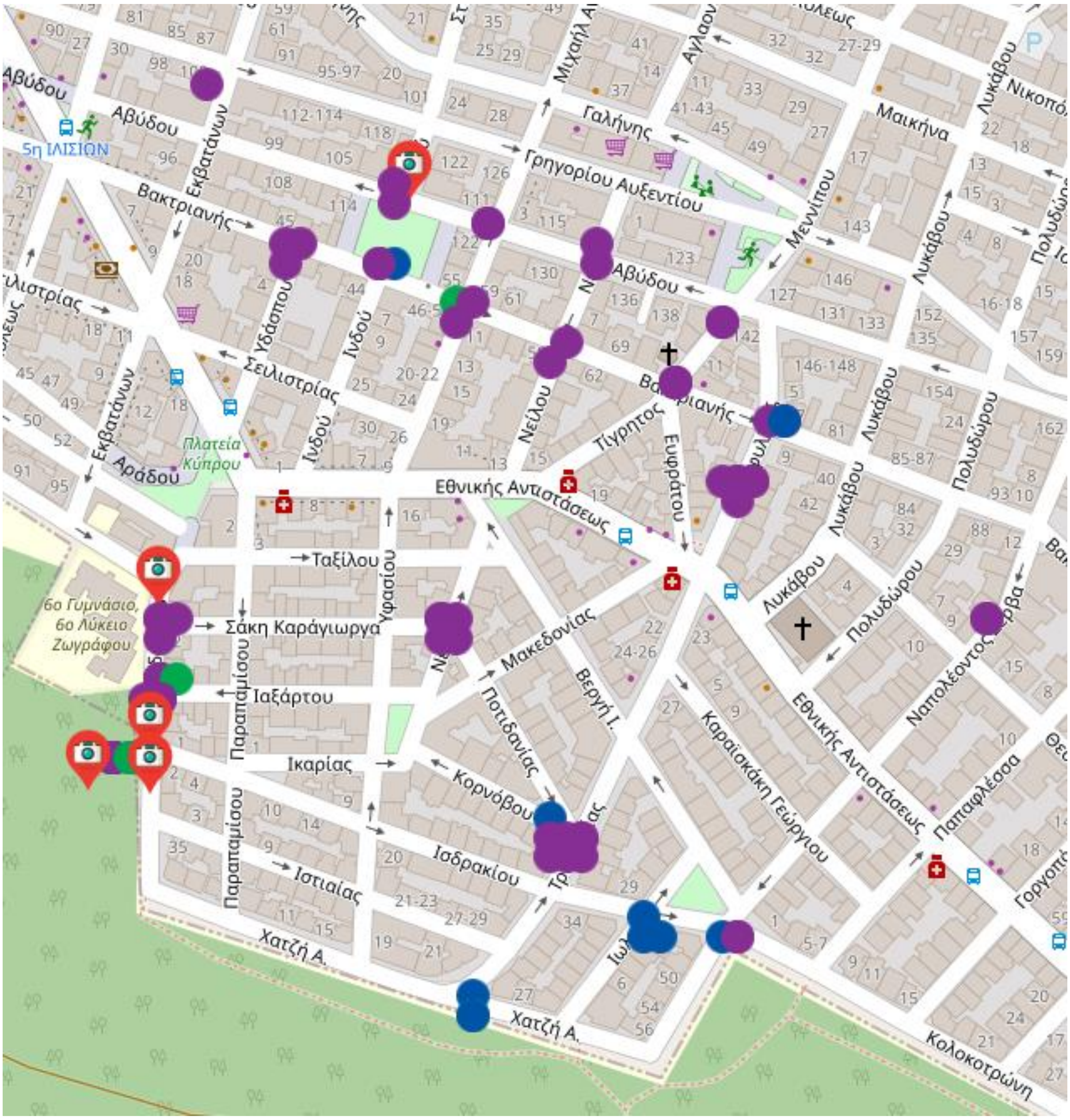

Figure 28: North area – maximum range measurements

The maximum distance we were able to achieve in this area is 652 meters and the SF that led to this result was SF 10. Next optimal values are observed in experiments with SF 9, 8 and 7 in this order.

Based on the above results, we conclude that the coverage in this area is rather low. However, the performance per SF is well expected, as we anticipate to reach longer distances by increasing the spreading factor parameter. In order to better understand this outcome, we examined several elevation profiles in the area.

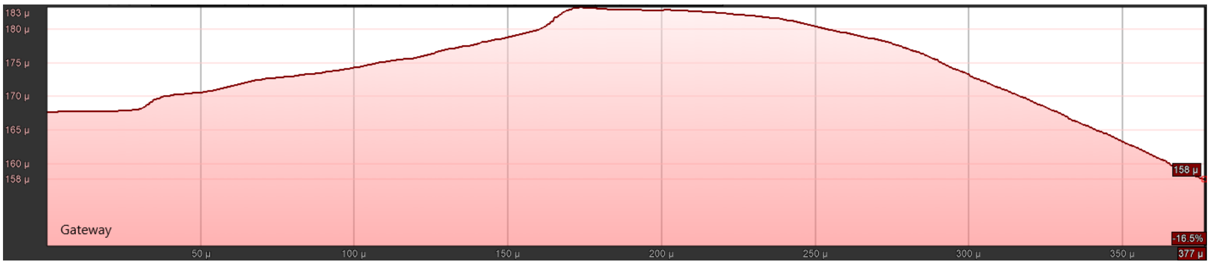

Figure 29: Elevation Profile – North – Distance 375m

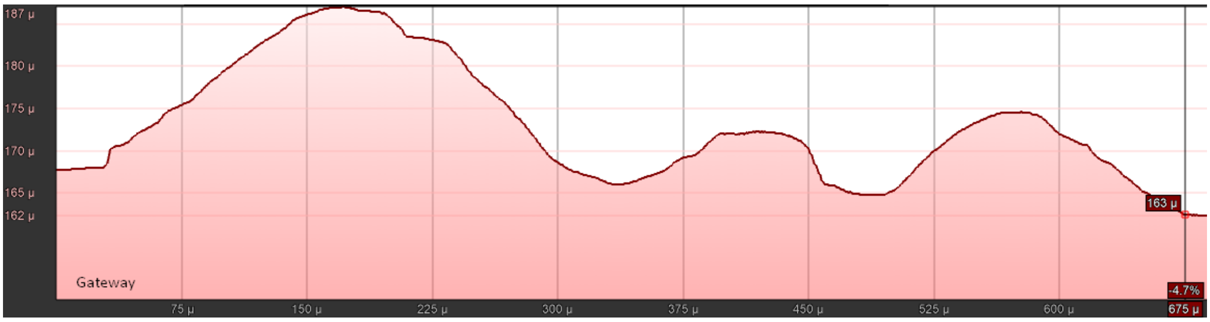

Figure 30: Elevation Profile – North – Distance 675m

In figure 29, we notice that just at 375 meters from the gateway we have lost all the height advantage we had up to 200 meters and thus our signal strength dropped significantly. Furthermore, in figure 30, we can see the elevation profile at the point we lost communication with the gateway with SF10. As we see there are 3 hills onto the path. The reason why we have more measurements near the 600-meter line, is because the third hill recovered some of the lost altitude for the node and the first hill was further from it at this point, thus blocking the Fresnel zone less. SF7 last point was at the top of the third hill and SF8 and SF9 reached a little further down. Only with SF10 we were able to reach the bottom, but at this point even the third hill was acting as an obstacle right in front of the node, so the communication was unachievable.

West Area:

This area has a slight negative slope as we move away from the gateway, however there almost no obstacles in the link path which will probably compensate for the distance and slope losses.

Table 15: West area maximum distance results per SF

SF	RSSI (dBm)	SNR (dB)	Distance (meters)
7	-115	-2.5	848
8	-115	-11.75	934
9	-119	-6.75	990
10	-117	-4.75	1035

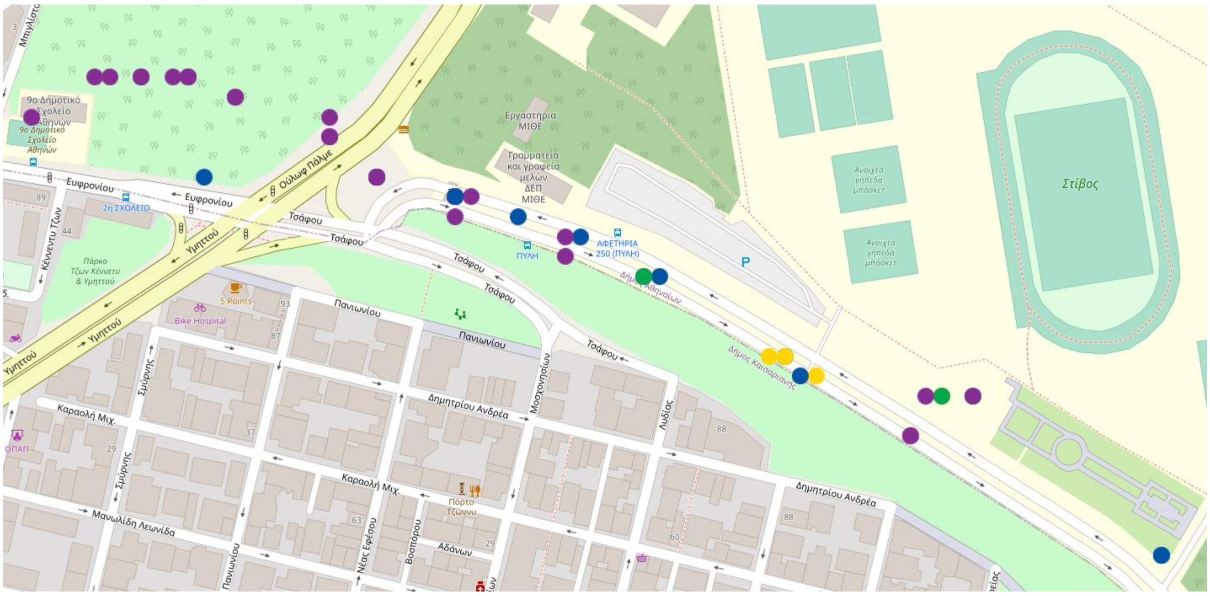

Figure 31: West area – maximum range measurements

It is clear that in this area, we had a better performance than previously overall as we were able to pass 1km. Once again, S10 was the best option we had and SF7 the least optimal. We can also review the elevation profiles to find out why this area is better when it comes to long distance communication.

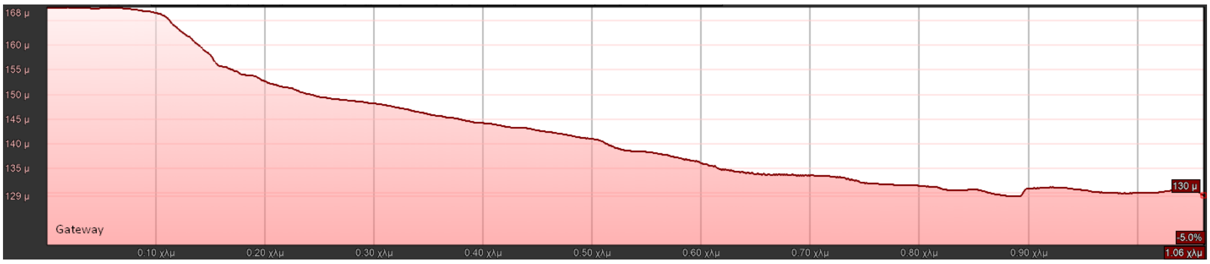

Figure 32: Elevation Profile – West – Distance 1060m

As we see, up to 200 meters, the slope is very steep, which resulted in poor signal strength in the previous scenario. But as we move further, the altitude decreases gradually, and this way the Fresnel zone gets unblocked as we do so. This recovers some of the losses we have because of the increasing transmitter-receiver distance. Another important benefit when conduct this test, is the fact that move on a road that is parallel with the university building. Basically, all our measurements lie on a straight line which is clear from obstacles and buildings as displayed in figure 33. So, we conclude to the hypothesis that the transmission happens in a line-of-sight scenario, and although the node is almost 40 meters lower than the gateway, we achieve an approximate of 60% coverage-range improvement compared to the north area.

<u>South area:</u>

In this experiment, we dealt with a mix of urban and rural environment. The first 500 meters are densely populated. Behind them, there is a small mountain with some trails, so we were not able to run tests in all of its surface. However, the results turn out very interesting due to the significant altitude gain of this area.

Table 16: South area maximum distance results per SF

SF	RSSI (dBm)	SNR (dB)	Distance (meters)
7	-117	-8.75	945
8	-117	-9.25	946
9	-118	-3.25	942
10	-117	-6.25	954

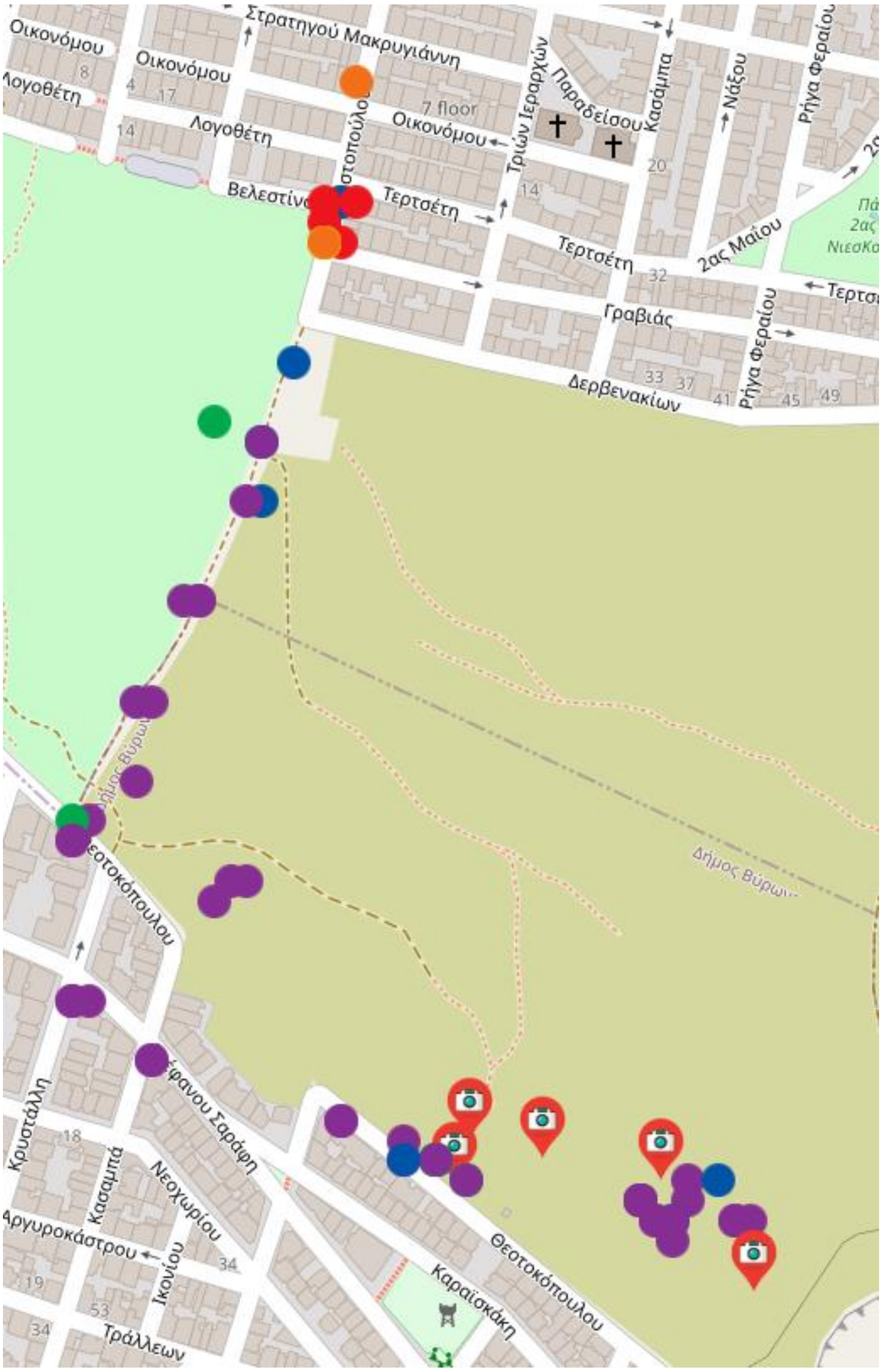

Figure 33: South area – maximum range measurements

The first noticeable thing is that all SFs had almost identical results as seen in table 15. The distance is slightly worse than the west side but the performance can be considered good overall. Also, SF 9 was surprisingly the least optimal selection here, but the deviation is too small to conduct a safe finding for this event.

Another thing to notice is, for the first time so far, we observed red metrics, which indicates a very strong signal level. This is, of course, is not close to the maximum distance we ended-up at, but it's easily explained when viewing figure 34.

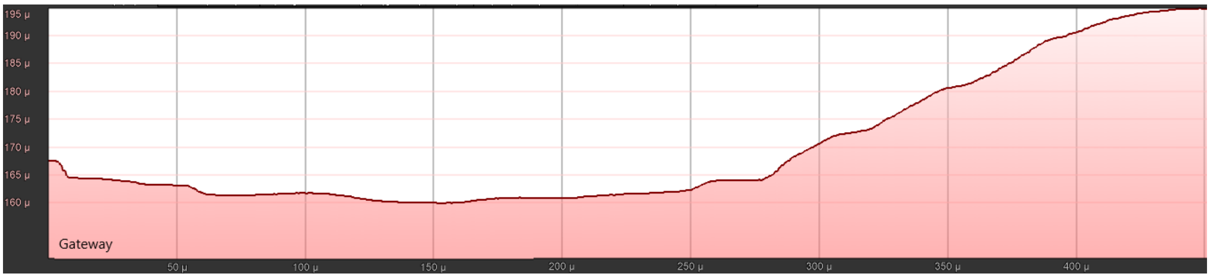

Figure 34: Elevation Profile – South – Distance 450m

At this point, we are 35 meters above the university structure and we can see the roof of the building, thus getting RSSI values down to 91dBm, the same level as the 100-meter radius in the first scenario.

Moving to the final point of signal coverage in this area, we placed our node in a spot with the elevation profile of figure 35.

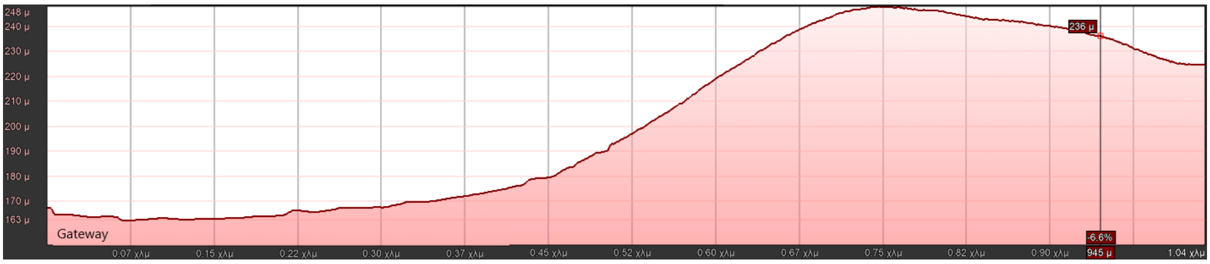

Figure 35: Elevation Profile – South – Distance 1040m

Up to 750 meters, we keep gaining altitude, so the signal is strong, but this changes once we move to the back side of the mountain. This led all of our tests to stop at the same spot, no matter what SF we were using.

<u>East Area:</u>

In this last case, the terrain is similar to the west area. The is some forestry at first, but then we kept moving along the two main roads of the university which guaranteed us a rather obstacle-free path for our link. In addition, this side has a positive slope in opposition to the west, so we assume that we will be able to communicate with the gateway at an even longer distance.

Table 17: East area maximum distance results per SF

SF	RSSI (dBm)	SNR (dB)	Distance (meters)
7	-117	-6.25	1480
8	-117	-10.75	1587
9	-116	-12.5	1641
10	-118	-12.75	1703

Figure 36: East area – maximum range measurements

The results here show without a doubt that this is the best area independently of the SF choice. All SF options led to maximum distances that are to be expected by what we have studied in theory. Moreover, this proves our initial hypothesis that a free link-path is the major parameter in achieving a long-distance communication with the gateway. However, we need to also examine the elevation of the terrain once again, as shown in figure 37.

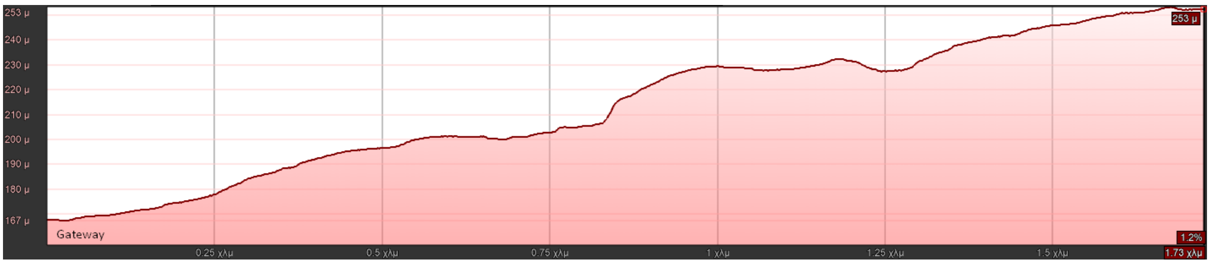

Figure 37: Elevation Profile – East – Distance 1730m

We notice that we gained a total of 85 meters during the process of moving across this area, which is a very significant difference to the node's favor. All in all, we conclude that these two conditions were the reason we managed to reach so far, despite the increased losses from the distance between the two devices.

2.2.7 General comparison

SF choice:

We can clearly see from the above tables that by incrementing the SF we can reach longer distances. More specifically, with greater value of SF we have larger processing gain and the signal can be received with less errors as it is more durable to noise.

Received Signal Strength Indicator:

In all our measurements, the last point we were able to still communicate with the gateway, got us similar RSSI values regardless of the SF option. More specifically all the values were at the range [-115dBm, -119dBm]. This can be explained by looking at our gateway antenna specifications. The sensitivity threshold of Lorix One is -120dBm, thus it is not possible for it to decode messages that arrive with RSSI lower than this level.

SNR:

In contradiction to the RSSI, here we were able to see the different SF impact on SNR. Using the bandwidth of 125kHz, the SNR limits for SF 7, 8, 9 and 10 are -7.5dB, -10dB, -12.5dB and -15dB respectively [16]. We did confirm this partially as with SF10 we saw SNR values down to -15.5dB. Judging from this example, the mentioned limits are flexible. Also, the fact that even though messages sent with SF7 were not decoded by the gateway at this level, we did transmit with -8.75dB SNR at a point. In general, we were able to push the limits of the successful transmission for each SF to the thresholds indicated by our equipment and the LoRa protocol.

Distance obstacles and environmental parameters:

Thanks to our antenna's location, we had the opportunity to examine different types of environments and understand which parameters affect the signal more. Overall, the experiments show us that the north side had the poorest performance, while the west and south brought us much better results. The east area is undoubtedly the ideal environment for this test, as we got a 160% range improvement compared to the worst case and 60% to the runner up. So, we conclude that the two most relevant parameters to establish a long-distance LoRaWAN communication is the transmitter-receiver altitude difference and the number of obstacles in the Fresnel zone of the link. On the one hand, we want to give both the gateway and the node as high altitude as possible. The first will offer better coverage in the area, but even the second will help our communication on an individual level. On the other hand, it is important that the node has line of sight contact with the gateway as we transmit, because the existence of buildings, trees, and other objects downgrade the quality of the link due to multipath phenomena [17].

3. MAP APPLICATION

3.1 Why do we need it?

The experiments we ran for the two scenarios produced a large amount of logs. In order to better understand the outcome and draw solid conclusions, we needed to manipulate this data to filter out the desired metrics. In addition, we looked for a comprehensible way to showcase the final results. Hence, we developed some Python scripts to filter out the useful data out of the initial log files and a web application to display the final results on a map.

3.2 Map data generation

The map API uses input datasets in JSON format. To generate these data, we need to organize our CSV logs per scenario as depicted in figure 38.

```
DataGeneration:.
|   circle.py
|   csvToJson.py
|   maxRange.py
|
+---scenario1
|       100m-sf7.csv
|       100m-sf8.csv
|       100m-sf9.csv
|       150m-sf7.csv
|       150m-sf8.csv
|       150m-sf9.csv
|       200m-sf7.csv
|       200m-sf8.csv
|       200m-sf9.csv
|
\---scenario2
    +---east
    |       sf10.csv
    |       sf7.csv
    |       sf8.csv
    |       sf9.csv
    |
    +---north
    |       sf10.csv
    |       sf7.csv
    |       sf8.csv
    |       sf9.csv
    |
    +---south
    |       sf10.csv
    |       sf7.csv
    |       sf8.csv
    |       sf9.csv
    |
    \---west
            sf10.csv
            sf7.csv
            sf8.csv
            sf9.csv
```

Figure 38: Data generation file structure

Afterwards, while in the root of the above directory, we need to execute two scripts for each scenario.

<u>Scenario 1:</u>

1. python ./circle.py ./scenario1/

2. python ./csvToJson.py ./scenario1.csv

<u>Scenario 2:</u>

1. python ./maxRange.py ./scenario2/

2. python ./csvToJson.py ./scenario2.csv

The first step produces a CSV file with the desired metrics using the data in the corresponding folder. The second step converts this file in JSON format. As a last step, we need to place the JSON files in *"~/src/assets/metrics/"* so that they can be utilized from the API.

3.3 Graphical user interface

The application was built with create-react-app. We used the ReactJS Framework (v17.0.2) and our map layout is constructed with the react-leaflet (v3.2.5) library and openstreetmap API. The user can navigate through the two scenarios from the layer control menu in the top-right corner. Apart from this, there are options to select any combination of SFs to display each time. Every colored circle on the map represents a set of measurements for the first case, or a single measurement for the second. The colors are filled based on the average RSSI or RSSI value accordingly for every scenario.

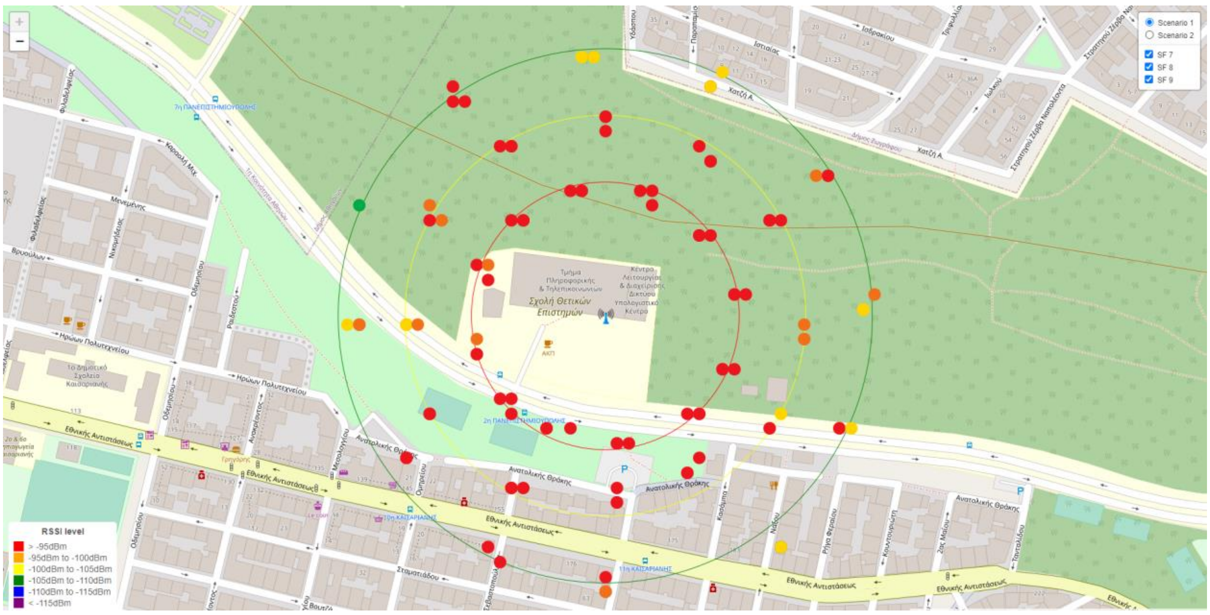

Figure 39: Map representation of scenario 1 results

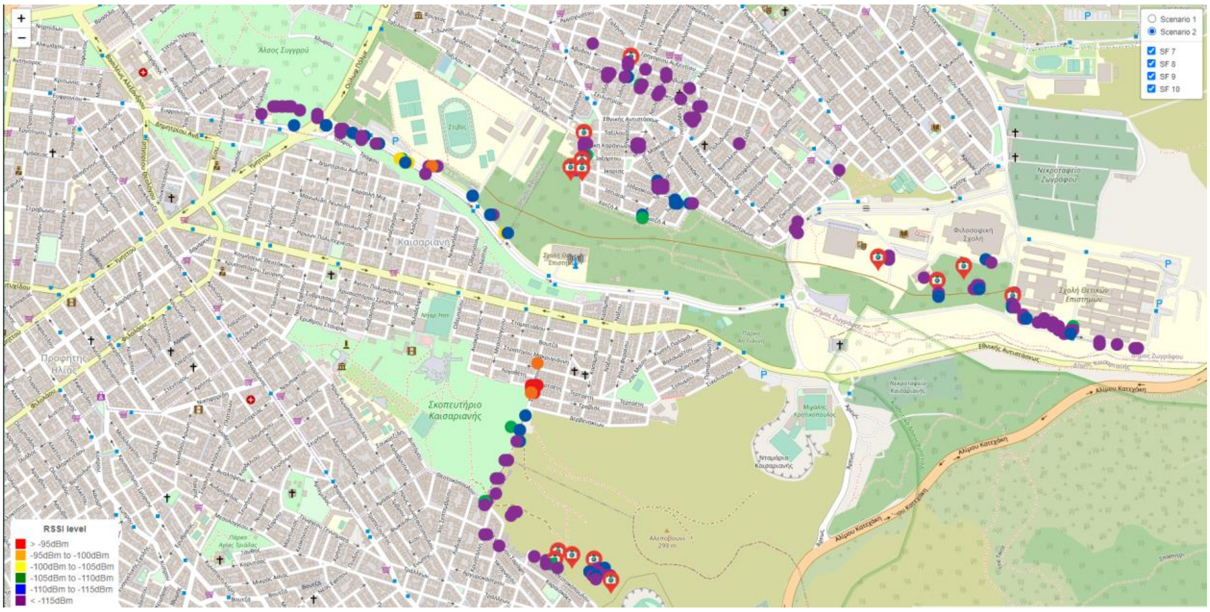

Figure 40: Map representation of scenario 2 results

Hovering over a point will reveal information about the range of measurements, average, median, minimum, and maximum metrics. Finally, there are some points of interest on the map, represented as markers, which feature images we captured during our tests in the physical environment.

Spreading Factor: 7
RSSI metrics: [-97, -91] dBm
Average RSSI: -94.6 dBm
Median RSSI: -94.5 dBm
SNR metrics: [6.75, 10] dBm
Average SNR: 8.65 dBm
Median SNR: 8.625 dBm
Measurements: 10
Packet Delivery Ratio: 100%

Figure 41: Scenario 1 – Map measurement point sample

Spreading Factor: 10
RSSI: -118 dBm
SNR: -12.75 dBm
Distance: 1703 m

Figure 42: Scenario 2 – Map measurement point sample

Figure 43: Sample point of interest – Taking measurements on the field

4. CONCLUSIONS

4.1 Scenarios outcome

This thesis main goal was to examine the reliability and the performance of the LoRa and LoRaWAN technologies via a couple of practical experiments.

In the first scenario, we took our measurements in an area with good coverage, in order to investigate which parameters, affect the physical layer communication between end device and gateway. We tried to give this analysis a statistical significance, by repeating the measurements at least 10 times for each setup. This way we managed to shed light to the effect of other environmental parameters, like the number and the type of obstacles in the communication path, in combination with the distance between the two communication end points.

The second scenario aimed to find out the maximum coverage of commercial off-the-shelf equipment in the area around the university. Thanks to this experiment, we explored the capabilities of the LoRa modulation and the impact of LoRaWAN settings in a real-world environment, and a variety of different terrains. The results were extremely promising, establishing communication of more than 1.5 km without using the highest and more robust SFs (SF11 and SF12), and without operator-level network planning. It is apparent, that LoRa communications range-wise have great potential.

We believe that both scenarios contributed to the upright planning of an LPWAN network which can be used for multiple purposes. By extracting the maximum coverage per area, we can narrow down the possible placement points of the end nodes, thus saving time and resources. Then, we can test out the remaining sites more exhaustively to create an efficient and reliable topology. For example, in our case, since the things network node features a temperature sensor, it could be part of an IoT-based physical disaster management framework.

4.2 Future work

It would be very interesting to implement the two scenarios under different weather conditions in order to focus on how environment conditions like temperature and humidity influence the results. Both the end device and the gateway that we used have the ability to record these metrics, so we can repeat these experiments in significantly lower temperatures or heavy rain, in an effort to examine their impact on receiver's sensitivity capabilities. Moreover, another interesting scenario is to test how a non-static end device would affect the signal strength. Specifically, we can take measurements in areas with good coverage, starting with a static end device. Then we can repeat the measurements by specifying levels of mobility (e.g., low mobility, high mobility), and extract result while moving with low speed as pedestrians (e.g., 10km/h), or moving with higher velocity using a car (e.g., 30km/h). This scenario would aim to the analysis of how RSSI and PDR values are affected by the existence of the Doppler effect.

5. ABBREVIATIONS – ACRONYMS

ABP	Activation by Personalization
AppEUI	Application Unique Key
API	Application Programming Interface
AppKey	Application Encryption Key
AppNonce	Application Nonce
AppSKey	Application Session Key
BT	Bandwidth Time Product
CFList	List of network parameters
CHIRP	Compressed High Intensity Radar Pulse
CRC	Cyclic Redundancy Check
CSS	Chirp Spread Spectrum
DevAddr	Device Address
DevEUI	End-device serial unique identifier
DLSettings	Downlink configuration settings
DSSS	Direct-Sequence Spread Spectrum
FHSS	Frequency-Hopping Spread Spectrum
ISM	Industrial Scientific and Medical Purposes
LoRa	Semtech’s Long-Range modulation
LoRaWAN	Lora Alliance’s Long Range Wide Area Network Protocol
MAC	Medium Access Control
NwkSKey	Network Session Key
OTAA	Over The Air Activation
PDR	Packet Delivery Ratio
PHY	Physical Layer
RSSI	Received Signal Strength Indicator
RX	Receiver
SF	Spreading Factor
SNR	Signal-to-Noise Ratio
ToA	Time on Air
TX	Transmitter

6. REFERENCES

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