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# Empirical Validation of LoRaWAN Network Coverage Strategies for IoT Deployments

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*With profound gratitude, I dedicate this thesis to my beloved mother, whose unwavering support has been my constant source of strength throughout my academic journey. I express sincere thanks to InkwellData company, Massimo Cesaro and Riccardo Degan for their incredible support and unwavering belief in me, both during my internship and in the subsequent phases of my career.*

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*Thank you*





## **Abstract**

Low-Power Wide-Area Network (LoRaWAN) infrastructure deployment is accelerating as the Internet of Things (IoT) ecosystem spreads. Network coverage planning efficiency is crucial for the LoRaWAN network. and for network coverage it is critical to decide gateways locations.

LPWANs for building Advanced Metering Infrastructure (AMI) has star-of-stars network topology where a central gateway connects multiple smart meters. In this thesis it is pointed out the challenge of setting up an AMI LPWAN (Low-Power Wide-Area Network) is geographical locations of gateways so they can cover as many smart meters as they can. To be able to achieve that there are many prediction models but the predictions may not meet with places practically available.

This thesis proposes a measurement tool called LoRaWAN Site Survey Tool (SST) for testing network coverage before and after installations. SST is a complete system including a SST client (LoRaWAN hardware and as a software an android application) and SST server part.

This tool provides an assessment method for wireless network planners to measure choosing a different gateway installation location other than predicted location affects the overall performance of Advanced Metering Infrastructure (AMI).







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# 1

## Introduction

Smart Meters are advanced electronic measuring devices that record information used in the utility industry to monitor and manage consumption in a more accurate and efficient way compared to the traditional meters. They collect data on consumption, such as electricity, water or gas and communicate the information to the user and supplier. In this study smart water meters are used. Smart meters have been mentioned in the literature already in the early 1990s, (De Almeida and Wine, 1993) and (Koponen et al., 1996)[1]. Since then smart meter usage has increased a significant amount and it causes problems such as the great amount of data which is captured by smart meters because of smart meter's constant real-time recording. This puts a significant burden on utility companies and system operators who need to gather data in an efficient way, process and analyze.

At that point the concept of Advanced Metering Infrastructure (AMI) becomes vital. AMI stands for a wide system that goes beyond individual smart meters. Advanced Metering Infrastructure (AMI) is an integrated smart meter system, communication network, and data management system that allows two-way communication between utilities and customers [2]. This communication is between customer and utility companies so it makes possible remote monitoring and control. This system also stores, processes and manages large amounts of which comes from all smart meters. It also can detect leaks, faults which reduces the downtime and the outcomes of data analyzing can capture patterns of high usage that can be used for control and reduce energy consumption.

The implementation of the Advanced Metering Infrastructure (AMI) system is

structured into networks and a few components as can be seen in figure 1.1; head-end system, the gateway, smart meters, and the communication channel. Connectivity between these devices is critical to support the Advanced Metering Infrastructure (AMI) service system. So the system needs a specific kind of technology and Low Power Wide Area Network (LPWAN) and Low Power Wide Area Network (LPWAN) is one of the technologies that is considered capable of supporting this system [4]. LPWAN is suitable for the system because of its ability to cover large areas, using low power, and handling data at a slower pace.

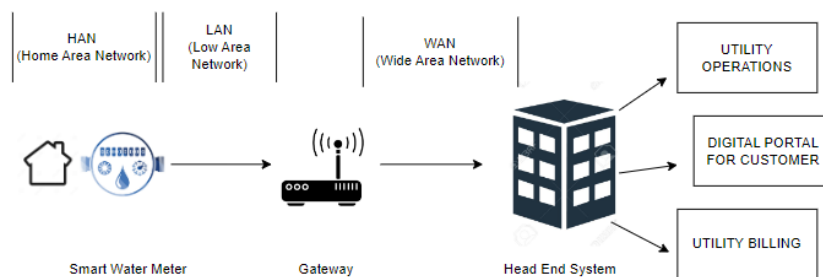


Figure 1.1: Advance Metering Infrastructure Architecture

Even though the structure looks basic, in real life, AMI includes lots of smart meters, Lora Devices and several gateways. It has always been a great challenge to locate gateways to be able to cover a large number of smart meters. For this problem prediction models had been used to determine potential gateway location but for Distribution System Operators (DSOs) there could be a practical limitation such as predicted physical assets availability, limited space, equipment restrictions. So there is a trade-off situation between the most suitable spot recommended by model and the spot which is actually available for installation.

To be able to optimize this situation this project proposes development of a measurement tool. With this tool wireless network planners can have an assessment of the effect of choosing the most available place over a predicted spot for station installation on the overall performance of the AMI LPWAN. This measurement process includes data collection from the field and using it creating a digital twin of the LPWAN that will be used in AMI operations optimization. To consider all those steps together, the main goal is to enhance the efficiency and effectiveness of AMI LPWAN installations by bridging the gap between outcomes of prediction models and real life practical availability.



## LoRa and LoRaWAN Technology

In the concept of IoT (Internet of Things) LoRa (Long Range) and LoRaWAN (Long Range Wide Area Network) are fundamental components. They both provide wireless communication with low power consumption between long distances. Even though they have many resemblances they serve different purposes.

LoRa is the radio signal that carries the data, and LoRaWAN is the communication protocol that controls and defines how that data is communicated across the network [4]. LoRa uses unlicensed radio frequency spectrum so applications can access without license; it still needs networking capabilities.

LoRa is the physical layer or modulation technique used for long-range, low-power communications links. LoRaWAN is a communication protocol and network architecture that sits on top of the LoRa physical layer [5].

As it is shown in Figure 2.1, LoRa defines physical layer characteristics of the communication and networking protocol LoRaWAN is built on top of LoRa for creating a wide-area network by utilizing the LoRa physical layer.

## 2.1. LORA

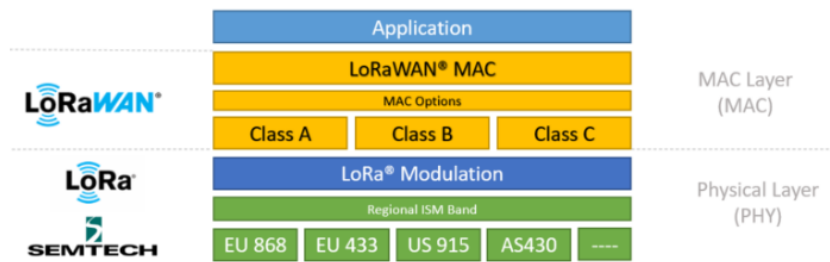


Figure 2.1: LoRa and LoRaWAN Protocol Stack [6]

LoRaWAN is an open, cloud-based protocol – designed and maintained by the LoRa Alliance [7]. LoRaWAN indicates how smart meters communicate with gateways and how data is handed over to application servers. In the meantime it brings security by data encryption and authentication.

At the end while LoRa technology brings wireless capabilities LoRaWAN brings up complete solutions for connecting and managing devices in a wide-area network.

## 2.1 LoRa

LoRa (Long Range) is a long range and low power wireless communication system that can send small amounts of data over great distances [5]. Data transmission can be done to a longer range when considering other wireless technologies like Wifi, Bluetooth or ZigBee which makes LoRa perfectly suited for connecting smart meters and collecting data from them.

It has been 10 years since the invention of LoRa, the long range, low power Internet of Things (IoT) platform currently implemented in over 100 million devices worldwide, accelerating the global adoption of IoT. Initially, the three founders were targeting the metering industry and aimed at adding wireless communication capabilities for gas, water and electricity meters. For this purpose, they used Chirp Spread Spectrum (CSS) modulation technology [8].

LoRa is a LPWAN technology which based on Chirp Spread Spectrum (CSS) as a physical (PHY)-layer modulation scheme, which allows a LoRa radio to send a packet at various data rates (e.g., 0.01837.5 kbps) to gateways several or even tens of kilometers away (515 km) [9].

Chirp Spread Spectrum (CSS) is a unique radio frequency technology that enables wireless communication [10]. CSS modulation is the key for LoRa data

transmission. This modulation technique provides data transmission over a wide range of frequencies. Transmitted signal's frequency is changing continuously over time. A signal that varies in frequency over time is called chirp[11]. As you can see the representation in Figure 2.2, chirps are moving up or down (up-chirp or down-chirp respectively) with a different speed [12].

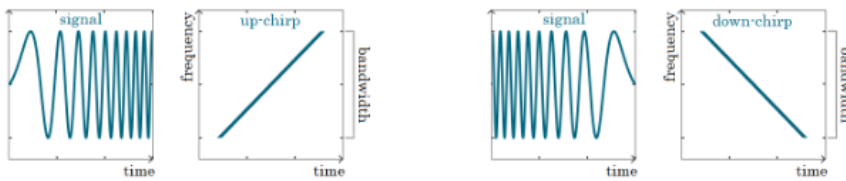


Figure 2.2: LoRa chirps spread spectrum [13]

Chirp is used to indicate bits of data. In other words, chirp is a signal and it begins with one frequency and changes to another. This modulation of a chirp signal is to encode digital information (bits of data), so chirp becomes a carrier signal to data transmission. Digital data that consist of 0s and 1s is encoded during this continuously changing frequency signal.

CSS spreads out this changing signal while encoding the data and the receiver listens for this frequency change and decodes the data. CSS modulation can reach low receiver sensitivity values so that long-distance communication can be done (Lim and Han as cited in Purnama, 2018, p.195)[14]. Which means even though the spreaded signal is weak it can be received from long-distance.

To sum up CSS is a way for data transmission by changing the frequency of a signal continuously and it provides robust data transmission, durable to interference and possible to reach long distances.

As a usage of LoRa, a typical use case is smart metering. For example, LoRa enabled meters will increase efficiency and optimize processes. For water management, sensors will monitor water pressure, water level or detect leaks [21].

LoRa modulation has parameters in the PHY (physical) layer; Bandwidth(BW), Spreading Factor(SF), Code Rate (CD). LoRa devices can be configured with several parameters and these parameters are important for optimization.

### **Bandwidth**

As it mentioned before chirps are used to change the signal among defined bandwidth which is decided while device configuration.

## 2.1. LORA

Bandwidth also represents the chip rate of the LoRa signal modulation. It has three programmable bandwidth settings 500 kHz, 250 kHz, and 125 kHz [15]. Data rate and range changes according to bandwidth selection.

The chosen bandwidth affects communication features. Wider bandwidth capable of higher data rate but decreases the receiver sensitivity. On the other hand when bandwidth is narrower it cannot provide that much speed for data but it provides better long distance reception.

Since the chirps are spread across a wide bandwidth, they become resilient against interference and capable of traversing difficulties.

### Spreading Factor

The spreading factor is a crucial parameter for CSS modulation technology. SF specifies the rate of change in frequency of a chirp signal; in other words, the spreading factor controls the chirp rate, and thus controls the speed of data transmission. Lower spreading factors mean faster chirps and therefore a higher data transmission rate. As it is shown in Figure 2.3, for every increase in spreading factor, the chirp sweep rate is halved, and so the data transmission rate is halved [16].

LoRa allows SF in the range of SF7 to SF12 so CSS uses spreading factors from 7 to 12 [17].

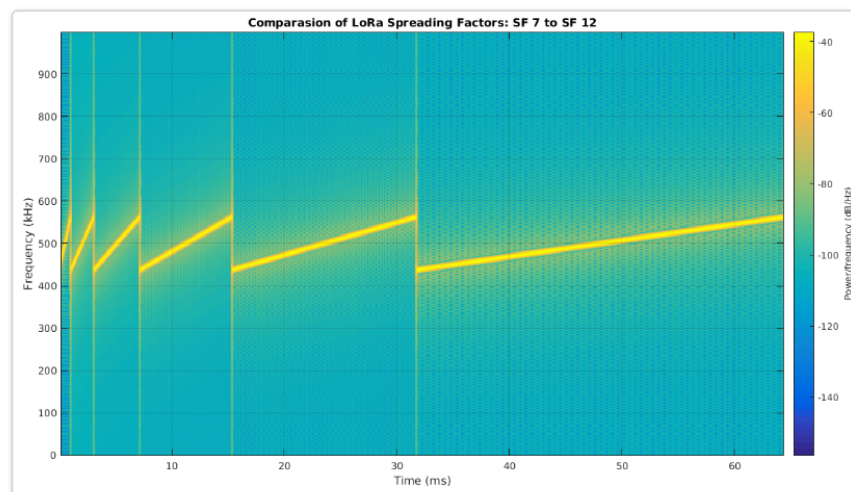


Figure 2.3: Different Spreading Factor Frequencies from SF7 to SF12 [18]

**Data Rate:** Lower SF decreases the LoRa range, providing higher bit speed. On the contrary higher SF makes transition slower but provides wider range.

**Packet Duration:** A signal chosen with the SF12 can be reached at longer distances than a signal modulated with the SF7.

**Receiver Sensitivity:** By using higher SF data transmission rate is lower but it is increased the likelihood of a gateway will detect the message because the receiver can recognize the data from noise. Also to be able to successfully decode data receiver sensitivity defines the minimum power level of received signal.

In Figure 2.4, it is shown that how as SF changes also Data Rate, Packet Duration and Receiver Sensitivity are affected.

SF	Packet Duration (s)	Data Rate (Kbps)	Receiver Sensitivity (dBm)	SNR (dB)
SF7	0.036	5.47	-123	-6
SF8	0.064	3.13	-126	-9
SF9	0.113	1.76	-129	-12
SF10	0.204	0.98	-132	-15
SF11	0.365	0.54	-134.5	-17.5
SF12	0.682	0.29	-137	-20

Figure 2.4: CSS Modulation of 25-bytes Message [19] (J. T. Lim and Y. Han as cited in Yusri, 2020)

As a trade-off receiver sensitivity even though with higher SF stands for higher receiver sensitivity, the probability of packet loss is also higher because of the low speed of data.

Higher spread factor also means data is sent slowly therefore data spends more time in the air so battery consumption of the device increases.

The network also uses spreading factors to control congestion. Spreading factors are orthogonal, so signals modulated with different spreading factors and transmitted on the same frequency channel at the same time do not interfere with each other [15].

In the application which is developed for this project for the purpose of testing places for gateway installation to be able to decide the most suitable location, users can decide the spread factor from the application. While a user selecting SF between 7-12, this is actually setting a data rate corresponding to wanted SF in inverse proportion for the transmission. It will be detailed in the further parts of the paper.

### **RSSI (Received Signal Strength Indicator)**

The RSSI is an indication of the power level being received by the antenna:

## 2.2. LORAWAN

higher is the RSSI level, stronger is the radio signal and then closer is the destination [20]. Even though it is directly related with distance, obstacles in the environment also affect RSSI. RSSI value can be less when there are interference such as high apartments, mountains. RSSI information is quite important for wireless networks because it indicates the received signal's quality. This information helps network planners to assess link quality, transmission and location of antennas. Unlike receiver sensitivity it is not related to the ability of the receiver to decode the signal it only shows strength of the received signal.

### Code Rate (CR)

LoRa modulation also adds a forward error correction (FEC) in every data transmission. This implementation is done by encoding 4-bit data with redundancies into 5-bit, 6-bit, 7-bit, or even 8-bit. These error correction bits are used at the receivers for restoring corrupted bits. Using this redundancy will allow the LoRa signal to endure short interferences [15][20].

Code Rate can be set according to the circumstances of the channel used for message sending. This lora parameter makes transition durable against interference. If interferences in the channel better choice would be increased Code Rate value.

There are 4 code rates used in LoRaWAN [15]:

- 4/5
- 4/6
- 5/7
- 4/8

If the code rate is 4/8, 8 bits of data would be generated for every 4 bits of useful information, the rest 4 bits are redundant, at the end 4 information bits, 4 error correction bits will be in the data.

## 2.2 LoRaWAN

LoRaWAN is a Media Access Control (MAC) layer protocol built on top of LoRa modulation. It is a software layer which defines how devices use the LoRa hardware, for example when they transmit, and the format of messages. The protocol itself is developed and maintained by the LoRa Alliance [16].



LoRa technology provides a wide-ranging wireless network to LoRaWAN protocol so LoRaWAN protocol is well suited for small data transmission between long range distances. Also LoRa modulation provides lower bandwidth when compared with other wireless communication technologies. Figure 2.5 shows Wi-Fi, cellular (4G, 5G) and LoRa comparison in the sense of bandwidth and range.

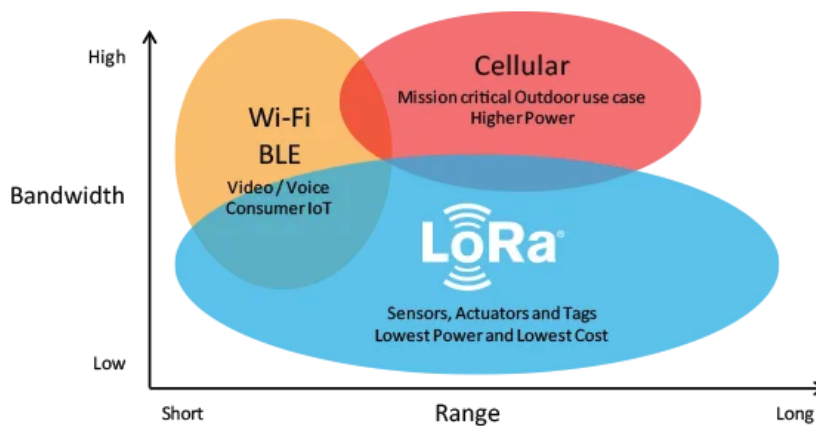


Figure 2.5: Lora and Other Wireless Technologies Comparison [16]

**LoRaWAN Network Architecture:** LoRaWAN architecture components are shown in figure 2.6.

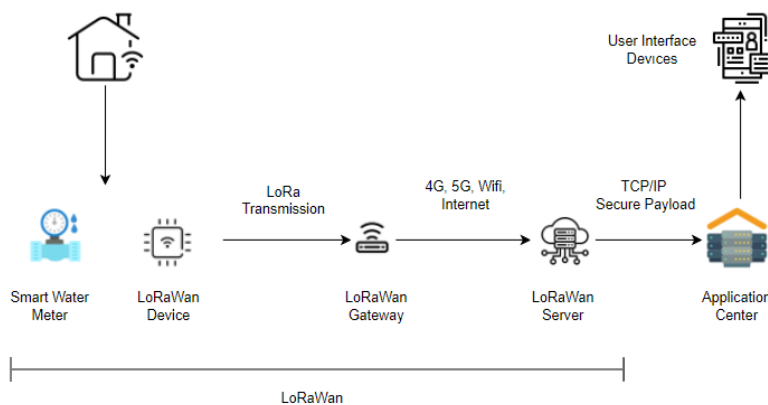


Figure 2.6: LoRaWAN Architecture]

End-devices (sensors) are the IoT devices (hardware) which collect data from smart meters and transmit them by using LoRa technology. They send the data to the nearest gateway.

## 2.2. LORAWAN

The objective of gateway nodes is to forward messages from end-devices to the Network Server. Their places are strategically decided to be able to cover as much of the end devices as possible.

Gateways are connected to the network server via standard IP connections and this simplicity in infrastructure provides easier deployment and maintenance[23]. Server gets all the data which comes from every end device that is in that LoRaWAN network and it is responsible for processing, storing and managing. Network Servers have high capacity to process millions of messages which came from tens of thousands of gateways. Additionally, it de-duplicates identical messages received from multiple gateways [24].

LoRaWAN Networks allows various communication models:

**Uplink Transmission:** LoRaWAN device, which is a low battery powered device (end-device), is a data collector to transmit them to gateways with LoRa technology. As an intermediate device nearest gateways take the data and transfer it to the network server. Network servers are a crucial component that controls the network and they take care of device authentication, encryption and routing. Network servers control whether the data reaches the application server or not. This process is called uplink.

**Downlink Transmission:** The network server can send messages (either for network management, or on behalf of the application server) through the gateways to the end devices [25].

Application Server is responsible for providing high-level services for end-users by using the uplink messages received from end-devices. In Application Server data processed, analyzed and used for particular applications or services. To gain access to the network, end-devices need to authenticate rst. The node responsible for this task is the Join Server. The Join Server conducts other security-related tasks such as authentication procedures and the storage of encryption keys [26]. Join server in charge of securely accessing end-devices to the LoRaWAN network. The security process involves device authentication and activation.

### LoRaWAN Network Topology

Network topology of LoRaWAN is based on a star-of-stars topology as presented in Figure 2.7. In this architecture, the multiple end-devices (e.g., sensor nodes) communicate directly with multiple gateways using the LoRa PHY wireless modulation [26]. Then gateways forward the message to the network server.

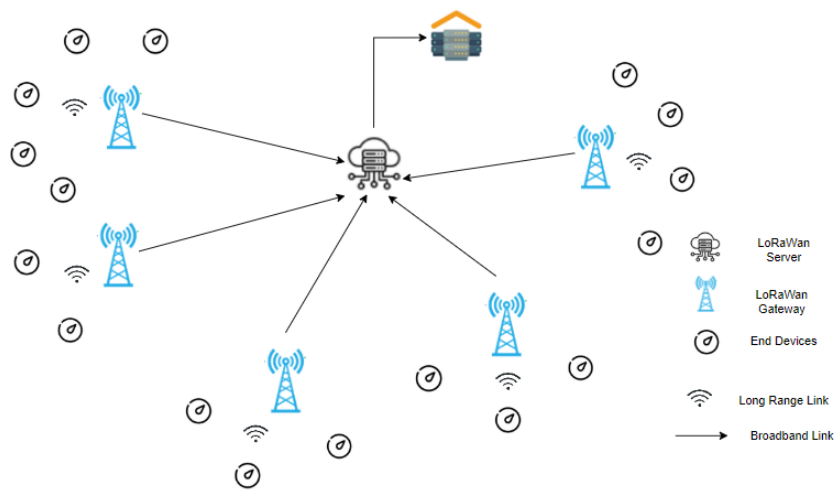


Figure 2.7: LoRaWAN Star of Star Topology

This star-of-stars topology in LoRaWAN networks allows gathering data in an efficient way from devices that are spreaded over a broad area with low power consumption and long-range communication. This topology offers scalability , when the network needs to be expanded. It is easy to add more gateways to cover larger fields without making major changes in infrastructure. Also with star-of-stars topology since gateways controlling local traffic of end-devices, network congestion is minimized. In addition to that, gateways can receive messages even from mobile devices. On the contrary of cellular networks LoRaWAN network can notice the current location of the end device without GPS.



# 3

## Network Coverage Planning

Network coverage planning is the primary part of wireless communication system designing and deploying, in this case the wireless communication network is LoRaWAN network for IoT applications. It requires careful assessment of geographic area intended to be covered, communication needs of devices in the network system and infrastructure required to provide reliable connectivity. The main idea of network coverage planning is designing and optimizing a communication network to ensure that its coverage is adequate for decided areas and sensors. In the context of LoRa networks, coverage planning includes deciding optimal locations for gateways and configuration of devices to ensure the end nodes can send messages in the network with enough signal strength and quality [27].

In this chapter the main components of network coverage planning will be explained such as link budget calculations and radio frequency models which are fundamental for a robust and efficient LoRaWAN IoT network.

### 3.1 LINK BUDGET

Link budget is a calculation for determining the maximum range of a wireless network and the number of nodes required to provide reliable connectivity. This calculation takes into account several factors such as transmitter power, receiver sensitivity, antenna gain, and path loss [18]. With link budget calculation it can be decided the maximum range between two communicating devices and the

### 3.2. RADIO FREQUENCY PROPAGATION MODELS

minimum signal strength needed for reliability.

The general formula for link budget calculation is defined [18] as:

$$\text{LinkBudget} = \text{TxPower} + \text{TxAntennaGain} - \text{PathLoss} - \text{RxAntennaGain} - \text{RxSensitivity} \quad (3.1)$$

- Tx Power is the power of the transmitter in dBm
- Tx Antenna Gain is the gain of the transmitter antenna in dBi
- Path Loss is the loss of signal strength due to distance and other factors in dB
- Rx Antenna Gain is the gain of the receiver antenna in dBi
- Rx Sensitivity is the minimum signal strength required by the receiver in dBm

$$PR = PT + Gt - PL + Gr \quad (3.2)$$

- PL: Path loss
- PR: Received power
- PT: Transmit Power
- Gt: Transmit antenna power gain
- Gr: Received antenna power gain

Path loss is the reduction in power density (attenuation) of an electromagnetic wave as it propagates through space. It is caused by various factors such as distance, frequency, obstacles, and environmental conditions [28]. Radio frequency propagation models are utilized to be able to calculate path loss. There are multiple approaches which all take into account environmental factors that cause weakening of the signal from transmitter to receiver.

## **3.2** RADIO FREQUENCY PROPAGATION MODELS

Radio Frequency Propagation models are used to estimate the maximum coverage area per site, the number of gateways required to cover a region, and the total required capacity to carry the aggregated traffic [29]. A Radio frequency propagation model is a mathematical model that defines how radio

waves propagate under conditions of a given environment such as urban, suburban, or rural areas and models differ at that point. This project three of them will be examined; Okumura-Hata, two COST-231 models; COST-231 Hata and COST-231 Walfisch-Ikegami.

The Okumura-Hata model is mainly used for urban areas. COST-231 models are expanded versions of Okumura-Hata, they are used both for urban and suburban areas. COST-231 Hata model is to be able to cover a wider frequency range according to the Okumura-Hata COST-231 Walfisch-Ikegami model is for urban areas again but with high-rise buildings. With the usage of these models to predict path loss, the link budget calculation can be performed more accurately to establish the required parameters to achieve desired quality of service in the wireless network.

### 3.2.1 OKUMURA HATA MODEL

The Okumura-Hata is a propagation model for path loss calculation based on the Okumura measurement and Hata propagation model. This model takes into consideration frequency, distance, terrain and obstacles to be able to estimate the signal strength and quality for the intended coverage areas at different points. In terms of frequency, this model only applies to the frequency range of 150 MHz to 1500 MHz. Also the model provides a correction factor, Hata said that loss on propagation for urban areas is the standard of the formula and provides the correction for different conditions. (T. S. Rappaport as cited in Yusri, 2020) [18].

Parameters of the model:

- Frequency Range : 150 MHz to 1500 MHz
- Height of Transmitter: 30m to 200 m
- Link Distance: 1 km to 20 km
- Height of Mobile Station: 1m to 10m

Okumura-Hatha mode's most use cases are urban areas and it is formulated [30] as:

$$L_u = 69.55 + 16.16 \log(f) - 13.82 \log(h_B) - C_H + (44.9 - 6.55 \log(h_B)) \log(d) \quad (3.3)$$

### 3.2. RADIO FREQUENCY PROPAGATION MODELS

For small and medium cities:

$$C_H = 0.8 + (1.1 \log(f) - 0.7)h_M - 1.56 \log(f) \quad (3.4)$$

For larger cities:

if frequency (150 MHz  $\leq$  f  $\leq$  200 MHz)

$$C_H = 8.29(\log(1.54h_M))^2 - 1.1 \quad (3.5)$$

if frequency (200 MHz  $\leq$  f  $<$  1500 MHz)

$$C_H = 3.2(\log(11.75h_M))^2 - 4.97 \quad (3.6)$$

- $L_U$  : Path Loss in Urban Areas
- $h_B$  : Height of base station antenna in meters (m)
- $h_M$  : Height of mobile station antenna in meters (m)
- f : Transmission frequency in MHz
- $C_H$  : Antenna height correction
- d: Base and mobile station distance in km

#### **3.2.2** COST-231 HATA MODEL

COST-231 Hata model is a Hata model extension model in order to cover a wider frequency range up to 2 GHz. The model merges empirical and deterministic approaches to predict path losses in urban areas. (COST Action 231 Final Report, as cited in Piechowiak et al., 2023)[31].

Parameters of the model [32]:

- Frequency Range : 1500MHz to 2000 MHz
- Height of Transmitter: 30m to 200 m
- Link Distance: 1 km to 20 km
- Height of Mobile Station: 1m to 10m



Formulation of COST-231 model (Oluwole & Olajide, as cited in Harinda et al., 2019) [32]

$$P_{LOSS} = 46.3 + 33.9 \log_{10}(f) - 13.82 \log_{10}(h_b) - ah_m + (44.9 - 6.55 \log_{10}(h_b) \log_{10}(d) + cm)$$

where

- $f$ : frequency in MHz
- $d$ : distance between gateway and end device in km
- $h_r$ : antenna height for gateway in meters
- $h_m$ : antenna height for end device in meters
- $cm$ : 0 dB for both suburban and open environments or 3 dB in urban areas

$ah_m$  value for urban areas is defined (Milanovi, Rimac-Drlje, & Majerski, as cited in Harinda et al., 2019) [32] as:

for  $f > 400$  MHz

$$ah_m = 3.20(\log_{10}(11.75 h_r))^2 - 4.97 \quad (3.7)$$

and for suburban or rural areas:

$$ah_m = (1.1 \log(f) - 0.7)h_r - (1.56 \log(f) - 0.8) \quad (3.8)$$

### 3.2.3 COST-231 WALFISCH-IKEGAMI MODEL

This model merges Walfish-Bertoni and the Ikegami model and it takes into account width, building heights, distance between buildings among other parameters (Ikegami, Takeuchi, and Yoshida as cited in Uyoata, 2022) [33]. These extra parameters improve path loss prediction due to there being more effects in large and medium size urban areas.

Parameters for the model [33]:

- Frequency Range: 800-2000 MHz
- Height of Gateway: 4m to 50m
- Link Distance: 0.02 km to 5 km
- End node Height: 1m to 3m

### 3.2. RADIO FREQUENCY PROPAGATION MODELS

Models mathematical formulation is diverse according to the existence of line-of-sight (LOS) and non-line-of-sight (NLOS) in the street [32]. If there is LOS in the street:

$$P_{LOSS} = 42.64 + 26\log(d) + 20\log(f) \quad (3.9)$$

In the case of NLOSS:

$$P_{LOSS} = L_0 + L_{rts} + L_{msd} \quad (3.10)$$

where

- $L_0$  : free space
- $L_{rts}$  : the rooftop to street diffraction and the scatter
- $L_{msd}$  : multiple screen diffraction loss

where  $d$  is distance between gateway and en device:

$$L_0 = 32.45 + 20\log(d) + 20\log(f) \quad (3.11)$$

where  $h_b$  gateway height,  $h_r$  end node height,  $w$  is the width of the roads and  $L_{ori}$  correction factor:

$$L_{rts} = -16.9 - 10\log_{10}(w) + 10\log_{10}(f) + 20\log_{10}(h_b - h_r) + L_{ori} \quad (3.12)$$

where  $\alpha$  is the street orientation angle:

$$L_{ori} = \text{for } 0^\circ < \alpha < 35^\circ = -10 + 0.35\alpha \quad (3.13)$$

$$L_{ori} = \text{for } 35^\circ < \alpha < 55^\circ = 2.5 + 0.0755(\alpha - 35) \quad (3.14)$$

$$L_{ori} = \text{for } 55^\circ < \alpha < 90^\circ = 4 - 0.0114(\alpha - 55) \quad (3.15)$$

where  $\alpha$  is the street orientation angle  $L_{msd}$ , the multi screen loss, defines diffraction loss from various obstacles and its formula is[32]:

$$L_{msd} = L_{bsh} + K_a + K_d\log(d) + k_f\log(f) - 9\log(s_b) \quad (3.16)$$

$L_{bsh}$  and  $k_a$  are correction factors which define path loss according to which the gateway is above and below the rooftop in order.  $k_d$  and  $k_f$  quantify the diffraction loss as a factor of the distance and frequency and are defined in (L. M. Correia as cited in E. Harinda, 2019, p. 154) [32]:

$$L_{bsh} = \begin{cases} -181 \log(1 + h_t - h_b) & h_t > h_b \\ 0 & h_t \leq h_b \end{cases} \quad (12)$$

$$k_a = \begin{cases} 54 & h_t > h_b \\ 54 - 0.8(h_t - h_b) & h_t < h_b \text{ and } d_{km} \geq 0.5km \\ 54 - 1.6(h_t - h_b)d & d_{km} < 0.5km \end{cases} \quad (13)$$

$$k_d = \begin{cases} 18 & h_t > h_b \\ 18 - 15(h_t - h_b)/h_b & h_t \leq h_b \end{cases} \quad (14)$$

$$k_f = -4 + \begin{cases} 0.7(f_{MHz}/925 - 1) & \text{for medium - size city and suburban} \\ 1.5(f_{MHz}/925 - 1) & \text{for metropolitan centers} \end{cases} \quad (15)$$



# 4

## LoRaWAN Network Planning

LoRaWAN network planning goal is keeping the cost minimum and designing and configuring the network infrastructure with less complexity while meeting desired performance requirements. In this process it is decided the number and the location of gateways, choosing the parameters for data transmission such as spreading factor, bandwidth, confirmation, transmission power used by end devices. At the end it is expected that the network provides reliable and efficient communication with minimum energy consumption and maximum network coverage.

Since it is aimed to cover maximum area with parameters of LoRa device, gateway features and geographical conditions, the network planning phase includes determining area to be covered. There are many tools able to simulate network and coverage mapping both as open-source or commercial. These tools are useful for LoRaWAN deployment to optimize device configurations and estimate signal propagation characteristics. For this project a commercial tool is preferred which is called CloudRF because commercial tools offer a more feature-rich and user-friendly approach and they are mostly utilized for professional deployments to plan and manage LoRaWAN networks.

After creating coverage maps the next steps are gateway placement and device configuration. They are the most critical decisions of LoRa network planning because configuring devices with suitable data rate and power setting optimize the communication, it affects communication range and battery consumption of end-device. Also gateway installment and finding an available location for the gateway are challenging and expensive procedures.

#### 4.1. NETWORK PLANNING TOOL

This chapter serves exploration of network planning key elements and how that is related with the suggested testing tool LoRaWAN Site Survey Tool. Network coverage map, considered gateway placement location which is simulated in the map and decided parameters for device configuration are inputs for LoRaWAN SST.

### 4.1 NETWORK PLANNING TOOL

Network planning tools are crucial for designing, deployment and optimization networks. It provides efficient usage for available spectrum and infrastructure by optimizing resource allocation such as base stations and antennas. Also it provides coverage mapping with given parameters. Some of them parameters are:

**Coordinates:**It represents the base station's location. In this case coordinates are in Via Zabarella, Padova, where the gateway is located.

**Height AGL (Height Above Ground):**This means height of the gateway from ground level, this value for this case is 10m.

**Signal Frequency:**There are two different frequency bands in Europe EU433 (433.05 to 434.79 MHz) and EU863-870 (868.1 to 868.5 MHz). However they have different limitations in the sense of efficient usage of spectrum. The ETSI standard (EN300220) regulations for the EU433 band include a maximum transmit duty-cycle of 10%. On the other hand The EU863 band can be used in any region where the ISM (Industrial, Scientific, Medical) radio spectrum is defined by the ETSI 307 standard [38].

Duty cycle aims to prevent network congestion and interference and it refers to the ratio of time a device is active (transmit or receive signals) compared to time that is a given time period. According to LoRaWAN requirements for end devices, the duty cycle limit is 1%. Since the LoRaWAN network includes a large number of devices sharing the same frequency band, lower duty-cycle prevent congestion and poor performance even with high density of devices transmitting too frequently.

Different frequency bands have different characters in wireless networks for example while 433 MHz is commonly utilized for short-range communication devices like remote controls, 863 MHz mostly used for various wireless communications, mostly implementations of IoT devices. Also 863 MHz radio frequency band provides a higher data rate compared to the lower frequency band.

In conclusion LoRaWAN end devices and the specific device which is used for this project (Wio-E5 Dev Board) are required to operate at least on channels 868.10 MHz, 868.30 MHz, and 868.50 MHz. These channels must have a bandwidth of 125 kHz at DR0 to DR5, and be restricted to a maximum duty cycle of 1% [39].

**RF Power:** According to EU regulations Tx power is limited for 868 MHz frequency to 14 dBm and that is used for smart meters.

**Bandwidth:** For simulation bandwidth is set 125 KHz.

CloudRF provides service for modeling radio propagation. By using these parameters with CloudRF, network coverage maps are created. As a propagation model COST321-Hata, Okumura-Hata and Longley Rice models are used to compare coverage areas but while testing Longley Rice model's coverage map will be accounted for.

In figure 4.1 it is shown network coverage map with Okumura-Hata propagation model with setting SF (spreading factor) 7.



Figure 4.1: Okumura-Hata SF7 Coverage Map

In figure 4.2 it is shown network coverage map with Okumura-Hata propagation model with setting SF12.



#### 4.1. NETWORK PLANNING TOOL



Figure 4.2: Okumura-Hata SF12 Coverage Map

In figure 4.3 it is shown network coverage map with COST-321 propagation model with setting SF7.



Figure 4.3: COST-321 SF7 Coverage Map

In figure 4.4 it is shown network coverage map with COST-321 propagation model with setting SF12.





Figure 4.4: COST-321 SF12 Coverage Map

In figure 4.5 the network coverage model with Longley Rice propagation model is represented with setting SF7.



Figure 4.5: Longley Rice SF7 Coverage Map

In figure 4.6 the network coverage model with Longley Rice propagation

## 4.2. GATEWAY PLACEMENT

model is represented with setting SF12.



Figure 4.6: Longley Rice SF12 Coverage Map

As it can be seen in among all the maps SF12 coverage map the area that can be covered is slightly bigger with less signal strength. Also from maps it can be understood that with the COST-321 propagation model the area that is covered is the largest and with the Okumura-Hata propagation model it is the smallest. Even though the difference among coverage areas are quite small, the accuracy is crucial while planning a network.

## 4.2 GATEWAY PLACEMENT

Finding the optimal location to install gateways is integral to the success of the LoRaWAN network. To consist of the largest coverage area and minimum interference depends on choosing the optimal location for the gateway.

As it is explained before in LoRaWAN end-devices transmit messages in broadcast meanwhile all gateways are listening for receiving and transmission happens when the received signal power at the gateway is higher than a minimum required Received Signal Strength Indicator (RSSI) [19]. When the gateway receives the data, the gateway decodes it and sends it to the network server via the internet. To be able to decode the data minimum required signal strength

of the received signal is called Receiver Sensitivity and in figure 4.2 Receiver Sensitivity values are indicated both for SF7 and SF12.

LoRaWAN site survey tool offers testing coverage map's accuracy before installing gateway. It gives the opportunity to test gateway placement before installing so the network planner can see RSSI values before fixing the location of the gateway.

### 4.3 DEVICE CONFIGURATION

Configuration of LoRaWAN nodes includes setting parameters to be able to communicate with the LoRaWAN network. These parameters are crucial for the device to join the network which means that the LoRaWAN node joins the network and also with setting parameters LoRaWAN nodes can transmit messages successfully.

In this project LoRaWAN AT commands are used for device configuration which are text-based commands that provide you configure and control LoRaWAN nodes. These commands are utilized for configuration of parameters, joining the network, sending and receiving messages.

Configuration parameters for LoRaWAN:

**DevAddr(Device Address):**32-bit length hex identifier.

- AT command to read DevAddr:

```
1 AT+ID=DevAddr
```

Code 4.1: Code to Read DevAddr

- AT command to change DevAddr:

```
1 AT+ID=DevAddr , "devaddr"
```

Code 4.2: Code to Change DevAddr

**DevEUI (Device EUI):** The DevEUI is a 64-bit globally-unique Extended Unique Identifier (EUI-64) assigned by the manufacturer, or the owner, of the end-device [34]. This is a static identifier also it is already written inside the device and it should be registered in the network server.

- AT command for reading DevEUI:

```
1 AT+ID=DevEui
```

Code 4.3: Code to Read DevEui



### 4.3. DEVICE CONFIGURATION

Even though it is possible to change this parameter it is not recommended for security reasons and to be able to avoid conflicts in all LoRaWAN devices.

- AT command for configuring DevEUI:

```
1 AT+ID=DevEui , "deveui "
```

Code 4.4: Code to Change DevEui

**AppEUI (Application EUI):** This is a 64-bit unique ID of the Application server and this is also obtained from IEEE. The AppEUI is unique to the Application Server and each Application Server will have its own AppEUI so that the end node can know which application server to send messages to. The AppEUI is usually provided to the end node manufacturers by the solution providers [35].

- AT command for reading AppEUI:

```
1 AT+ID=AppEui
```

Code 4.5: Code to Read AppEUI

Even though it is possible to change this parameter it is not recommended for security reasons and to be able to avoid conflicts in all LoRaWAN devices.

- AT command for configuring AppEUI:

```
1 AT+ID=AppEui , "appeui "
```

Code 4.6: Code to Change AppEUI

**AppKey (Application Key):**The AppKey is a 128-bit shared encryption key to encode the messages between end nodes and Application Server [35].

**Join Mode:** LoRa devices can join network in two different modes: OTAA (Over-The-Air-Activation) or ABP (Activation-By-Personalization).

All end devices that participate in a LoRaWAN network must be activated and for activation there are two methods you can choose: over-the-air activation (OTAA) or activation by personalization (ABP). Both activation methods result in session keys both end device and network server hold that are used for security while message sending and receiving. In ABP, these session keys are stored on the end device during the manufacturing process. In OTAA, the session keys (Network Session Key (NwkSKey), Application Session Key (AppSKey)) are generated during a series of exchanges with the network server [36]. Therefore OTAA is a more secure way and OTAA option is used for this project also it is recommended in general using OTAA.

- Here is the command to set the device OTAA mode:

```
1 AT+MODE=LWOTAA
```

#### Code 4.7: Code to Set OTAA mode

Before activation, the AppEUI, DevEUI, AppKey, and NwkKey should be stored in the end device. The AppEUI and DevEUI are not secret and visible to everyone.

For the rest of the project this activation procedure will be called 'enrollment' to the network server. Enrollment process prepares LoRa devices to communicate with the network and establish secure communication. For enrollment LoRa devices provide DevAddr, DevEui and AppEui information to the server and LoRaWAN network responds with NewSKey and AppSKey along with the parameters. This exchange ensures that device has authorization for communication with the network.

As it is mentioned before AppSKey is for encrypting and decrypting the data. LoRa devices use AppSKey to encrypt data when sending messages and then the network server uses the same AppSKey to decrypt it. NewSKey is used by the network server while sending data from server to end device for network specific operations and uses AppSKey again to encrypt data. After that, the device uses the same one to decrypt the data.

OTAA procedure follows by joining the network. In the OTAA method end devices have to go through the joining process before starting to send messages. Join request messages are not encrypted, instead they are plain text.

In figure 4.7 it is shown the LoRaWAN join process.

### 4.3. DEVICE CONFIGURATION

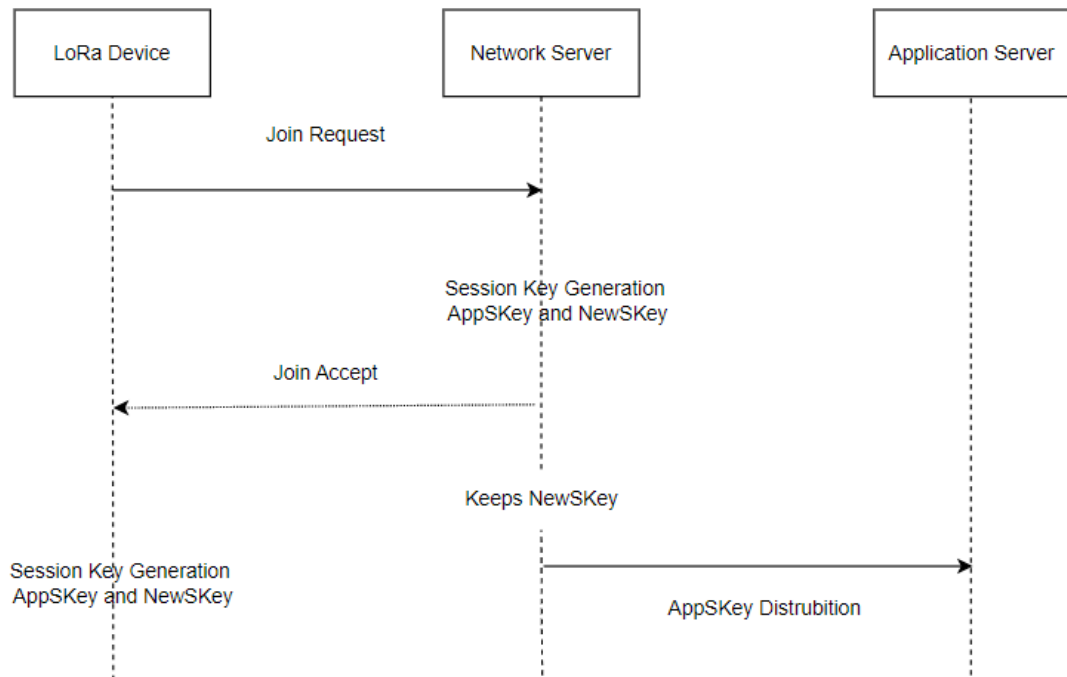


Figure 4.7: LoRa Device Join Process to the Network

Before enrollment AppEUI, DevEUI and AppKey should be in the LoRa device and also the same key should be provided to the network server.

Join process starts with the end device sending a request message to the network. Since the join request is not encrypted, AppKey is not sent with the message.

The Join-request message can be transmitted using any data rate and using one of the region-specific join channels. For example, in Europe an end device can transmit the Join-request message by randomly choosing among one of these channels: 868.10 MHz, 868.30 MHz, or 868.50 MHz [37]. Message goes to gateways into the network.

The network server decides whether or not to accept the request; it depends if the device has permission to join the network and generate session keys. If the join is accepted, this message is encrypted with AppKey and the network server sends it to the end node with downlink. Network server holds NwSKey and distributes AppSKey to the application server. LoRa devices decrypt messages with the same AppKey and generate session keys. At the end of enrollment DevAddr, NwkSKey and AppSKey are stored in the end device.

**Spreading Factor (Data Rate):** Spreading factor can be chosen between 7 and 12 and it determines the rate of transmission. As it is said before, the higher the spreading factor, the lower the rate but also higher spreading factor can send

data for further distances.

**TX Power:** Transmit power is related to the communication range. It is decided according to regulations and requirements of the network.

**Channel Plan:** LoRaWAN devices frequency band should be chosen according to the region, for Europe it is 863-870 Mhz. According to location devices should be configured with appropriate channels and frequencies.

**Confirmation:** Device can be configured to be able to require acknowledgement (ACK) for confirmed uplink messages. This feature can be used when the user wants to be sure if the message is delivered or not.





# 5

## LoRaWAN Site Survey Tool

A LoRaWAN site survey tool is a software and hardware technology solution conducted to assess RF (Radio Frequency) environment and optimize deployment of LoRaWAN network. This project involves both software and hardware and for the rest of this thesis it will be called 'probe'. Probe is combination of LoRaWAN node driven by an android application.

The probe is connected to an android smartphone or tablet using the USB-C connector that is used for both data link and powering the probe. It is also possible to add an additional power supply to the probe through a dedicated connector on the box.

In figure 5.1 probe is shown:



Figure 5.1: Probe

RF environment is geographical conditions of the area of the transmitter such as frequency bands, interferences, noises, signal strength, regulations etc. The main goal of site surveys is collecting information about RF environment and conditions of a particular location to be able to optimize placement of gateway and end devices for better coverage and reliable performance.

There are several published works about surveys that focus on different aspects of LoRa technology and LoRaWAN networks. Some of these surveys were conducted as mobile with a car [40] or by pedestrian surveyor [41] or stationary. In this sense surveys will be classified as active site survey and on-a-stick site survey. Suggested Site Survey Tool which will be called LoRaWAN-SST in this project is suitable for both types of surveys.

**Active Site Survey:** With active site survey, a person or a tool actively sends packets to the gateway to collect data or test coverage area. This type of survey provides insights about real world conditions in the case of the LoRaWAN network.

**On-A-Stick Site Survey:** On the contrary, on-a-stick survey devices are placed on a stick and send messages. The aim of this is to simulate coverage area for

the network.

In existing surveys the the surveys are about deciding best path loss algorithm according to environmental conditions (urban or suburban), testing coverage area and assessing gateways placement. The suggested site survey tool LoRaWAN-SST also can be used for all of those purposes but it can be also used for designing a new LoRaWAN network which is the unique feature of LoRaWAN-SST among other site survey tools.

All site survey devices rely on GPS because knowing locations of every data which send during the survey gives information about coverage area. Also probe uses android devices GPS service to acquire location during survey activity.

In figure 5.2 and 5.3 it is shown the device which is one of the latest devices screen which is (RAK10701) :



Figure 5.2: Test Device

## 5.1. SITE SURVEY PROCEDURE



(a) Test Device Setting Screen

(b) Test Device Result Screen

Figure 5.3: Test Device Screens

While using these testing devices, users can see their current location only as longitude and latitude values and these devices show max and min distance to the gateways around without any specifications.

With LoRaWAN-SST, users can see the current location on the map and also they can see the distance of their location with respect to the gateways which provides network planners crucial information to be able to design an efficient LoRaWAN network.

## 5.1 SITE SURVEY PROCEDURE

A site survey procedure is defining systematic steps for evaluating environmental conditions where considered areas to deploy a wireless network.

Here is the outline of the process for site survey:

1. **Definition of Objectives:** Objectives should be defined for the site survey such as coverage area testing, collecting data for a new network designing process. This definitions also consider coverage area, data rate needs and specific application in this case it is AMI.
2. **Pre-Planning:** Deciding gateway placement and other network elements if it is necessary then checking constraints like frequency bands, channels environmental factors and potential interferences.
3. **Equipment:** Preparing software and hardwares.
4. **Survey Type:** Decide survey type active or site-stick.

5. **Mapping:** Creating a map of the deployment area and noting obstacles could help understanding survey data outcomes.
6. **Gateway and End-Device Placement:** After surveys determine optimal places for gateways and end-devices.
7. **RSSI Measurements:** At several points conduct surveys and check signal strength to assess coverage quality and analyze interferences.
8. **Post Survey:** It is important to record and document outcomes of surveys and analyze data for designing a new network at the same time optimize the performance.

Site surveys can be required iteratively such as before deployment and also after deployment.

## 5.2 SITE SURVEY TOOL (SST) IMPLEMENTATION

Survey is a project which is going to allow surveying with the purpose to collect RSSI (Received Signal Strength Indicator) values from different locations in a particular zone. Every survey will be inside of a particular zone. Implementation of site survey tools includes both software and hardware which is called probe. As it is mentioned before, probe's software is an Android Application and hardware is a LoRa device. Software of the probe will be explained in two segments which are SST (Site Survey Tool) Client and SST Server. SST client will be used by the user who will carry out surveys and the server part is the backend part of the project. SST server provides administrative parts such as defining all variables which will be stored in the system and creating surveys etc. Those two parts are working together to be able to gather data during surveys, store and visualize them.

### 5.2.1 SST CLIENT

#### A. LoRaWAN SST SOFTWARE (ANDROID APPLICATION)

Software part of LoRaWAN-SST is an application that can be run on tablet or smartphone devices with the Android operating system and it is available from Google Play Store. To be able to use the application, the user should log in or register into the SWaRM system which belongs to InkwellData Ltd. [42]. In the Log-in Page users log into the SWaRM so that it will be known if the user

## 5.2. SITE SURVEY TOOL (SST) IMPLEMENTATION

is authenticated by the company or not. It is shown in figure 5.4 the Log-in page which is the first page when application launch:

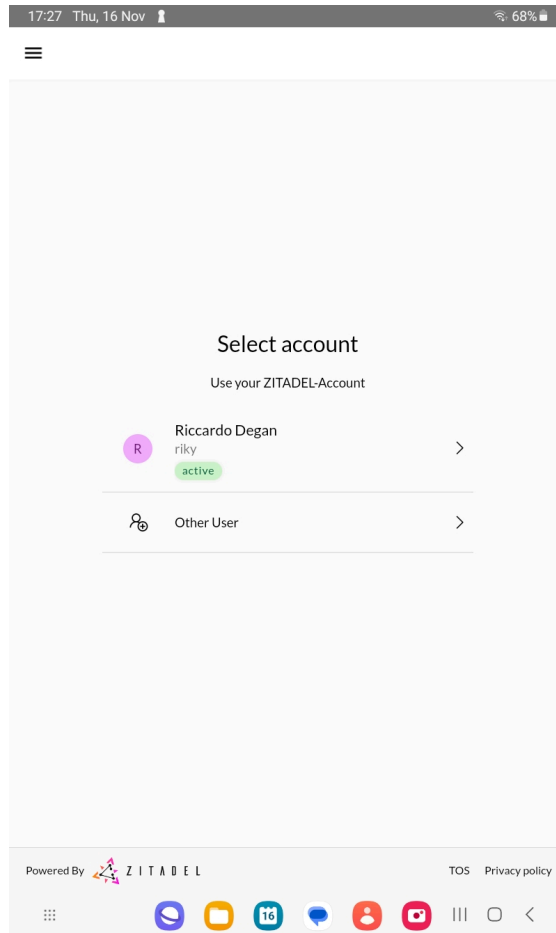


Figure 5.4: LoRaWAN-SST Login Page

If the user eligible, after user log-in the surveys page will appear as it is seen in figure 5.5:

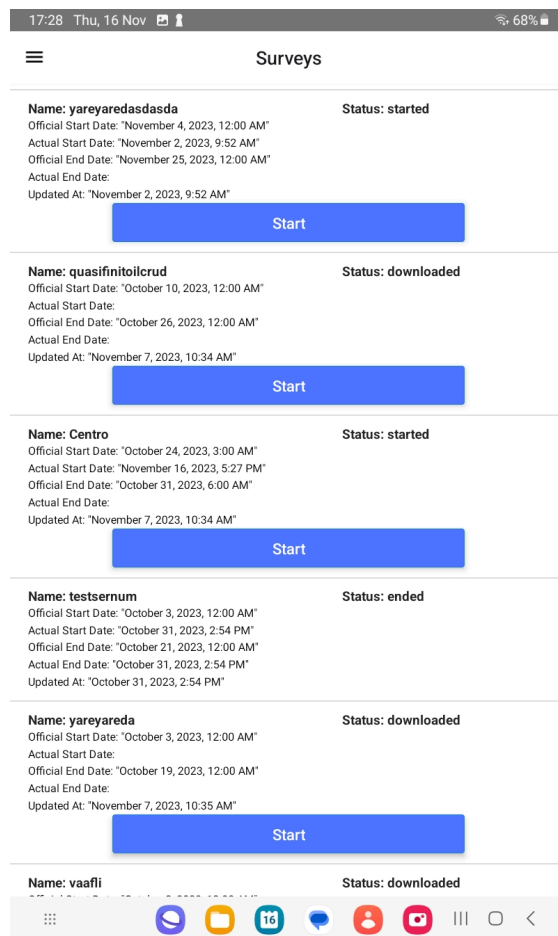


Figure 5.5: LoRaWAN-SST Surveys List Page

Operator, which is the user who conducts surveys, can see the surveys in this page which are assigned to that particular operator. After this point the operator can manage surveys according to information that is provided for each survey. Such as if the survey ended already or if it started before and paused now or if it has not started at all. In this page it is also seen the start date of the survey and end date. Start date represents the first starting time of the survey; it does not update when it is paused and started again.

LoRaWAN-SST application can be also used when there is no internet connection. For that all surveys are saved to local storage which is used inside of the application.

After operator decides and click start for a particular survey this page that shown in figure 5.6 is appear:



## 5.2. SITE SURVEY TOOL (SST) IMPLEMENTATION

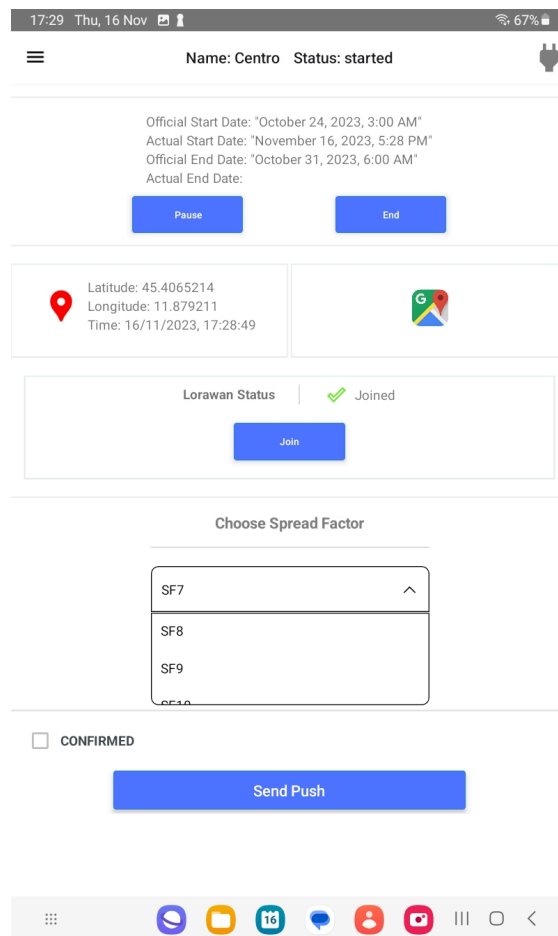


Figure 5.6: LoRaWAN-SST Message Sending Page

This page is the core of the application. Users can see the survey's name on the header and other information about the survey; start and end dates, status. Under survey information there is join status of the LoRa device. At the beginning it says 'Not Joined' because the device should join the network before starting sending messages.

In this page the operator can decide configuration such as spreading factor and the message type as in confirmed message or not. Confirmed messages AT command is:

```
1 AT+MSGHEX="xx xx xx xx"
```

Code 5.1: Code for Confirmed Message

The answer of this message:

```
1 MSGHEX: Start
2 MSGHEX: Wait ACK
3 MSGHEX: FPENDING
```



```

4 CMSGHEX: ACK Received
5 CMSGHEX: Port: 8, RX: "8876349042832736"
6 CMSGHEX: RXWIN1, RSSI -82, SNR 9.0
7 CMSGHEX: Done
    
```

Code 5.2: Answer of the Confirmed Message

Since it is a confirmed message it returns acknowledgement so in the matter of message transmitting time the confirmed message takes longer.

Not confirmed messages AT command is:

```

1 AT+MSGHEX="xx xx xx xx"
    
```

Code 5.3: Code for Not Confirmed Message

The answer of this message:

```

1 MSGHEX: Start
2 MSGHEX: Port: 8, RX: "8876349042832736"
3 MSGHEX: RXWIN1, RSSI -74, SNR 11.0
4 MSGHEX: Done
    
```

Code 5.4: Answer of the Not Confirmed Message

In figure 5.7 it is shown the flow when operator sends a message:

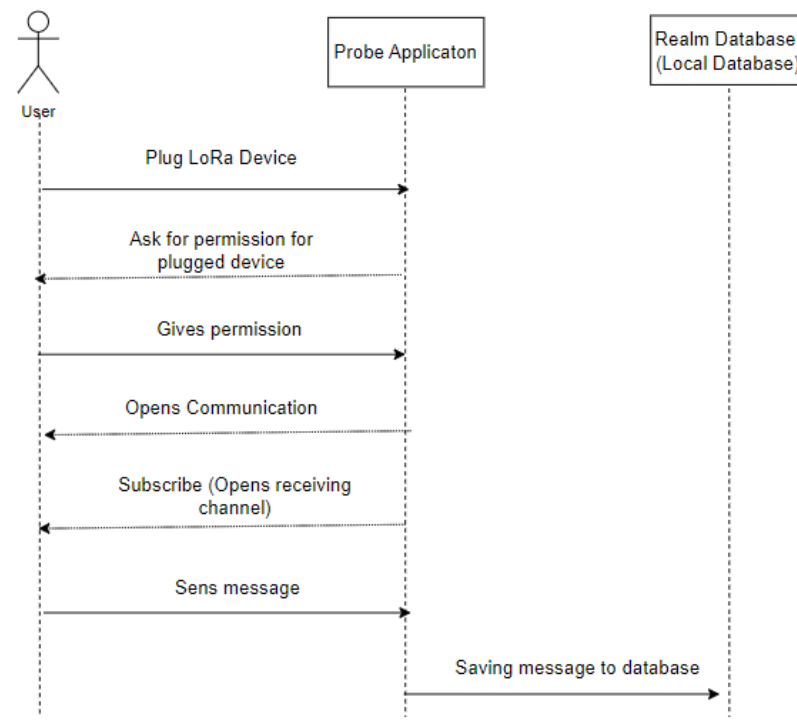


Figure 5.7: Message Sending Process Between Probe and Gateway

## 5.2. SITE SURVEY TOOL (SST) IMPLEMENTATION

When the LoRa device first plugged probe asks for permission from the user, then it establishes serial communication between probe and gateway including receiving channel to be able to receive answer from gateway. This part is happening once only when the user plug LoRa device first, after that user can send messages without going through those steps. All sent messages are stored in the local database as like this:

```
1 Message ID: 65563fcaacbabd0
2 SF: SF11
3 CreatedAt: 2023-11-16T16:14:02.810Z
4 Confirmed: Not Confirmed
5 Latitude: 45.4065214
6 Longitude: 11.879211
7 Result: true
```

Code 5.5: Stored Message on Application Local Database

As it is explained in the Device Configuration part, to be able to join the network LoRa device should be enrolled into the network. For this project probe must be enrolled in the lorawan server of the Altior system. In figure 5.8 it is shown the enrollment process of LoRa Device into the network:

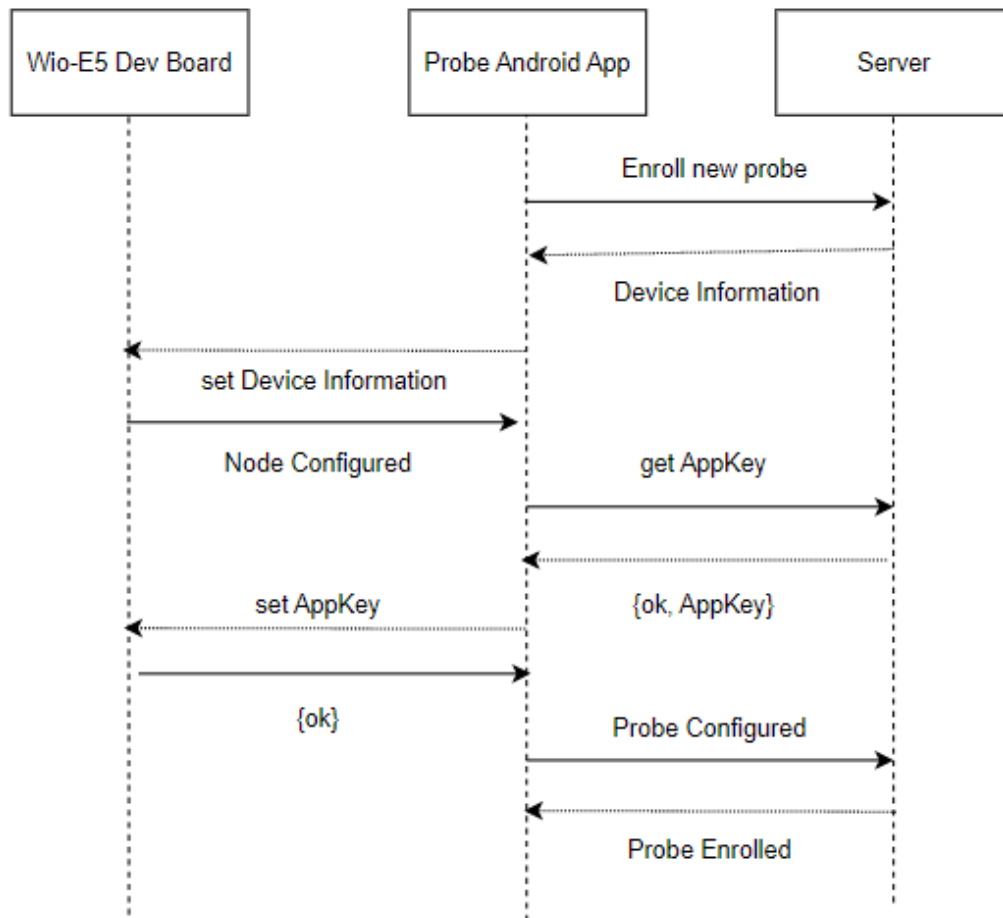


Figure 5.8: Enrollment Process

1. The probe is queried for LoRa device's MAC (device) address using the command AT+ID. Altior system allows probe only if it is authorized probe which means device is configured before enrollment process in the Altior system.

If it is authorized the result of AT command message includes these informations:

```

1 AT+ID
2 +INFO: Input timeout
3 +ID: DevAddr, 31:31:D0:81
4 +ID: DevEui, 2C:F5:F5:25:35:35:D5:85
5 +ID: AppEui, 85:55:55:55:55:00:00:06
  
```

Code 5.6: Result of AT+ID Message

2. The app configures the LoRa node with the information.
3. The app requests the lorawan application key
4. The app configures the application key on the node
5. After a successful key configuration, the app notifies the completion of the procedure to the server

## 5.2. SITE SURVEY TOOL (SST) IMPLEMENTATION

6. The server acknowledge the enrollment and creates the digital twin instance of the probe

After the probe is enrolled in the system, the application will log into the server using the DevEui value as the user ID and the AppKey as the password. In figure 5.9 Login Process is represented:

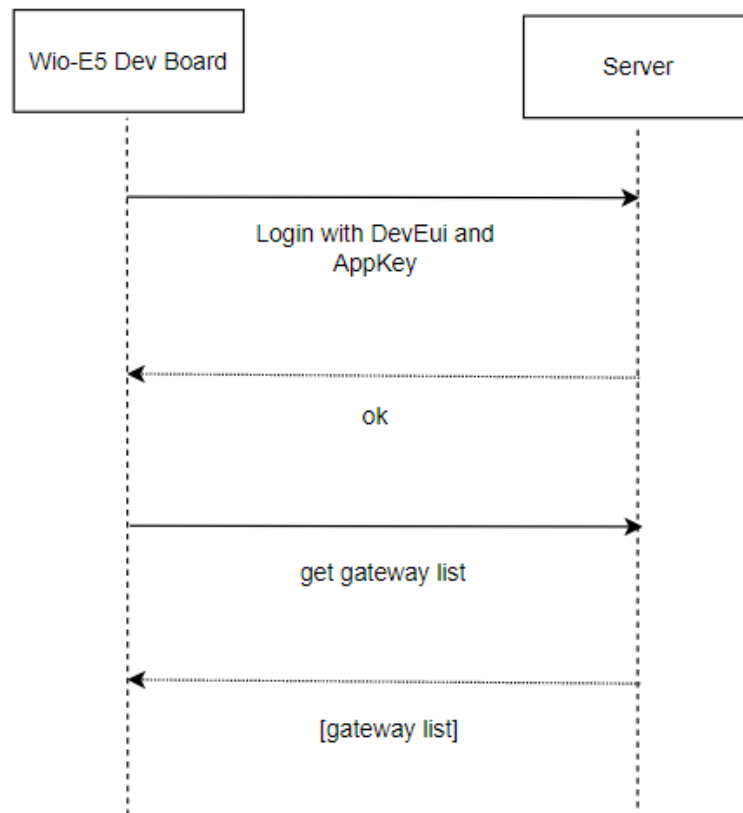


Figure 5.9: Login Process

If the login is successful, the app will request the list of the LoRaWAN gateways available for the application.

The gateway list is used to pinpoint the gateway locations during the site survey activities and is presented on the map. In this page users can see gateways that survey's zone and operator's current location.

For the first version of the application, probe enrollment and probe log-in processes do not exist. These parts will be added to the next release. In 5.10 it is seen the mockup of gateway list map:

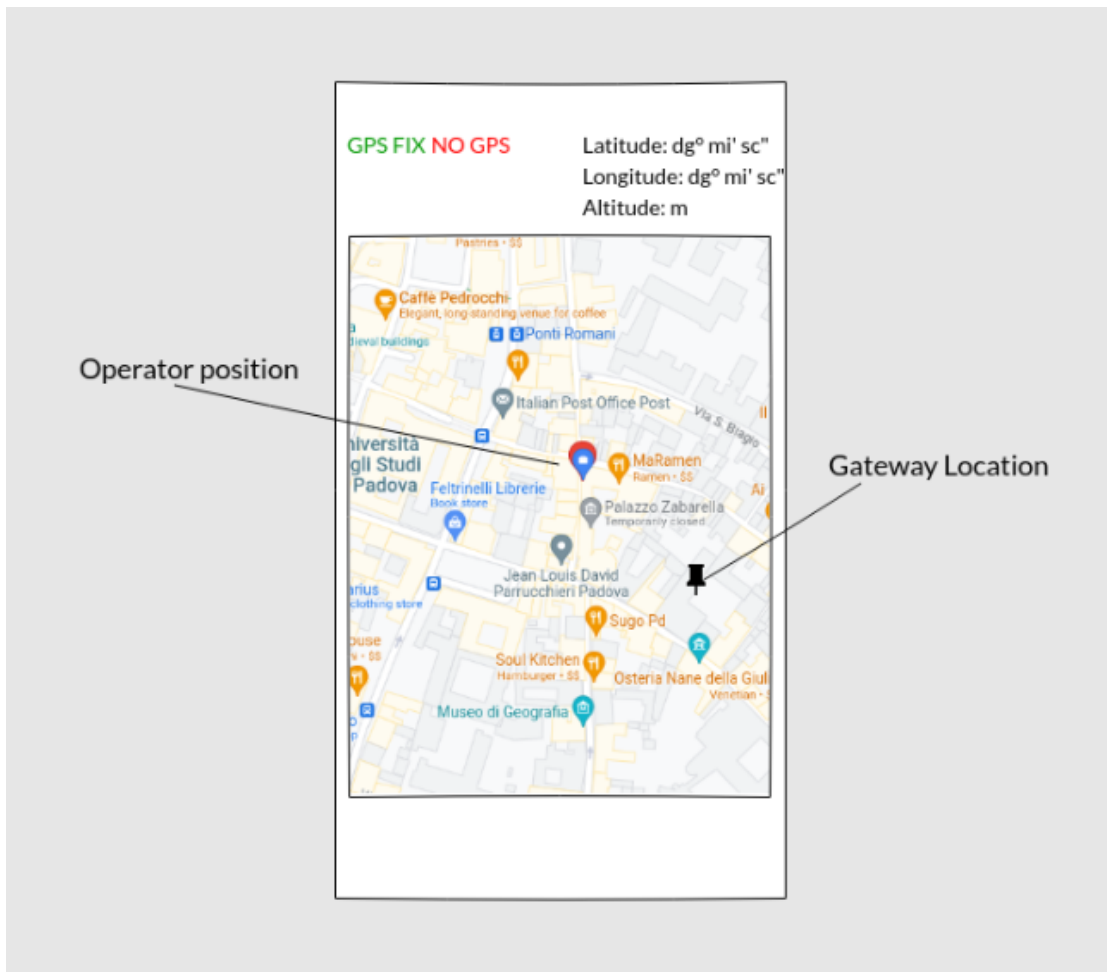


Figure 5.10: Mockup of Gateway List Page

As it is seen in figure 5.11 Main Page users can navigate to the Messages Page with the drawer navigator on the left top.

## 5.2. SITE SURVEY TOOL (SST) IMPLEMENTATION

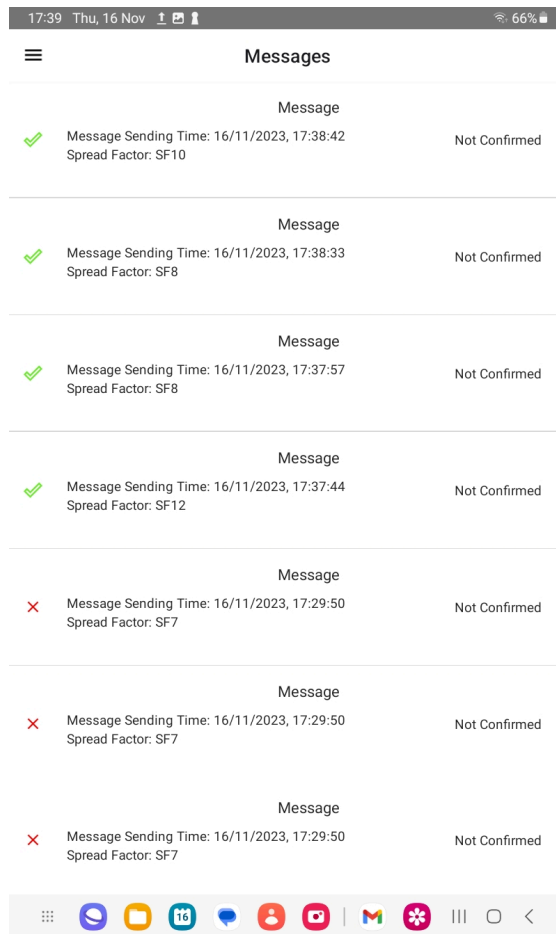


Figure 5.11: Messages Page

In this page the operator can see all messages that is sent. All messages are stored also in the database of the application just like messages. If an error occurred and the message sending process to the gateway resulted negatively there is a red cross icon otherwise there is a green tick icon on the left of every message item in the list.

### B. LoRaWAN SST HARDWARE

The LoRaWAN node is based on a Seeed studio LoRa-E5 Dev Board which is built on the STM32WLE5JC SoC.

The Wio-E5 Development Board incorporates the Wio-E5 STM32WLE5JC Module, offering compatibility with the LoRaWAN protocol across the global frequency band. In the open fields transmission range up to 10 km and it is designed with high sensitivity between -116.5 dBm -136 dBm [43].

In figure 5.12 LoRa node is shown:



Figure 5.12: LoRa Node

LoRa node is the main hardware for the project because it enables communication to probe with the gateway by using the LoRaWAN protocol.

## 5.2.2 SST SERVER

SST server is the backend part of software. While the application is for conducting surveys by operators there is a second part of the project which is for the admins. In the project there are two types of users; operators and admins. Admin is the person who assigns surveys to an operator according to user\_id and by this unique user\_id that every operator has one, operators can see surveys list that surveys assigned to them.

### A. THE ALTIOR PLATFORM FOR DIGITAL TWINS

Altior platform plays a crucial role in the integration of digital twins within this project. Digital twins are created for representation of LoRaWAN nodes and they mirror the physical devices. Digital twins provide monitoring and simulation. The platform ensures seamless communication between the physical nodes and their digital twins, facilitating the exchange of survey data and

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contributing to a more comprehensive understanding of network performance. SWaRM, a smart water metering application developed on Altior, Inkwell Data Ltd.'s digital twin platform. As the term itself implies, a digital twin can be broadly defined as a digital replica of a physical asset. From physical simulation to industrial processes models, digital twins are a way to prototype and evaluate the effectiveness of a digitalization strategy. Altior is a digital twin enabling technology created by Inkwell Data; it is designed with a focus on the domain of industrial IoT applications and services [44].

### B. SST CLIENT DIGITAL TWIN

While operators perform surveys via application in the backend part, the gateway receives a message from probe, then the message is forwarded to its digital twin. This digital twin carries out decryption and decoding by interfacing with Aegis for decryption and codec manager for deciding. After those processes the digital twin transmits message to Swarm via RabbitMQ which is the part messages waiting in the queue before arriving at Swarm.

Digital twin acts as a bridge between physical probe application and backend server, providing easier integration of survey data into the Swarm Messages database.

This digital twin architecture enhances the reliability and resilience of the surveying process, ensuring that data is efficiently managed and transmitted throughout the survey lifecycle.

### C. CREATING SURVEY

Admins can create and manage surveys in SwarmUI with a form. Form will contain survey name, device id, official start date and official end date fields to fill by admins. After admin creates survey it will be stored in Swarm Backend Server database and it will these fields:

- **Name:** the name of the survey
- **Device Id:** ID of the device which is used for surveying
- **Official Start Date:** Expected date to start survey
- **Official End Date:** Expected date to finish survey
- **Actual Start Date:** When operator actually starts the survey
- **Actual End Date:** When a survey actually ends



- **User Id:** Id of the user which assigned with the survey
- **Status:** Defines the status of the survey. Status can be 'created', 'downloaded', 'started', 'paused' and 'ended'. When the admin creates the survey status is indicated as 'created' by default.

In figure 5.13 it is shown the form for creating a survey on Swarm:

The screenshot displays the 'Create Survey' form within the Swarm web application. The interface features a dark blue header with the 'Swarm' logo and a user greeting 'Welcome Riccardo Degan'. A left-hand navigation menu lists various system components like Dashboard, Devices, Metering services, Surveys, Manage, Create survey, Digital Twins, Users, Groups, worklist, Districts, Gis, Alarms, Network, Data services, and Customer. The main content area is titled 'Create Survey' and contains several input fields: 'Name \*', 'Start date', 'End date', 'Device', and 'User'. A 'CREATE' button is positioned at the bottom right of the form. The footer of the page shows 'Version: 0.1.31' and 'Copyright © 2023 Inkwell Data Ltd'.

Figure 5.13: Create Survey Form on Swarm

#### D. SST DATA COLLECTION

Operators can see the list of surveys assigned to them and it is expected from the operator to choose a survey and conduct a survey respecting the official start date and official end date of the survey.

When the Survey Page opens on an android device with an internet connection on the android device all 'created' status are changed 'downloaded' automatically. Which means they are downloaded automatically to the local database of the device and surveys can be conducted even when there is no internet connection.

On the Surveys page when operator press start button status becomes 'started' and actual start date field filled by current time. Also as it is explained before, after pressing the start button Message Sending Page will appear and the operator starts moving around the survey's zone and sends messages using probe application.

On the Message Sending page the operator can manage survey: when operator

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pauses the survey status becomes 'paused', and when operator clicks end status becomes 'ended' and the actual end date field be filled with current time automatically as well.

Operator move around the defined zone for the survey and send messages to gateways by pressing 'Send Push' button. These messages contain information about the RSSI (Received Signal Strength Indicator) from the current location, as well as the name of the survey and the coordinates of the location from which the message is sent.

Probe sends message to the gateway in an encoded hex format for example:

```
1 Message Sent :  
2 41542b4d53474845583d847239303532343332383634393438303630313  
3 766743268793 46482fb4046b4094a2b9d3dfb4027c2223abd6b301a652f89bb
```

Code 5.7: Message Example in Hex Format

In the string format example for not confirmed message:

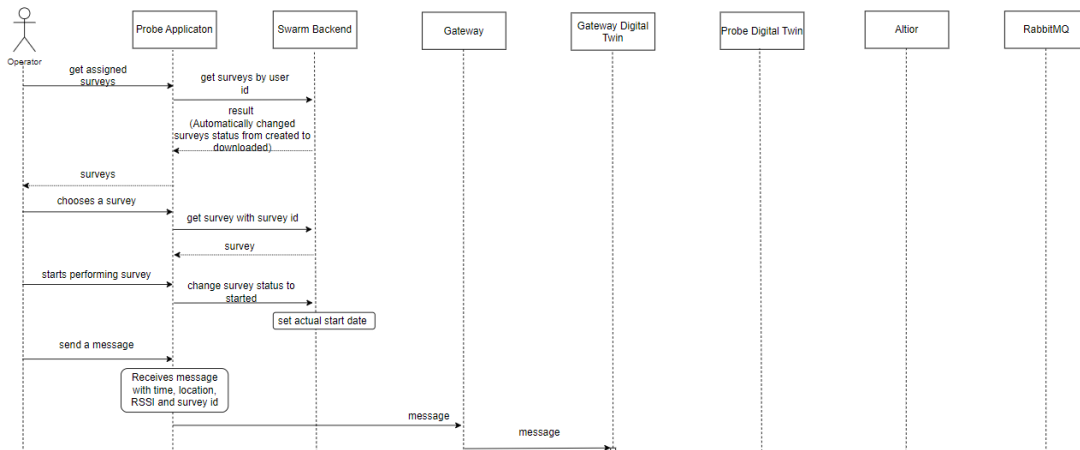
```
1 AT+MSGHEX=["905243286494806017", "34243", [45.4065335, 11.8791674], "  
2023-11-16T16:14:02.810Z"]
```

Code 5.8: Message Example in String Format

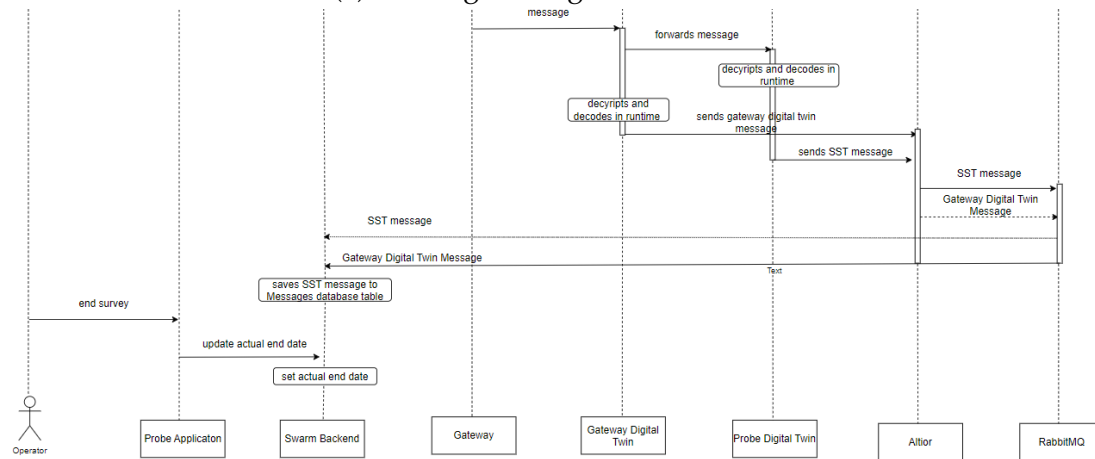
Message includes ids for survey and message, current location and current time. These information is put as a payload to AT command message.

Bringing together every component explained up to this point, the admin creates surveys for a decided zone on Swarm then the operator who is the user of the probe sees all the surveys from the application and conducts surveys which means collect data by sending messages to the gateways. For the case of there is no available gateway to receive messages from the probe application, messages are stored in android devices which can be seen by the user in Messages Page. When the device has internet connection messages are sent to the Altior. Since those messages are not received by any gateway they do not have RSSI value but only coordinates of the location from which the message is sent and the sending time. Survey results are stored in the Swarm Backend database which is accessible through Swarm UI.

Diagram in figure 5.16 describes the flow for message sending:



(a) Sending Message Process Part-I



(b) Sending Message Process Part-II

Figure 5.14: Sending Message Process

### E. SST DATA VISUALIZATION

Visualization of collecting data includes vital information for network designers. These outcomes enable them to analyze so that they can test coverage area and/or design networks by comparing results.

To be able to do that Swarm is serving a user friendly solution to the admins. The results will be seen via Swarm UI. Users can access a table with all the performed surveys, admin can choose one and see its results. Then a window opens including the name of the survey and a table with all the messages received from the probe application during surveying will appear. The table will have columns for the timestamp of the moment the message was sent to the gateway, the coordinates of the location where the RSSI value is obtained and the RSSI value itself (low values will be colored with green, middle values with

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orange and high values with red).

Retrieving survey results are filtered based on two criteria: device id and timestamp. All messages from the database which have the same device id as the one associated with the survey and messages that fall within a specific time range. This range is only messages with timestamps later than or equal to the survey's official start date and earlier than or equal to the survey's official end date are considered. This approach allows the same device to be used for multiple surveys. By filtering based on the device ID and timestamps associated with each survey, the system ensures that results are specific to each survey while maintaining the ability to use the same device for future surveys.

In summary, this process ensures that survey results are accurately retrieved and displayed by considering both the device ID and the timestamp range associated with a particular survey. It provides a systematic way to manage and present survey data while allowing for the reuse of devices for multiple surveys.



## Conclusion

In conclusion, this thesis has delved into the empirical verification of network coverage plans for LoRaWAN IoT infrastructures, with a particular focus on the development and implementation of a comprehensive test tool.

By examining the complexities of LoRa and LoRaWAN, including considerations such as chirp spread spectrum modulation, bandwidth, spreading factors, and code rate, it has laid a solid foundation for understanding the key elements that influence network performance.

Additionally, the exploration of network coverage planning, encompassing link budget analysis and radio frequency propagation models such as Okumura Hata, COST231, and Walfisch-Ikegami, has provided valuable insights into the complexities of ensuring robust and reliable LoRaWAN connectivity.

The test tool introduced here facilitates the collection of geo-located LoRaWAN messages, proving to be an invaluable resource for both pre- and post-installation site surveys. LoRaWAN-SST testing tool offers network planners a much better user experience than existing testing tools. Users can reach surveys and their android devices and configure LoRa devices on a big screen with a user-friendly UI and see message results on the device. Also digital twin technology enables real time monitoring of node behavior. Digital twins contribute to the optimization of the surveying project by allowing operators to simulate different scenarios and configurations. This can include evaluating the impact of changes in device placement, network parameters, or environmental conditions on data collection and signal strength. Optimization efforts can be informed by insights gained from digital twin simulations.

Moreover, the incorporation of digital twin technology through the Altior platform signifies a forward-looking approach to network planning and optimization. Future research endeavors may explore the full potential of digital twins in simulating and predicting network behavior, thereby aiding in the development of more robust coverage plans.

The method employed in this study can be extended to other LPWAN (Low Power Wide Area Network) technologies, such as wireless Meter-Bus (MBUS) adopted for smart metering operating at 169 MHz a European Union standard widely adopted for smart gas metering, shares key characteristics with the technology under consideration. Furthermore, this approach is adaptable for upcoming LPWAN technologies like Mioty [45] an LPWAN solution designed for industrial IoT applications. Its versatility makes it a valuable tool for optimizing a range of LPWAN deployments, keeping pace with the evolving IoT landscape.



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