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Empirical verification of network coverage plans for LoRaWAN IoT infrastructures

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*To every single one of you
who believed in the success
of this thesis,
Mariji,
a Giulia*

Abstract

In the domain of LoRa technology and LoRaWAN networks, various surveys have been conducted, each focusing on different facets. Two main types of site surveys are prominent: active site surveys and on-a-stick site surveys. The proposed Site Survey Tool, referred to as LoRaWAN-SST in this project, accommodates both these survey types. Active Site Survey involves actively sending messages to the gateway to collect data and assess the coverage area. This type of survey provides valuable insights into real-world conditions within the LoRaWAN network. On the other hand, on-a-stick site survey devices are placed on a stick and transmit messages, simulating coverage areas for the network.

While existing surveys mainly focus on determining the best path loss algorithm based on environmental conditions (urban or suburban), testing coverage areas, and evaluating gateway placements, the suggested LoRaWAN-SST stands out by not only supporting these purposes but also enabling the design of a new LoRaWAN network. This unique feature sets LoRaWAN-SST apart from other site survey tools.

The implementation of the LoRaWAN-SST is a large project and as such it was done as a team effort. I was a part of this team during my internship at the Inkwell Data company and was in charge of planning and developing the server side part of the software.

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List of Acronyms

IoT Internet of Things

LoRa Long range

LoRaWAN Long range wide area network

LPWAN Low power wide area network

DSO Distribution System Operators

GSM Global System for Mobile Communication

RSSI Record signal strength

SF Spreading factor

RF Radio frequency

Chirp Compressed High Intensity Radar Pulse

CSS Chirp Spread Spectrum

RTE Real time environment

ADR Adaptive Data Rate

HMI Holistic Metering Infrastructure

ANI Altior Network Interface

ACK Acknowledgement



Introduction

The industrial Internet of Things (IoT) has seen substantial growth in large critical infrastructures, particularly in public utilities such as energy, gas, and water distribution. This expansion is facilitated by the deployment of low-power, wide-area networks (LPWAN) operating in the unlicensed radio frequency spectrum (LPWAN-U), exemplified by technologies like LoRaWAN, Sigfox, or Weightless networks. These LPWANs empower distribution system operators (DSOs) to establish proprietary communication networks, specifically for advanced metering infrastructure (AMI).

In AMI implementations using LPWAN, a common approach involves star-topology networks, where a central data concentrator or gateway connects to multiple smart meters and sensors. The challenge arises in determining the optimal number and placement of gateways to effectively cover a vast number of smart meters. The AMI deployment process involves predicting the number and geographical locations of gateways, similar to wireless cellular networks. However, the unique nature of smart meter installations—whether outdoor, indoor, or below ground—requires careful consideration.

While DSOs may have existing assets like buildings or substations for gateway installation, achieving adequate coverage often necessitates different locations or a greater number of base stations than initially predicted. Consequently, the actual installation sites for gateways become a trade-off between the model predictions and the practical availability of installation sites.

This thesis aims to introduce a measurement tool that enables wireless network planners to assess the impact of diverse base station installation sites on the

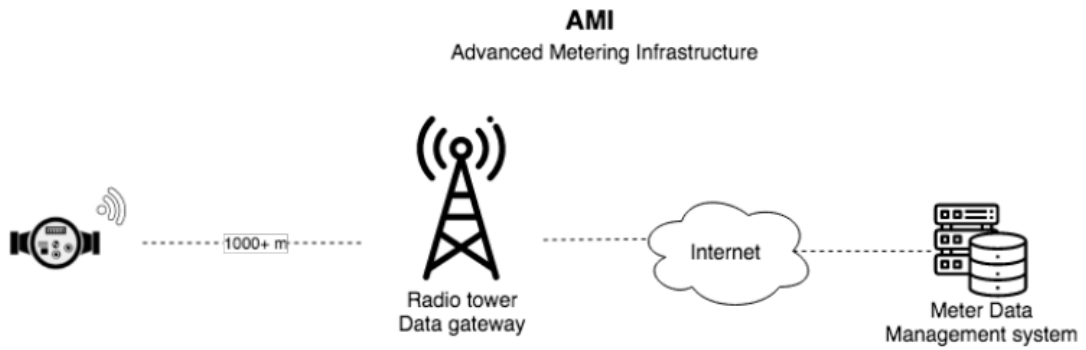


Figure 1.1: Advanced metering infrastructure [14]

overall performance of the AMI. The measurement process is embedded within a site survey procedure, where field-collected data are processed to create a digital twin of the LPWAN for optimizing AMI operations. This approach seeks to bridge the gap between predictive models and real-world conditions, offering a valuable tool for enhancing the efficiency and effectiveness of LPWAN-based AMI deployments.



LoRaWAN networks for IoT

In the evolving field of the Internet of Things (IoT), where billions of devices are connecting, communicating and generating data, efficient and long-range wireless communication is crucial. LoRaWAN (Long Range Wide Area Network) emerges as a go-to solution to address the connectivity challenges of IoT devices spread across wide geographic areas. Unlike traditional cellular networks, LoRaWAN offers low-power, long-range wireless communication that is specifically designed to satisfy the unique requirements of IoT applications. In this chapter, the fundamental principles and key features of LoRaWAN are presented, as well as the technology's architecture, deployment considerations and the versatility it offers for connecting an array of IoT devices.

2.1 LoRa

LoRa (long range) is a low-power WAN specified by the LoRa industry alliance. [29] It operates in the unlicensed spectrum on several bands starting from 169 to 430 MHz, with 868 MHz (Europe) and 915 MHz (North America) being the most common. Its range is on the order of 10 km in open areas and closer to 1 km in densely populated spaces such as cities. The bandwidth is up to 50 Kbps, depending on the distance and transmit power. Payload size is in the range of about 50 bytes to 250 bytes, depending on the frequency band. The network is effectively halfduplex, that is bidirectional communication but in only one direction at a time. Consequently, senders and receivers need to coordinate in taking directional turns. LoRa specification consists of PHY and

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MAC layers that can support applications with raw data or IP network layers above. [28]

LoRa specification consists of PHY and MAC layers that can support applications with raw data or IP network layers above. It defines three types of nodes:

- Bidirectional end devices (Class A) Each device uplink transmission is followed by the two short downlink receive windows. Low-power nodes, no downlink-initiated communication is supported.
- Bidirectional end devices with scheduled receive slots (Class B) In addition to Class A random receive windows, class B devices open extra receive windows at scheduled times.
- Bidirectional end devices with maximum receive slots (Class C) Have nearly continuously open receive windows, closed only when transmitting. Usually mains-powered devices, lowest latency for server to device communication.

LoRa uses spread spectrum modulation and supports an Adaptive Data Rate (ADR) algorithm that allows data rates on individual links to vary based on signal strength and radio power. Data rates can range between 0.3 and 27 Kbps. As indicated, Class A nodes can initiate communication with the server when desired only to collisions. However, communication latency from the server can be practically unbounded, as it depends on endpoints to initiate transmissions. Class B nodes rectify this somewhat, but their latency for opening a receive window can be on the order of 128256 s. Network topology is star of stars, with end nodes having direct link to radio gateways that use a back-end network to connect to LoRa WAN servers. Being a star with the gateway at the center, nodes can connect with the radio gateway directly and use it as an intermediary to exchange messages with other nodes. Radio gateway operates at the PHY layer only, forwarding messages to the server or other nodes as needed. [28]

A gateway is specified to be able to support thousands of nodes. MAC layer is terminated and processed by the LoRa WAN network server which is connected to the center of the star of stars topology. The network server is required in LoRa installations for MAC layer handling and other management purposes. Network server manages the network including the radio frequency and data rate of each endpoint by means of the ADR algorithm. It also performs frame and address checks and authentication, forwards message to application and joins servers. Those servers can host applications and manage network joins, respectively. [28]

A single network server can manage multiple LoRA gateways. A LoRA network can and often does include multiple gateways for extended and improved coverage. LoRA nodes do not have a fixed association with a gateway. Consequently, their messages may be received by more than one gateway. One of the functions of the network server is to detect and filter duplicates, check security and pick the optimal gateway to send acknowledgment.

The LoRa WAN protocol architecture is not based on the Internet network layering. LoRa applications can exchange data with endpoints in raw format with no intervening translations. This, of course, requires advanced knowledge of the endpoint data formats and requires custom coding for each individual type of data source that a destination needs to support. Alternatively, application protocol stacks, such as ZigBee or CoAP, can be layered on the network server or an intermediary and used for data structuring and interoperability with a broader range of devices. [28]

LoRa supports roaming with the use of home server and defined handoff procedures. Devices can be activated by personalization and via over-the-air (OTA) activation that can also deactivate decommissioned or compromised devices. The specification includes definitions of device commissioning and activation procedures. LoRa networks provide security at the MAC layer that achieves endpoint authentication via the network server. In addition, LoRa WAN packets are protected by symmetric encryption based on AES. The LoRa alliance provides certification to insure cross-vendor interoperability. [28]

LoRa has revolutionized IoT by enabling data communication over a long range while using very little power. Networks with LoRa, such as those leveraging the LoRaWAN standard, fill the technology gap of Cellular, Wi-Fi and Bluetooth Low Energy (BLE) networks that require either high bandwidth or high power, or have a limited range or inability to penetrate deep indoor environments. In effect, LoRa devices and the LoRaWAN standard are flexible for rural or indoor use cases in a wide range of industries including smart cities, homes and buildings, communities, agriculture, metering and utilities, healthcare, environment and supply chain and logistics. Figure 2.1 depicts the comparison of LoRa with other wireless technologies.

2.1. LORA

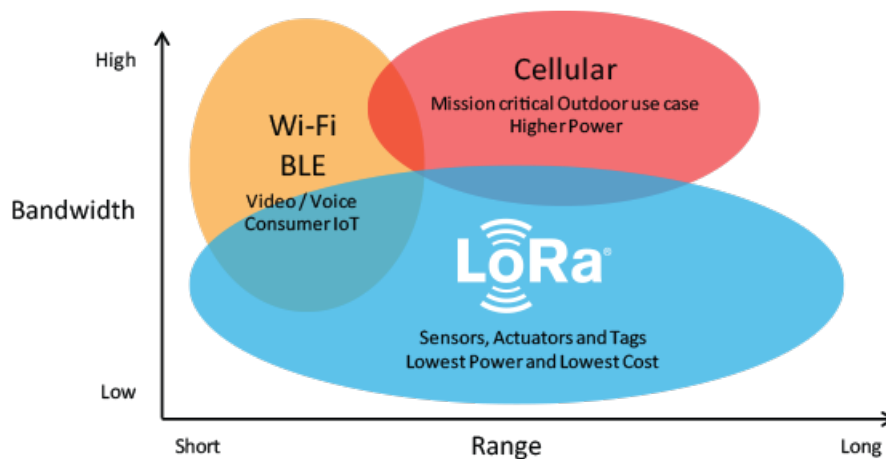


Figure 2.1: Comparison of LoRa with other wireless technologies [1]

2.1.1 CHIRP SPREAD SPECTRUM MODULATION SCHEME

Chirp stands for 'Compressed High Intensity Radar Pulse'. It is a signal which frequency either increase or decrease with time. It is also used in spread spectrum. [2]

Chirp Spread Spectrum (CSS), is a long-range radio-frequency technology for wireless communication that can be leveraged to detect and track the location of people, assets and devices both in and outdoors, across large-scale facilities. Its long-range performance with high-reliability, strong resistance to radio interference and low-power consumption, make chirp uniquely suited for applications in large, noisy environments, like industrial facilities. Like other communication protocols including UWB and Bluetooth, chirp can be used to transmit data between devices through radio waves. It does so by using a wide band modulation technique, that creates linear frequency modulated signals also known as chirps. [3]

LoRa uses 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., 0.018 37.5 kbps) to gateways several or even tens of kilometers away (5 15 km). Users and developers can follow the technical specification to customize their own LoRa networks for application demand and academic purposes in various ways. [23]

Chirp Spread Spectrum modulation offers unique advantages for specific applications, particularly in IoT deployments where long-range, low-power com-

munication is essential. However, it also presents challenges related to complexity, bandwidth usage and synchronization that need to be addressed when designing and deploying CSS-based systems. Careful consideration of the specific use case and environmental factors is crucial to leverage the benefits of CSS effectively.

2.1.2 WIRELESS COMMUNICATION PARAMETERS IN LoRa NETWORKS

LoRa (Long Range) modulation, modulation has parameters in the PHY (physical) layer, it offers flexibility in terms of bandwidth, spreading factors and code rates. These parameters can be adjusted to meet the requirements of specific use cases and network conditions. LoRa devices can be configured with several parameters and these parameters are important for optimization.

The following paragraph gives an overview of LoRa bandwidth, spreading factors and code rates and RSSI:

Bandwidth: LoRa allows for the selection of different bandwidth options, typically ranging from 125 kHz to 500 kHz. The choice of bandwidth directly impacts the data rate and signal robustness. Smaller bandwidths (e.g. 125 kHz) provide longer communication range but result in lower data rates. Larger bandwidths (e.g. 500 kHz) can achieve higher data rates but may sacrifice range and are more susceptible to interference.

Spreading Factors:

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. For every increase in spreading factor, the chirp sweep rate is halved and so the data transmission rate is halved. [4]

LoRa offers a range of spreading factors, typically from SF7 (fastest data rate, shortest range) to SF12 (slowest data rate, longest range).

2.1. LORA

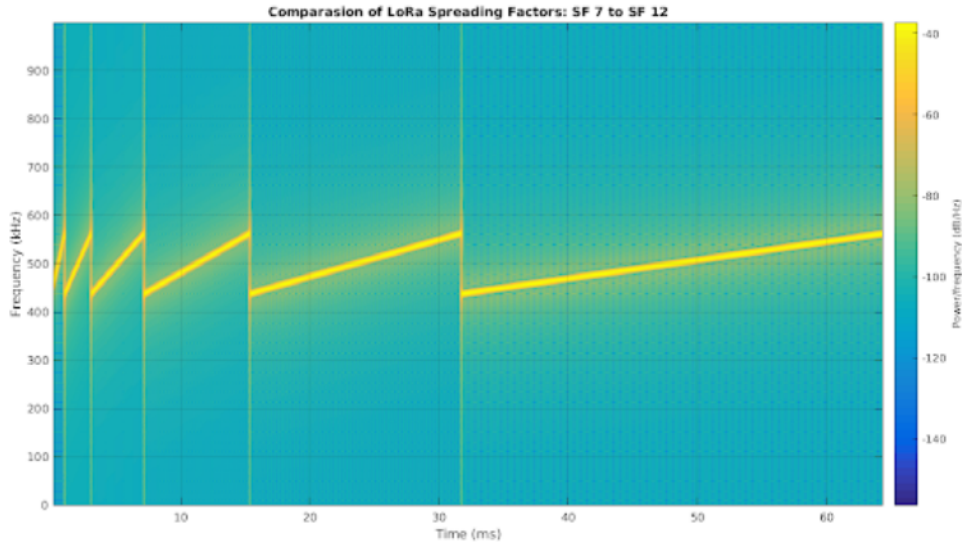


Figure 2.2: LoRa modulation simulation with different SF [32]

Figure 2.2 illustrates the time that takes to transmit a symbol from SF7 to SF 12 with bandwidth equals to 125kHz. The higher the SF, the longer the time-on-air. [32]

Lower spreading factors reduce the range of LoRa transmissions, because they reduce the processing gain and increase the bit rate. Changing spreading factor allows the network to increase or decrease data rate for each end device at the cost of range. 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. [4]

Code Rate: Code rate, also known as coding rate or error correction rate, refers to the amount of error correction used in LoRa transmissions. In LoRaWAN, code rates typically include $4/5$, $4/6$, $4/7$ and $4/8$, representing the ratio of error-correcting code bits to total bits transmitted. Higher code rates (e.g., $4/8$) provide stronger error correction but result in lower usable data rates. Lower code rates (e.g., $4/5$) offer higher data rates but provide less error correction.

LoRa technology offers flexibility in configuring bandwidth, spreading factors and code rates to adapt to specific IoT use cases and network conditions. This flexibility allows network planners to strike a balance between communication range, data rate and robustness, depending on the requirements of their

applications. The choice of these parameters should consider factors such as coverage area, desired data throughput and susceptibility to interference.

Received Signal Strength Indicator:

The RSSI is an indication of the power level being received by the antenna: higher is the RSSI level, stronger is the radio signal and then closer is the destination. Generally, radio component reports the current RSSI value each time a valid packet is received. [21]

Two main categories of RSSI-based techniques are introduced: range-free and range-based, with a subsequent discussion on the limitations of RSSI.

RSSI-based and Range-free Protocols:

Range-free algorithms do not estimate distances between sensors, instead, connectivity information to identify nodes within radio range and estimate their positions. One specific category of range-free techniques involves RSSI profiling [13]. These algorithms create an RSSI map within the deployment area, obtained either offline through measurements or online using dedicated sensors (sniffers) strategically placed at known locations. Each entity, whether a non-sniffer or non-anchor, measures the received signal strength from each anchor and provides a vector sort of "fingerprint." This fingerprint is then compared to the map to determine the sensor's position.

RSSI and Range-based Protocols:

The range-based protocols use RSSI as a distance metric. According to this distance estimation, they generally try to determine node position.

A common position estimation method uses the multilateration. From the estimated distances d_i between unknown position of the node $(x;y;z)$ and known positions of the anchors $(x_i;y_i;z_i)$ we derive the following system of equations:[21]

$$\left\{ \begin{array}{l} (x_1 - x)^2 + (y_1 - y)^2 + (z_1 - z)^2 = d_1^2 \\ \vdots \\ (x_n - x)^2 + (y_n - y)^2 + (z_n - z)^2 = d_n^2 \end{array} \right\}$$

RSSI Limitations:

Mapping RSSI to Distance Challenge: Difficulties arise in establishing a reliable relationship between RSSI and distance due to path loss, fading and

2.2. LORAWAN

shadowing effects.

Path Loss: Represents the reduction in power density of an electromagnetic wave as it propagates, influenced by the path loss exponent.

Fading: Deviation in signal attenuation influenced by geographical position, time and radio frequency, often modeled as a random process. Multiple frequencies may be measured to reduce fading effects.

Shadowing: Loss of signal due to obstacles between a transmitter and a receiver. Shadowing induced by obstacles can create unpredictable variations, requiring measures such as frequency averaging to mitigate these effects.

RSSI-based techniques play an important role in localization, with range-free and range-based protocols addressing different aspects of position estimation. However, challenges exist in accurately mapping RSSI to distance due to path loss, fading and shadowing phenomena.

2.2 LoRaWAN

LoRaWAN, or Long Range Wide Area Network, stands at the forefront of IoT connectivity solutions. It offers a unique blend of long-range wireless communication, low power consumption and scalability, making it an ideal choice for a diverse range of IoT applications. In this chapter, the fundamental principles, capabilities and real-world applications of LoRaWAN technology are explored.

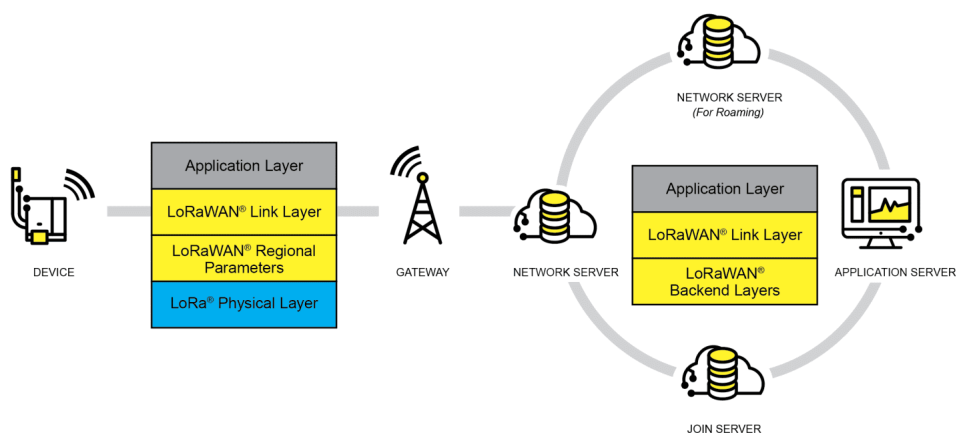


Figure 2.3: LoRaWAN network architecture [5]

LoRaWAN (Long Range Wide Area Network) is a popular protocol built on

top of LoRa technology that defines the communication standards and network architecture for deploying LoRa networks. LoRaWAN enables secure and scalable IoT deployments by providing standardized communication between LoRa devices and network gateways. Overall, LoRa technology plays a crucial role in enabling long-range, low-power connectivity for IoT devices, making it the best choice for IoT deployments with extended coverage requirements and power constraints.

2.2.1 NETWORK TOPOLOGY

LoRaWAN (Long Range Wide Area Network) networks typically employ a star-of-stars network topology (figure 2.4). In this network topology, IoT devices (nodes) communicate with gateways (also known as base stations) and gateways forward the data to a centralized network server.

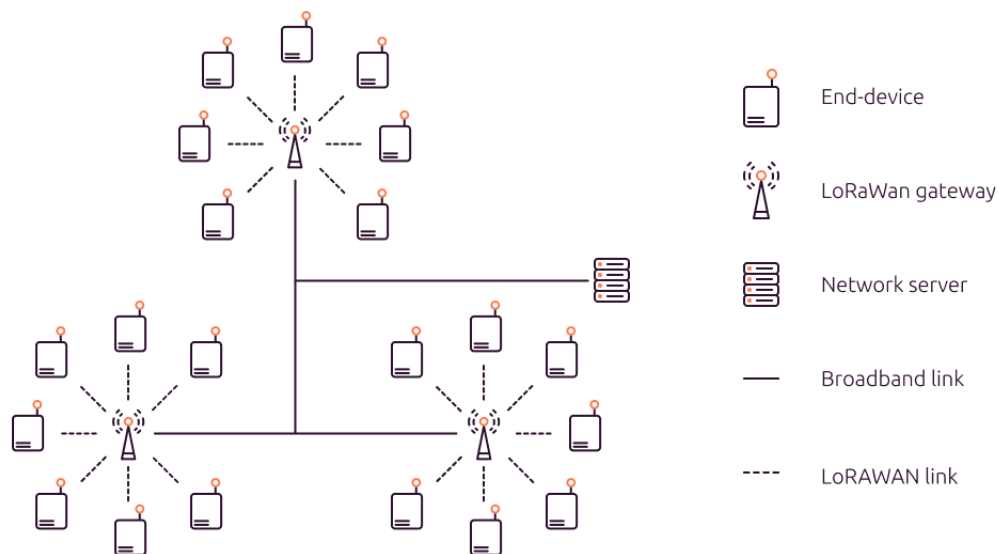


Figure 2.4: LoRaWan Star of Star Topology [6]

COMPONENTS OF THE LORAWAN NETWORK TOPOLOGY:

IoT Devices (Nodes): These are the end devices in the LoRaWAN network. IoT devices can be sensors, actuators, or any other smart devices that need to transmit data to and receive data from the network. Each IoT device is equipped with a LoRa radio module and typically operates on low power.

2.2. LORAWAN

Gateways (Base Stations): Gateways serve as intermediaries between IoT devices and the network server. They receive data transmitted by nearby IoT devices and relay that data to the network server. Gateways are usually connected to the internet via wired or wireless connections. Depending on the network's coverage requirements, multiple gateways may be deployed across an area.

Network Server: The network server is a central component of the LoRaWAN network. It manages the communication between IoT devices and applications. When data is received from gateways, the network server routes the data to the appropriate application server or application within the IoT ecosystem.

Application Server: Application servers process and analyze data received from IoT devices. They enable various IoT applications by interpreting sensor data, triggering actions, or providing data insights. Application servers can be cloud-based or on-premises, depending on the deployment.

Bidirectional Communication: LoRaWAN supports bidirectional communication, allowing IoT devices to both transmit data to the network and receive commands or configuration updates from the network. This bidirectional capability is essential for many IoT applications.

Device Classes: LoRa specification consists of PHY and MAC layers that can support applications with raw data or IP network layers above. It defines three types of nodes(class A, B and C) as mentioned before.

LoRaWAN networks implement robust security mechanisms to ensure data privacy and device authentication. IoT devices are typically provisioned and activated securely within the network to prevent unauthorized access. LoRaWAN networks are highly scalable and can support a large number of IoT devices within a single network. This scalability makes it suitable for applications with varying device densities.

The star-of-stars network topology of LoRaWAN provides a simple and efficient means of connecting a multitude of IoT devices over long distances while optimizing power consumption and network management. This topology is well-suited for various IoT applications, including smart cities, agriculture, asset tracking and environmental monitoring.



Network coverage planning

In the realm of telecommunications, effective network planning is essential to ensuring optimal coverage and quality of service. The coverage plan is tied to geographical and environmental factors, including terrain type and the urban, suburban, or rural nature of the area under consideration.

A very important concept in network planning is "location probability" representing the likelihood of achieving a signal strength higher than the sensitivity threshold in the target area. This prediction relies on radio propagation models, which can either be standardized based on general characteristics of the designated network area or personalized for increased accuracy. While standard models offer cost and time efficiency, personalized models provide a higher level of precision.

To predict coverage areas effectively, network planners employ propagation models, conduct drive tests, and establish correction factors. Standard models, though less accurate, are widely adopted due to their efficiency. Conversely, personalized models demand more resources but offer a custom approach to network planning.

For optimal GSM signal coverage, network planners often use both omnidirectional and sector antennas. The deployment of antennas results in the creation of radio cells, with the distance between antennas requiring careful consideration. Proximity between antennas requires strategic planning to avoid overlap, which can escalate deployment costs. Conversely, excessive spacing may lead to coverage gaps in the GSM network.

Efficient network planning is a delicate balance between utilizing standard-

3.1. LINK BUDGET

ized models for cost-effectiveness and investing in personalized models for enhanced accuracy. The deployment of antennas, guided by considerations of distance and coverage, plays a crucial role in achieving an optimal GSM signal footprint.

3.1 LINK BUDGET

On coverage planning, parameters such as antenna, power transmit, the power received, loss, and receiver sensitivity are the strong points. These parameters are needed to calculate the Link Budget value in order to obtain the maximum range of gateway and the number of gateways needed. [31]

Link Budget calculation is crucial in a wireless radio planning. Link Budget needs to know the estimated loss that will happen when signals propagate from transmitter to receiver. An accurate and comprehensive model is essential to predict the power transmitter and receiver sensitivity needed [17].

Link Budget calculation is for uplink and downlink. The formula for Link Budget can be written, as follows. [31]

$$Prx = Ptx + Gtx + Grx - Loss \quad (6)$$

Where:

- Prx = Received Power (dBm)
- Ptx = Transmitted Power (dBm)
- Gtx = Transmitter Gain (dBi)
- Grx = Receiver Gain (dBi)

3.2 RADIO FREQUENCY PROPAGATION MODELS

Empirical radio propagation models [19] build the ability to predict the received signal strength on the field measurement data and statistical analysis.

These models provide researchers and wireless network operators with the capability to estimate and analyze network coverage, allowing for a comprehensive understanding of radio wave propagation parameters and aiding in the

strategic planning of network deployment. The site-specific nature of propagation effects, influenced by factors like terrain, operating frequency, and antenna height, underscores the importance of accurate channel characterization using fundamental parameters and statistical models.

3.2.1 THE HATA-OKUMURA MODEL

The Hata-Okumura Model (Hata 1981 & Neskovic et al. 2000), incorporates the graphical information from the Okumura Model (Okumura et al. 1968). The Hata Model for Urban Areas (also known as the Okumura-Hata model), is a widely used propagation model for predicting path loss in urban areas. [16]

This model is a comprehensive propagation model that incorporates the impact of diffraction, reflection, and scattering induced by urban structures. Specifically designed for urban environments, this model offers formulations to predict path loss in both Suburban and Open Areas, providing a versatile tool for estimating signal strength in diverse scenarios.

The parameters for Hata Model for Urban Areas are following :

- *Frequency Range*: 150 MHz to 1500 MHz
- *Transmitter Height*:: 30 m to 200 m
- *Link distance*:: 1 km to 20 km
- *Mobile Station (MS) height*:: 1 m to 10 m

Hata Model for Urban Areas is formulated as:

$$L_U = 69.55 + 16.16 \log(f) - 13.82 \log(h_B) - C_H + (44.9 - 6.55 \log(h_B) \log(d)) \quad (1)$$

For small or medium sized cities (where the mobile antenna height is not more than 10 meters),

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

For large cities,

for frequencies 150 MHz $\leq f \leq$ 200 MHz

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

3.2. RADIO FREQUENCY PROPAGATION MODELS

for frequencies 200 MHz $\leq f \leq$ 1500 MHz

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

- 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 = Frequency of Transmission in megahertz (MHz)
- C_H = Antenna height correction
- d = Distance between the base and mobile stations in kilometers (km)

The Hata Model for Suburban Areas is a commonly utilized method for predicting path loss in areas situated on the outskirts of cities or in other rural locations where man-made structures exist but are not as high and densely packed as in urban settings. This model is an extension of the Hata Model for Urban Areas, incorporating the median path loss observed in urban environments. It provides a useful framework for estimating path loss in suburban scenarios with varying characteristics from densely populated urban areas.

The equation for Suburban Areas is formulated as:

$$L_{SU} = L_U - 2(\log f / 2B)^2 - 5.4$$

Where,

- L_{SU} = Path loss in suburban areas in decibels (dB)
- L_U = Average Path loss in urban areas in decibels (dB)
- L_U = Average Path loss in urban areas in decibels (dB)

The Hata Model for open areas predicts path loss in open areas where no obstructions block the transmission link. This model is suited for both point-to-point and broadcast transmissions. Hata model for open areas is formulated as,

$$L_O = L_U - 4.78(\log(f))^2 + 18.33\log(f) - 40.94$$

Where,

- L_O = Path loss in open area. Unit: (dB)

- LU = Path loss in urban area. Unit: decibel (dB)
- f = Frequency of transmission. Unit: (MHz)

As the height of the transmitter and the receiver is measured relative to the ground, an effective Tx antenna height (h_{eff}) is determined to account for the topographical impact. The transmitter antenna height above ground H_b , used in both the formulas of the Okumura-Hata propagation model and in the formulas of the Extended Hata model, is equal to h_{tx} if $h_{eff} \leq h_{tx}$, and is equal to h_{eff} if $h_{eff} > h_{tx}$. This improves the accuracy of the prediction. Figure 3.1 depicts effective antenna height for the Okumura-Hata propagation model.[7]

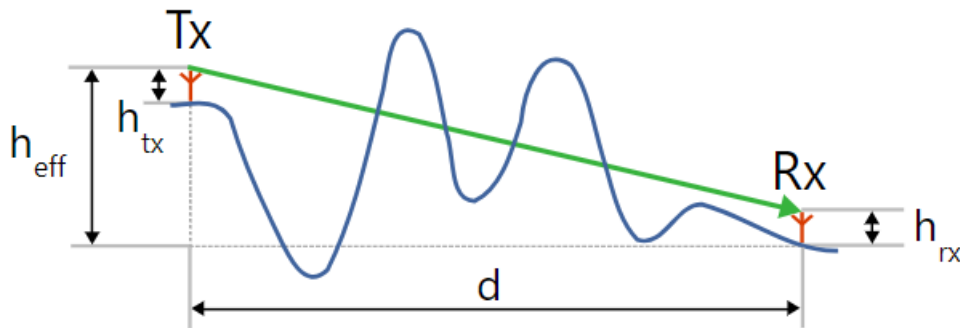


Figure 3.1: Effective antenna height for the Okumura-Hata propagation model [7]

3.2.2 COST-231 HATA PROPAGATION MODEL

COST 231-Hata-Model is an extension of Hata model to cover a wider range of frequency band. The models path loss prediction is based on the basic system parameters ranging between 1500-2000 MHz for frequency, 1-20 km for distance, and 1-10 m and 30-200 m for end-device and gateway antenna height respectively. The mathematical formulae for various application of this model are [20]:

$$P_{Loss} = 46.3 + 33.9 \log_{10}(f) - 13.82 \log_{10}(h_b) - a h_m + (44.9 - 6.55 \log_{10}(h_b)) \log_{10}(d) + c_m \quad (3)$$

where, f is operating frequency in MHz, d is distance between the end-device and gateway in km. h_r and h_m are antenna height above the ground in meters for the gateway and end-device respectively. The variable c_m equals 0 dB for

3.2. RADIO FREQUENCY PROPAGATION MODELS

both suburban and open environments or 3 dB in urban areas. The variable ah_m for urban areas is defined [26] as:

$$ah_m = 3.20(\log_{10}(11.75h_r))^2 - 4.97, \text{ for } f > 400\text{MHz} \quad (4)$$

and as below for sub-urban or rural areas:

$$ah_m = (1.1\log_{10}f - 0.7) h_r - (1.56\log_{10}f - 0.8) \quad (5)$$

3.2.3 COST-231 WALFISH-IKEGAMI

Abbreviated as COST-WI [18], the model is a compound of Walfish and Ikegami models, and improves the path loss prediction through the consideration of more data to characterise large and medium-sized urban environments [27], that is, the buildings heights h_{Roof} , the widths of roads w , the separation between buildings b , and the angle with respect to the direct radio path. The range of fundamental parameters considered are between 800-2000 MHz for frequency, 0.02-5 km for distance, 1-3 m and 4-50 m for end-device and gateway antenna height respectively. The model makes a difference between the line-of-sight (LOS) and non-line-of-sight (NLOS) [22] and the mathematical formulae for both cases are defined in (6) and (7) below. If there exists a LOS in the street, the path loss is defined as:[20]

$$P_{\text{Loss}} = 42.64 + 26\log_{10}(d) + 20\log_{10}(f) \quad (6)$$

In the case of NLOS, the path loss is defined as a combination of path loss due to free space L_o , the rooftop to street diffraction and the scatter L_{rts} , and the multiple screen diffraction loss L_{msd} . This path loss totality is mathematically described as follows [27]:

$$P_{\text{Loss}} = L_o + L_{\text{rts}} + L_{\text{msd}} \quad (7)$$

where: L_o , the attenuation due to free space is given as:

$$P_{\text{Loss}} = 32.45 + 20\log_{10}(d) + 20\log_{10}(f) \quad (8)$$

L_{rts} , the diffraction loss from the rooftop to street is determined as in the following formula:

$$L_{rts} = -16.9 - 10\log_{10}(w) + 10\log_{10}(f) + 20\log_{10}(h_b - h_r) + Lori. \quad (9)$$

Here, w is width of the roads, h_b and h_m are the height of building and end-device mobile station respectively. The street orientation correction factor, $Lori$ [30] is given as:

$$L_{ori} = \begin{cases} -10 + 0.35\alpha & \text{for } 0^\circ < \alpha < 35^\circ \\ 2.5 + 0.0755(\alpha - 35) & \text{for } 35^\circ < \alpha < 55^\circ \\ 4 - 0.0114(\alpha - 55) & \text{for } 55^\circ < \alpha < 90^\circ \end{cases} \quad (10)$$

where α is the street orientation angle. L_{msd} , the multi-screen loss, represent diffraction loss from multiple obstacles and it is determined by the following mathematical representation:

$$L_{msd} = L_{bsh} + K_a + K_d \log_{10}(d) + k_f \log(f) - 9 \log_{10}(s_b) \quad (11)$$

where: the correction factors, L_{bsh} and k_a represent path loss when the gateway is above and below the rooftops respectively. The terms k_d and k_f quantify the diffraction loss as a factor of the distance and frequency, and are defined in [15] as follows:

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

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

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

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

3.2. RADIO FREQUENCY PROPAGATION MODELS

3.2.4 LONGLEY-RICE MODEL

Also known as Irregular Terrain Model (ITM). This model seems to be the most widely used. The Longley-Rice model is designed for the calculation of the radio coverage over a heterogeneous landscape. It is claimed that this model works at frequencies up to 20 GHz and distances up to 2000 km. It can be used to calculate the attenuation both at a single point and in a given area. The arbitrary profile of the Earth's surface landscape and the effects of the over-the-horizon propagation can be taken into account within this model. Geometric optics and Fresnel-Kirchhoff diffraction theory are used for the calculation. There are modifications of this method for calculation of the field over the urban areas. [25]

4

LoRaWAN network planning

LoRaWAN network planning involves the strategic design and deployment of LoRaWAN infrastructure to ensure reliable, efficient, and cost-effective connectivity for Internet of Things (IoT) devices. Proper network planning is important for achieving optimal coverage, capacity, and performance in LoRaWAN deployments.

When planning LoRaWAN networks, factors such as coverage area, data rate, latency, and device density need to be considered. To optimize the network plan, planners turn to research performed by a site survey to assess the physical environment where the LoRaWAN network will be deployed. Using this approach, planners are able to identify potential obstacles, interference sources, and suitable locations for gateways.

Coverage analysis tools can be used to predict the expected signal coverage and evaluate whether additional gateways are needed to achieve the desired coverage.

Gateways should be strategically placed to ensure adequate signal coverage and minimize coverage gaps with factors such as gateway height, antenna placement, and line-of-sight to optimize gateway performance taken into consideration. Frequency band and channel allocation need to be based on regional regulations and available spectrum. Urban environments may require more gateways compared to rural areas, thus density based on the coverage area should be calculated.

To protect data transmitted over the LoRaWAN network, it is important to implement strong security measures, including device authentication and

4.1. LORAWAN NETWORK PLANNING TOOLS

encryption.

LoRaWAN network planning requires careful consideration of technical, logistical, and regulatory factors. By following these steps and conducting thorough planning, organizations can deploy LoRaWAN networks that provide reliable and efficient connectivity for their IoT applications, whether in smart cities, agriculture, industrial automation, or other use cases.

4.1 LORAWAN NETWORK PLANNING TOOLS

Network planning tools are essential software applications designed to facilitate the strategic design, analysis, and optimization of communication networks. These tools play an important role in ensuring the efficient deployment and performance of networks, including wireless networks like LoRaWAN. Network planning tools are used to predict signal strength, quality, identify areas with interference or obstacles, analyse terrain, buildings, and obstacles that may impact signal propagation, determine optimal frequency bands and channel allocations, consider factors such as gateway height, antenna placement, ensure network capacity to handle device traffic

Many other parameters can be discovered using these tools when developing a network. Network planning tools vary in features and capabilities, ranging from open-source solutions to commercial software. The choice of a specific tool depends on the requirements, scale, and complexity of the network deployment. Primary difference between open source and commercial tools for network planning lies in their licensing, cost structure, and accessibility.

Open source tools are released with licenses that allow users to view, modify and distribute the source code freely, while commercial tools typically have proprietary licenses. Users are usually restricted from viewing or modifying the source code, which is not the case with open source tools.

Open source tools can be highly customizable, and users can adapt them to specific requirements. However, the range of features may vary. On the other hand, commercial tools often come with a wide set of features and may integrate seamlessly with other tools or platforms.

The network planning tool used for exploration into network coverage planning is CloudRF, it is one of the commercial tools that offers a free plan. It provides coverage mapping with provided values for parameters.

Some important parameters are:

- *Coordinates*: Represents the coordinates of the base stations location. The provided coordinates for the following examples are the Inkwell Data company's address, Via Zabarella 24, Padova, where the gateway is located.
- *Height AGL (Height Above Ground)*: Represents the height of the gateway from ground level, for our gateway this value is 10m.
- *Bandwidth*: Represents the bandwidth value, for the following examples it is set to 125 KHz.
- *RF Power*: The EU regulations mandate RF power for 868 MHz frequency to be limited to 14 dBm.
- *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 the 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 regio where the ISM (Industrial, Scientific, Medical) radio spectrum is defined by the ETSI 307 standard. [8]

Duty cycle resembles a traffic rule for devices in the LoRaWAN network. It's about how much time a device can talk or listen within a certain time period. In LoRaWAN, the rule is that a device can only be active (sending or receiving signals) for 1% of the time. This rule helps prevent too many devices from talking at the same time, which could cause problems.

In laymen terms, it is like giving each device a limited time to speak so that there's no traffic jam in the network. Different frequency bands, like 433 MHz or 863 MHz, have different uses. For example, 433 MHz is often used for short-range devices like remote controls, while 863 MHz is more common for various IoT devices. The 863 MHz band also allows for faster data transfer compared to the lower frequency band.

LoRaWAN end devices and the device used in 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%. [9]

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. However, for testing Longley-Rice models coverage map will be accounted for.

4.1. LORAWAN NETWORK PLANNING TOOLS



Figure 4.1: Coverage Map with Hata Okumura SF7

The figure 4.1 shows network coverage map with Okumura-Hata propagation model with spreading factor SF7.



Figure 4.2: Coverage Map with Hata Okumura SF12

The figure 4.2 shows network coverage map with Okumura-Hata propagation model with spreading factor SF12.



Figure 4.3: Coverage Map with COST-321 SF7

The figure 4.3 shows network coverage map with COST-321 propagation model with spreading factor SF7.



Figure 4.4: Coverage Map with COST-321 SF12

The figure 4.4 shows network coverage map with COST-321 propagation model with spreading factor SF12.

The spreading factor of 12 results in a wider covered area, however it produces a weaker signal for both the Hata Okumura and COST-321 propagation models.

4.1. LORAWAN NETWORK PLANNING TOOLS

The figure 4.5 shows network coverage map with Longley-Rice propagation model with spreading factor SF7.



Figure 4.5: Coverage Map with Longley-Rice model SF7

The figure 4.6 shows network coverage map with Longley-Rice propagation model with spreading factor SF12.

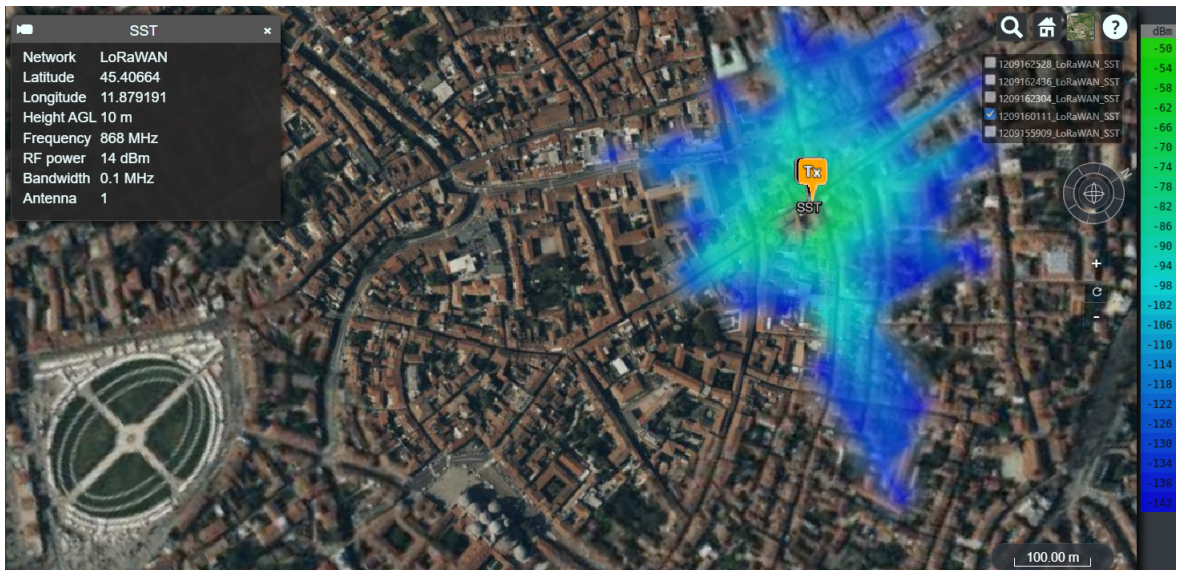


Figure 4.6: Coverage Map with Longley-Rice model SF12

4.2 GATEWAY PLACEMENT AND DEVICE CONFIGURATION

GATEWAY PLACEMENT

Gateway placement and device configuration are critical aspects of LoRaWAN network planning. Properly planned placement of gateways and configured IoT devices are essential to ensure reliable and efficient communication within a LoRaWAN network.

Finding the ideal placement for gateways is very important for optimizing the performance of a LoRaWAN network. The coverage area and interference levels are directly impacted by the strategic positioning of gateways.

In a LoRaWAN network, end-devices broadcast messages, and gateways listen for these transmissions. The actual transmissions occur when the signal strength received at the gateway surpasses a specified minimum threshold known as the Received Signal Strength Indicator (RSSI) [31]. Upon receiving the data, the gateway decodes it and forwards it to the network server over the internet. Successful decoding requires the received signal strength to meet or exceed a parameter known as Receiver Sensitivity.

The LoRaWAN site survey tool is an indispensable asset for estimating the accuracy of the coverage map before gateway installation. This tool allows network planners to test RSSI values before finalizing gateway locations. In this way, planners gain insights into signal strengths, enabling informed decisions about optimal gateway placement for maximizing coverage and minimizing interference.

For the purpose of the project, a gateway is installed in the office of the Inkwell Data company. Coordinates of the gateway are: latitude 45.406524, longitude 11.879232.

DEVICE CONFIGURATION

In this project, device configuration implies configuring LoRaWAN devices (LoRaWAN nodes) by setting the parameters to communicate with the LoRaWAN network. The first step is configuring the LoRaWAN node with the parameters to join the LoRaWAN network and the second step is setting parameters that allow the LoRaWAN node to transmit messages in the network. In the project, the LoRaWAN node is based on a Seeed studio LoRa-E5 Dev Board shown in 5.3.

4.2. GATEWAY PLACEMENT AND DEVICE CONFIGURATION

Commands used for its configuration are text-based LoRaWAN AT commands. These commands are utilized for the configuration of parameters, joining the network and 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 for reading DevAddr

AT command to change DevAddr: ,

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

Code 4.2: Code for changing 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 [10]. This is a static identifier that 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 for reading 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. [11]

AT command for reading AppEUI:

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

Code 4.4: Code for reading AppEUI

AppKey (Application Key): The AppKey is a 128-bit shared encryption key to encode the messages between end nodes and Application Server [11].

Join Mode: LoRa devices can join networks in two different modes: OTAA (OverThe-Air-Activation) or ABP (Activation-By-Personalization).

All end devices that participate in a LoRaWAN network must be activated. There are two activation methods to choose from: 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 sending and receiving messages. 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 [12]. Therefore the OTAA is a more secure method and it is the approach used in this project. It is a general recommendation to use OTAA.

The command to set the device OTAA mode:

```

1 AT+MODE=LWOTAA

```

Code 4.5: Code for setting 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 are visible to everyone. For the rest of the project this activation procedure will be called enrollment to the network server. The 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 the device has authorization for communicating with the network. As mentioned before, the AppSKey serves 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. The NewSKey is used by the network server while sending data to end devices 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, they are plain text. The figure 4.7 shows the LoRaWAN join process.

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

4.2. GATEWAY PLACEMENT AND DEVICE CONFIGURATION

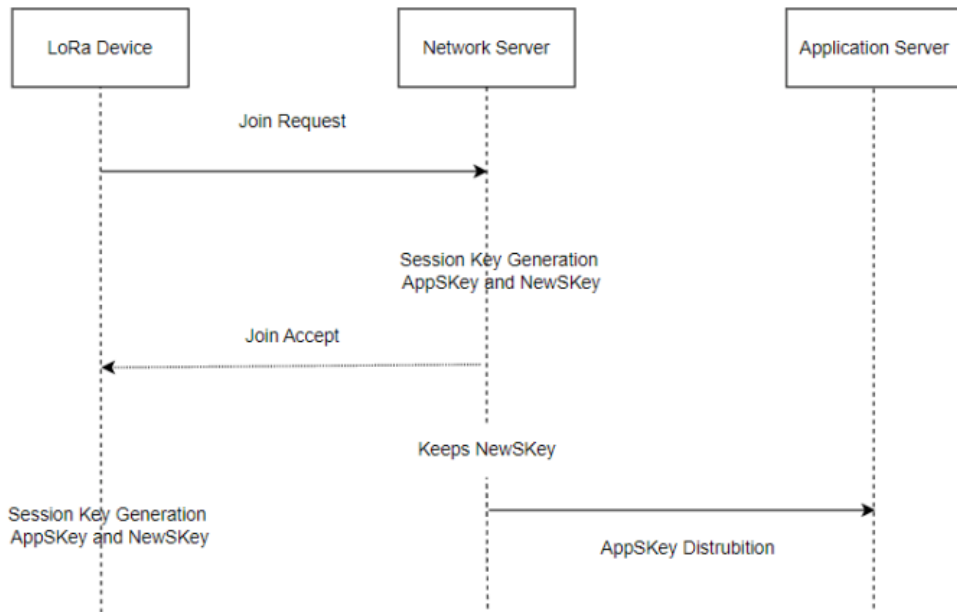


Figure 4.7: LoRa Device join network flow

The 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. The message can only be sent to gateways within the network.

The network server decides whether or not to accept the request; it depends on whether the device has permission to join the network and generate session keys. If the join is accepted, this message is encrypted with the AppKey and the network server sends it to the end node with a downlink. Network server holds the NwSKey and distributes the AppSKey to the application server. LoRa devices decrypt messages with the same AppKey and generate session keys. At the end of the 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. Higher spreading factors produce lower rates, but can transmit data over 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 needs to 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: LoRa-E5 Dev Board can be configured to require acknowledgement (ACK) for confirmed uplink messages.

5

The LoRaWAN Site Survey Tool

A LoRaWAN Site Survey Tool is specialized software or hardware used to assess and optimize the physical environment for deploying LoRaWAN infrastructure, including gateways and IoT devices. These tools help gather data and make informed decisions about gateway and device placement within a LoRaWAN network. They are essential for ensuring the reliability and performance of LoRaWAN-based IoT deployments by aiding in network planning and optimization.

LoRaWAN Site Survey Tools assess the signal strength and coverage area of LoRaWAN gateways. They measure the received signal strength indicator (RSSI) and signal-to-noise ratio (SNR) to determine signal quality and predict coverage range. These tools assist in finding optimal locations for LoRaWAN gateways to ensure adequate coverage and minimize coverage gaps. Network planners can visualize gateway coverage on maps and make optimized decisions about placement.

All existing site survey devices heavily rely on GPS because knowing the locations of every data point sent during the survey provides important information about the coverage area. The probe in LoRaWAN-SST utilizes the GPS service on Android devices to acquire location data during survey activities.

Figure 5.1 depicts one of the latest devices, RAK10701. While using conventional testing devices, users can only view their current location as longitude and latitude values and these devices display the maximum and minimum distances to the gateways without further specifications.

5.1. THE SITE SURVEY PROCEDURE



Figure 5.1: Test device setting and device screen

LoRaWAN-SST enhances the user experience by allowing them to view their current location on a map. Additionally, users can see the distance from their location to the gateways, providing network planners with information needed to design an efficient LoRaWAN network. This advanced functionality sets LoRaWAN-SST apart, offering a more comprehensive and user-friendly approach to site surveys.

As a practical part of this thesis, a server side of LoRaWAN Site Survey Tool which retrieves RSSI values for different locations is designed and developed.

The LoRaWAN Site Survey Tool is made of a LoRaWAN node driven by an Android application used to verify LoRaWAN gateways coverage in a potential or existing LoRaWAN network roll out using the active or on-a-stick site survey model. A probe is a combination of a LoRaWAN node and an Android application. Each 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 shown on the figure 5.2. It is also possible to add an additional power supply to the probe through a dedicated connector on the box. An application for managing the surveys exists, it is presented in the section about the SST client.

5.1 THE SITE SURVEY PROCEDURE

A well-executed site survey is essential for designing and deploying a robust LoRaWAN network that meets the specific requirements of your IoT application while minimizing potential issues related to coverage gaps, interference and suboptimal performance.

Procedure for performing a LoRaWAN site survey can be presented as the following:

- **Defining Objectives and Requirements:**

The objectives of the site survey should be defined clearly as well as the specific requirements of the IoT application, such as coverage area, device density and expected data rates.
- **Selecting Survey Tools:**

Choosing the appropriate Site Survey Tools, which may include LoRaWAN-specific survey software, spectrum analyzers, RF signal measurement equipment, GPS devices and mapping tools.
- **Gateway Placement and Configuration:**

Preconfiguring LoRaWAN gateways with the required settings. Establishing communication between the gateways and a network server for data collection.
- **Gateway Deployment:**

Installing LoRaWAN gateways at predetermined locations within the survey area. Ensuring that gateways are correctly positioned, elevated if necessary and oriented for optimal signal reception.
- **Signal Strength and Coverage Analysis:**

Measuring and recording signal strength and coverage characteristics at each survey point. Consider using LoRaWAN-specific site survey software to visualize coverage areas and identify any coverage gaps or areas with poor signal quality.
- **Interference Detection:**

Identifying potential sources of interference, such as other wireless networks, electronic equipment, or environmental factors. Documenting interference sources and their impact on network performance.
- **Data Logging and Documentation:**

Keep detailed records of all survey measurements, observations and findings. This documentation is essential for making informed decisions during network planning and optimization.
- **Network Optimization:**

Optimizing the LoRaWAN network using the survey findings, including gateway placement, channel selection and configuration adjustments, to meet the requirements of your IoT application.

5.2 SST IMPLEMENTATION

The LoRaWAN Site Survey Tool is made of a LoRaWAN node driven by an Android application used to verify LoRaWAN gateways coverage in a potential or existing LoRaWAN network roll out using active or on-a-stick site survey models. The LoRaWAN node is based on a Seeed studio LoRa-E5 Dev Board which is shown in figure 5.3.

The LoRaWAN Site Survey Tool allows surveying with the purpose to collect RSSI (Received Signal Strength Indicator) values from different locations in a predefined zone. Each survey is going to be assigned with the appropriate zone and is going to be performed by one user.

We distinguish between two types of users: user administrator and user operator.

The administrator has permissions to create new surveys and assign them to the user operator who is going to perform them.

The operator is going to be assigned with one or more surveys to perform. The operator chooses a survey to perform and is supposed to do the route scheduled for the specified period (by the location, start date and end date parameters). The location is known based on the name of the survey. Meaning that the operator is going to move around the zone predicted for the survey and send messages to a gateway. 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.

The results will be visible via the Swarm UI (Swarm is presented in one of next sections). Users are able to access a table with all the performed surveys, choose one and view its results. A window containing the name of the survey and a table with all the messages received from the probe application during surveying will appear. The table has 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 (high values will be colored in green, middle values in orange and low values in red).



Figure 5.2: Probe

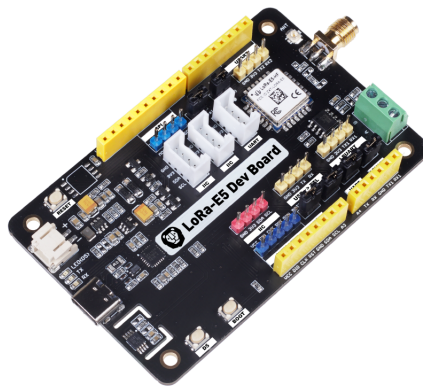


Figure 5.3: LoRa-E5 Dev Board

THE ALTIOR PLATFORM FOR DIGITAL TWINS

The concept of digital twins was first envisioned in 1991 and implemented for product lifecycle management (PLM) a decade later. Coined officially by NASA in 2010, the term has since gained popularity across various industries. [24] In essence, a digital twin is a digital model representing a physical object, encompassing its processes and systems. It serves as a replica template for a real device, such as a sensor, capturing all interactions with the physical world.

Altior by Inkwell Data is a comprehensive digital twin development technology, streamlining the integration of physical assets with their digital twins. It facilitates real-time data flow from IIoT devices and seamless integration

5.2. SST IMPLEMENTATION

with operational information from enterprise systems. Altior expedites digital twin design by mapping physical object features to digital twin "properties", identified by name, data type and supported interactions. This simple data structure definition allows for the creation of a device twin, enabling data collection and operation of devices, such as a thermostat, across supported network technologies. Altior handles communication processes transparently, managing properties like "Temperature" and "Setpoint" for efficient control and monitoring. Additionally, Altior automatically incorporates essential base properties for effective object management.

Table 5.1 is an example

Digital	Twin Property Purpose
Unique ID	Uniquely identify a digital twin instance
GPS coordinates	Current geographical position of the device twin
Security provider	Security mechanism used for the device communication
Version	The device twin version (may vary for the same kind of object)
Manufacturer	Manufacturing company of the physical device
Network adapters	A list of communication network types

Table 5.1: A selection of Altior device twin basic device properties [24]

Altior's digital twin definition goes beyond basic attributes, allowing for features like images, communication security and custom device manufacturer attributes. Altior supports diverse data types, including complex structures like lists and maps. The web-based interface simplifies the design process, guiding users through property definition to create a reusable digital twin template. Once validated, the template is stored for generating software using the Altior builder function. This function takes the digital twin definition, automatically producing correct source code, compiled into an executable format and deployed to the Altior runtime service server for managed execution.

Upon completing and validating the digital twin template in Altior, the platform is poised to handle the connection between physical objects and their digital counterparts. The initial step involves creating a device twin instance linked to the corresponding physical object. This is achieved by assigning property values from the base template to uniquely identify the associated physical object.

Figure 5.4: Creating device twin instances

In the provided example, Altior will generate a device twin instance identified as IWDTHSTAT_01, facilitating communication with a specific physical thermostat.

With the same identifier, such as the serial number and utilizing an LPWAN network protocol, the device twin instance communicates through an IoT gateway, which could be a common Wi-Fi access point or a dedicated LPWAN gateway. A network adapter, acting as a bridge between the digital and physical worlds, connects the device twin instance to its corresponding physical object. Once created on Altior, the device twin instance mirrors the state of the physical device. Any state modification on one side is instantly reflected on the other. For instance, in the thermostat example, if the room temperature changes, the temperature sensor property of the device twin is promptly updated. Similarly, if an Altior application adjusts the "Setpoint" property of the device twin, the new setting is transmitted to the physical thermostat.

Device twin instances in Altior essentially serve as state representations for associated physical objects, managed within the Altior subsystem called the "runtime environment" (RTE). The RTE acts as a process container for all device twin instances, accommodating various types, such as thermostat and smart meter device twins. Each device twin instance is an isolated lightweight process independently handled by the RTE, ensuring that a fault in one instance doesn't affect others. The RTE efficiently manages millions of device twins on commodity server hardware, utilizing CPU power and RAM memory. Altior

5.2. SST IMPLEMENTATION

enables simple vertical scalability by adding resources or horizontal scalability by replicating the RTE on different servers, creating an RTE cluster. Clustering is transparent to users, requires no specific cloud infrastructure and is cloud-agnostic.

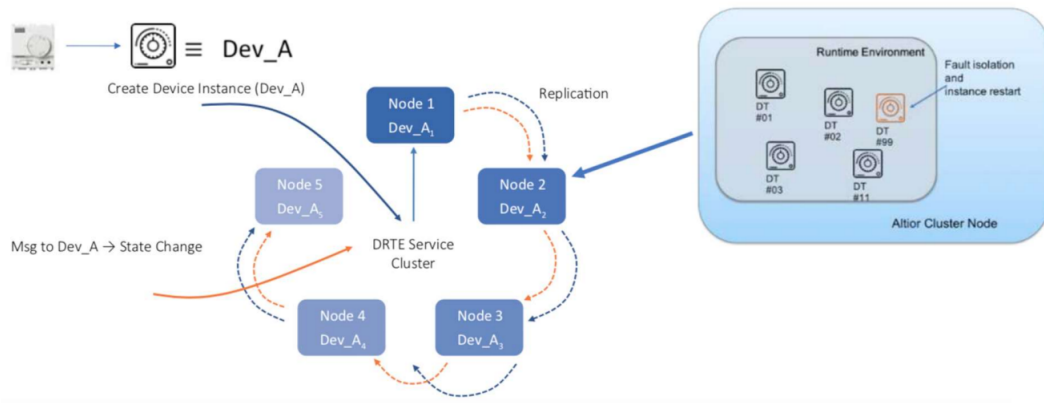


Figure 5.5: The Runtime Environment RTE

Altior’s clustering extends beyond the RTE, working for every Altior function. The setup is flexible, supporting load balancing and addressing peak requests resulting from external events. Device twin instances in the RTE are temporary, reflecting real object states without the need to track changes over time. This design ensures Altior RTE’s responsiveness even under heavy loads and for a large number of managed objects. For situations requiring state change persistence, Altior provides options to implement application-specific storage strategies using the Altior API or deployment tools.

The Altior platform serves as a key enabler for Industrial IoT application development, leveraging the digital twin concept. With Altior’s device twin abstraction, the modeling scope extends beyond physical devices to include communication networks and business processes.

SMART WATER METERING APPLICATION - SWARM

Swarm is a web application for water metering developed on Altior, Inkwell Data Ltd.s digital twin platform.

Altior components allow the user to define digital twins for most sensors and devices used in industrial applications, as well as to create virtual networks to communicate with the physical world. In the smart water application domain,

Altior digital twins are built for devices such as meters, pressure sensors and data loggers, as well as their communications infrastructure, including public cellular networks and private low power, wide area networks (LPWANs). [14]

Upgrading standard water meters to communicating water meters simplifies meter reading. This involves adding a data communications component, often a radio frequency transmitter, to collect consumption data from a sensor on the meter. The transmitter sends readings to a collection system and, subsequently, to a data management system for validation and billing.

Inkwell Data addresses the complexities of large-scale water smart metering projects through its Altior digital twin platform, forming the Holistic Metering Infrastructure (HMI). HMI integrates diverse stakeholder requirements, prioritizes end-user needs and remains adaptable to current and future metering and communication technologies. Inkwell Data's SWaRM, a smart metering service, is at the core of HMI, offering unified meter reading and management, leveraging industrial IoT digital twins for versatility across transmission technologies.

At the data transport level, Altior creates a virtual network interface (ANI, Altior Network Interface), where the binary frames coming from the smart meters are stripped of their low level transport protocol. [14]

At the digital twin level, the usually encrypted binary data is further processed by a security service provider, enabled by Inkwell Data's security platform, Aegis and rendered in unencrypted form. [14]

SWaRM is designed for an easy integration with the existing IT infrastructure of water companies. The web-based SWaRM user interface is highly customizable without programming. The SWaRM user interface can be accessed by any modern browser supporting the TLS security standard. The function menu gives access to the main SWaRM functions. [14] One of the newly added Swarm functions is LoRaWAN site surveys. It was developed as an extension to existing Swarm's core project.

THE SST CLIENT DIGITAL TWIN

Every device in this LoRaWAN network has its own digital twin.

The surveying process involves operators who use the Android application to send messages, gateways receives the messages from probes and forward them to their respective digital twins. The digital twins are responsible for decrypting and decoding the messages, interfacing with Aegis for decryption

5.2. SST IMPLEMENTATION

and a codec manager for encoding. Once these processes are completed, the digital twins transmit the messages to Swarm via RabbitMQ message broker, where they wait in a queue before reaching Swarm.

The digital twin serves as a link between the physical probe application and the backend server, facilitating seamless integration of survey data into the Messages database. This architectural approach significantly improves the reliability and resilience of the surveying process, ensuring efficient management and transmission of data throughout the survey lifecycle.

5.2.1 SST SERVER

The solution is implemented by developing an extension for SWaRM, it is written in the Elixir programming language, using the Phoenix standard. A new CockroachDB database has been created, followed by the context, controllers, using ecto functionalities, functionalities of Filterable library as well. For managing user's authorization, the Bodyguard library has been used.

CREATING AND MANIPULATING THE SURVEY

A user authenticated as an administrator is able to create a new survey using the form via Swarm UI. The form is going to contain the following fields: `survey_name`, `device_id`, `official_start_date` and `official_end_date`, `user_id`. By clicking the "Create" button, a new survey instance is going to be created in the Surveys database table which is going to contain the following fields:

- **name:** the survey's name, it is unique.
- **device_id:** ID of the device which is used for surveying.
- **official_start_date:** date when the surveying is expected to begin
- **official_end_date:** date when the surveying is expected to end
- **actual_start_date:** date when the surveying is actually started by the operator
- **actual_end_date:** date when the surveying is actually ended by the operator
- **user_id:** ID of the user assigned to the survey (type: integer).
- **status:** Indicates the status of the survey (its value can be: "created", "downloaded", "started", "paused" "ended"), by default its value is "created".

The values of the status field are limited to:

- **"created"** - set by default when the survey is created
- **"downloaded"** - set when an operator downloads the survey to probe device
- **"started"** - set when an operator starts a survey (it will trigger setting the `actual_start_date` to the current date and time)
- **"paused"** - set when an operator chooses to make a break, finishes for that day or simply needs to use the probe to perform another survey
- **"ended"** - set when an operator chooses to end a survey (it will trigger setting the `actual_end_date` to the current date and time)

Instances of Survey can be manipulated using implemented CRUD (Create, Retrieve, Update, Delete) operations (via API endpoints or User Interface).

Implemented CRUD (Create, Retrieve, Update, Delete) operations:

- **list_surveys** allows retrieving all surveys matching the provided filters from the Surveys database table
- **create_survey** allows inserting a new survey instance in the Surveys database table
- **retrieve_survey** allows getting the survey identified by its id
- **update_survey** allows updating a single row in the Surveys database table, providing new values for specified variables
- **delete_survey** allows deleting a survey instance from the Surveys database table (with a constraint that the status field cannot have different value but "created")

Diagram shown in figure 5.6 depicts the CRUD operations administrators can do with an instance of survey.

5.2. SST IMPLEMENTATION

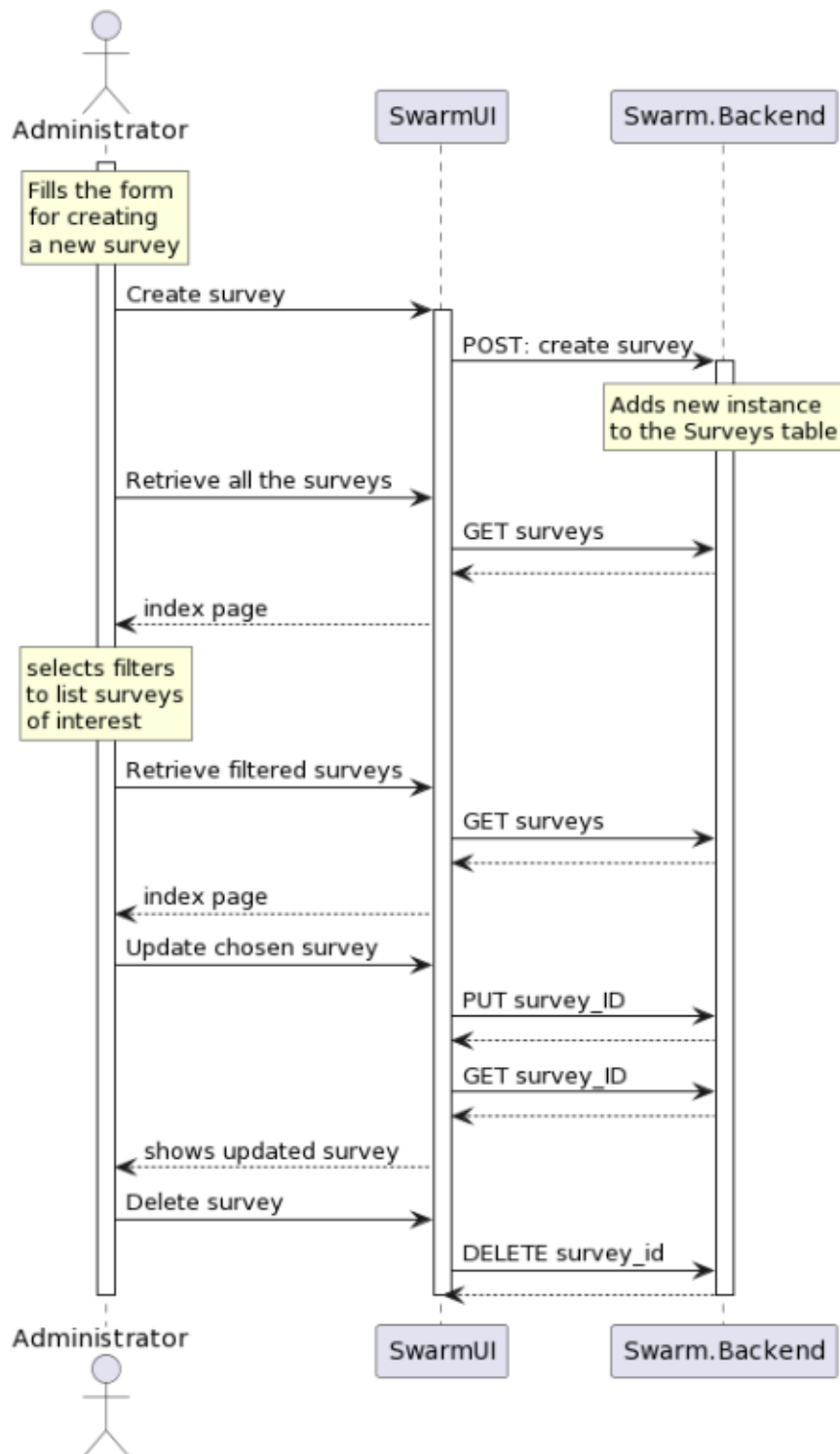


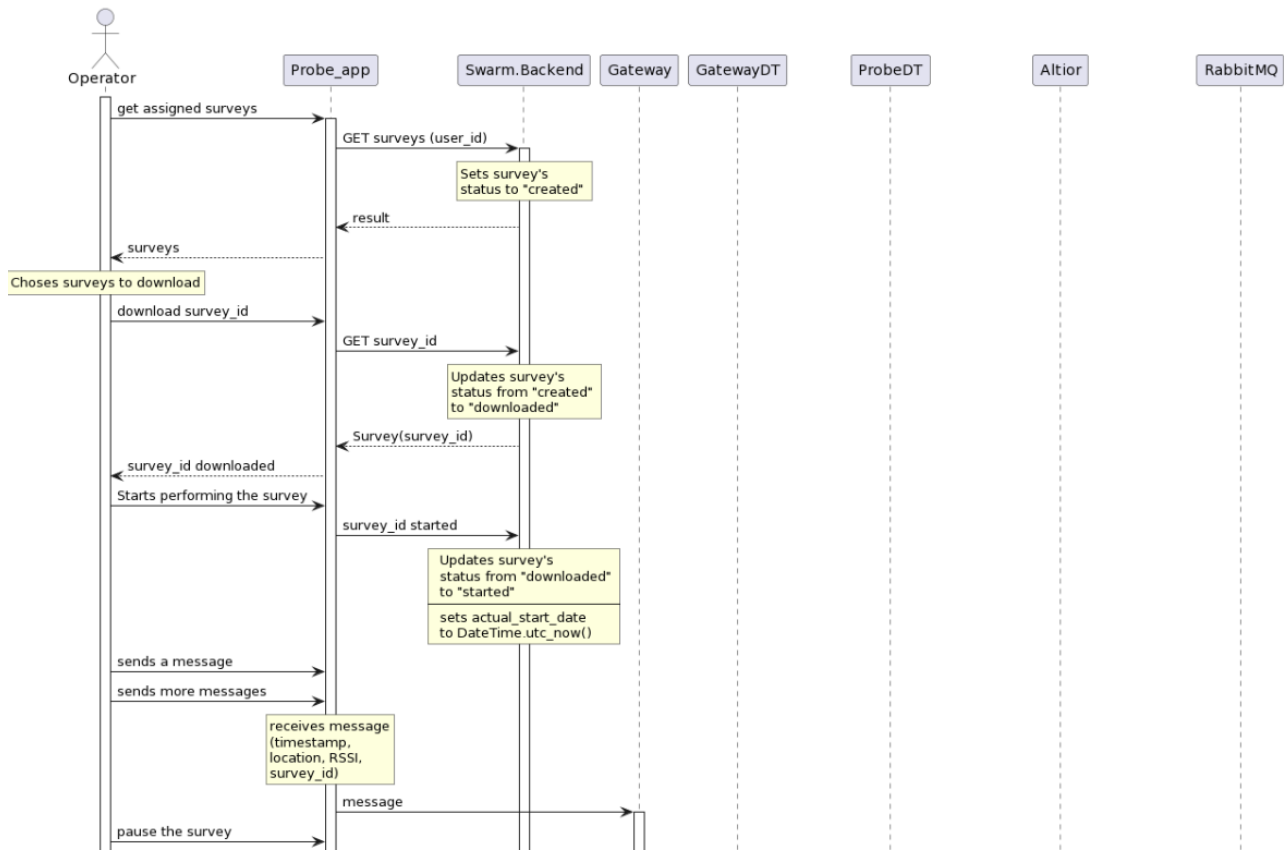
Figure 5.6: CRUD operations administrator

PERFORMING A SURVEY

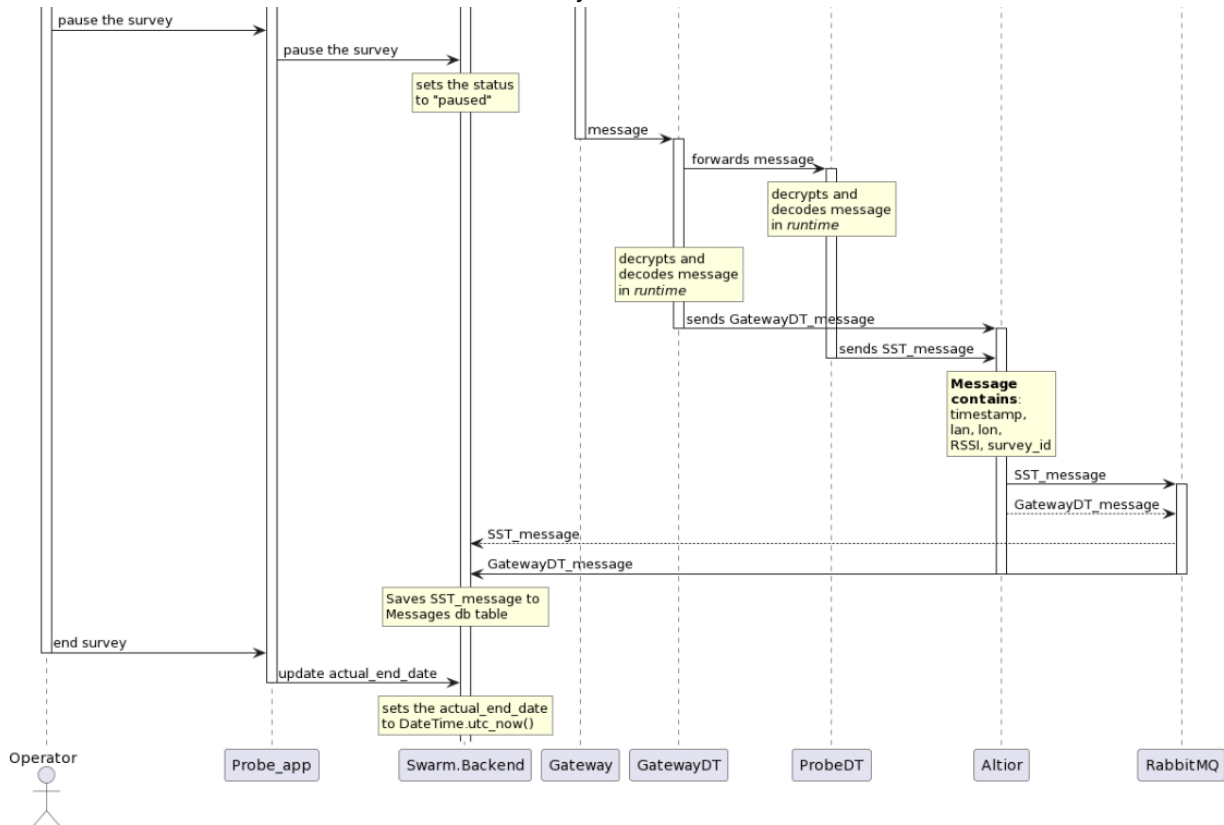
When operators choose to perform a survey, they are presented with a list of surveys assigned to them and they can choose the one they want to perform (respecting the `official_start_date` and `official_end_date` of the survey). To perform the survey, the operator has to download it to the probe application, it will then be stored locally in order to allow performing surveys in the absence of an internet connection. By choosing the survey and clicking the **DOWNLOAD** button, automatically, the status of the survey will be changed from "created" to "downloaded". To start performing the survey, the operator has to click **START SURVEY** button (which is going to change the status value from "downloaded" to "started"). The operator is going to move around the survey's zone and send messages to the gateway using the probe application. Once the operator is done with the survey, by clicking **END SURVEY**, survey's status is going to change to "ended".

When a gateway receives a message from a probe, the message is sent to its digital twin. The gateway forwards the message to the probe's digital twin and it decrypts it (sends it to Aegis to decrypt it) and decodes it (via a codec manager) and sends it to Swarm (via the RabbitMQ message broker). The probe's digital twin also decrypts and decodes the received message and sends it to Swarm. In case there is no gateway available to receive messages from the probe application, messages are going to be stored on the Android device. When it connects to the internet again, all stored messages are going to be sent directly to Altior (messages with type: "outbound"). Those messages are not going to have RSSI values, but only coordinates of the location where the operator tried to send them from. The following diagram describes the message's flow from the moment the user sends it, to the moment it is stored in the Messages database table. Entire performing survey flow is shown on the figure 5.7a 5.7b

5.2. SST IMPLEMENTATION



(a) Perform survey flow



(b) Perform survey flow

API ENDPOINTS

CREATE

Only users with the administrator role have permission to create a new survey. Administrators create a new instance of survey by filling in the form via Swarm UI, where they:

- name the survey with a unique name,
- select the operator to perform the survey (from a drop-down menu where all the users who have the role "operator" are displayed),
- select the probe with which to perform the survey (from a drop-down menu where all probe devices are displayed)
- provide the `official_start_date` and `official_end_date` for the survey.

All the fields are mandatory.

Upon clicking on the CREATE button, a request for creating a survey instance is submitted.

In case an administrator tries to create a survey with a name already assigned to another survey, the message *"The provided survey's name has already been taken"* will be displayed and the administrator needs to change it to submit the request successfully.

In case an administrator tries to create a survey with an `official_end_date` value which is before the `official_start_date` value, the message *"Invalid time provided, you have to select official_end_date which is after official_start_date"* will be displayed and the administrator needs to change it to submit the request successfully.

If all submitted fields are provided with valid values, a new survey is created and by default it is going to have the "created" value in the status field.

In case an administrator tries to create a survey with an `official_start_date` value which is in the, the message *"The provided survey's official_start_date must be in the future"* will be displayed and the administrator needs to change it to submit the request successfully.

INDEX

Administrators have permission to access the list of all the surveys and filter them by parameters of interest. In case they do not use any filters, all surveys

5.2. SST IMPLEMENTATION

present in database will be displayed. Results are paginated.

The list of surveys can be filtered by:

- The status of the survey (e.g. list of all surveys with status: "created" will display all surveys that are created but still not started). *For displaying surveys of the status of interest, Surveys will be filtered with the status filter.*
- The operator the surveys are assigned to (by selecting the user_id, surveys assigned to this operator will be displayed). *When filtering by user_id, administrator must select an operator from a drop-down menu where all users who have the role "operator" are present.*
- The probe assigned to the survey (by selecting device_id, all the surveys which have used, are using or will use the selected device will be displayed).

Administrator will select the device from a drop-down menu where all probe devices are present.

Users with the role "operator" are going to be able to access the list of surveys and to filter it with the same filters except for the operator filter, but only surveys assigned to them will be filtered.

SHOW

In case of users with the role "administrator", the SHOW endpoint returns a single survey, retrieved by its id.

In case of users with the role "operator", the SHOW endpoint returns a single survey, retrieved by its id, only if the requested instance of survey is assigned to them.

UPDATE

Users authenticated as administrators, after listing the surveys and selecting the one of interest (it can be selected only if its status is "created"), are authorized to update it. Administrators can update:

- user_id: Operator assigned to the survey, by selecting a new one from a drop-down menu where all users who have the role "operator" are present.
- device_id: Probe assigned to the survey, by selecting a new one from a drop-down menu where all probe devices are present.
- official_start_date or official_end_date predicted for the survey.

- name: Survey's name.

Users authenticated as operators are authorized to update the status of the survey. They do so while using the probe application. By choosing to download a survey to the probe application, the operator updates the survey's status from "created" to "downloaded". When the operator starts performing the survey, the status is going to change from "downloaded" to "started". By ending the survey, the operator changes the survey's status from "started" to "ended".

DELETE

An administrator is authorized to delete only survey instances from the Surveys database table with the "created" status, identified by its ID.

Operators do not have permission to delete any survey instance.

5.2.2 SST CLIENT

The client side of LoRaWAN-SST is a Swarm web application and a mobile application compatible with tablets and smartphones running the Android operating system. This application is accessible on the Google Play Store. Users need to log in or register within the Swarm system to gain access to the application.

Users with the role of administrator use the Swarm application to create surveys (shown on the figure 5.8, assign them to operator users who then perform surveys using the Android application. Administrators use the Swarm application to update surveys if needed, track the progress and access the results of surveys. Both applications are using the same API collection.

5.2. SST IMPLEMENTATION

Swarm

Welcome Riccardo Degan

Home / Surveys / Create

Create Survey

Name *

Start date

End date

Device

User

CREATE

Copyright © 2023 Inkwell Data Ltd

Figure 5.8: Create survey page

Once the application is launched, the user is presented with a login page, shown in figure 5.9.

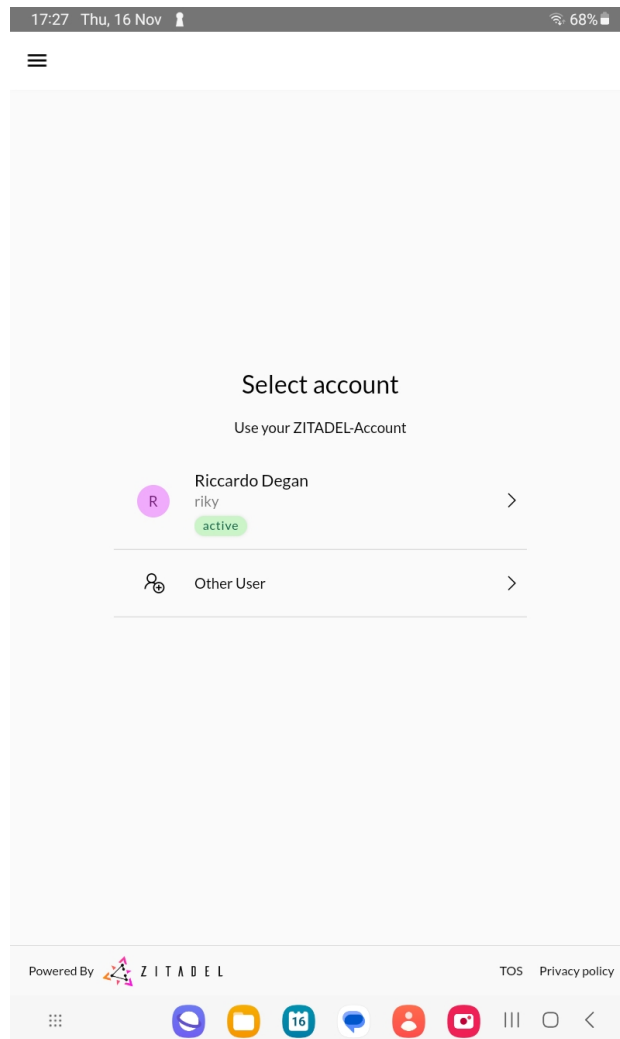


Figure 5.9: Application login page

After the log in process, the list of all surveys assigned to the current user is presented. In case the probe device has internet connection, both surveys which are downloaded and those which are not are shown. If there is no active internet connection, only surveys which are already downloaded to the local storage are going to be visible. All the surveys are displayed with their status and the period they are predicted to be performed in. Figure 6.1 shows the page where surveys are shown.

At this point the user can manage surveys according to the information that is provided for each survey. Such as the status of the survey which provides the information whether the survey has already ended, if it started earlier and paused now, or if it has not started at all. This page also shows the predicted start and end dates of the survey.

5.2. SST IMPLEMENTATION

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

The next step would be choosing a survey to perform by clicking on the **start** button. The chosen survey is going to be shown with all its details and it is ready to send a message to the gateways inside the LoRaWAN network after joining it. An example is shown in figure 5.10.

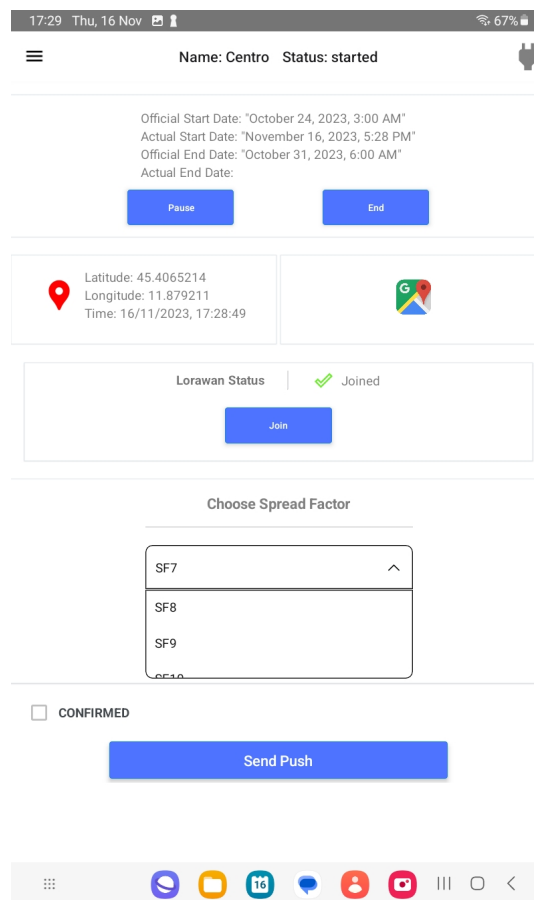


Figure 5.10: Survey show

The join status of the LoRa device is also visible. At the beginning it says Not Joined because the device should join the network before starting sending messages. Here, the user can chose the spreading factor value and if message should be confirmed or not. Confirmed message expect an acknowledge message to be received. 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 CMSGHEX: Start
2 CMSGHEX: Wait ACK
3 CMSGHEX: 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

As it is a confirmed message it returns acknowledgement and that's the reason why message transmitting time lasts longer with confirmed messages.

Not confirmed messages AT command is:

,

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

Code 5.3: Code for Not Confirmed Message

The answer for not confirmed 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 for not Confirmed Message

Figure 5.11 depicts the flow of sending message process.

5.2. SST IMPLEMENTATION

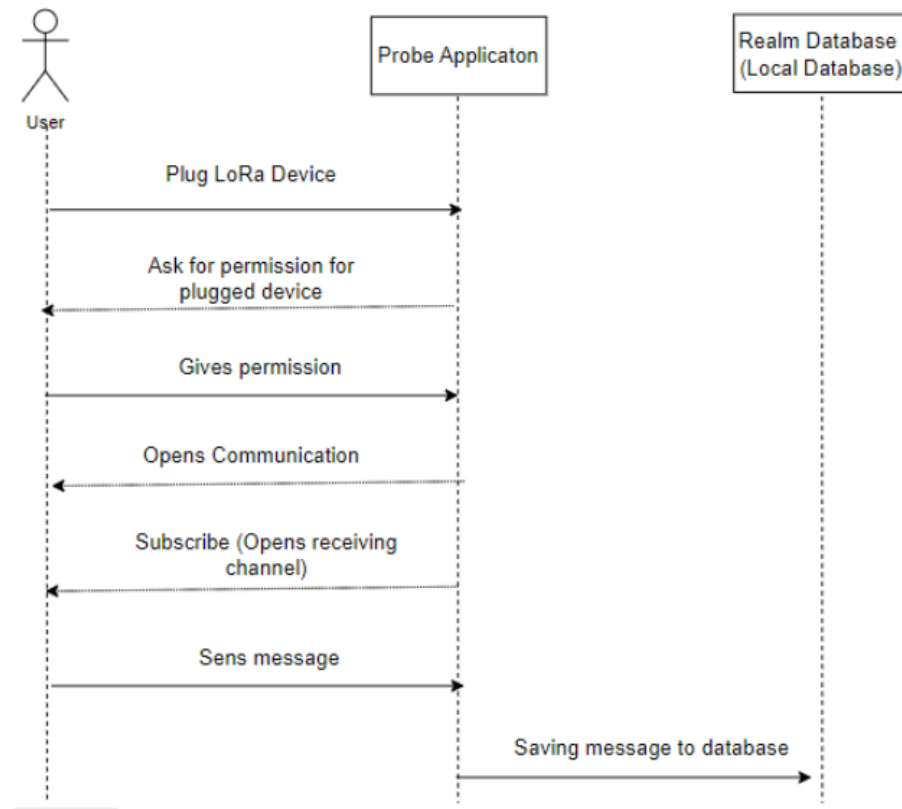


Figure 5.11: Sending message flow

When the LoRa device is plugged in for the first time, the probe asks for permission from the user, then it establishes serial communication between the probe and the gateway, including the channel for receiving messages from the gateway so it can accept answers from the gateway. This includes setting up a channel for getting replies from the gateway. This initiation happens only once when the LoRa device is plugged in for the very first time. All the sent messages get saved in a local database, similar to keeping a record of your conversations. The stored messages look like the following:

```
1 Message ID: 65563fcaacbadd0
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: Message stored to the local database

To be able to join a network, LoRa devices need to be enrolled into the network. For this project probes must be enrolled in the LoRaWAN server of the Altior system. Figure 5.12 shows the enrollment process of the LoRa device into the network:

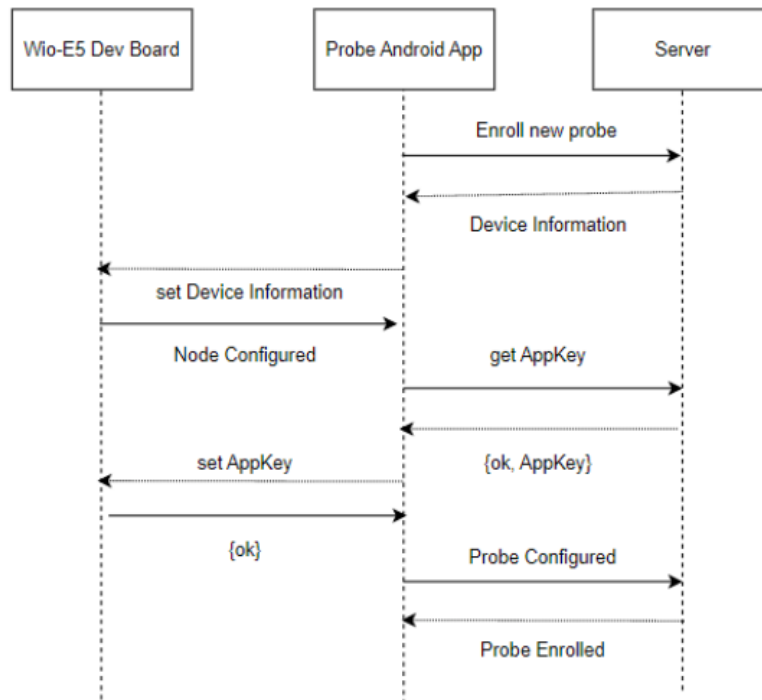


Figure 5.12: Enrolment process

Enrolment process:

1. The probe is queried for the LoRa devices MAC (device) address using the command AT+ID. Altior system allows access to probes only if they are authorized, which means devices must be configured before the enrollment process in the Altior system. If it is authorized the result of AT command message includes this information:

```

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 information.
3. The app requests the LoRaWAN application key
4. The app configures the application key on the node

5.2. SST IMPLEMENTATION

5. After a successful key configuration, the app notifies the server that the procedure has been completed
6. The server acknowledges the enrollment and creates a 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. The figure 5.13 depicts the login process:

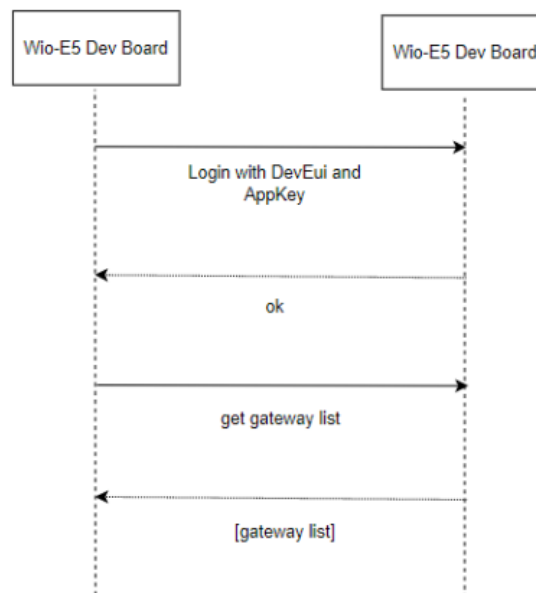


Figure 5.13: Login process

If the login is successful, the application will request the list of 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. On this page users can see gateways in the surveys zone and the operators 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.

Figure 5.14 shows the mockup of the gateways list map:

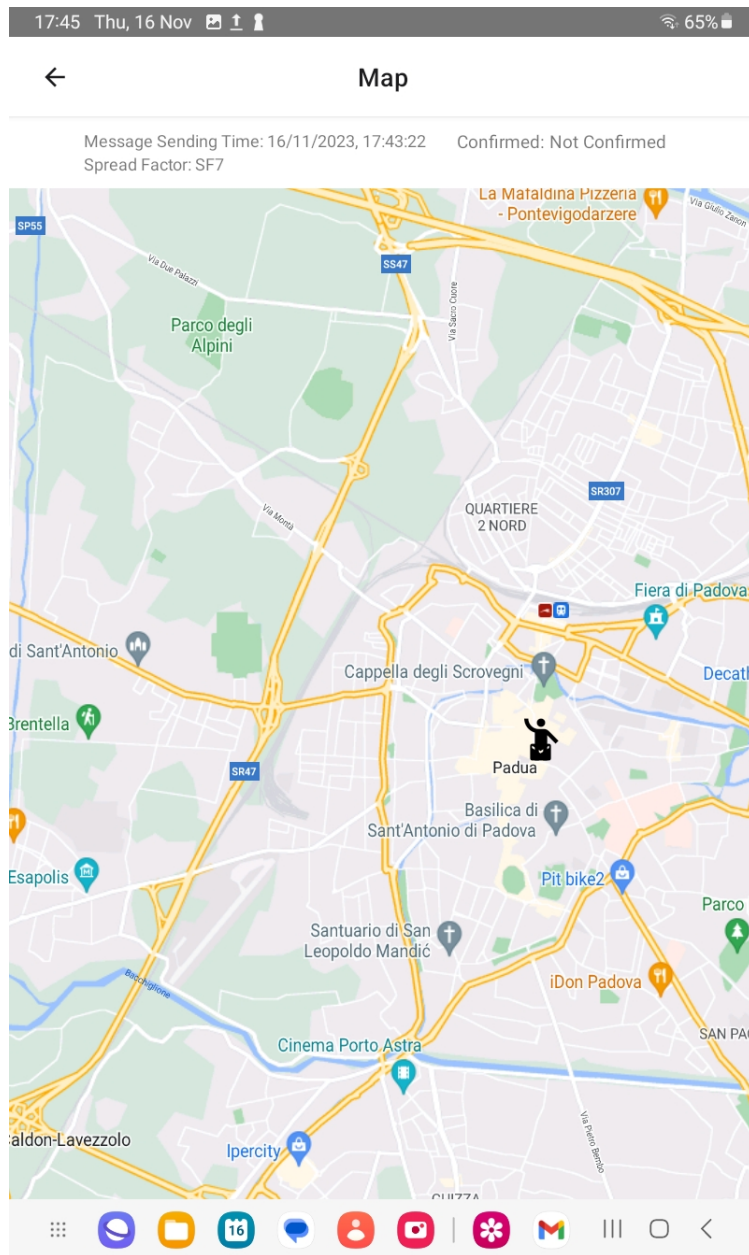


Figure 5.14: Application, map with details

In the application, the operator can view all the messages that are sent as part of a particular survey. These messages are stored in the application database. In case an error appears, the message is not sent to the network and it is marked with a red cross icon. On the other hand, if everything went well and a message is sent, it will be marked with a green tick icon. An example of the messages page showing all the messages sent within the survey is shown in figure 5.15.

5.2. SST IMPLEMENTATION

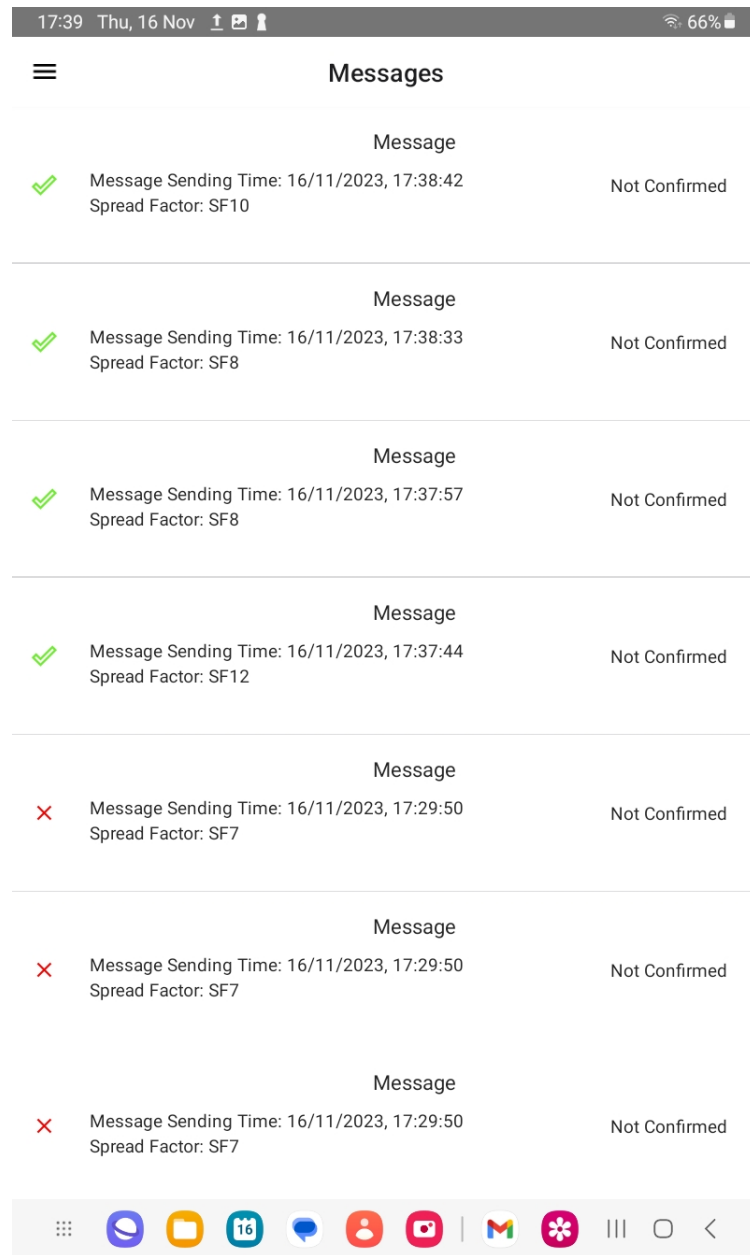


Figure 5.15: Sent messages

Figure 5.16 shows the list of all available surveys for logged in user. For each survey, besides the details the option to start or continue (if already started) the survey is available. By choosing a survey to start, user is presented with 5.10 where spreading factor can be chosen and message can be sent by pressing Send push button.

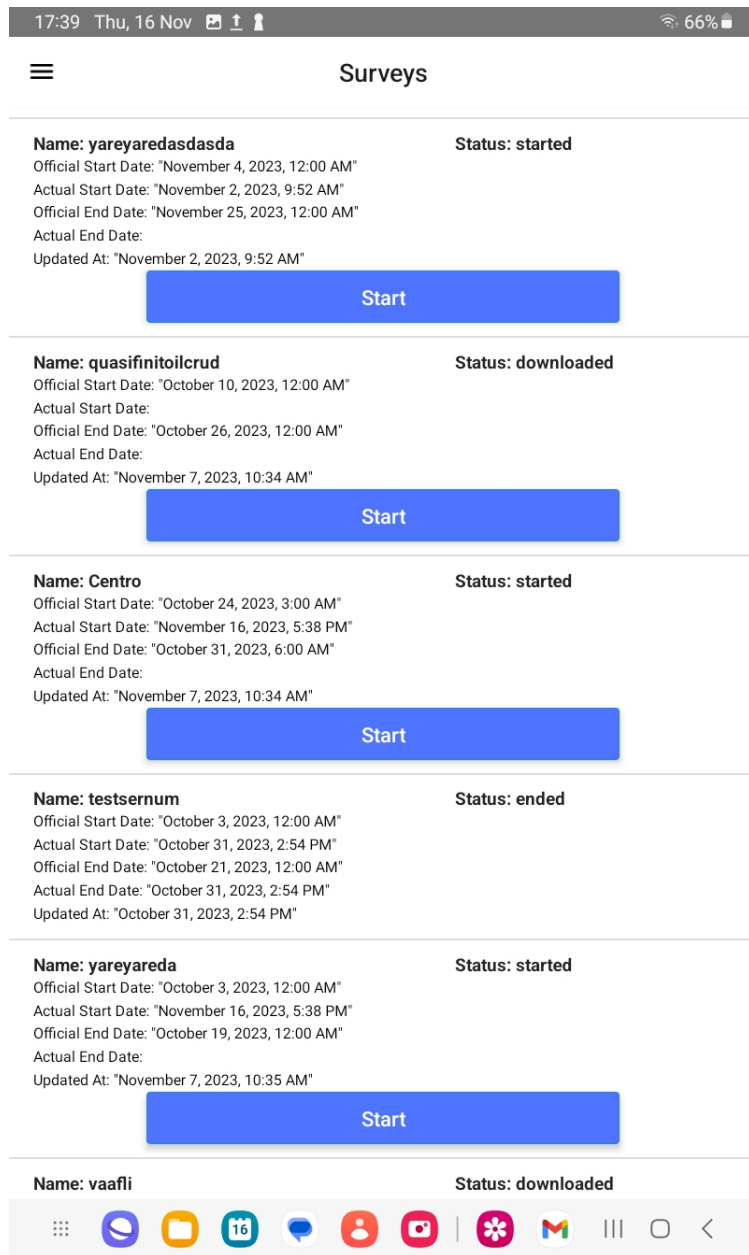


Figure 5.16: Application surveys page

6

SST data collection and result representation

6.1 SST DATA COLLECTION

Messages of all digital twins are collected through time, and stored to the database. In the case of a probe's messages, all of them are sent to its digital twin and stored to the database. These messages can be filtered by the probe's identifier in order to list messages of a particular probe device. The entire message is being saved. It is possible to retrieve values of interest from the message. Since the values of interest in this case are RSSI values and the SF values to which the RSSI corresponds, as well as the coordinates of the location the message has been sent from, we parse the message to obtain these values.

6.2 RESULT REPRESENTATION

The results of each survey represent the most important values collected from exchanged messages between probes and gateways in our LoRaWAN network. In our case, the values of interest are RSSI generated using various SF from different locations. This information is given to users through Swarm UI. Users can access a list of surveys, an example is shown in figure 6.1.

6.2. RESULT REPRESENTATION

The screenshot displays the Swarm application interface for survey management. The header shows the Swarm logo and the user name 'Benvenuto Meliha Duman'. Below the header, there is a breadcrumb trail 'Sondaggi' and a search form. The main content area contains a table with the following columns: Nome, Sonda, Utente, Stato, Data inizio ufficiale, Data fine ufficiale, Data di aggiornamento, and Azioni. Two survey entries are listed:

Nome	Sonda	Utente	Stato	Data inizio ufficiale	Data fine ufficiale	Data di aggiornamento	Azioni
Demo 2			paused	28 novembre 2023 alle ore 00:00:00	31 dicembre 2023 alle ore 00:00:00	6 dicembre 2023 alle ore 09:57:15	
Demo			ended	28 novembre 2023 alle ore 00:00:00	30 novembre 2023 alle ore 00:00:00	30 novembre 2023 alle ore 17:34:48	

At the bottom right of the table, there is a pagination indicator '1-2 of 2' with navigation arrows.

Figure 6.1: Lists of surveys

Then, users can chose a single survey to see its details, as shown in figure 6.2. From that page, beside the survey's details, there is an option to update the survey through the update form, respecting the authenticated user's role permits and survey's status.

The screenshot shows the Swarm web interface for a survey named 'Survey Demo 2'. The interface includes a header with the Swarm logo and user information, a breadcrumb trail, and a main content area with a form and a table.

Update form

Nome * Demo 2

Stato paused

Data di inizio 11/28/2023 12:00 AM

Data di fine 12/31/2023 12:00 AM

Device 2CF7F1203230E196

Utente

UPDATE

Nome	Stato	Sonda	Utente
Demo 2	paused		
Data inizio ufficiale 28 novembre 2023 alle ore 00:00:00	Data fine ufficiale 31 dicembre 2023 alle ore 00:00:00	Data di aggiornamento 7 dicembre 2023 alle ore 14:17:16	Data di inizio attuale 30 novembre 2023 alle ore 17:37:00
Data di fine attuale La data non è ancora definita			

Probes readings

Figure 6.2: Survey's details

On the same page the current results are visible. Results are shown through the list of messages sent within the survey, with a map next to the table that shows the locations from which each message was sent. By clicking on a pinned location, RSSI and SF values appear (shown in figure 6.3). In this case, probe was used as an active site survey, with the spreading factor SF7, displayed messages are those which have reached the getaway.

The RSSI values are color coded on the map and each color represents a predefined range:

- green: $\text{RSSI} > -80$
- orange: $-81 < \text{RSSI} < -110$
- red: $\text{RSSI} < -140$

The SF values are also shown on the map next to their corresponding RSSI value.

6.2. RESULT REPRESENTATION

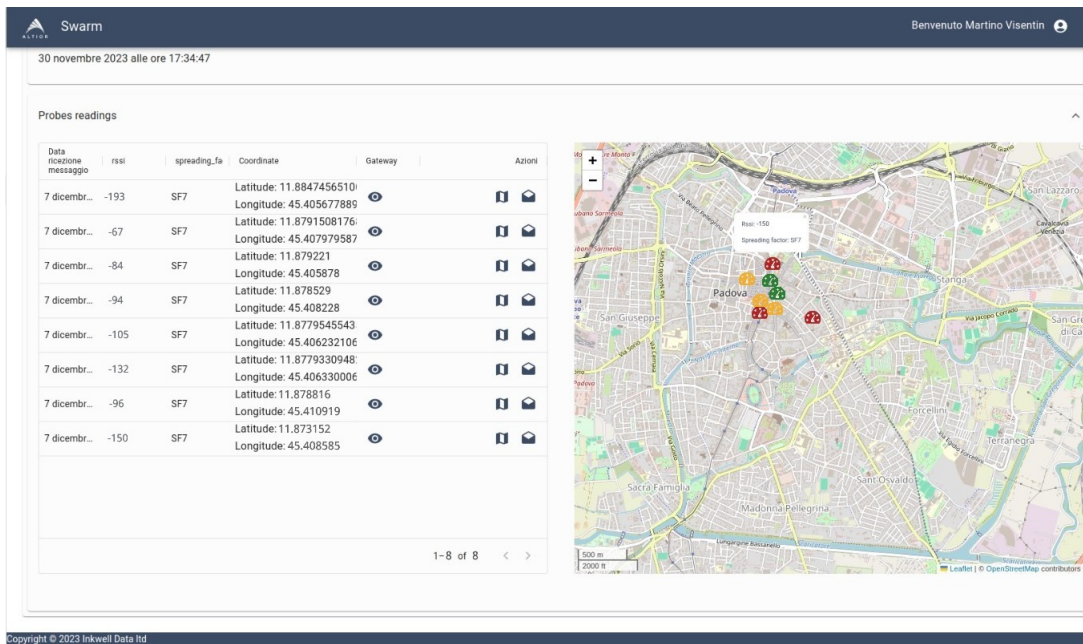


Figure 6.3: Survey's result page

The list on the left side contains the messages filtered by the probe's identifier and the time period from `actual_start_date` to `actual_end_date`, since these parameters provide us with the information when the survey has been performed. The results table contains information about date and time when the message was sent, RSSI value, spreading factor, coordinates of the location the message has been sent from and the information whether there was a gateway to receive the message. In the last column, there are two actions available: the first one shows the details of the message on the map, the second is for viewing the message. Figure 6.4 shows the example of a whole message.

There is also option to view details of each probe. Figure 6.5 shows the page with survey's detail. From that page it is possible to navigate to the table with detail of all messages sent from that probe. This table (6.6) provides the user with information of the date and time when the message was sent, the type of message (depends of the network at the moment when the message was sent), the information if message reached any gateway in the network and the message's content.

CHAPTER 6. SST DATA COLLECTION AND RESULT REPRESENTATION

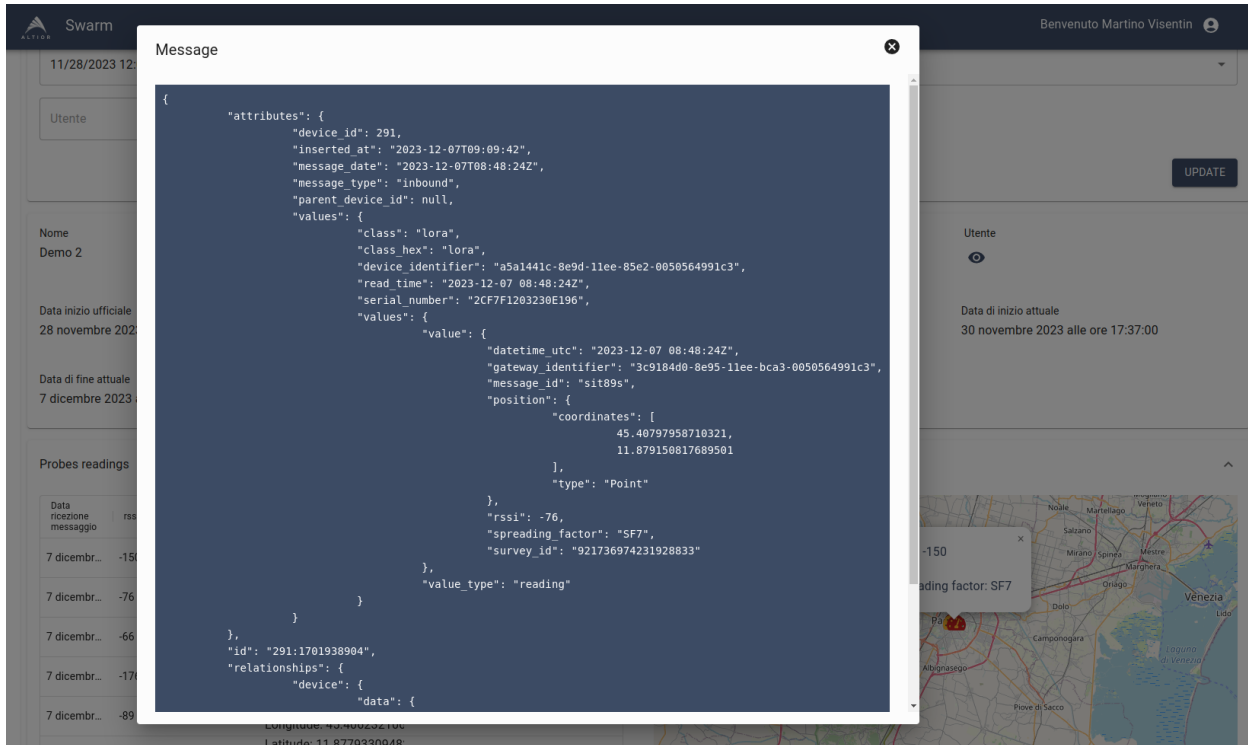


Figure 6.4: Example of the probe's message

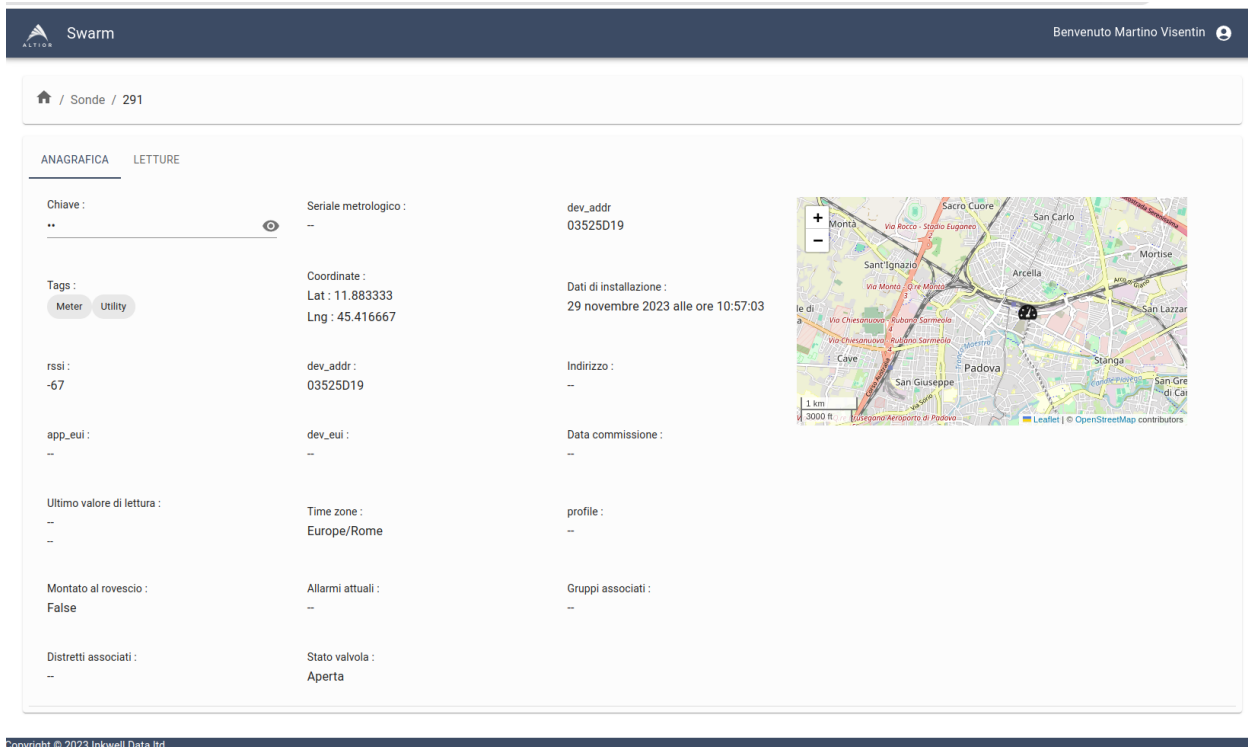


Figure 6.5: Probe's details

6.2. RESULT REPRESENTATION

The screenshot displays the Swarm application interface. At the top, there is a dark blue header with the Swarm logo on the left and the user name 'Benvenuto Martino Visentin' on the right. Below the header, a breadcrumb trail shows 'Sonde / 291'. The main content area has two tabs: 'ANAGRAFICA' and 'LETTURE', with 'LETTURE' being the active tab. A table lists the received messages with the following columns: 'Data ricezione messaggio', 'Tipo di messaggio', 'Gateway', 'Valori', and 'Azioni'. The table contains 11 rows of data, showing various message dates and times, all of which are 'inbound'. The 'Gateway' column indicates the status of each message, with red 'X' marks for failed messages and blue eye icons for successful ones. The 'Valori' column contains JSON-like strings representing message attributes. The 'Azioni' column contains envelope icons. At the bottom right of the table, there is a pagination indicator '1-10 of 31' and navigation arrows. A copyright notice 'Copyright © 2023 Inkwell Data Ltd' is visible at the very bottom of the page.

Data ricezione messaggio	Tipo di messaggio	Gateway	Valori	Azioni
7 dicembre 2023 alle ore 09:48:24	inbound	✗	{"attributes":{"device_id":291,"inserted_at":"2023-12-07T0...	✉
7 dicembre 2023 alle ore 09:48:24	inbound	👁	{"attributes":{"device_id":291,"inserted_at":"2023-12-07T0...	✉
7 dicembre 2023 alle ore 09:48:24	inbound	✗	{"attributes":{"device_id":291,"inserted_at":"2023-12-07T0...	✉
7 dicembre 2023 alle ore 09:48:24	inbound	👁	{"attributes":{"device_id":291,"inserted_at":"2023-12-07T0...	✉
7 dicembre 2023 alle ore 09:48:24	inbound	👁	{"attributes":{"device_id":291,"inserted_at":"2023-12-07T0...	✉
7 dicembre 2023 alle ore 09:48:24	inbound	👁	{"attributes":{"device_id":291,"inserted_at":"2023-12-07T0...	✉
7 dicembre 2023 alle ore 09:48:24	inbound	👁	{"attributes":{"device_id":291,"inserted_at":"2023-12-07T0...	✉
7 dicembre 2023 alle ore 09:48:24	inbound	👁	{"attributes":{"device_id":291,"inserted_at":"2023-12-07T0...	✉
4 dicembre 2023 alle ore 12:51:54	inbound	✗	{"attributes":{"device_id":291,"inserted_at":"2023-12-04T1...	✉
4 dicembre 2023 alle ore 12:51:54	inbound	👁	{"attributes":{"device_id":291,"inserted_at":"2023-12-04T1...	✉
1 dicembre 2023 alle ore 10:35:18	inbound	✗	{"attributes":{"device_id":291,"inserted_at":"2023-12-01T0...	✉

Figure 6.6: List of probe's messages



Conclusions and Future Works

Through the process of implementing LoRaWAN Site Survey Tool, the empirical verification of network coverage plans for LoRaWAN IoT infrastructures has been explored. The focus was on developing and implementing a comprehensive test tool. The study examines the details of LoRa and LoRaWAN, for understanding key elements influencing network performance. The research extended to network coverage planning, including link budget analysis and radio frequency propagation models such as Okumura Hata, COST231, Walfisch-Ikegami and Longley Rice. These insights proved crucial for ensuring robust and reliable LoRaWAN connectivity. The introduced test tool serves as a valuable resource for geo-located LoRaWAN message collection, benefiting installation site surveys. The LoRaWAN-SST testing tool enhances user experience, allowing surveys on Android devices with configuration on a larger screen. The incorporation of digital twin technology through the Altior platform enables real-time monitoring of node behavior, contributing to survey optimization by simulating various scenarios and configurations. Digital twins play very important role in evaluating changes in device placement, network parameters, and environmental conditions on data collection and signal strength. This forward-looking approach to network planning and optimization, supported by the Altior platform, emphasizes the significance of digital twin technology. Future research may explore the full potential of digital twins in simulating and predicting network behavior, contributing to the development of more robust coverage plans.

At the moment, locations predicted for performing surveys are known only

by their name. Users define these locations before creating the surveys. The future version will have a map using which the users will be able to input the coordinates of polygon representing the zone in which surveys are going to be performed.

For the purpose of this project, we decode only a handful of parameters present in the message. The message contains other parameters that can be used for future analysis to optimise infrastructure of the LoRaWAN network. For example, the information about number of gateways that received message from probe can be obtained. This is significant information for network planners. Future research projects may explore the full potential of digital twins in simulating and predicting network behavior, thereby contributing to the development of better coverage plans.

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