Article

LoRaWAN and Urban Waste Management – A Trial

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Abstract: The city of Lisbon, has any other capital of a European country, has a large number of issues while managing the waste and recycling containers spread throughout the city. This document presents the results of a study promoted by the Lisbon City Council for trialing LPWAN technology on the waste management vertical under the Lisbon Smart City initiative. Current waste management is done using GSM sensors, and the aim is to use LPWAN to reduce the costs, improve range and reduce provisioning times when changing the communications provider. After an initial study, LoRa was selected as the LPWAN of choice for the trials. The study is composed of multiple use cases at different distances, types of recycling waste containers, placements (underground and surface) and different kinds of waste level measurement LoRa sensors, deployed in order to assess the impact of the different use cases on the LoRa sensor usage. The results shown that the underground waste containers present the most difficult challenge, where the container itself imposes attenuation levels of 26dB on the link budget. The results promoted the deployment of a city wide LoRa network available to all departments inside the Lisbon City Council, and considering the network capacity the network, the network is also available to citizens to be used freely.

Keywords: LoRa; LoRaWAN; Trial; Waste Management; Smart City; Internet of Things;

1. Introduction

Lisbon, as many other large cities, manages its waste by employing a number of systems associated to the smart city paradigm, such as monitoring waste levels in the containers, up to optimizing waste truck routes for each of the recycling waste types (common, organic, paper, plastic and glass). The current system is based on legacy cellular technology, that poses a number of technical challenges and costs to the Lisbon City Council.

Within the scope of the Lisbon Smart City project, underway at the Lisbon City Council (CML), it is intended to provide the city of Lisbon with an LPWAN (Low-Power Wide-Area Network) network, which will cover the entire city by making available a platform for low-speed communication with the set of sensors integrated in the municipality, also commonly called IoT (Internet of Things). This network will allow the municipality to integrate a set of vertical applications, supported by a common communications network and platform, which will allow greater cost-effectiveness among different departments (and corresponding verticals).

In order to support the sensors, different LPWAN technologies are currently available on the market that could be adopted by the municipality. Among the possible alternatives [**Error! Reference source not found.**], the following stand out:

- LoRaWAN (Low Range Wide Area Network) — The complementary network layer to the LoRa technology, which, by itself, only specifies the physical layer of communication. This technology will be described in Section 2;
- SIGFOX — An alternative network also used for communication with sensors, based on a closed business model, in which the network is always supported by an

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operator, also called SIGFOX. This is the key difference to other technologies, there is only one operator;

- NB-IoT (Narrow Band IoT) — Technology supported by public mobile communications networks, resulting from an evolution of the widely deployed LTE technology. NB-IoT is the most recent IoT technology, its operating model is based on the conventional models of public mobile operators, based on a subscription.

One of the vertical applications in the municipality, with a project already underway, consists of sensing the city's waste containers. This project is supported by a set of sensors installed in the waste containers, which periodically report information on the filling level, this information is then integrated into a central management platform for this type of applications. Communication with the installed set of sensors is currently supported through modems that use public mobile communications networks (based on GSM/GPRS) to transmit the container waste level measurement data.

1.2 Purpose

Taking into account the knowledge obtained from the existing sensor network, CML determined that strategically it should define a Municipal strategy for building a common LPWAN to address all Smart City verticals. Within this scope, CML requested ISEL (one of the oldest engineering higher education institute in Portugal) a study on the applicability of the LoRa technology in order to support this network. As a use case the objective was to determine if LoRa was able to address the most demanding scenarios. The use case was then set to be the transmission of information for monitoring the filling level of waste containers used in recycling throughout the city, including the demanding underground waste containers, where GSM/GPRS wasn't able to be used without introducing physical adaptations on the containers. Thus, the objective of this document is to present the results of the tests carried out and to conclude on the technical feasibility of applying LoRa in this typical Smart City vertical application.

1.3 Organization of the document

The document is organized in 5 main sections, starting with an introduction to LoRa technology in Section 2. Followed by related work in Section 3, Section 4, presents the trials performed are described, including the sensors used and conditions considered in the definition of the different test scenarios.

In Section 5 the main evaluation results are presented and finally in Section 6 the conclusions are presented.

2. LoRa Technology – Long Range

LoRa technology is a high-range, low-power wireless transmission technology that defines the physical layer of communication between devices, operating in an unlicensed band (in Europe it operates in the 863-870 MHz band). This is the underlying technology of the LoRaWAN protocol [2], which specifies the upper layers of communication.

The main characteristics of this technology are described below.

2.1 LoRa

The main innovations introduced by LoRa are low consumption and long range, thus providing a basis for creating an LPWAN (Low Power Wide Area Network) to support the Internet of Things (IoT) and associated Smart City applications.

When operating in an unlicensed band, LoRa technology competes with all existing communications in the same band. However, it also allows any entity to install and operate its network without the need for additional licensing, also implying that limitations on the number of messages transmitted are introduced by regulatory domains. In the European case, the limitation is imposed by the so-called duty cycle, which represents the activity rate of the radio channel, with a value of 1% (in most frequencies), indicating that a device cannot transmit for more than 1% in a given period.

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The LoRa technology is patented and owned by Semtech, which is the main manufacturer of radio components, however it is supported by the LoRa Alliance organization, composed of several manufacturers and integrators, from where the standardization of the LoRaWAN protocol arose, which allows the creation of a network structure based on LoRa transmission technology.

LoRa technology uses a modulation scheme with spectrum spreading, of the CSS type (Chirp Spread Spectrum), using spreading factors between 7 and 12, depending on the transmission rate and signal level of the connection, being the factor 12, the one that introduces better guarantees of the signal reaching the destination, but also the one that has a lower transmission rate. Additionally, in order to optimize the reception of the signal, an error correction mechanism is used, and the Link Budget of a LoRa transmission can reach values of 168 dB [3]. The Link Budget is the determining factor when considering the network coverage of a device in any environment.

2.2 LoRaWAN

The LoRaWAN protocol is a link layer and network layer protocol, considering the OSI model, allowing sensors with a LoRa radio interface to communicate with applications connected to the Internet. It is promoted by the LoRa Alliance and free to use.

A LoRaWAN network is based on 4 components, as shown in Figure 1:

1. The sensor device, usually with energy and computational limitations;
2. The gateway, a network element that receives and transmits data from and to devices;
3. The network server, which forwards messages received by a set of gateways to the applications and vice versa;
4. The application, somewhere on the Internet, that receives and sends data to the sensors through the network server.

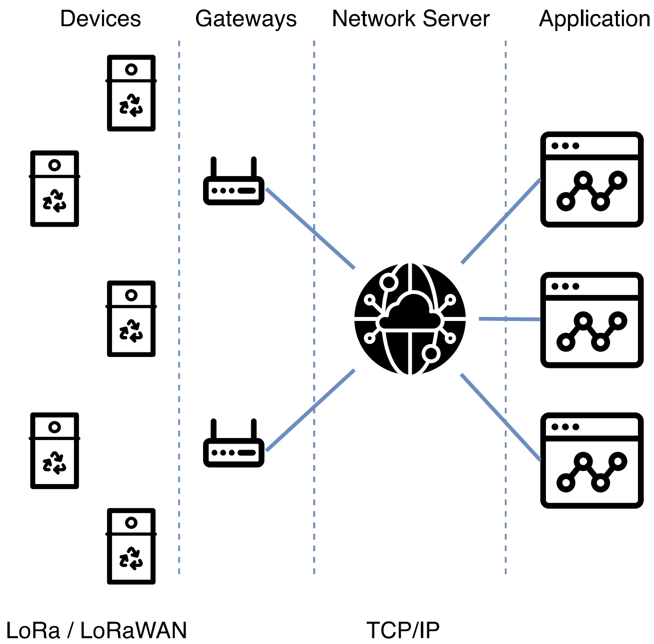

Figure 1. LoRaWAN Architecture.

LoRaWAN defines 3 device classes. The first, the most used, is Class A, which features devices that are mostly asleep, battery powered, and transmit information (uplink) only when necessary. It is possible to return some information to these devices (downlink) using reception windows that are located after the transmissions from the devices. Class B devices are devices that regularly receive information and as such combine with the network the times when they will wake up to receive that information. Finally, Class C devices are always active and can always receive information when needed.

In terms of security, LoRaWAN specifies two levels of security, the first between the device and the network, the second between the device and the application. This ensures that only the application can interpret the data sent by a device.

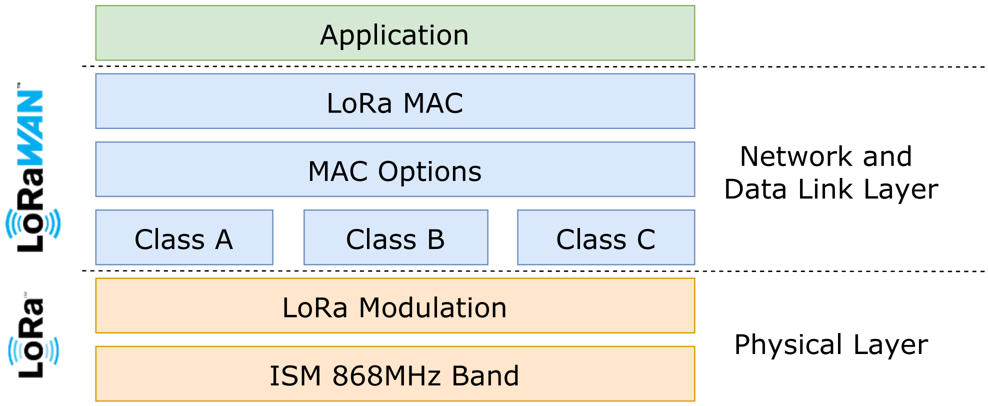

Figure 2. LoRaWAN Layers.

The LoRaWAN protocol also introduces extra features, such as the Adaptive Data Rate, which allows the network to negotiate with the devices the parameterization of the physical LoRa transmission that optimizes consumption and spectral efficiency. **Figure 2** presents a layer diagram for LoRa and LoRaWAN.

3. Related Work

The applicability of LoRa to Smart Cities has long been studied and researched. In [4] the authors evaluate the applicability of LoRa to Smart Cities by tracking the number of published works and the same Smart City vertical this paper addresses. From here they determined that the Waste Management is the second most addressed vertical on a Smart City by research with environment leading the table.

LoRa is not the only technology used for Waste Management on Cities. On [5-13] multiple Low Power Wide Area Networks types are used to address the Waste Management problem, specifying complete solutions from the sensor to the application, addressing intelligent routing of waste trucks [14-16] and energy [17-50] as two of the main issues with this kind of application.

However, regarding the practical application of LoRa based commercial sensors to commercial waste containers, in place and being used daily, the related research is scarce, being [14,51,52] some of the most relevant works that address the research on the sensor type up to the application and business case. In [14] the city of Salamanca was used as a use case, the authors used sensors developed by themselves together with commercial waste containers (although only surface ones), and in [51] the authors also developed the sensors and mostly addressed the business case, also using TheThingsNetwork as the underlying network for their trials, the same the one used on the trials presented below, however, using our own commercial gateways. In [52] the authors depict a case study in Luxembourg for improving the waste collection process. The presented case study uses Sigfox as an underlying LPWAN for the filling level sensors placed at the waste containers. In this study, authors included commercial sensors and waste containers, placing them at indoor scenarios, unfortunately the main objective of this study was the optimization of the waste collection process and not the evaluation of the impact of the different scenarios on the connectivity.

The lack of related works who address specifically trials on the network planning and connectivity requirements when using commercial solutions leads us into this work, thus effectively validating the research on sensors, networks, energy efficiency and

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communication technologies when applied to real use cases considering the currently used waste containers on a large city, it's landscape, and a network using commercially available equipment.

4. Trials

Taking into account the objectives determined for the present study, focused on the application of monitoring solid waste containers, it is essential to carry out and a set of tests that confirm the applicability of the LoRa technology. This applicability must be confirmed at two levels:

- Radio coverage, confirming whether the need to monitor containers installed on the surface and buried, is compatible with the coverage levels of the LoRa technology;
- Capacity, confirming whether the capacity offered by the network for data transmission is sufficient to satisfy the need for the application in question.

Having these objectives in mind, tests were carried out, using gateways and sensors acquired for the purpose, which are presented below.

4.1 Network deployment

In order to support the tests with urban waste, two gateways were purchased and installed, with different characteristics and positions, in order to increase the degree of validity of the tests. The gateways are integrated into TheThingsNetwork (TTN), which provides the backend network component to support gateways, namely network servers and application servers. Table 1 shows the main characteristics of the gateways used. The gateway installed in the Amoreiras building uses the existing RSB tower as support for the purpose.

Table 1. Gateways used.

Location	Model	Antennas	GNSS Position	Altitude
ISEL	Cisco IXM-LPWA-800-16-K9	2	N38°45'22.7" W9°06'57.3"	100 m
Amoreiras	Lorix One	1	N 38°43'24.0" 9°W09'47.5"	175 m

Figure 3 shows the installation of these devices. It should be noted that the equipment installed at ISEL is operating in diversity mode, with two antennas, in order to increase the probability of success in receiving messages.

(**a**) (**b**)

Figure 3. LoRa Gateways deployed at: **(a)** ISEL and **(b)** Amoreiras.

4.2. Sensors

Considering the aim and purpose of the tests, it is intended that they are based on sensors with different characteristics, allowing meaningful conclusions. For this purpose, two types of filling level monitoring sensors for waste containers were purchased, both commercial, but from different manufacturers and different cost range:

- IoTsens Waste Sensor, high-end sensor, with quality specifications and higher costs (~300€);
- Dingtek DF702, sensor with lower specifications, also corresponding to lower costs (~70€).

Both sensors use the general principle of ultrasound measurement, in which the sensor is placed on top of the container and measures the distance between the sensor and the waste. Thus, a lower distance reflects a higher filling level. This form of measurement has as its main advantages the ease of use and low cost and as disadvantages its inability to deal with situations of non-homogeneous filling levels and false positives in situations of low-density waste (such as cardboard). This implies that the position of the sensor placement and its processing capacity greatly influence the reported level.

4.2.1 IoTsens Waste Sensor

In **Figure 4**, the IoTsens sensor is shown, in which the main highlight of this device is the volumetric sensor used by Maxbotix, allowing to measure different distances up to 5 meters. Also noteworthy is its ability to measure temperatures (allowing the detection of fires), inclination of the container (for detecting dumping situations) and battery capacity (26Ah).
In terms of communications, IoTsens uses a modem from RisingHF, with a PCB printed antenna.

Figure 4. IoTsens Waste Sensor.

4.2.2 Dingtek DF702

The Dingtek DF702 device, shown in **Figure 5**, is a sensor with a lower cost, associated with its lower characteristics, namely the limitation in measuring distances greater than 2 meters and a battery of only 7Ah. These limitations prevent its installation in some scenarios, namely in underground deep containers.

Like the IoTsens sensor, the modem used is RisingHF, however using a helical antenna.
Despite the low cost, the Dingtek DF702 sensor has superior mechanical strength, observable by the thickness of the box and in the form of a seal to guarantee its tightness.

Figure 5. Dingtek DF702.

4.2.3 Sensor deployment

Given the characteristics of the sensors, we opted to apply IoTsens to underground waste containers and Dingtek to Iglô and Cyclea. For this purpose, metal supports compatible with the containers and sensors under test were developed.
Figure 6 shows both containers (Iglô and Cyclea) at ISEL during its installation phase. Dingtek DF702 sensors were installed in both containers, using different fixings and adapted to each type of container.

Figure 6. Cyclea (blue) and Iglô (green) containers installed at ISEL.

In Figure 7 it is possible to observe the installation of the sensor in an Iglô and in Figure 8 it is possible to verify the installation of the sensor in a Cyclea container. Cyclea containers are used for different types of waste, however they share the same support for the sensor.

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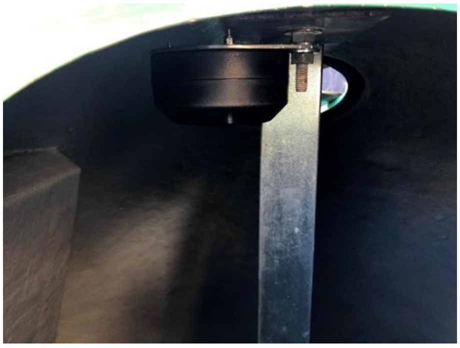
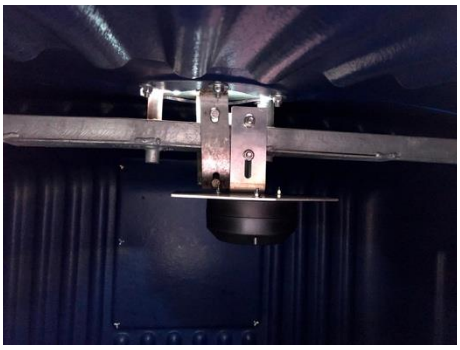


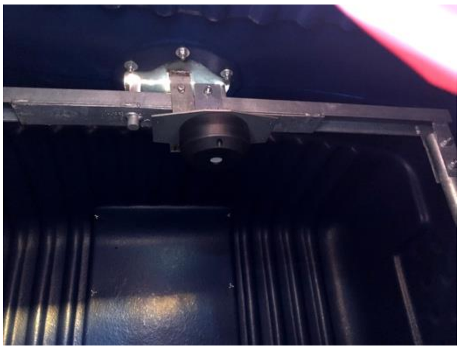
(a)

(b)

Figure 7. Dingtek DF702 installed in the Iglô: **(a)** Side view; **(b)** Bottom view.



(a)



(b)

Figure 8. Dingtek DF702 installed in the Cyclea: **(a)** Side view; **(b)** Bottom view.

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(a) (b)

Figure 9 shows the installation of the IoTsens Waste Sensor in an underground container. The installation was made using two holes already existing on the underside the metallic cover. In this same cover, it is possible to observe the legacy sensor installed and in use, this sensor needs an external cellular antenna to communicate correctly. The IoTsens sensor was installed in a position that facilitates the measurement, but that technically presents greater difficulties in the transmission of information, due to the distance from the waste collection shaft. This position was chosen for reusing existing wholes, not requiring any new drilling, but also for introducing more challenges to the correct operation.

(a) (b)

Figure 9. IoTsens installed on the underground waste bin: **(a)** General view; **(b)** Cover underside view.

4.2. Use cases

During the tests, three different use cases were selected. The first at a short distance (~ 100m), the second at an average distance (~ 1km) and a third at a longer distance (~ 5km). These three use cases allowed to evaluate the capacities of the sensors to transmit information in different conditions of radio propagation. The short distance scenario would have an expected success and served as a baseline for the others.

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(a) (b)

Figure 10. Map showing the distances from the sensors at the underground containers (RU) to the LoRa GW at ISEL.

Thus, the short distance sensor, Iglô, was installed in ISEL (N38°45'19.7" W9°06'58.0"), visible in Figure 10, the medium distance sensor was installed in an underground container, next to Spacio Shopping (N38°45'42.3" W9°06'52.3") and finally the Cyclea container was installed at a long distance, at Largo da Princesa in Belém (N38°41'41.9" W9°12'57.4"), visible in Figure 11.

Figure 11. Map showing the distance from the sensor to the LoRa GW at Amoreiras.

5. Evaluation

The test results, carried out according to the conditions defined in the previous section, allow to assess the applicability of the LoRa technology to the application of measurement and level of filling of urban waste containers. Thus, the following section presents the radio coverage results obtained in the different scenarios.

Results will also be presented regarding the impact of installation conditions on the level of radio coverage, which may be useful, not only within the scope of this study, but also in the context of producing specifications, allowing for more correct radio coverage requirements to be established. for different applications.

5.1. Radio Coverage

As expected, the reduced distance scenario presented no challenges to the LoRa technology, with all data received constantly. However, the longer distance scenario (~ 5 Km), proved to be too demanding, and not a single transmission of the sensor installed in Belém was ever heard at Amoreiras.

A more detailed analysis of the terrain profile in the situation and the longer distance, shown in Figure 12, shows that there will be no line of sight between the location of the container installation and the nearest gateway, due to the morphology of the terrain, namely Monsanto (a large city managed forest/park), but also due to the urban landscape existing on the radio route.

Figure 12. Distance profile between the waste container at Belém and the LoRa gateway at Amoreiras.

The scenario of the underground container, presents challenges in terms of good reception of the signal due, not only to the installation site, but also due to the metallic construction of the container, particularly the steel cover and pavement applied on the cover upper surface. This installation context prevents, for example, direct radio communication with the legacy sensors currently installed with GSM/GPRS technology, requiring the placement of an external antenna, outside of the waste container, in order for it to work correctly. Installing an external antenna voids the watertightness of the waste container and is undesirable.

Figure 13 shows the terrain profile between the ISEL gateway and the underground waste container, where it is also visible that there is no line-of-sight communication. This factor aggravates the existing bad radio conditions, but it is a good opportunity to study the performance of technology in unfavorable situations.

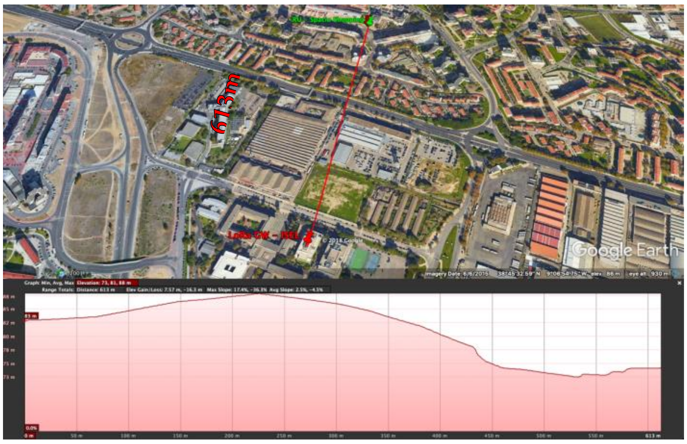

Figure 13. Distance profile between the waste container at Spacio Shopping and the LoRa gateway at ISEL.

In Figure 14, the values reported by the filling level measurement sensor are presented. It presents the measurements reported by the sensor from its installation to its collection. It should be noted that for about two months, starting in mid-March, there were no measurements, due to an fault in the existing gateway. This situation led to the need to replace the gateway with new equipment that entered service on May 15.

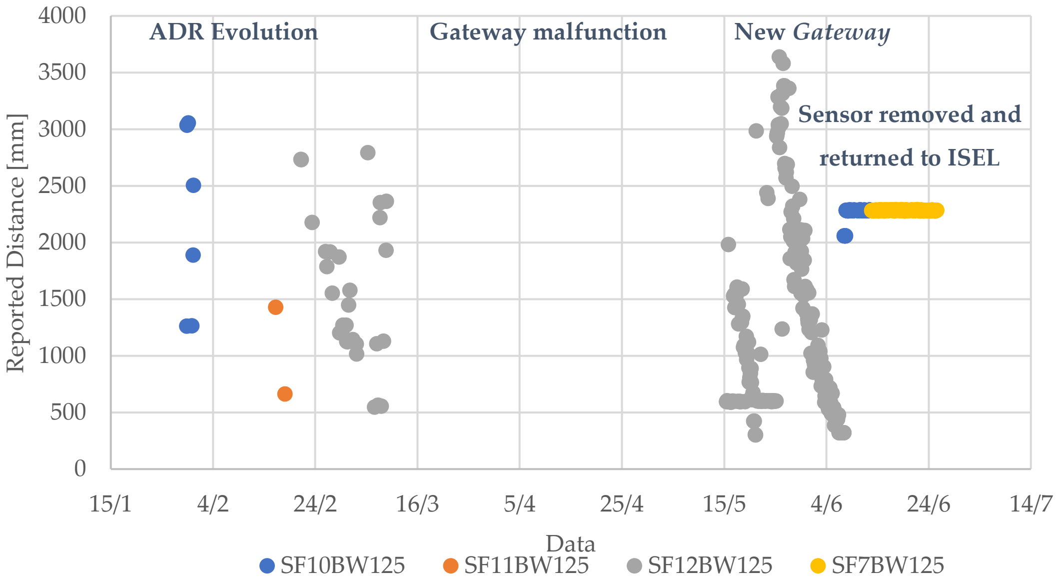

Figure 14. Measurements received from the underground container at Spacio Shoping.

The evolution of the spreading factor due to the ADR (Adaptive Data Rate) of the LoRa is visible in the initial part of the chart. This automatic adaptation mechanism allows the system to switch spreading factor (between 7 and 12) according to the radio conditions, allowing to optimize the relationship between the transmission rate, duty cycle and energy consumption, leading to greater spectral efficiency and energy. A lower spreading factor leads to a higher transmission rate and a lower channel occupation time. However, it requires a better signal-to-noise ratio (SNR), which is only possible if the attenuation of the radio link is low and the level of noise and interference too. On the contrary, a maximum spreading factor leads to a lower rhythm and consequently a much longer emission times, with greater energy consumption. Thus, the system uses the scattering factor that optimizes this equation.

In the figure it is possible to observe that the first messages were received with SF10BW125, which corresponds to a spreading factor of 10. However, there is a lack of continuous reception of messages, caused by a high error rate. Thus, it is possible to observe the transition to the spreading factor 11 and, later, to the maximum of 12. From that point, the frequency of receiving messages increases. Finally, after collecting the sensor, for a more favorable position (office at ISEL), the spreading factor decreased again, until the minimum value of 7 (purple in the figure).

It should be noted that the validation of the reported distance to waste values is not the object of this study. However, it is possible to observe that, after the new gateway goes into operation, the gradual filling pattern of the container is clearly identified and a situation in which the distance returns to the maximum value, which should correspond to the collection of accumulated waste, thus leading the sensor to report maximum distance from the sensor position to the bottom of the container.

5.2 Deployment conditions impact

In order to deepen the knowledge about the limitations imposed by the material used in the containers, tests were carried out that allowed to determine the impact of different materials on the transmission. These tests were then carried out for Iglôs (Empty and Full) and for underground containers (Full). For the tests, a probe was developed, visible in Figure 15, which sends 5 messages of two different dimensions (4 and 8 bytes), using each of the different parameters of the LoRa modulation (SF7 to SF12), which totals 60 messages sent in each of the tests. The sizes depict the actual size of the data sent by the Dingtek (4

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Bytes) and IoTsens (8 Bytes) sensors. Algorithm 1 depicts the implementation of the network assessment procedure.

Figure 15. LoRa probe installed on top of an Iglô.

Algorithm 1 Network Probe

Input: Datarates and Payloads do be tested
Output: Perceived RSSI of each message

initialize radio at device
initialize application connected to TTN
for each payload **in** payloads[] **do**
    for each datarate **in** datarates[] **do**
        set datarate
        send payload
        sleep in order to comply with the duty cycle
collect RSSI values from application

5.2.3. Iglô

Two tests were performed on different glass containers, one full and one completely empty. Table 2 shows an analysis on the signal level (RSSI – Received Signal Strength Indicator) of the messages sent by the probe when installed inside and outside each one.

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Table 2. RSSI measurements on Iglôs containing glass.

Scenario	RSSI value [dBm]			
	Min	Max	Avg	StdDev
Iglô full				
Interior	-91	-66	-73,75	5,18
Exterior	-83	-65	-71,82	3,69
Difference	**-8**	**-1**	**-1,93**	
Iglô empty				
Interior	-85	-62	-70,07	5,18
Exterior	-72	-59	-63,98	3,38
Difference	**-13**	**-3**	**-6,09**	

In terms of impact on the signal, it is observable that the Iglô introduces an average attenuation of 6 dB when empty and about 2 dB when full. It should be noted that the measurements were made in containers whose model is identical, but were in different positions within ISEL. The measurements were also made on different days and at different times of the day, so the comparative analysis should focus on inside/outside conditions, that is, the difference in the RSSI value, representing the impact of the waste container build material.

5.2.4. Underground container

The underground container, as expected by its steel construction, introduces a much greater attenuation, reaching average attenuation values above 26dB. These values are visible in Table 3. This fact will imply that in terms of dimensioning the radio network it will be necessary to account for this increase in terms of link budget, in order to allow the use of sensors without external antennas.

Table 3. RSSI measurements on underground containers.

Scenario	RSSI value [dBm]			
	Min	Max	Min	StdDev
Underground Container				
Interior	-127	-111	-121,31	2,32
Exterior	-115	-87	-94,90	6,29
Difference	**-12**	**-24**	**-26,41**	

6. Conclusions

The objective of the study presented here was to verify the applicability of LoRa technology to support the transmission of information, to monitor the level of filling of waste containers throughout the city of Lisbon. With this objective, a set of tests were carried out, under different conditions and scenarios, allowing the conclusions presented here to be supported by empirical knowledge, which complements the existing technical and scientific information.

In the case of coverage over long distances, the failure to receive messages confirmed the criticality of rigorous network planning, in order to ensure adequate radio coverage of the city. It is therefore essential to adopt project margins compatible with existing conditions. It also demonstrated the importance of the characteristics of the antenna used in the sensor and its impact on the performance of radio communication.

Regarding the coverage of underground waste containers, a situation that is expected to be more unfavorable than the other different verticals, there is the possibility of radio coverage that makes communication possible, even in a situation of no line of sight. Thus,

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the tolerance to high levels of attenuation of LoRa is confirmed. It was therefore interesting to verify the performance of this technology, in comparison with the solution currently installed (GSM/GPRS), under the same installation scenario, even in the most adverse conditions.

Based on the results presented, it is possible to conclude that LoRa allows to fully support the transmission of data to monitor the filling level of waste containers. This possibility applies at the following levels:

- Capacity, where it was possible to confirm that the capacity offered by technology for data transmission is sufficient to satisfy the need for the application in question, even in unfavorable conditions, which imply a lower transmission rate;
- Radio coverage, showing the feasibility of using LoRa technology to support communication with sensors installed inside the different types of containers. This possibility was validated in the most unfavorable situation, namely in underground containers, with additional attenuations, associated with the penetration of the radio signal.

Ultimately, this research led to the deployment of a municipality wide local area network to support the Waste Management Department and the Public Park Management Department of the Lisbon Municipality as well as preparing the grounds for other initiatives promoted by Lisbon City Council.

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