

Deployment of a Lorawan Network and Evaluation of Tracking Devices in the Context of Smart Cities

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Research

Keywords: Internet of Things, Smart cities, LoRaWAN, GPS, tracking device

Posted Date: October 27th, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-95995/v1>

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RESEARCH

Deployment of a LoRaWAN network and evaluation of tracking devices in the context of smart cities

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Abstract

Recent public cooperation between the Federal University of Technology Paraná and Toledo Municipality plans to implement the concept of smart cities in this city. In this context, one of the applications under development intends to track the recyclable garbage collector trucks in real time over the Internet. Actually, fleet vehicle tracking is one of the main applications for smart cities. LoRaWAN stands out among network technologies for smart cities due to operating in an open frequency range, covering long distances with low power consumption and low equipment cost. However, the coverage and performance of LoRaWAN is directly affected by both the environment and configuration parameters. In addition, tracking devices must be able to send its coordinates to the Internet even when the vehicle goes through zones where there are obstacles for electromagnetic waves, such as elevated buildings or valleys. In this paper we perform experimental investigations to evaluate four LoRaWAN tracking devices, two out of the box commercial and two assembled and programmed. The behavior of each tracking device is analyzed when moving through three representative urban areas. As the devices depend on the quality of the signal offered by the network, we also present the results of the development and evaluation of the LoRaWAN network, planning its coverage throughout the city. Results of tracking devices were analyzed under quantitative and qualitative aspects, including the received signal strength indication (RSSI), signal-to-noise ratio (SNR), package delivery ratio (PDR), and spreading factor (SF) for the geographic coordinates received.

Keywords: Internet of Things; Smart cities; LoRaWAN; GPS; tracking device

1 Introduction

Despite there is still no consensus on what characteristics or requirements define smart cities, some definitions are technology-based [1]. In this sense, the combination of sensing technologies, long-range wireless networks, and computational infrastructure for processing large volumes of heterogeneous data enables the development of intelligent and scalable solutions to deal with the challenges of large urban centers [2].

A fundamental requirement for any smart city application is the ability to transmit their data through a communication network [3]. In a smart city, a data communication network is not used to exclusively connect people, but any object [4]. The Internet of Things (IoT) concept is used to define objects connected to the Internet

capable of generating useful data and being represented in the virtual world [5]. Such objects have particular characteristics regarding the use of a network: (i) they send small amounts of data periodically; (ii) connect directly to the Internet or to each other via a wireless link; (iii) are powered by batteries and/or solar panels; (iv) they may be spread over areas of difficult access and (v) they are fixed or moving – on a utility pole or in a moving vehicle, for example. In this scenario, Low Power Wide Area Network (LPWAN) is a class of networks characterized by low power consumption and coverage of large areas designed to provide connectivity for the IoT objects, particularly for typical smart city applications [6, 7, 8].

Among the main LPWAN technologies and protocols are NB-IoT (Narrowband IoT) [9], SigFox [10] and LoRaWAN (LoRa Wide Area Network) [11]. Although they share several similarities, the main difference is in the cost of licensing use. The NB-IoT network is based on the licensed LTE (Long Term Evolution) network, also known as 4G, and already existing in cellular operators. SigFox acts as a conventional telecommunication operator, deploying the necessary infrastructure to operate the network, but charging the customer for its use. On the other hand, the open standard LoRaWAN operates on wireless technology LoRa (Long Range) [12] and does not charge any fee for the use of the network. However, is the user's responsibility to deploy and maintain the LoRaWAN infrastructure.

Recently, the Federal Technological University of Paraná (UTFPR) and the Municipality of Toledo entered into an agreement to develop the concept of smart cities. LoRaWAN is the network chosen to support the smart cities initiative in Toledo mainly because it is possible to install and expand the network whenever necessary with a relatively low investment. One of the applications under development is fleet vehicles tracking [13]. The municipality would like a system to track the recyclable garbage collector truck. Through a GPS (Global Positioning System) device attached to the vehicle, it is possible to track it within the city and make its route available in the cloud in real-time. Additionally, applications running in the cloud can estimate vehicle speed and also emit alerts when it approaches or distances from an origin or deviates from a predefined route.

However, the success of the tracking application depends directly on its ability to send the coordinates to the Internet even when the vehicle goes through zones where there are obstacles for electromagnetic waves, such as elevated buildings, trees, flatlands, or valleys. The obstacles and irregular terrain profile attenuate the signal, reduce communication distance, and can even prevent communication. Despite the physical layer of LoRaWAN advocates to range 5 km in urban areas, being robust against a high degree of interference in addition to multi-path and Doppler effects [8, 14], we need to know how LoRaWAN behavior in the field, including its real range, with moving objects to perform possible optimizations and properly configure the network and applications aiming its implementations in a real scenario. In the other hand, the IoT market currently offers several end devices with GPS and LoRa transmitter with the promise of real-time tracking [15, 16, 17]. Therefore it is essential to check whether these devices can in fact be adopted in a real scenario.

In this paper we perform experimental investigations to evaluate commercial and assembled LoRaWAN tracker devices aiming to understand the behaviour of such

devices in order to select the most suitable to be installed in the recycling garbage trucks in the future. Although the literature presents important investigations on how to correctly configure LoRa parameters, including when there are mobile nodes, in different environments [18, 19, 14, 20], as far as we know there are no practical evaluations comparing commercial and non-commercial LoRaWAN tracking. Furthermore, each environment presents particular a set of characteristics that make it unique and challenging for radio propagation, as vegetation, climate, Line-of-Sight (LoS), etc.

We assessed four tracking devices, two out of the box commercial devices, and two assembled and programmed. Both commercial devices are projected for tracking on LoRaWAN networks. The third device has a built-in GPS and LoRa transmitter, being the LoRaWAN layer programmed using the LMIC library[21]. The fourth device was assembled using an Arduino Uno, a GPS transmitter, and a commercial LoRaWAN transmitter. All four devices were attached to a vehicle, simulating the recyclable garbage collector truck. The evaluation took place in three areas around the university campus, with approximate sizes of 0.34 km^2 , 0.77 km^2 and 9.6 km^2 . The results show the packet delivery ratio (PDR) as the efficiency of each device in the three areas. PDR is the number of packets delivered in total to the total number of packets sent from a device to the LoRaWAN gateway. There is also a qualitative evaluation, which considers received signal strength indicator (RSSI), signal-to-noise ratio (SNR), and spreading factor (SF) for the geographic coordinates received. The cost benefit of each device is also presented.

The evaluation of tracking devices is strictly linked to the signal quality offered by the LoRaWAN network. Therefore, we deployed the LoRaWAN network on the rooftops of a building in our campus with an SX1301 LoRa gateway and have conducted simulations and practical experiments to evaluate both RSSI, SNR and PDR parameters inside campus surroundings and also in some more distant city locations. In Toledo there is no study on radio frequency propagation in the 915 MHz spectrum, so the data obtained are compared with a network coverage model obtained by the CloudRF tool [22]. In this sense, UTFPR is located in a privileged region, which allows evaluating the network signals in both rural and urban areas. With the results both of the network and tracking devices in hand we also present in this work the network expansion plan to cover the municipality.

This paper is organized as follows. Section 2 summarizes the main LPWAN standards with emphasis on LoRa and LoRaWAN and also presents a review of main related works. Section 3 describes the deployment of the LoRaWAN network, the tracking devices assessed, and the evaluation methodology in the context of this network. Section 4 presents and discuss the results obtained. Finally, Section 5 presents the conclusion and future work.

2 LPWAN networks

LPWAN is a class of wireless standard that has becoming a promising technology for supporting the growing of Internet of Things paradigm mainly because of its low power, long range, and low-cost communication characteristics [23, 24, 8]. Among the main LPWAN technologies are NB-IoT (*Narrowband Internet of Things*) [9], SigFox [10], and LoRaWAN [11], described next.

The working group 3GPP (3rd Generation Partnership Project) started to work on the specifications for NB-IoT in 2014 and completed the standardization on June 2016 [25]. The network makes can coexist with the existing network infrastructure of cell phone operators (e.g., LTE or GSM) under licensed frequency bands. NB-IoT occupies a frequency band width of 200 KHz, which corresponds to one resource block in GSM and LTE transmission. The modulation employed is the quadrature phase-shift keying modulation (QPSK) and the data rate is limited to 200 kbps for the downlink and to 20 kbps for the uplink. The maximum payload size is 1600 bytes for each message. The range is estimated at 1 km for urban areas and 10 km for rural areas. One of the great advantages of the standard is that network infrastructure services are provided by operators, enabling the rapid deployment of IoT systems. In Brazil, the operator TIM implemented in June 2018 a pilot NB-IoT network in the city of Santa Rita do Sapucaí, Minas Gerais state [26].

Sigfox is a French global network operator founded in 2010 that offers an end-to-end IoT connectivity solution based on its patented technologies. In this standard, the customer acquires a license to use the network. SigFox deploys its base stations equipped with cognitive software-defined radios. Base stations are connected to servers using an IP-based network. The end devices connected to SigFox base stations using binary phase-shift keying (BPSK) modulation in an ultra-narrow band (100 Hz) sub-GHz ISM band carrier. The operator allows a range of 3 km to 10 km in urban areas and 30 km to 50 km in rural areas. It has a data rate of 100 bps carrying up to 12 bytes of uplink, limited to sending 140 messages per day and 8 bytes of downlink with 8 messages per day. WND Brasil is the Sigfox Operator for Brazil [27]. Currently there is no no SigFox network installed in Toledo, a city with population close to 140,000 inhabitants located in the western region of Parana state.

NB-IoT and SigFox require an infrastructure provided by operators through the payment of periodic subscriptions and licenses. On the other hand, LoRaWAN does not require any payment and allows anyone to install the infrastructure needed for its operation. Next we present LoRa, LoRaWAN and some related work that implement geolocation and tracking applications on the LoRaWAN technology.

2.1 LoRa and LoRaWAN

LoRa is a physical layer technology for bidirectional wireless communication developed and patented by Semtech [28]. The technology modulates the signal in the sub-GHz frequency range using chirp spectral spreading (CSS), which allows it to cover long distances with low levels of interference. A LoRa message can be of two types: uplink or downlink. The message structure is similar in both cases, however, only the uplink message adds a verification code (CRC) to ensure the integrity of the payload (PHYPayload).

LoRa uses unlicensed ISM (Industrial, Scientific and Medical) bands, i.e., 868 MHz in Europe, 915 MHz in Australia and North America, and 433 MHz in Asia [8]. In Brazil, LoRa uses the 915 MHz band, comprising 902 MHz to 907.5 MHz and 915 MHz to 928 MHz. In 2018, the Brazil National Telecommunications Agency (ANATEL) published the act *n*^o 6,506 which approves the procedures to assess the conformity of radiocommunication equipment with restricted radiation, allowing

the operation of LoRa devices in the national territory [29]. Although it is possible to use two transmission bands, the American and the Australian [11], the latter has been adopted in Brazil. The Australian standard has 72 channels for uplink and 8 for downlink. The uplink channels range from 0 to 63 and use a bandwidth of 125 kHz with a coding rate of 4/5, starting at 915.2 MHz with a linear increment from 200 kHz to 927.8 MHz. On the other hand, the channels from 64 to 71 have a bandwidth of 500 kHz starting at 915.9 MHz, increasing linearly from 1.6 MHz to 927.1 MHz. The downlink channels range from 0 to 7 and have a bandwidth of 500 kHz, starting at 923.3 MHz with linear increment from 600 kHz to 927.5 MHz.

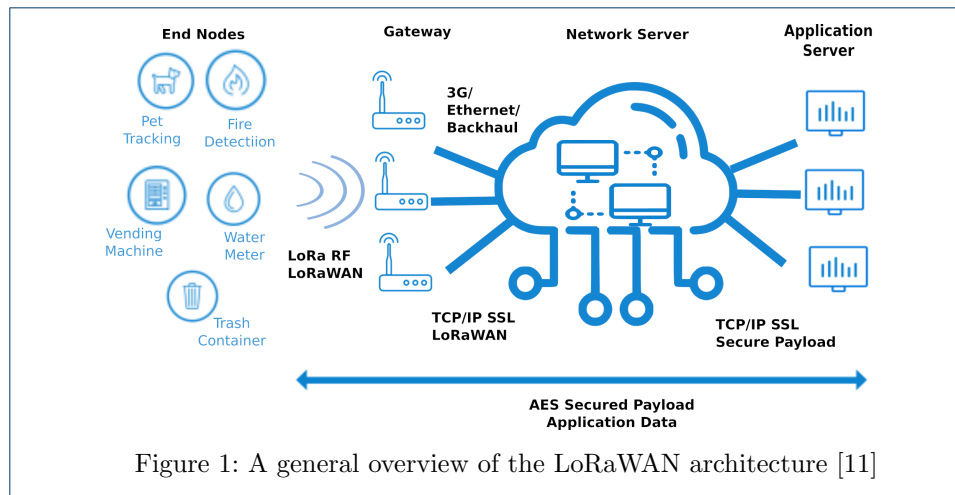
There are four configuration parameters for the LoRa physical layer that determine power consumption, transmission range and noise resilience [30, 31]:

- Carrier Frequency (CF): this is the frequency used for the transmission band and it is defined according to the region of operation of the equipment;
- Code Rate (CR): the CR is the degree of redundancy implemented by the forward error correction (FEC) used to detect errors and correct them. This rate is fixed at 4/5 for the LoRaWAN protocol;
- Spreading Factor (SF): determines the number of chirps required to represent a symbol (one or more bits of data). LoRa defines six different values for the SF parameter (SF7-SF12). The larger the spreading factor, the farther the signal will be able to be received. In the same channel, a packets using different spreading factors are orthogonal, i.e. they are invisible to each other;
- Bandwidth: this is the range of frequencies used in the transmission band and can assume three determined values, 125 kHz, 250 kHz or 500 kHz, suffering a displacement of up to 20% that will not influence the decoding.

The LoRa physical layer may be used with any MAC layer. However, LoRaWAN is the currently proposed MAC which operates a network in a simple star or star-of-star topology. LoRaWAN is an open communication protocol for LoRa networks managed by the open and non-profit entity LoRa Alliance, which brings together more than 500 members around the world. An overview of the architecture of a LoRaWAN network is shown in Figure 1. A gateway connects the devices on the LoRaWAN network to the Internet through the network server, which manages the communication of the devices with the application server. The end nodes are objects equipped with sensors and/or actuators. The application server provides the information from the devices to the end user [11].

An important feature of the LoRa technology, called adaptive data rate (ADR), resides in the network server. ADR allows adapting and optimizing the data rate for the static end devices. For mobile end devices data rate should be fixed once mobility can cause significant temporal variations for the radio channel characteristics [14].

The MAC layer of LoRaWAN defines pure ALOHA for the access of the medium. In this layer, end devices can take one of three configurations. Class A is the mandatory configuration in all classes. In this class, the end device initiates communication with the gateway, making a transmission and opening two windows to receive data from the gateway. In class B, the process is similar to that of class A. The class B device also opens two reception windows after performing a transmission. However, in addition, class B devices open reception windows with scheduled times, configured through beacon messages sent by the gateway. In class C, the end device



performs a data transmission, opens two reception windows and keeps one window open until the next transmission, making the final device require a constant source of energy.

In terms of security, LoRaWAN relies on the standardized AES cryptographic algorithm and offers two levels of cryptography. The first is located in the network layer to guarantee the authenticity of the end device. The second is located in the application layer in order to guarantee the confidentiality and integrity between the end device and the application server. There are two types of authentication: OTAA (Over The Air Activation) and ABP (Activation By Personalization). The first is more secure because it is the device itself that manages its activation.

2.2 Geolocation and Tracking through LoRa/LoRaWAN

In [32, 33] two practical works are proposed. James and Nair [32] proposed an alternative to conventional public transport tracking systems normally based on GPS. The proposed model uses LoRa wireless transmission to communicate between bus stop points and a base station. Communication between buses and points takes place via RF transmitters. Whenever a bus approaches a stop, the data is directly transmitted to the gateway, which in turn makes the bus geolocation available to users. Among the advantages of the adopted solution are the low cost of the installation, since it does not use GPS, and the low energy consumption. However, the solution requires predefined routes and a fixed point to collect vehicle data in order to estimate its geolocation.

Hattarge, Kekre and Kothari [33] state that deploying traditional GPS trackers can significantly reduce the maintenance cost by using LoRaWAN instead of GSM/GPRS modules. They provide a GPS localizing system based on LoRaWAN technology combined with an Android application for a smart public transport system. A prototype was built and tested using Arduino Uno as transmitter and NEO-6M as GPS module. Works described in [34, 35] also propose tracking systems based on LoRa, GPS and Arduino to estimate the speed and geolocation of tourist boats in a protected park in Malaysia and tracking troops in Thailand, respectively.

Geolocation in LoRa with the absence of an GPS is studied in [36, 37]. Podevijn *et al.* [36] propose a solution where Time Difference of Arrival (TDoA) is processed at

network level in a public LoRa network. The work provides experimental quantification of TDoA geolocation performance. The authors also investigate and determine the best LoRa spreading factor to use with respect to updating frequency and positioning accuracy. According to the authors the median accuracy of 200 m was obtained for the raw TDoA output data. Fargas and Martin [37] also propose a system where geolocation is calculated applying a multilateration algorithm on the gateways timestamps from received packages. However their solution demonstrated to be able to locate a static spot with an accuracy of around 100 meters, the solution does not present good results for real-time tracking application.

Experimental works, including mobility, are developed in [14, 19, 18]. Petäjäjärvi *et. al.*, carry out experimental validations of various performance metrics of LoRa through different configurations and scenarios in Finland [38, 39, 14]. In relation to mobility [14], LoRa's performance in the presence of the Doppler effect is analyzed experimentally. Results show that for an SF=12 (which allows greater distances to be reached) and when the relative speed exceeds 40 km/h, the communication performance deteriorates. On the other hand, with the same SF and lower speeds, below 25 km/h, communication is still sufficiently reliable. The conclusion is that LoRa can be used in monitoring or tracking applications. The authors also state smaller SFs should be less affected by the Doppler effect and thus more suitable for mobile scenarios.

The work of Liando *et al.* [19] perform measurements to evaluate LoRa, including the Doppler effect in mobile nodes. They employed a mobile LoRa gateway by the roadside and attached an end device to a car used as moving transmitter. The speed of the car varied from 50 to 80 km/h. In the experiment, they fixed SF=12 and ensuring Line of Sight (LoS) between the end device and the gateway during the experiment. In this scenario, they conclude more 85% of sent messages were received taking in account all speeds. Other studies about LoRa, including mobility, were conducted in Romania [20] and Singapore [19].

In Brazil, Ferreira *et al.* [18] study the propagation of LoRa signals in forest, urban, and suburban vehicular environments. One of the goals is to understand how LoRa could be used for alternative applications such as geolocation of hikers in a natural park. They build LoRa prototype nodes using Arduino Uno R3, LoRa transmitter and receiver, and GPS receiver. The authors do not employ LoRaWAN because the work focus on propagation and communication device-to-device. The scenario with mobile transmitter takes place in both a suburban and rural zones where a mobile device is moving at a speed of approximately 90 km/h. As [14], they also conclude that LoRa devices configured with an SF=12 and moving at a moderate speed (around 40 km/h) do not disrupt LoRa communications, while a device at a high speed (around 90 km/h), increases the probability of disrupting the link. Other works found in Brazil study the application of LoRaWAN for smart grids [40, 41] and deployment of LoRaWAN in rural areas [42].

Unlike [14, 18, 19], in our work the SF was not previously defined in the tracking devices. During the experiments we recorded the SF of each message sent from all tracking devices to the gateway. Results obtained from SFs are analyzed in Section 4.2.2. Also, unlike [18] we focus on LoRaWAN and communication device-to-gateway. As far as we know this is the first study to evaluate and compare both commercial and assembled tracking devices in a LoRaWAN network.

3 Methodology

In this section, we present the methodological approach used in this work to deploy the LoRaWAN network and evaluate the tracking devices.

The smart cities project in Toledo/Brazil aims to develop applications in typical smart city domains such as environmental monitoring [43, 44], public transport [32], and fleet vehicles tracking [13]. As the first step, we deployed the LoRaWAN network at the UTFPR-Toledo campus. Then, a theoretical coverage model of the network signal was defined using a simulation tool and taking into account the deployment characteristics and hardware features. After that, an empirical evaluation of the theoretical network coverage model was conducted for a set of n predefined places. The results obtained were the input for defining the areas where de tracking devices were evaluated. Each device was evaluated through a quantitative and qualitative analysis. The results helped us to understand the behavior of the LoRa signal within the previous defined area and the behaviour of each device inside the area. We detail each step next.

3.1 The LoRaWAN network deployment

Firstly, the gateway was installed on the fourth floor of one of the UTFPR buildings (denoted as “Building E” in the following figures), and a 6 dBi omnidirectional antenna was positioned about 20 meters high on the top of this building. The gateway is compound by a Raspberry Pi 2 and one LoRaWAN hub which uses a digital baseband chip Semtech SX1301. This gateway communicates with the LoRaWAN network server The Things Network (TTN) [45] and with the application server TagoIO [46].

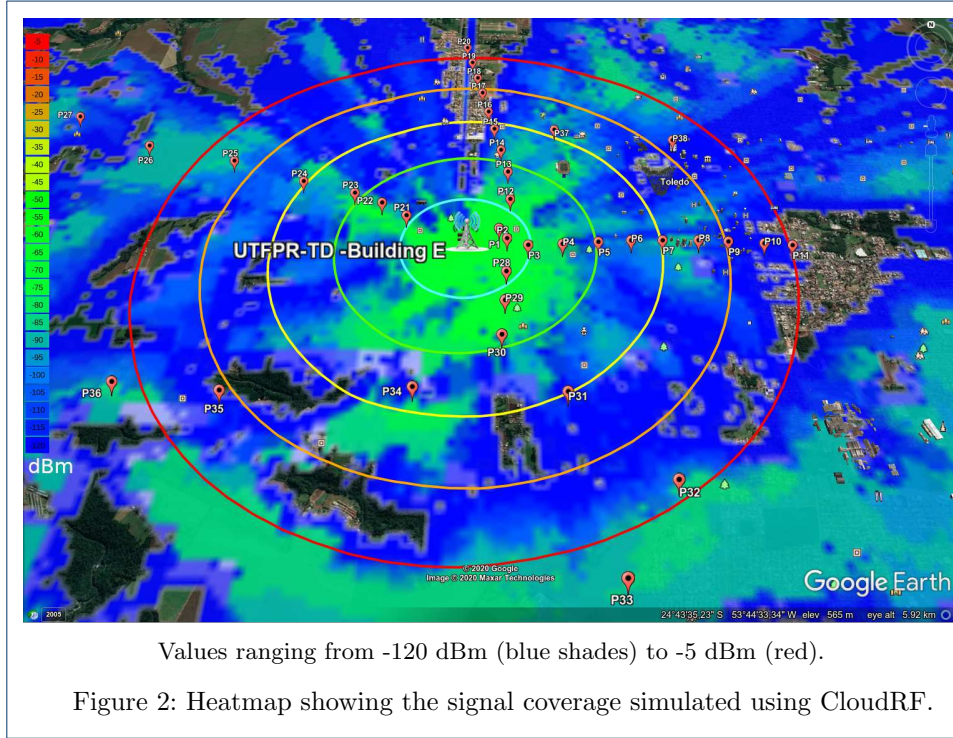
3.2 Network coverage estimation and evaluation

Once the network was installed, Google Earth was employed to make an evaluation scenario aiming to assess the network’s coverage considering the radio-frequency (RF) propagation using 915 MHz range. Associated with the Google Earth, the CloudRF [22] online service was used to model the RF propagation signal into the interior area of interest. Table 1 lists the parameters and respective values used such as the LoRa frequency, gateway geolocation, and antenna specificities. The propagation model adopted was the Irregular Terrain Model (ITM), also known as the “Longley Rice” model, with 90 meters of terrain resolution within a 40 Km radius.

<i>Parameter</i>	<i>Setting</i>
<i>Frequency</i>	915 MHz
<i>Latitude</i>	-24.733594
<i>Longitude</i>	-53.763812
<i>Height AGL</i>	20 m
<i>Azimuth</i>	359°
<i>Antenna Gain</i>	6 dBi
<i>Height(s) AGL</i>	1,5 m
<i>Gain</i>	5 dBi
<i>Propagation model</i>	ITM/Longley-Rice (< 20GHz)
<i>Terrain resolution</i>	90 m/198 ft (DMS)
<i>Radius</i>	40 Km

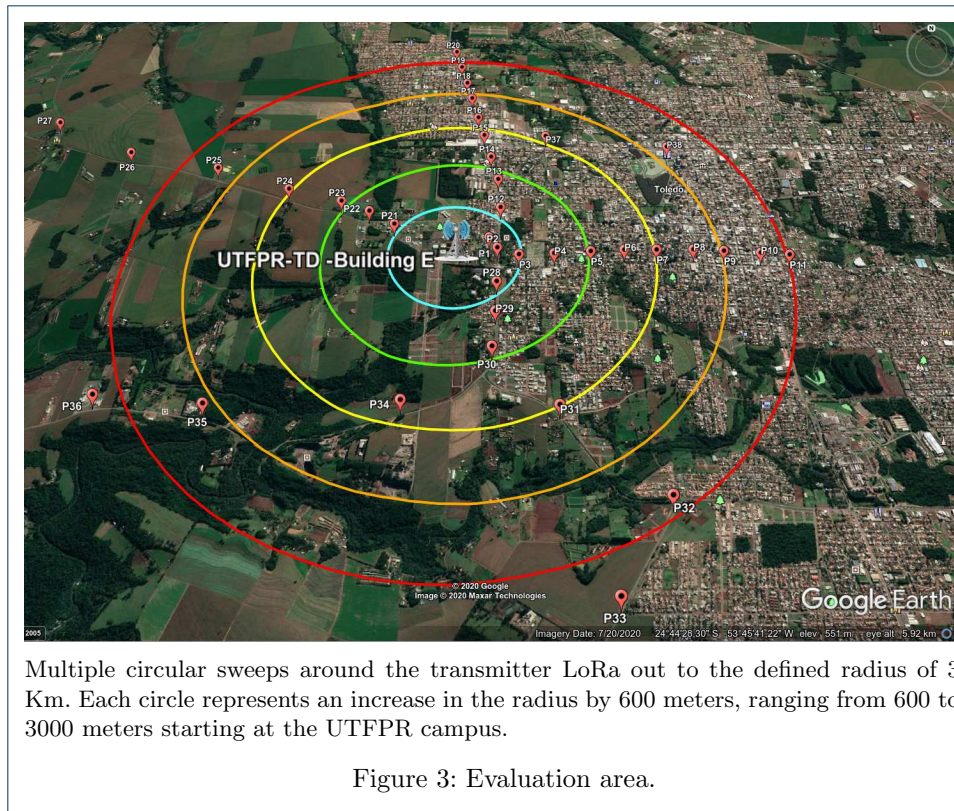
Table 1: CloudRF configuration parameters.

Figure 2 shows the simulation of pronation based on relief using CloudRF. CloudRF does not taking into account obstacles such as buildings, trees and others. The heatmap (colored layer on the map) shows which areas have the dB coverage as indicated by the color schema on the left. For the sake of readers' understanding, the limiting circles and respective evaluating points were overlaid to the covered area predicted by the simulation model.



It's worthy to mention that the location of the building where the LoRaWAN gateway was installed is strategic, as it allows assessing both the urban and rural areas. This particularity can be seen in the Figure 3. A maximum radius of three kilometers from the gateway was defined (the outer circle in red), covering an area of approximately 28.4 km^2 , elevation varying between 428 and 567 meters in relation to sea level. A set of n predefined places, called evaluation points P_i , where $0 < i \leq n$, were scored every 600 meters from the gateway. The spatial distribution of the evaluation points can be seen in Figure 3. Obstacles that could possibly hamper communication were identified to aided posteriorly with the analysis.

Aiming to validate empirically the theoretical model (Figure 2 it was used an end device equipped with a LoRa transmitter Semtech SX1276. Table 2 shows the parameters setup to the LoRa transmitter. This device was attached to an IoT-USB base module adding a USB interface that once connected to a laptop allowed sending messages to a LoRaWAN application. Basically the message is a tuple containing the geographic coordinate of the place associate with the label of the evaluated place, e.g., "P1", "P2", etc. Upon receiving the message, the gateway calculates the signal strength and the signal-to-noise ratio of the received message. At each point in the test area, 5 messages were sent. The most distant evaluation points ($P_{39} - P_{46}$) had 10 messages sent. Such distant points are located between 10 Km



and 30 Km from the gateway, far from the most outer circle and therefore they are not shown in Figure 3. The messages were stored on the TagoIO application server indicating the communication of the final device with the gateway and with the network and application servers. The amount of messages received by application server and the total number of messages sent from the device to the gateway gives the PDR.

Data Rate	Spreading Factor	Bandwidth	Coding Rate	Authentication
0	SF10	125 kHz	4/5	ABP

Table 2: Radioenge LoRa transmitter parameters.

3.3 Tracking devices evaluation

3.3.1 Tracking devices description

The four devices evaluated in this work are described in Table 3. Rak5205 and Rak7200 are commercially-available tracking devices. The first is commonly used to make rapid prototyping of LoRa-based IoT solutions and has several different sensors e.g. temperature and humidity. The second is commercialized as a general-purpose tracking device, being small it could be fixed in a person's belt, for instance. Both allow to set configurable parameters but are not programmable. On another hand, the tracking device TTGO T-Beam is an end device compound by a PCB using a dual-core ESP32 chip and LoRa and GPS extra modules. As a microcontrolled device, it's necessary to programming the T-Beam modules to perform the

desired functions. Arduino is an open platform for electronics prototyping. It is extensible using proper small PCBs (named as shields) and software libraries. In this work were used both shields GPS and LoRa. Similarly to the T-Beam, the Arduino was coded using open-source libraries. Considering the cost, the Rak5205 is the most expensive of the used devices, possibly due to their additional sensors included. Those unnecessary sensors were disabled for the experiments. Finally, the T-Beam is cheaper but presents more memory capacity and processing power when compared to the others.

	RAK7200	RAK5205 WisTrio	T-Beam	Arduino + Shield
Microcontroller	ST STM32L073 Arm Cortex M0 32-bit 32 KHz – 32 MHz	ST STM32L1 MCU Arm Cortex M3 32-bit 32 KHz – 32 MHz	TTGO Tensilica LX6 32-bit 240 MHz	Microchip ATmega 328P-PU 8-bit 20 MHz
Flash Memory	192 KB	512 KB	4 MB	32 KB
RAM Memory	20 KB	80 KB	520 KB	2 KB
LoRa Transmitter	Semtech SX1276	Semtech SX1276	Semtech SX1276	Semtech SX1272
LoRa Antenna	interna	2 dBi	2.5 dBi	2.15 dBi
GPS Transmitter	Sony-Semicon CXD5603GF	Ublox Max 7Q	Ublox Neo-6M	Ublox Neo-6M
Antenna GPS	internal	external	external	external
Power supply	rechargeable battery	rechargeable battery	rechargeable battery	external 5V CC
Cost (US\$)	39.50	49.50	26.50	45.00

Table 3: Details of the evaluated devices.

We employed the LMIC library [21], modified by the MCCI Corporation, to programming the T-Beam’s LoRa module. This library implements a hardware abstraction, working as a state machine and it is responsible for the communication between the LoRa physical layer and the other gateway devices. The NEO-6M module was programmed using the TinyGPS++ library [47] which performs the data flow control based on NMEA (National Marine Electronics Association) – a common standard communication used by many electronic tracking devices, including GPS receivers. Arduino was coded using the TinyGPS++ library, SD library for the SD card and TimeLib for providing the time. The communication between Arduino and LoRaWAN transmitter occurs through a software serial port and AT commands (Hayes command set).

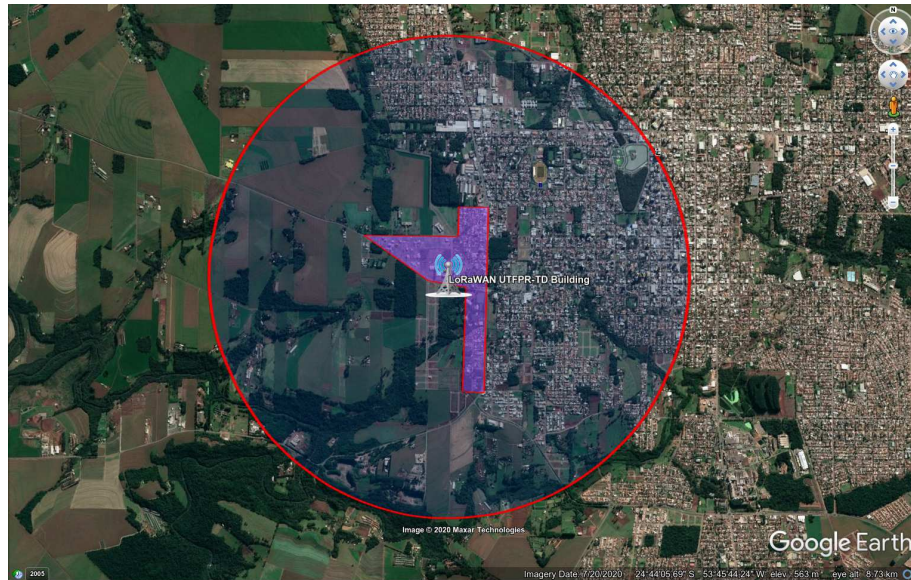
3.3.2 Tracking devices evaluation scenario

With the results of the network simulation and the empirical evaluation of Figures 5 and 6 (detailed in Section 4.1) in hand, next step was to evaluate the custom-programmed devices in relation to the commercial devices. We defined three different assessment regions named “Area 1”, “Area 2”, and “Area 3”. The red polygon shown in Figure 4a corresponds to the Area 1, covering about $0.34km^2$. Area 2 extends the Area 1 to about $0.77km^2$ and it is limited by the magenta polygon highlighted in Figure 4b. The red circle that could be seen in both Figures is the Area 3 which covers about $9.6km^2$. Despite presenting overlapped regions, each area was evaluate separately. The data were collected during three strides in distinct days using the four devices described in the Table 3. The vehicle was driving

at average velocity of 20 km/h. Such velocity was chosen to simulate the velocity of the real vehicles following the established route for the recyclable garbage collector truck. The option for constant velocity – instead of simulating all the possible stops inherent to the collection process – is explained by the tendency of the movement to affect the signal quality due to the well known Doppler effect. Actually the results obtained from the four tracking devices also contribute to evaluate the LoRa network coverage.



(a) The red polygon limits Area 1, corresponding to $\approx 0.34\text{km}^2$



(b) The magenta polygon limits Area 2, corresponding to $\approx 0.77\text{km}^2$

Figure 4: Evaluation areas. The red circle limits the Area 3.

The devices were set up to send their geolocation data every 10 seconds creating a measuring point every 5.6 meters. Thus, it is also possible to evaluate the even-

tual interference of buildings on the transmission process, such as the university's own buildings as well as residential and commercial buildings. Considering the different precision between the four tracking devices could exist discrepancies in the geolocations data for the same registered point.

The devices were evaluated considering the following criteria:

- (a) **Signal quality:** based on the received signal strength indication (RSSI), and the signal-to-noise ratio (SNR), both measured for each geolocation point using the tool TTN Mapper. RSSI is a negative value measured in dBm indicating the received signal power in milliwatts. In a typical LoRa network, an RSSI of -30 dBm indicates a strong signal while an RSSI of -120 dBm represents a signal weak, being -120 dBm the minimum RSSI. The closer the RSSI is to zero, the better the signal. SNR is defined as the ratio between the received power signal and the noise floor power level. The noise floor is the area providing the interfering signal sources which potentially can corrupt the transmitted signal causing retransmissions. An $\text{SNR} > 0$ indicates that the received signal operates above the noise floor, and an $\text{SNR} < 0$ denotes the received signal operating below the noise floor. Typical LoRa SNR values range from -20 dB to +10 dB. A received signal presenting an SNR value closer to +10 dB means the received signal is less corrupted.
- (b) **Sending measurement capacity:** also named packet delivery ratio (PDR) is obtained comparing the expected sending point to the geolocation effectively received from the devices. Besides, we also have analyzed possible reasons that have weakened device communication, such as buildings or natural obstacles.
- (c) **Cost-benefit:** It was considered the balance between the equipment's financial cost and quality metrics achieved by the device.

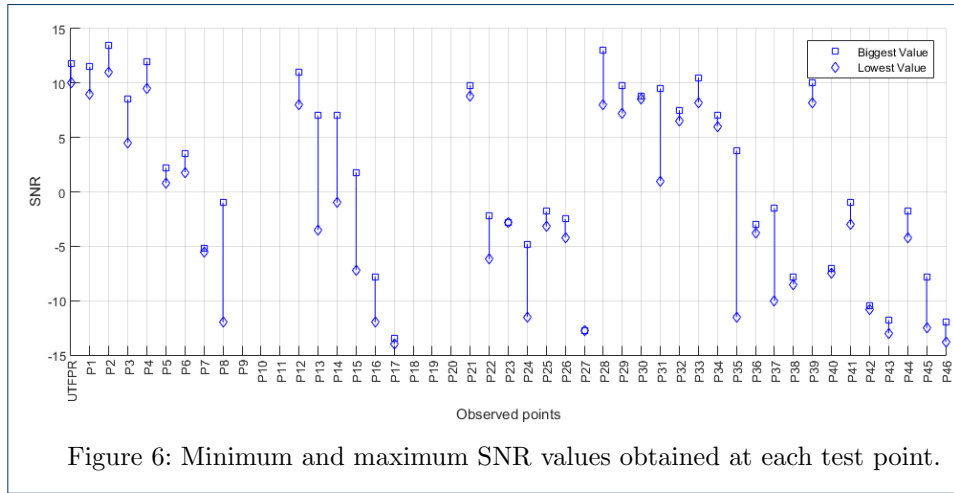
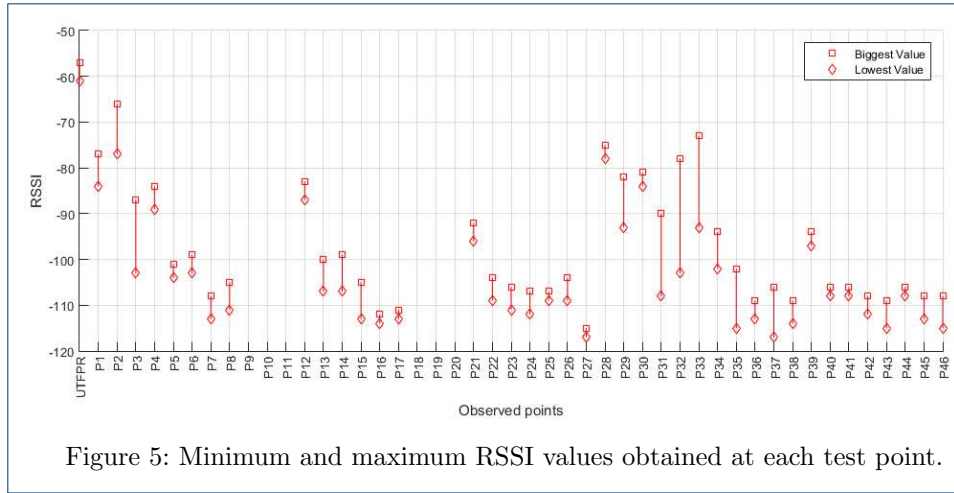
4 Results and discussion

We present results of the evaluation of the LoRaWAN network installed on the UTFPR campus and the results of the evaluation of the devices in Sections 4.1 and Sections 4.2, respectively.

4.1 LoRaWAN signal evaluation

Figures 5 and 6 present the minimum and maximum values of RSSI and SNR, respectively. Such metrics were obtained from the empirical tests at the points described in Figure 3. Points P_1 to P_{11} are located in the urban area which has several buildings. Despite these points are ordered in relation to the distance from the UTFPR gateway, there are points that are farther but with higher RSSI. This is caused by variations in the altitude of the location of the points. For instance, points P_5 to P_7 are placed behind of a terrain elevation, as shown in the black rectangle in Figure 7. That is, those points present no LoS. Also, points P_9 – P_{11} are placed in a lower area, which results in packets not received by the gateway.

Similar behavior can be observed for points P_{12} – P_{20} , despite those points are located in a region with fewer buildings when compared to the region of points P_1 to P_{11} . There is an elevation from points P_{12} to P_{15} , but from P_{16} to P_{20} there is a constant decrease in altitude, obstructing the LoS and reducing both RSSI and SNR. Also, there are an elevation in the path of the points, as depicted by the

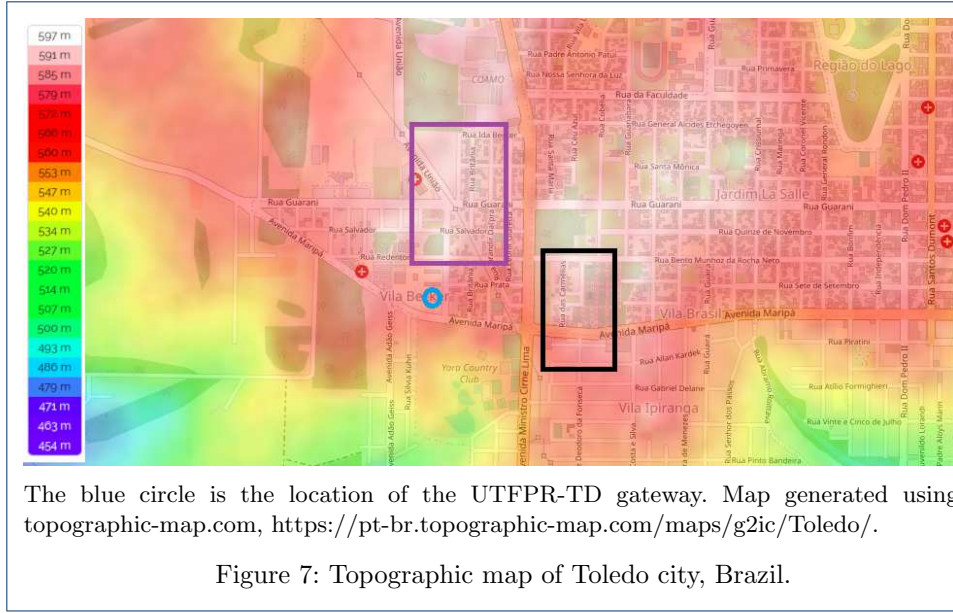


magenta rectangle in Figure 7. That's why communication failed from points P_{18} to P_{20} .

Once the points from P_{21} to P_{27} are located in a rural area, the propagation scenario is analogous to open field communications. The RSSI from the points presents low variations, and most of the points also present low SNR variation. Despite the altitude being reduced from P_{21} to P_{27} , the points are not behind an elevated point, as occurs with points P_1 to P_{11} and P_{12} to P_{20} , resulting in better coverage and no outage points.

From points P_{28} to P_{33} , there is a mix of rural and urban areas, indicated by different variations of RSSI and SNR. From points P_{34} to P_{36} , the propagation is mainly in rural areas, resulting in low SNR variation (except for P_{35}). Points P_{37} and P_{38} are able to overcome the obstacles presented for the points P_{12} to P_{20} . For the long distance points, P_{39} to P_{46} , the RSSI and SNR variations are lower (except the SNR variation for P_{45}), and despite the higher distance, they were able to communicate with the gateway.

Finally, considering the PDR, points that received at least one message presented 100% of PDR, i.e., these points are located where there is good network coverage.



In contrast, there is no network coverage for points P_9 to P_{11} and P_{18} to P_{20} , for example, since PDR was 0%.

In essence, these results corroborate that the relief of the installation area and the environment are key factors of the LoRaWAN network deployment, as concluded in [19, 14]. It was possible to reach a distance greater than 30 km in the rural area, according to points P_{39} to P_{46} , so that neighboring municipalities could be reached as well. In the urban area, the maximum range varied between 2 km and 2.5 km, according to points P_8 and P_{17} to the east and north (Figure 3), respectively. However, still in the urban area, point P_{33} is more than 3 km away. Unlike the other furthest points in the urban area, P_{33} presents clear LoS, that is, like [19] we highlight the importance of a clear LoS between the application and the gateway. Although the simulation performed with CloudRF does not contain obstacles, the results of the practical assessment corroborated the simulation results regarding the signal coverage. More antennas, or antennas located at higher places, could improve the signal propagation and achieving a good coverage for the city area. This inherent requirement is taken into account for planning the future network expansion, discussed in Section 4.3.

4.2 Tracking devices evaluation

In this section we present results obtained from the experiments carried out with the tracking devices in twofold: qualitative and quantitative. Firstly, the quantitative analysis presents the device capacity to send a coordinate (geolocation) while moving through the areas. For each device, it was used the TTN Mapper tool to get the number of coordinates received by the gateway. Secondly, to assess the signal quality, the qualitative analysis took into account the noise and the spreading factor (SF) present in the received coordinates.

4.2.1 Quantitative analysis

As stated in Section 3.3, an interval of 10 seconds for each device to send its geolocation is defined. However, both T-Beam and commercial Rak devices did not managed to operate with this interval. Arduino was the only one that actually managed to send a coordinate every 10 or 11 seconds. Such behavior of T-Beam can be explained because it is configured to use class A. So it is ready to transmit only after sending a packet to the gateway what opens two receive data windows of about 1 to 3 seconds. Therefore, the T-Beam interval for each data transmission is approximately 13 seconds. For Raks devices, the first step is searching for the GPS signal and the second step is sending data to the network. As consequence, an interval greater than 10 seconds is always required to send each coordinate. In addition, Raks takes about 120 seconds searching for the satellite in the first transmission followed by a latency of 2–10 seconds to obtain a coordinate from satellites. Thus, the total time both Raks taken to send a geographic coordinate in practice was on average 24 seconds.

Tables 4 and 5 present the efficiency of each device in the three evaluated areas considering the amount of geographic coordinates received by the gateway, i.e., the PDR. The “SD card” entry refers to the data stored by Arduino in the external storage card. That device stores the coordinate into its memory card before sending it to the gateway. That makes it possible to know the number of unsent coordinates by Arduino.

Table 4 shows the data obtained from Areas 1 and 2. The “coordinates” column shows the number of coordinates stored on the SD card and received by the gateway from Arduino, T-Beam, RAK5205 and RAK7200 devices. For example, the SD card stored 250 coordinates for Area 1 and 503 coordinates for Area 2. However, the gateway only received 212 coordinates for Area 1 and 457 coordinates in Area 2 from Arduino. That is, 38 and 46 geographic coordinates for Areas 1 and 2, respectively, have not been successfully sent by the Arduino device. The “average time” column presents the average time in seconds the gateway took to receive a geographic coordinate. For example, a coordinate was recorded every 12 seconds for the Arduino and every 33 seconds for the RAK7200 for Area 1, according to the TTN Mapper tool. As we describe previously, RAK7200 can only send a new coordinate every 24 seconds. For Area 2, Arduino successfully sent a coordinate every 11 seconds. RAK7200 sent a coordinate every 37 seconds which means that many packets were lost.

The column “expected coordinates” considers the time expected to receive a geographic coordinate from each device, that is, 10 seconds for the Arduino, 13 seconds for the T-Beam and 24 seconds for the Raks. From the time expected and the total time of the experiment it is possible to calculate the number of coordinates that should actually be received by the gateway and stored on the card from. Considering Area 1, for example, 254 coordinates should be stored on the Arduino’s memory card and 253 coordinates should have been received by the gateway from Arduino. For T-Beam, 195 coordinates should have been actually sent to the gateway. The RAK5205 and RAK7200 devices should have sent 105 and 106 coordinates, respectively.

The efficiency of each device is a ratio between the obtained coordinates and the expected coordinates. The SD card did not show an efficiency of 100% because a coordinate was stored between 10 and 11 seconds (and not 10, as expected). For Areas 1 and 2, the T-Beam presented the best efficiency, although it sent less coordinates to the gateway when compared to Arduino. In this work, we defined efficiency as the device's ability to successfully send as many of its expected coordinates as possible. For Area 1, Arduino achieved an efficiency close to that of RAK5205. RAK7200 had the worst efficiency, 71.73%. In Area 2, Arduino was more efficient than the Rak. In turn, the RAK5205 and RAK7200 devices had an efficiency of 68.08% and 64.97%, respectively. For Area 1, the efficiency of the devices was above 70%, possibly because it is close to the gateway. As for Area 2, which contains a zone further away from the gateway, all devices presented a lower efficiency compared to the Area 1, particularly for the Rak.

	Coordinates		Average time (s)		Expected coordinates		Efficiency (PDR)	
	Area 1	Area 2	Area 1	Area 2	Area 1	Area 2	Area 1	Area 2
SD card	250	503	10	10	254	512	98.46 %	98.22 %
Arduino	212	457	12	11	253	512	83.79 %	89.21 %
T-Beam	186	347	14	15	195	362	95.50 %	95.90 %
RAK5205	90	115	28	35	105	169	85.82 %	68.08 %
RAK7200	76	133	33	37	106	205	71.73 %	64.97 %

Table 4: Behavior of the evaluated devices in Areas 1 and 2.

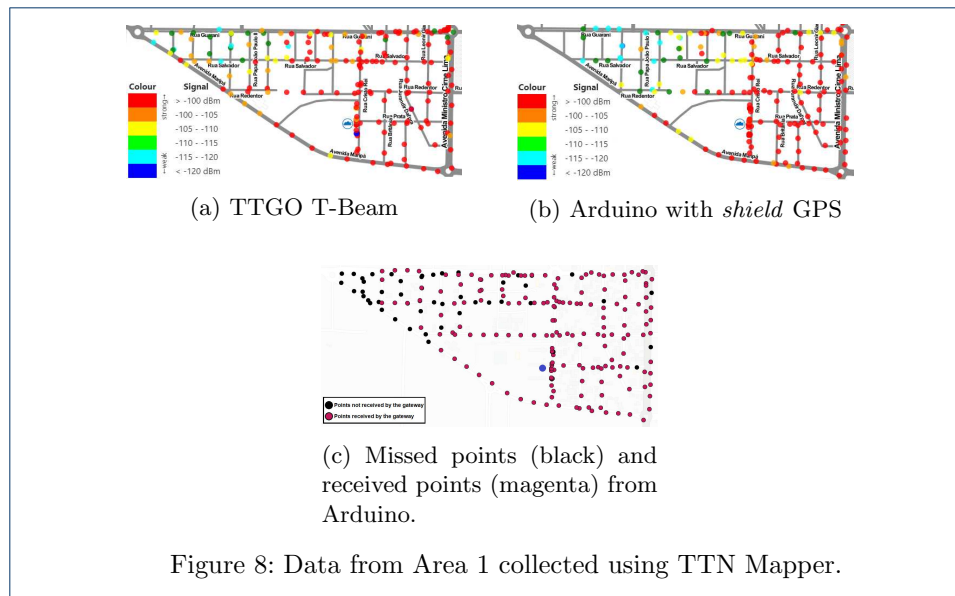
Table 5 presents data from Area 3. This area was segmented into three routes, called Route 1, 2 and 3, due to its large size. For Area 3, we present only the geographic coordinates received by the gateway and the efficiency of each device on each route, including data stored on the Arduino's SD Card. Route 2 is the closest to the gateway. Route 1 is further north and Route 3 is further east in relation to the gateway, however both Route 1 and 3 are far from the gateway. We noticed that the devices presented different efficiencies depending on the route. In general, T-Beam was the most efficient. Arduino oscillated between 25% efficiency for Routes 1 and 3, and 70% efficiency for Route 2. That is, the data show that the Arduino did better near the gateway. The Raks had the worst efficiency for Area 3.

	Route 1		Route 2		Route 3	
	Coordinates	Efficiency	Coordinates	Efficiency	Coordinates	Efficiency
SD card	944	98.00 %	247	98.37 %	1021	94.72 %
Arduino	325	25.07 %	151	70.40 %	262	25.90 %
T-Beam	550	68.31 %	204	67.37 %	413	69.04 %
RAK5205	60	15.71 %	31	24.60 %	94	24.87 %
RAK7200	36	6.73 %	13	9.32 %	24	5.98 %

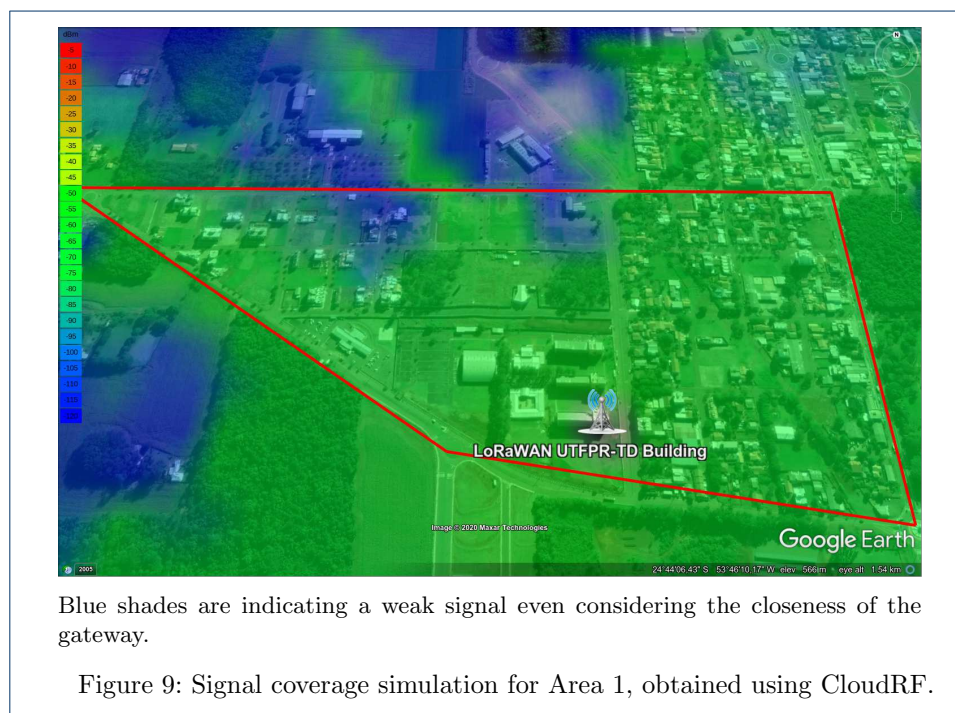
Table 5: Area 3 segmented into three distinct routes.

4.2.2 Qualitative analysis

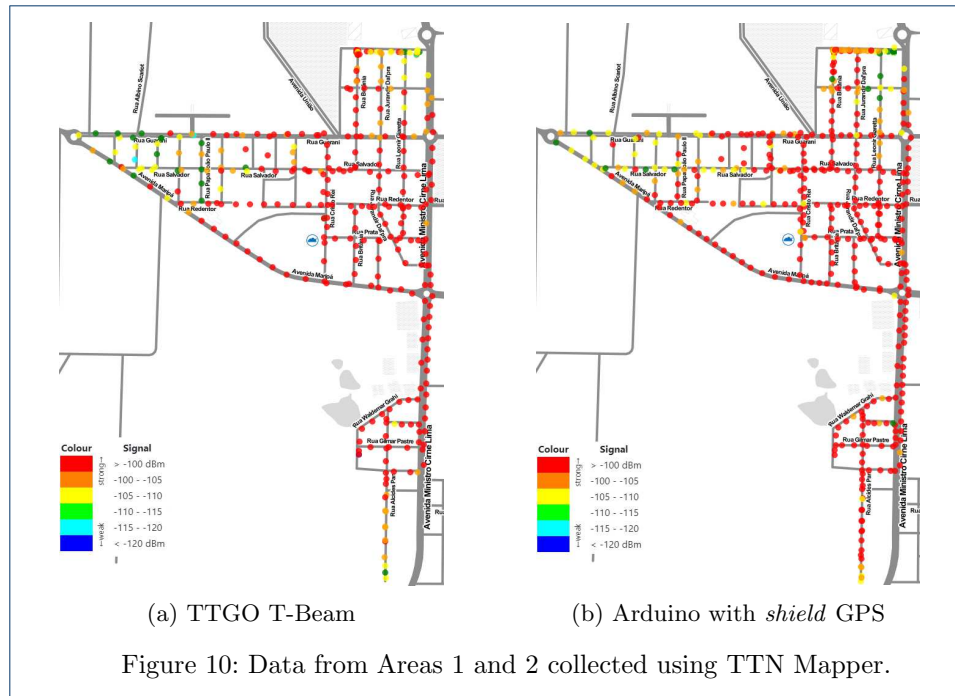
Figures 8 – 11 were obtained through the TTN Mapper tool from the geographical coordinates received by the gateway. As Area 1 is contained in Area 2, the results of Figure 10 can be used together with those of Figure 8 to analyze Area 1. The color of the points in Figures 8.(a)-(b), 10.(a)-(b) and 11.(a)-(b) refers to the received signal strength, including both RSSI and SNR. Based on quantitative results



that demonstrated the lower efficiency of the Raks, analysis of RSSI and SNR are performed only for T-Beam and Arduino devices. In Figures 12 and 13 all devices are evaluated when analyzing SF and CDF (Cumulative Distribution Function) of RSSI and SNR.



Arduino and T-beam successfully sent 212 and 186 coordinates for Area 1, respectively, as shown in Figures 8a - 8b. However, Arduino were not able to send its coordinates when transversing the upper left corner of this area. This does not happen in Figure 10 where Arduino was able to send its data from the same zone.



This result may indicate Arduino gets a weak network signal from that specific zone. Figure 9 presents the CloudRF simulation for Area 1. Note that blue shades are indicating a weaker signal, although this region is close to the gateway. Another explanation is arduino has an antenna with slightly lower gain (2.15 dbi versus 2.5 dbi for T-Beam).

As the Arduino saves all the coordinates captured by the GPS on a memory card, it is possible to check which of them are not received by the gateway. The result is shown in Figure 8c: black dots represent coordinates not received by the gateway, and the magenta dots represent the coordinates received by the gateway. The upper left corner zone has several geographic coordinates that have not been received. However T-Beam was able to send coordinates from that zone - not necessarily the same amount of coordinates than Arduino once the GPS sampling intervals are different for the two devices. That is, compared to Arduino, T-beam sends data from that zone even with a weak network signal.

Figure 10 presents the qualitative analyzes for Area 2. Results from quantitative analysis show Arduino and T-beam sent 457 and 347 coordinates, respectively, i.e., a satisfactory performance even in more distant areas. The south zone of Area 2 (at bottom at Figure) is far from the gateway, but it has few homes and buildings with a clear line of sight (LoS) in relation to the gateway. In turn, the upper right area has few buildings as well, being dominated by small residential buildings.

Area 3 is presented in Figure 11. In this area we find the most interesting results. As show in Table 5, T-beam has an efficiency of 68.31% and 69.04% against 25.07% and 25.90% of the Arduino for Route 1 and Route 3. However, the efficiency of the Arduino for Route 2 was superior (70.40% against 67.37%). When we analyze Figure 11, both devices present quite similar behaviour in some particular small zones (the central and southern zones in relation to the gateway). However, T-beam is far

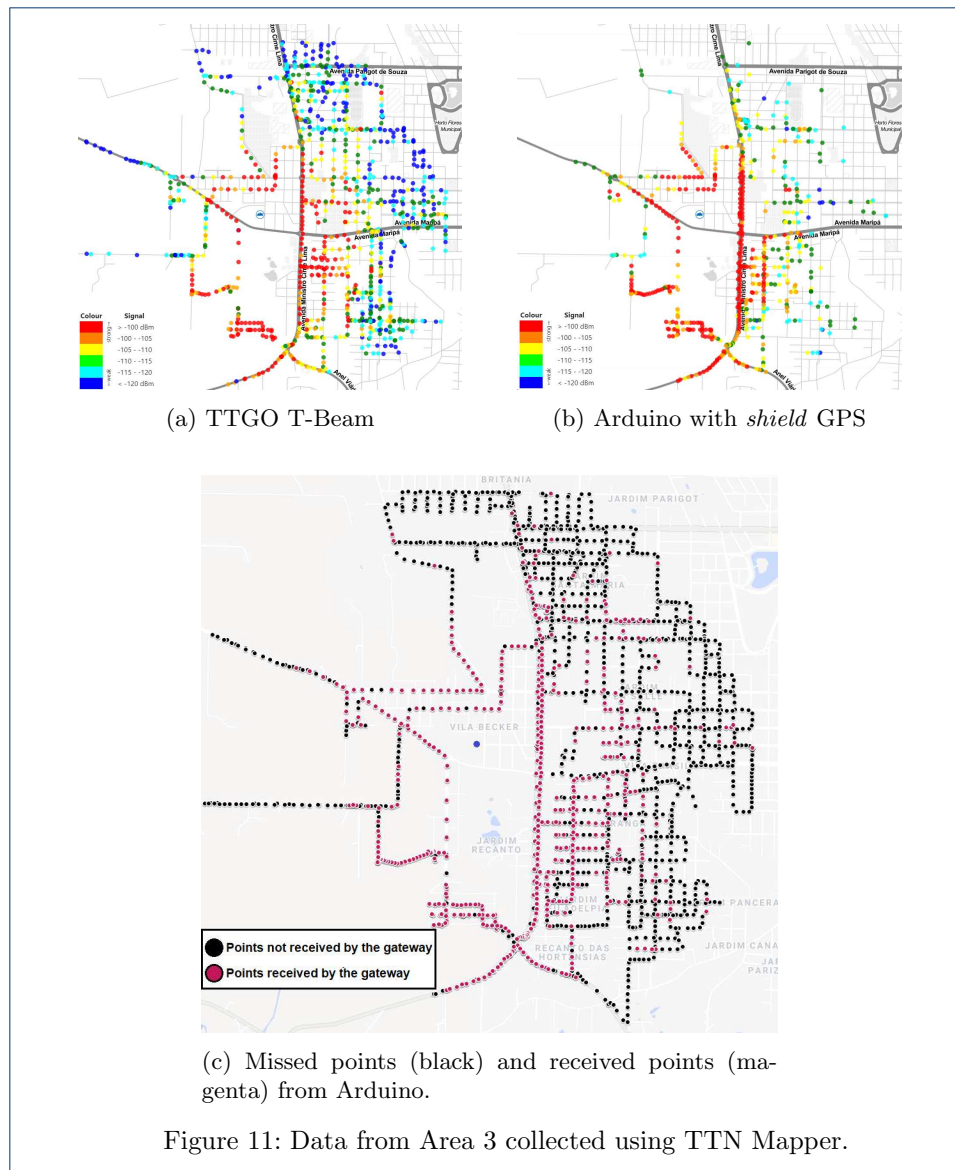
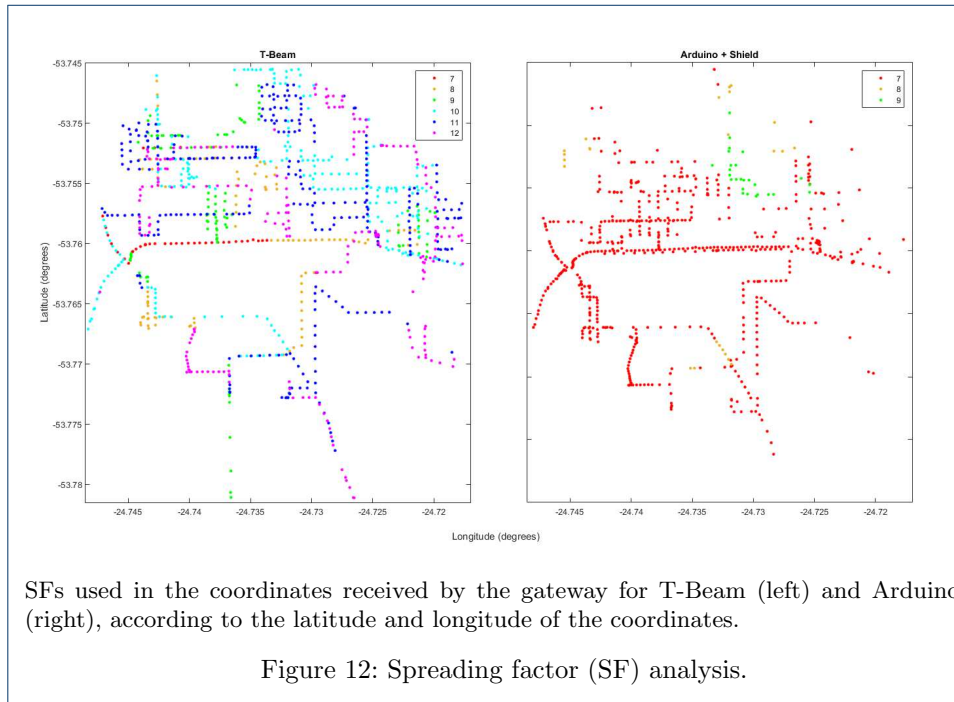


Figure 11: Data from Area 3 collected using TTN Mapper.

superior when we see the all picture. With the help of Figure 11c, we highlighted that there is a large amount of coordinates sent from Arduino, but not received by the gateway. The analysis of topographic maps showed that some of these zones are located after an elevation of relief, in addition to being more inhabited and densely built. However, the comparison between the devices shows that T-Beam was able to send its data - even Raks devices proved to be quite limited in these regions. Note when comparing Figure 11a with the data collected from Arduino in Figure 11c that there is a zone in the upper left area that was not also covered by T-Beam.

One explanation for the failure of devices to send coordinates from some zones is due to the current elevation of the gateway, installed on top of a four-floor building of UTFPR. To mitigate this limitation, the University and the City Hall are studying installing the new gateways in higher places as presented in Section 4.3. The feasibility study for such sites are left to future work.

To understand why T-Beam had an advantage over the Arduino, we analyze the packets received by the gateway. One of the parameters recorded by the TTN Mapper is the spreading factor (SF) used by each device to send its coordinates, together with the chosen bandwidth. Smaller bandwidths combined with higher SFs are useful to have a more reliable data transmission despite of the penalty of reducing the data rate. Figure 12 shows the SF chosen by the T-Beam and Arduino devices to send their coordinates to the gateway in Area 3. The geographic coordinates were plotted according to their latitude and longitude. Arduino mostly adopted SF 7, which is one of the shortest factors, while the T-Beam adopted SF values ranging from 7 to 12. In areas with few coordinates received from Arduino, mainly in the upper right zone, T-Beam adopted SF values between 10 and 12, which helped it to have more coordinates received. The RAK5205 device behaved similarly to the Arduino, operating with factors between 7 and 9, while the RAK7200 used SFs between 7 and 12, but most of them used SFs between 7 and 10.

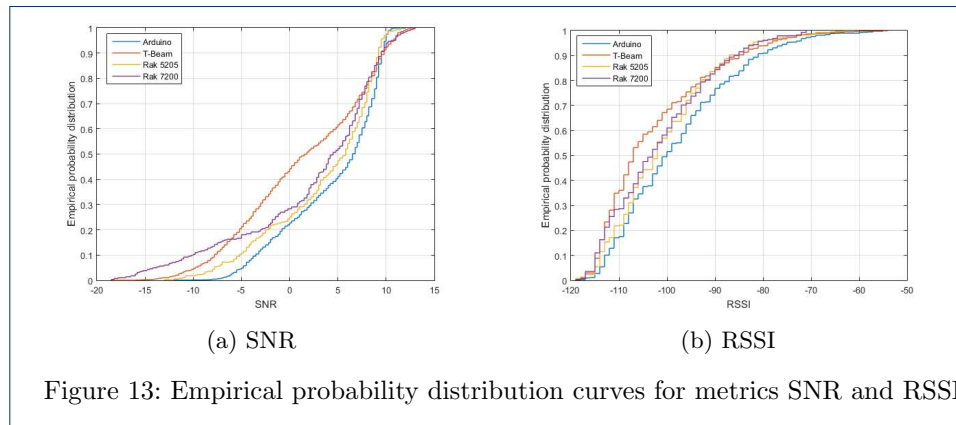


What explains a possible advantage of the T-Beam device is the use of the LMIC library. LMIC provides internal SF adjustment mechanisms even with ADR (Adaptive Data Rate) inactivated. We follow the LMIC documentation that recommends not using ADR on mobile nodes [21]. Thus, the presence of an adjustment mode without ADR has made the T-Beam to adapt better to different environments and covering an area greater than that covered by Arduino and RAK devices.

Although studies such as [18, 19, 14] have carried out evaluations with mobile nodes in the LoRaWAN network, all of them have fixed the SF=12. Our result indicates that the best coverage of the T-Beam is due to the SF variation and not only due to its superior hardware. Regarding the hardware, what could give the T-Beam an advantage over the others is its antenna and the SX1276 transmitter.

SX1276 offers slightly better receive sensitivity than SX1272 [48]. However, Raks also have an SX1276 transmitter.

Finally, Figure 13 shows the empirical probability distributions (CDF) for SNR and RSSI. Note that T-Beam SNR curve presents lower SNR values, since it was able to collect more distant points. The same occurs with the RSSI curve. The SNR can vary in points of the same RSSI, which justifies observing the two curves. It is also noticed that the curve of the RAK7200 has more points in low SNR (remembering that each one collected a number of different points). One of the causes that can contribute to this behavior is the use of an internal LoRa antenna, while the others devices use external antennas. In terms of RSSI, the devices are quite balanced, with T-Beam receiving more points with less RSSI and Arduino receiving more points with greater RSSI (in proportion to the respective points).



4.3 Future network expansion

Figure 14 presents the network expansion plan to cover the entire urban area totaling six LoRaWAN gateways. For the best radio signal performance, studies are being conducted to select public municipality buildings that offer minimal infrastructure and be located in elevated terrain avoiding obstacles in the Fresnel zone [49]. Finally, considering the experimental results of this work is expected that each gateway covers a minimum radius of 2.5 Km. Thus, the more dense urban central-region will be covered by the interception of at least 4 antennas.

5 Final considerations

This work presented the deployment of a LoRaWAN network along side with quantitative and qualitative analysis of four tracking devices that use an LPWAN network to send their geolocations while they move across three representative urban areas. This two-fold analysis was helpful for (a) to understand the behavior of each tracking device under the LoRaWAN network, (b) to evaluate how the intrinsic network characteristics can to influence the mobile data acquisition, and (c) to subsidize the development of a truck tracking solution for selective waste collection in the Municipality of Toledo. In general, the quantitative analysis points out that the T-Beam device presented better efficiency. On the other hand, the qualitative analysis indicated that the T-Beam was able to vary the spreading factor while

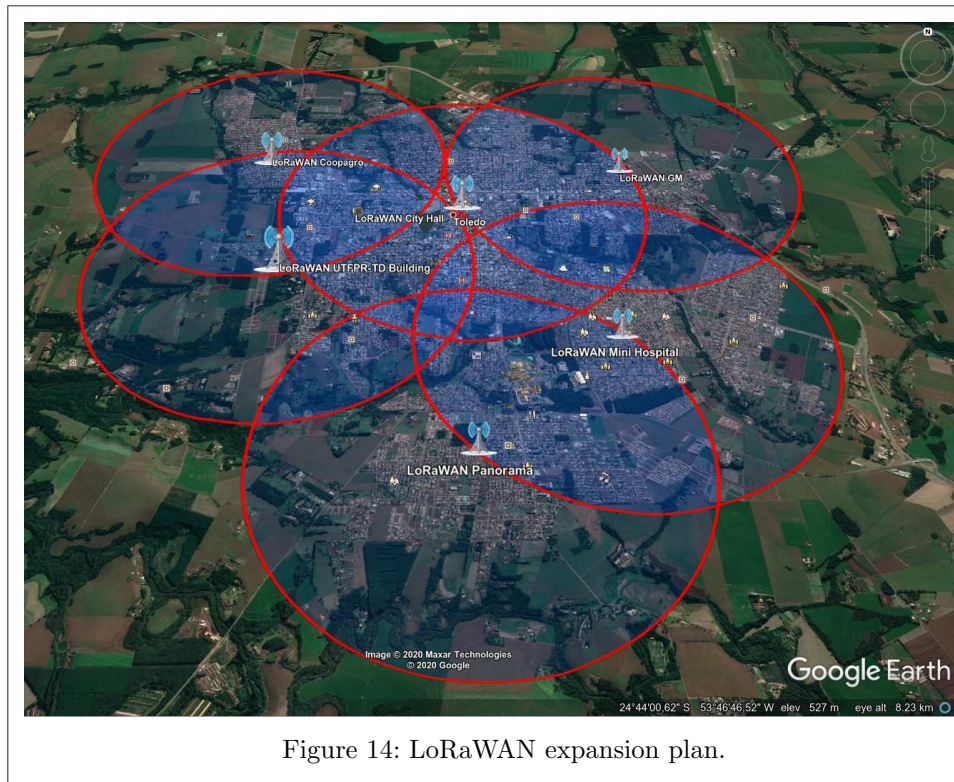


Figure 14: LoRaWAN expansion plan.

moving and it may be contributed to the better performance of this device. Different from [18, 19, 14] we do not set a fixed spread factor. Thus, the T-Beam programmed using the LMIC library presented the best cost-benefit between the assessed devices.

Based on the study conducted in this work, we agree with [14] which describes LoRaWAN technology as a viable option that can be used to subsidize applications like monitoring and tracking. In our experiments, the relative speed was 20 km/h. New experiments with higher speed can be carried out to verify the statements in [14, 18] that when the relative speed exceeds 40 km/h the performance of the communication deteriorates.

The results mainly have highlighted that LoRaWAN technology can achieve a good long-range covering and this signal covering could be extended avoiding obstacles. Furthermore, more broad coverage was obtained by programmable devices. In this aspect, the commercial solutions were limited possibly due to their respective firmware. As future work the following possibilities are underlined: a) to evaluate the devices energy consumption considering different configuration scenarios; b) determine an ideal spreading factor that may optimize the reduction in energy consumption by maximizing the signal strength and coverage area; c) implement a strategy allowing devices to send their geolocation just when a network good signal is detected, and d) plan a structure of gateways to satisfactorily cover the entire municipality of Toledo.

Abbreviations

3GPP: 3rd Generation partnership project; ABP: Activation by personalization; AES: Advanced encryption standard; CDF: Cumulative distribution function; CF: Carrier frequency; CR: Code rate; CSS: Chirp spread spectrum; FEC: Forward error correction; GPS: Global positioning system; GPRS: General packet radio service; GSM: Global system

for mobile communications; ICT: Information and communications technologies; IoT: Internet of things; ISM: Industrial, scientific and medical; ITM: Irregular terrain model; LMIC: LoRaWAN-MAC-in-C; LPWAN: Low power wide area network; LoRa: Long range; LoRaWAN: LoRa wide area network; LoS: Line of sight; LTE: Long term evolution; NB-IoT: Narrowband IoT; NMEA: National marine electronics association; OTAA: Over the air activation; PCB: Printed circuit board; RF: Radio-frequency; RSSI: Received signal strength indicator; SD: Secure digital; SF: Spreading factor; SNR: Signal-to-noise ratio;

Availability of data and materials

The datasets generated and/or analyzed during the current study are not publicly available yet due they are under the curation process but are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

Funding

Not applicable.

Authors' contributions

ETC proposed the experiments. ETC, FAS, and ARCS carried out the experiments and interpreted the data. The writing and review of the work was done equally by all authors. All the authors have read and approved the final manuscript.

Acknowledgements

We would like to thank the municipality of Toledo, Parana, Brazil, for supporting the project and the undergraduate students Jonas Rossato, José Souza, Marcos Silva, and Thiago Vinney whose aided in the field's data collection. This research was partially supported by Fundação Araucária, CNPq, and UTFPR.

Consent for publication

Not applicable.

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Figures

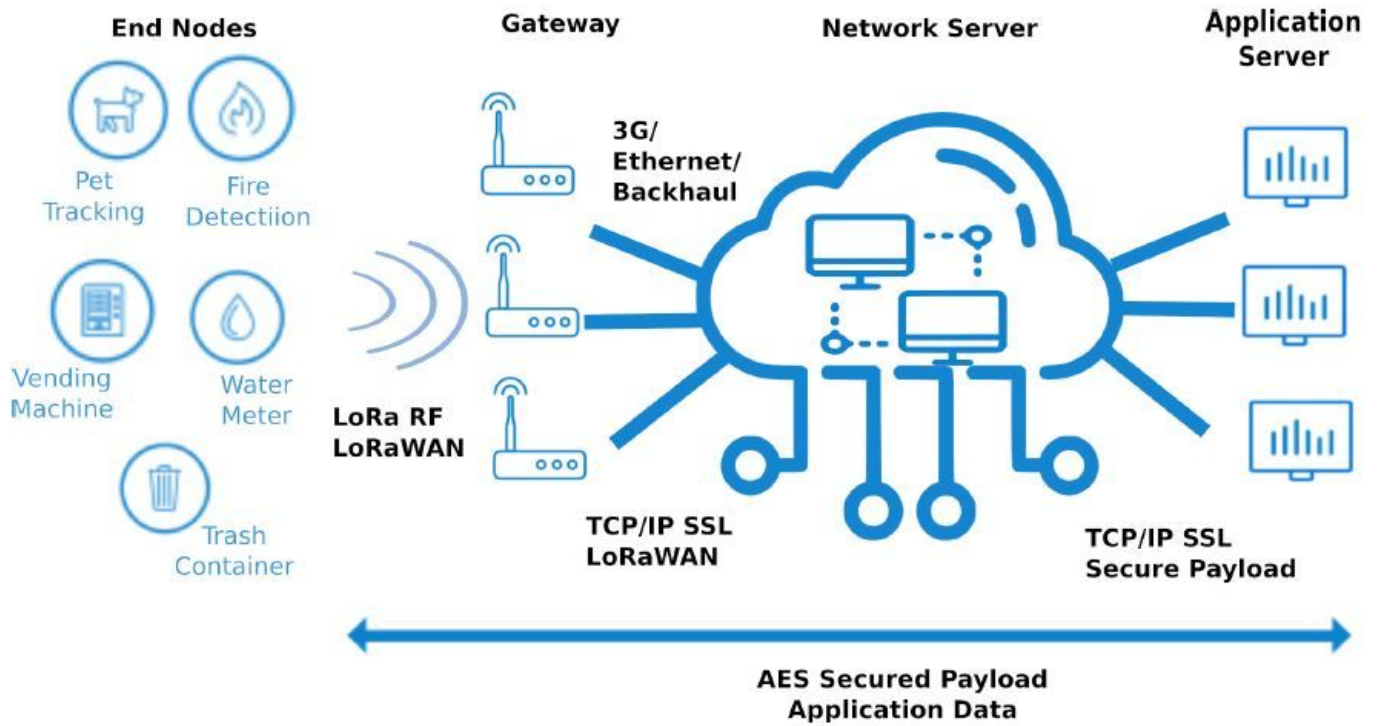
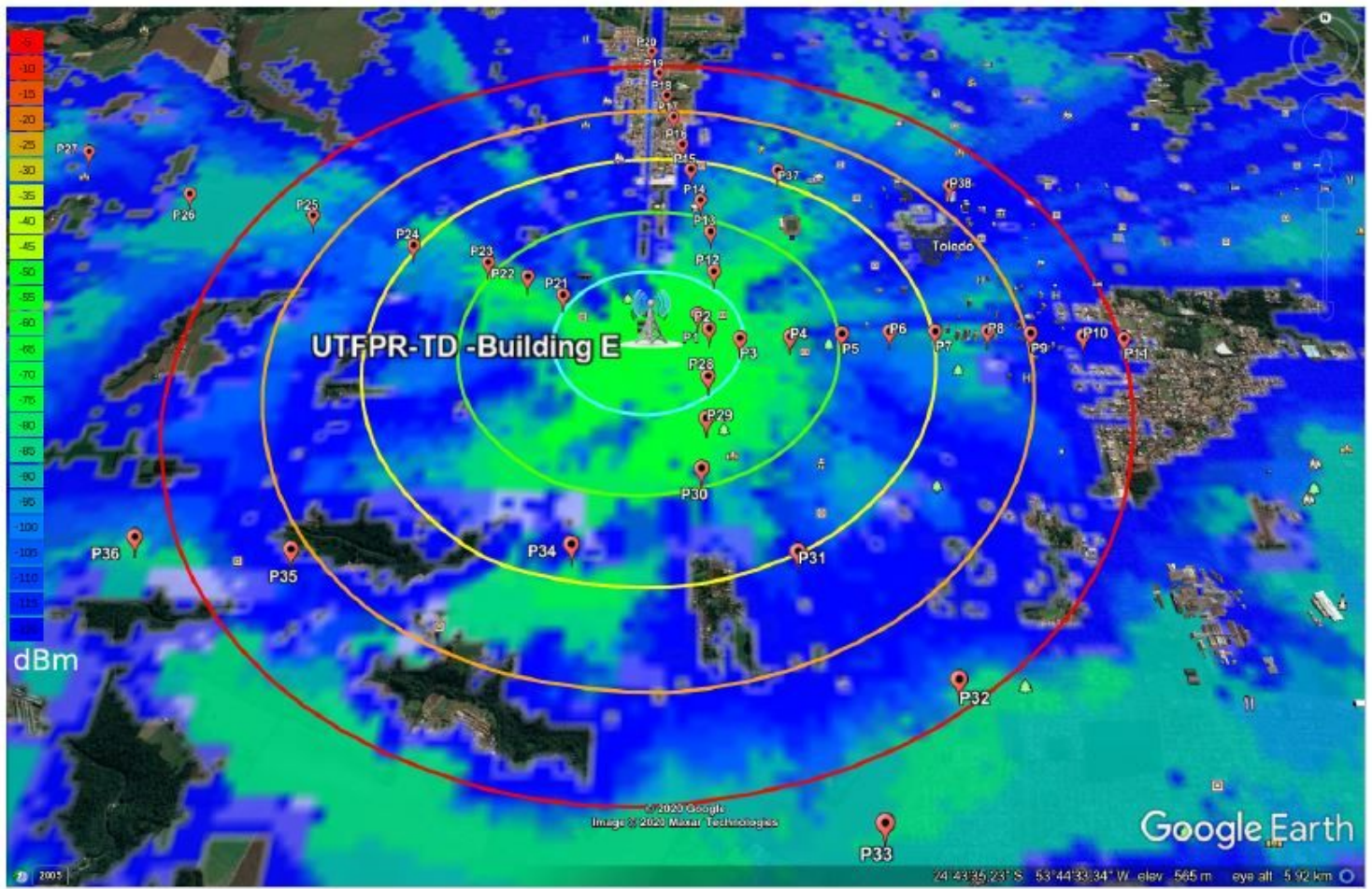


Figure 1

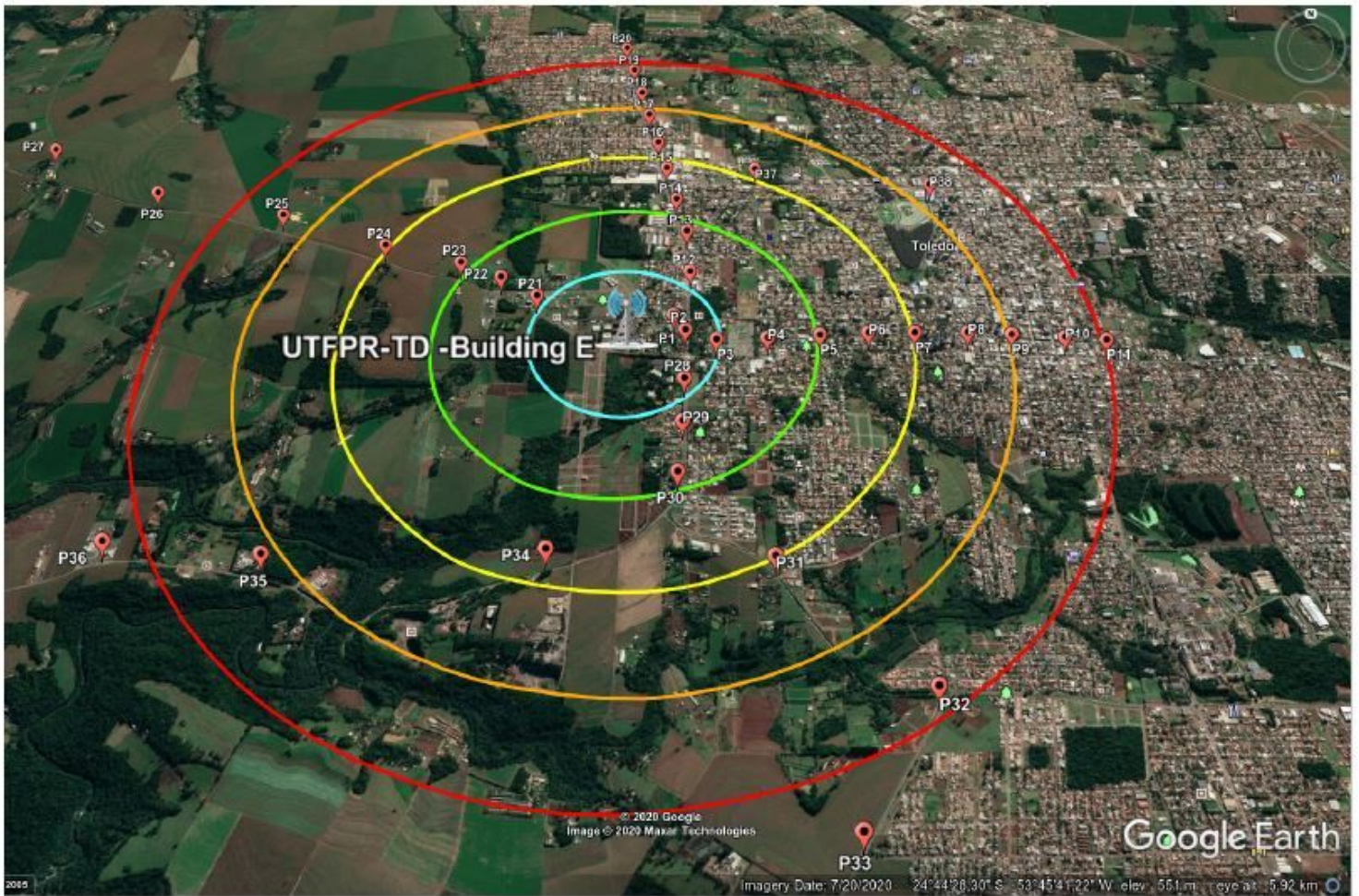
A general overview of the LoRaWAN architecture [11]



Values ranging from -120 dBm (blue shades) to -5 dBm (red).

Figure 2

Heatmap showing the signal coverage simulated using CloudRF. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



Multiple circular sweeps around the transmitter LoRa out to the defined radius of 3 Km. Each circle represents an increase in the radius by 600 meters, ranging from 600 to 3000 meters starting at the UTFPR campus.

Figure 3

Evaluation area. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



(a) The red polygon limits Area 1, corresponding to $\approx 0.34\text{km}^2$



(b) The magenta polygon limits Area 2, corresponding to $\approx 0.77\text{km}^2$

Figure 4

Evaluation areas. The red circle limits the Area 3. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

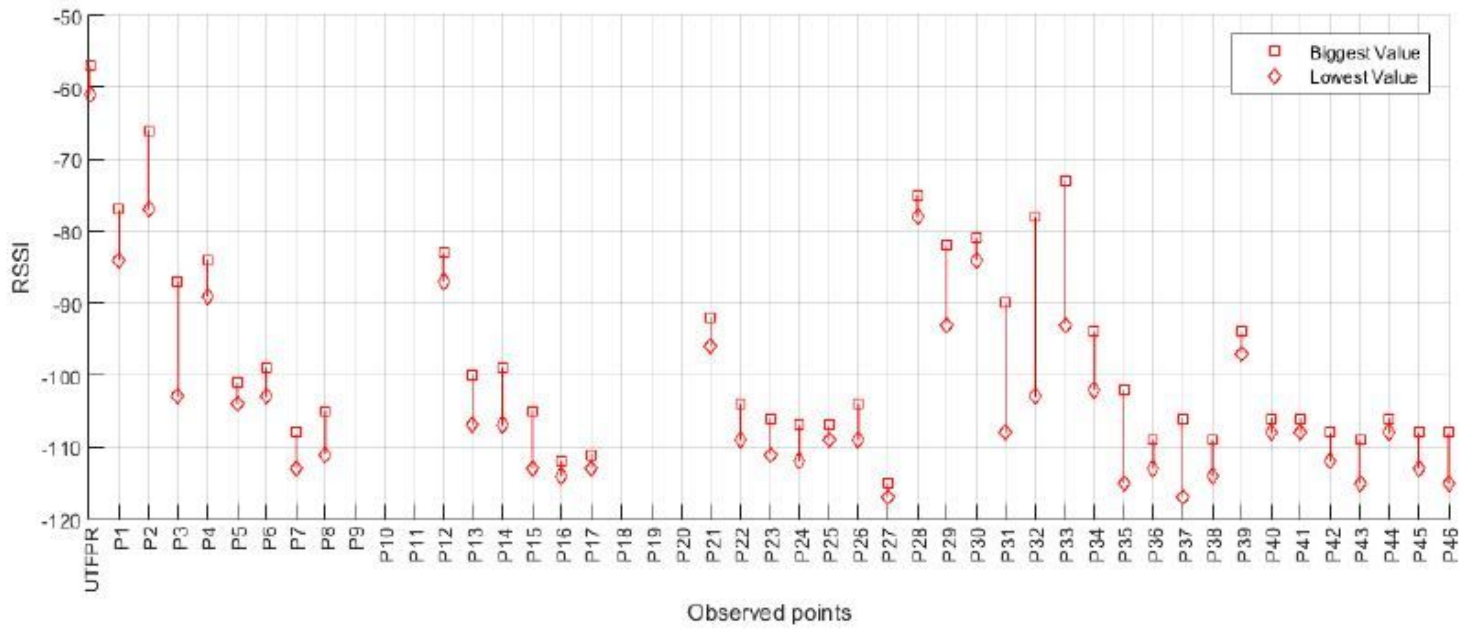


Figure 5

Minimum and maximum RSSI values obtained at each test point.

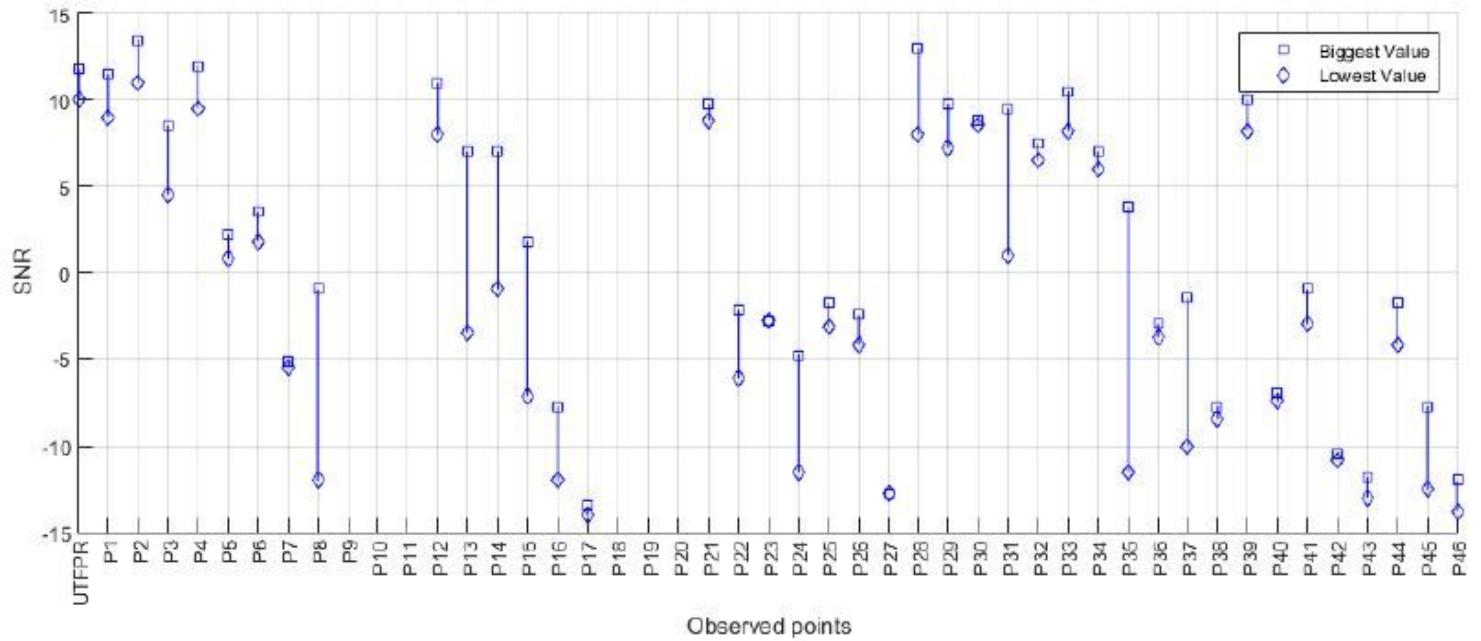
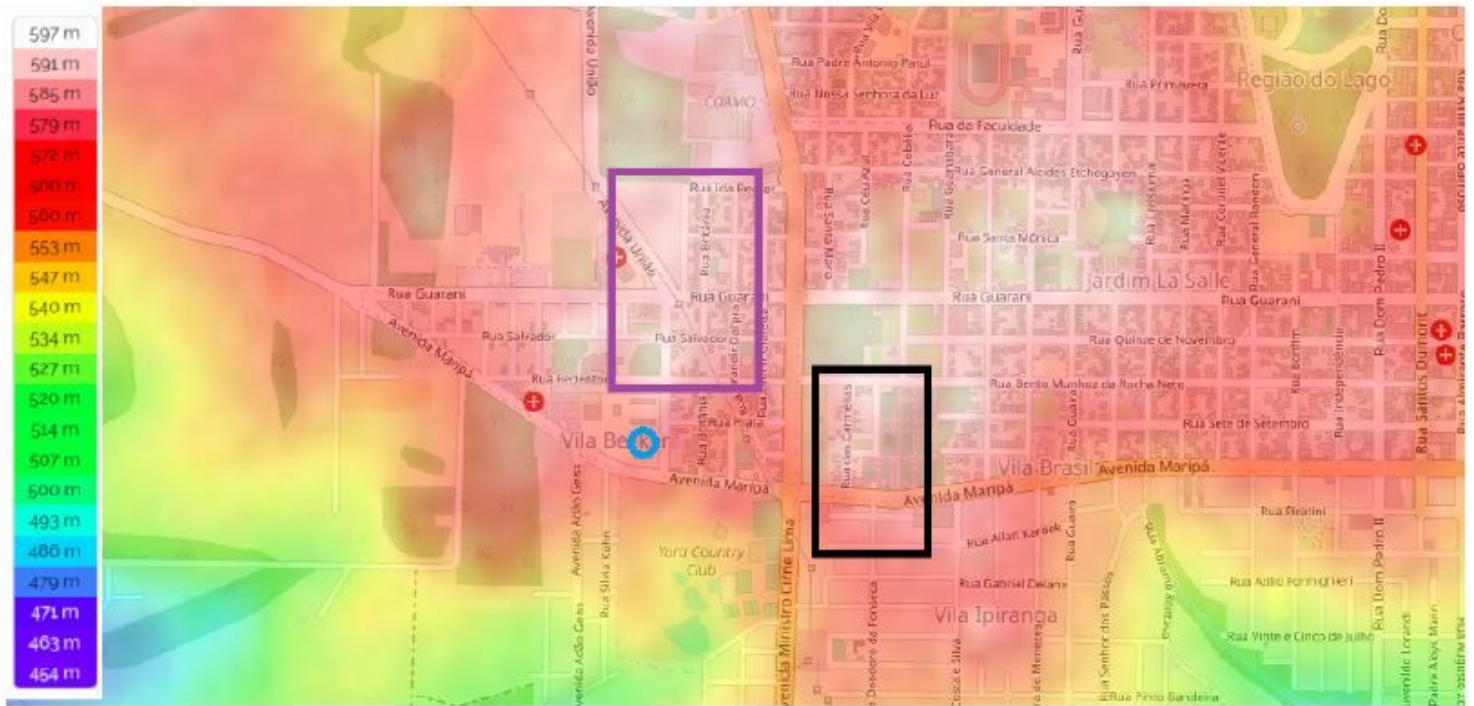


Figure 6

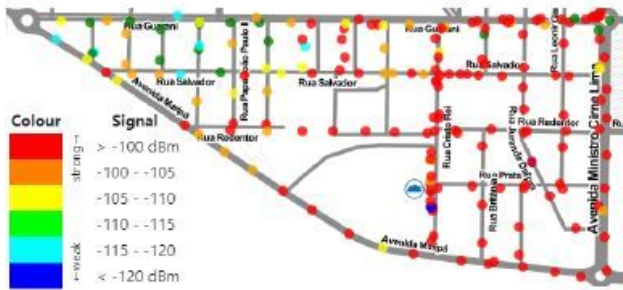
Minimum and maximum SNR values obtained at each test point.



The blue circle is the location of the UTFPR-TD gateway. Map generated using topographic-map.com, <https://pt-br.topographic-map.com/maps/g2ic/Toledo/>.

Figure 7

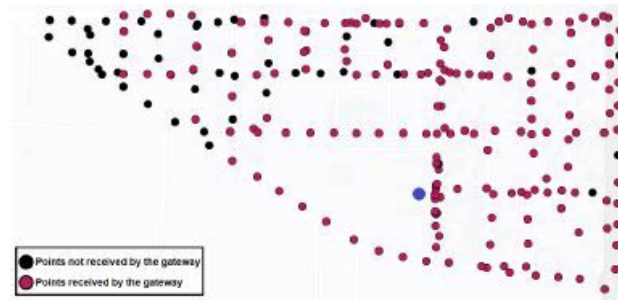
Topographic map of Toledo city, Brazil.



(a) TTGO T-Beam



(b) Arduino with *shield* GPS



(c) Missed points (black) and received points (magenta) from Arduino.

Figure 8

Data from Area 1 collected using TTN Mapper.



Blue shades are indicating a weak signal even considering the closeness of the gateway.

Figure 9

Signal coverage simulation for Area 1, obtained using CloudRF. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



(a) TTGO T-Beam



(b) Arduino with *shield* GPS

Figure 10

Data from Areas 1 and 2 collected using TTN Mapper.

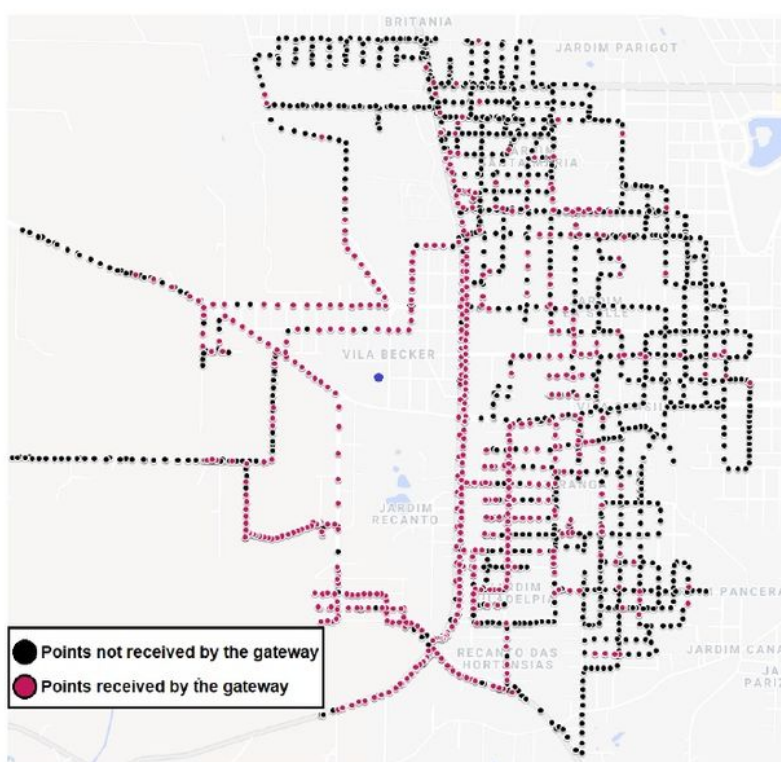
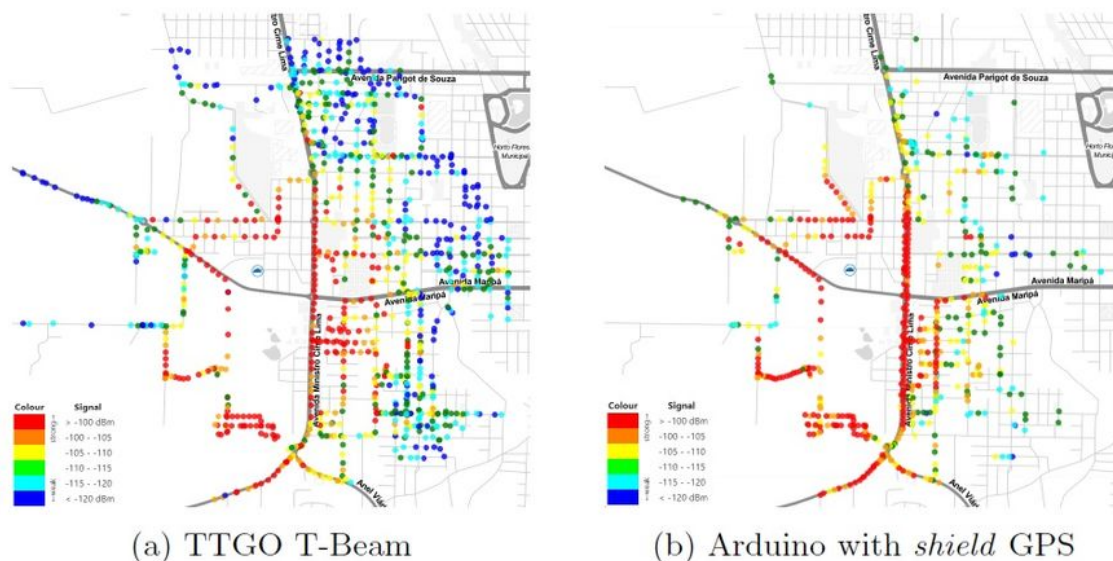
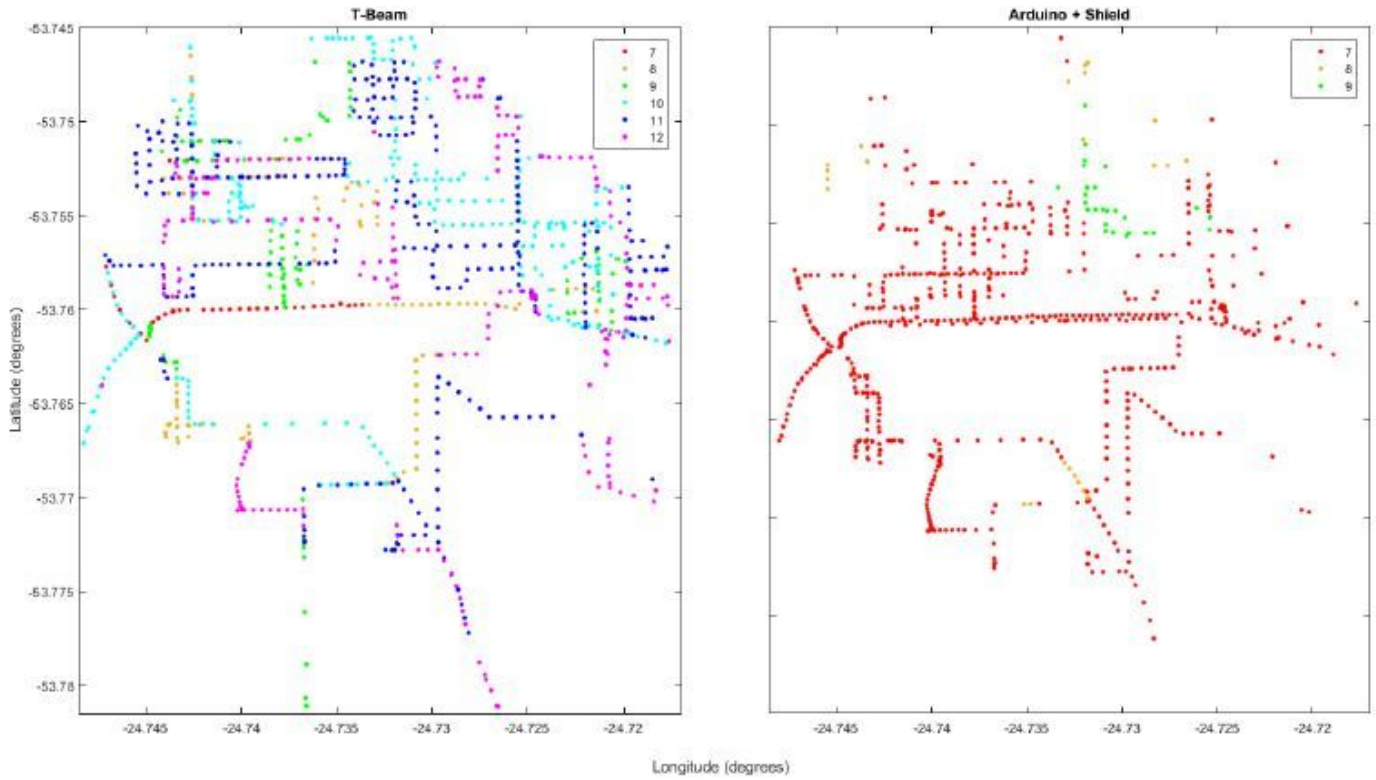


Figure 11

Data from Area 3 collected using TTN Mapper. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



SFs used in the coordinates received by the gateway for T-Beam (left) and Arduino (right), according to the latitude and longitude of the coordinates.

Figure 12

Spreading factor (SF) analysis.

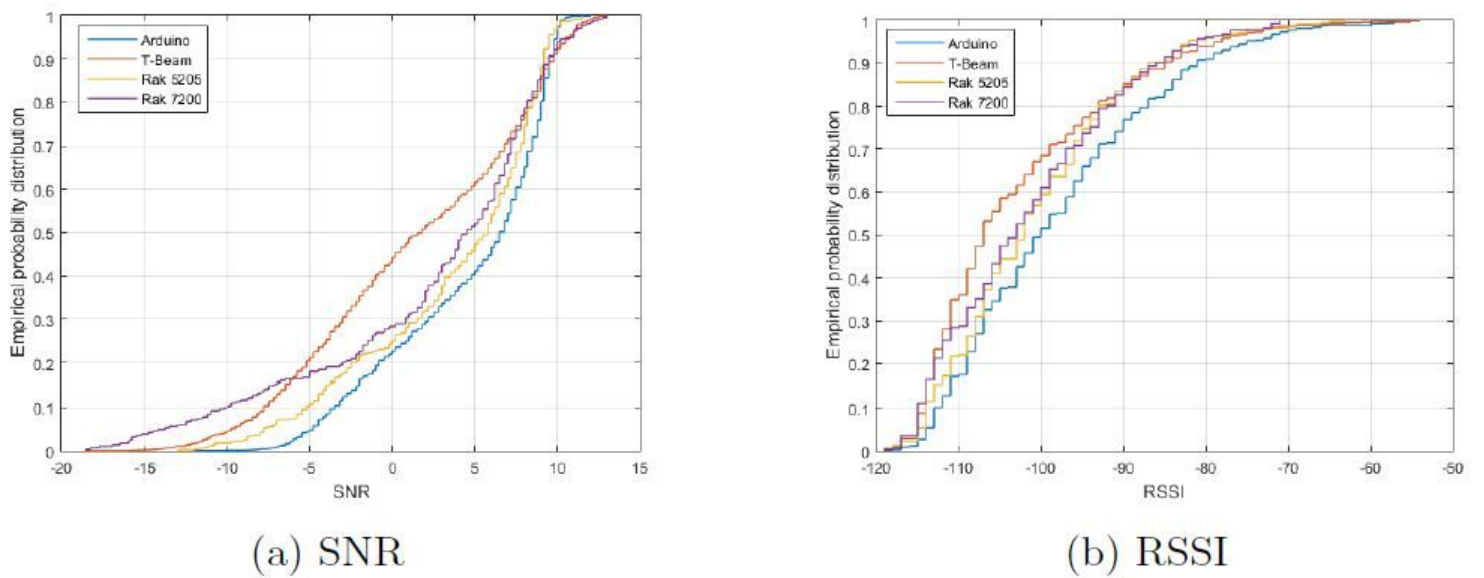


Figure 13

Empirical probability distribution curves for metrics SNR and RSSI.

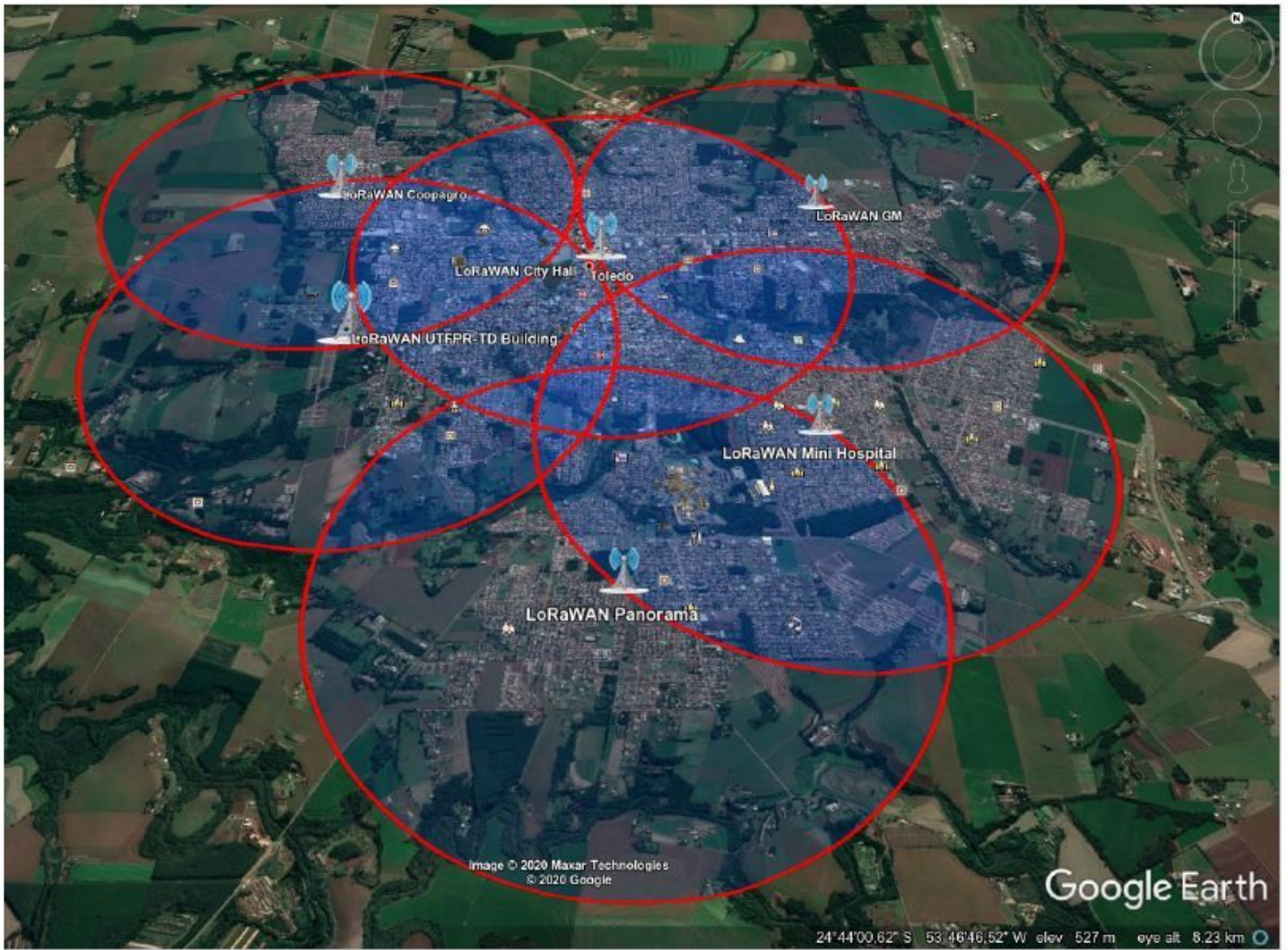


Figure 14

LoRaWAN expansion plan. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.