Coverage and Performance Analysis of a Private LoRaWAN Network Deployed in Urban Areas

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***Abstract*—The rapid expansion of the Internet of Things (IoT) requires communication protocols capable of supporting long-range connectivity, low power consumption, and robustness against urban interference. LoRaWAN has emerged as a promising Low Power Wide Area Network (LPWAN) technology, but most existing studies have evaluated its performance in controlled or rural environments. This work investigates the coverage and performance of a private LoRaWAN network deployed in Manaus, Brazil, focusing on urban conditions where reflections, obstacles, and multipath phenomena significantly affect communication. The methodology consisted of conducting four testbeds across different city regions using a mobile end device equipped with a LoRa transceiver (RAK3172) configured with AU915 MHz, Adaptive Data Rate, and periodic message transmission intervals of ten seconds and one minute. Messages containing geolocation and timestamps were sent to eleven gateways distributed throughout the city, with data collected and analyzed in terms of signal quality (Received Signal Strength Indicator - RSSI, Signal-to-noise ratio - SNR) and network performance (Packet Delivery Ratio – PDR). The experimental results demonstrated RSSI values mostly between –100 and –120 dBm, remaining within the operational limits of LoRaWAN, although strongly affected by environmental noise and non-line-of-sight conditions. SNR values varied from –19.8 to +13.3 dB, reflecting interference and mobility impacts.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/9788

***Index Terms*— Lorawan, Lora, Lpwan, IoT.**

I. Introduction

THE Internet of Things is an emerging paradigm in which objects are equipped with internet connectivity, allowing them to collect and exchange information with each other [1]. Currently, many IoT applications can be found in transportation, smart homes, health, manufacturing, automotive, and agriculture industries [2]. These applications are increasingly demanding requirements such as long-range, robustness to interference from the physical environment, and low power consumption. One of the most prominent IoT technologies to meet these requirements is the *Long Range Wide Area Network* (LoRaWAN), which is part of the *Low Power Wide Area Network* (LPWAN) [3] group of technologies.

Several papers have explored and analyzed the performance and coverage range of LoRaWAN networks in outdoor and indoor environments. However, most of them focus on controlled environments, such as laboratories and universities, which have few nodes and gateways [4] available. Therefore, papers that also study the performance of LoRAWAN technology in densely populated urban environments need to be further investigated and explored, given the great variability of urban landscapes and the physical phenomena to which message traffic is subject, such as reflections and multipath [5].

In this context, the main contributions of this study are to (i) carry out communication tests using the private LoRaWAN network deployed in the city of Manaus, the capital of Amazonas (northern Brazil); (ii) analyze and evaluate the data collected concerning signal quality and packet delivery; and finally, (iii) make the data collected available to ensure reproducibility and contribute to future research and discussions on LoRaWAN networks in urban environments.

The rest of the paper is organized as follows: Section II presents the technologies and concepts used in this article, Section III describes recent studies on LoRaWAN network coverage, Section IV describes the proposed methodology, and finallly, Section V presents the experiments carried out and the discussion of the results obtained; and finally, Section VI presents the conclusions and future research directions.

II. Technological Background

A. LoRa

Long Range (LoRa) is a technology developed by *Semtech Corporation*. It operates in ISM radio bands (*Industrial*, *Scientific*, *Medical*), which are unlicensed radio frequency spectrums. This technology is designed to establish long-range communications, reaching up to 5 km in urban areas and more than 15 km in rural areas, especially under line-of-sight (LOS) conditions [6]. The *Chirp Spread Spectrum* (CSS) modulation technique is used to achieve this high coverage. This technique is a proprietary form of the spread spectrum and increases the sensitivity of signal reception, allowing effective communication even in challenging conditions while also enabling high energy efficiency by maintaining low power consumption [7]. The LoRa radio's parameters can affect the communication distance and data transfer rate; therefore, they are crucial for adapting the technology to the specific needs of each application. The main parameters are [8]:

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- **Carrier frequency (CF)**: Is used for the transmission band. In Brazil, CF is in the 915 MHz to 928 MHz band.
- **Spreading Factor (SF)**: This parameter represents the number of chirps per symbol.Its value is an integer ranging from 7 to 12. A higher SF value increases the receiver's resilience to noise, enabling successful demodulation even at lower signal-to-noise ratios (SNRs). Though it also leads to a longer transmission time for a packet.
- **Bandwidth**: represents the set of frequencies in the transmission band. It can only be chosen from three options: 125 kHz, 250 kHz, or 500 kHz. If fast transmission is required, a frequency of 500 kHz is better. However, if a long range is required, a value of 125 kHz should be set.
- **Coding rate**: indicates that every four useful bits are encoded by 5, 6, 7, or 8 transmission bits. The lower the coding rate, the longer the airtime required to transmit the data.

B. LoRaWAN

The LoRaWAN is an open network protocol that provides secure two-way communication, mobility, and location services standardized and maintained by the LoRa Alliance. It defines the MAC layer that operates on top of the LoRa PHY layer. This protocol and the network architecture have the greatest influence on determining the state of a network's capacity, quality of service, and security [6]. LoRaWAN networks are deployed in a star topology and are made up of the following elements [9]:

- **End devices**: can be sensors, actuators, or both. They are connected to the LoRaWAN wireless network via gateways using LoRa modulation. They are usually battery-operated. The end devices send and receive LoRa messages via the gateways. The LoRa Alliance defines three classes of devices:
  - **Class A**: supports bidirectional communication, allowing both sending and receiving messages to/from the gateway. After transmitting messages, the device opens two reception windows to listen for responses from the server. This is the class with the lowest power consumption;
  - **Class B**: extends the capabilities of class A devices by adding synchronization through a *beacon* to the network server, allowing the scheduling of additional receive windows to receive downlink packets;
  - **Class C**: has a receive window that is always open, except when they are transmitting a message. This design makes communication between the network server and the end devices more efficient but also results in increased energy consumption.
- **Gateways** (GW): receive LoRa messages from end devices and forward them to the LoRaWAN network server (LNS). Each GW is registered on an LNS using specific configuration settings. GWs connect to an LNS through backhaul options such as cellular networks (3G/4G/5G), WiFi, Ethernet, fiber optics, 2.4 GHz radio links (e.g., proprietary short-range radio or LoRa for gateway mesh backhaul);
- **Network server**: consists of software running on a server that manages the entire LoRaWAN network, managing gateways, end devices, applications, and the routing of data to support user applications;
- **Application server**: processes the application-specific data messages received from end devices. It also generates all the application layer downlink payloads and sends them to end devices connected via the network server;
- **Join server**: assists in the secure activation of the device, the storage of the root key (root key), and the generation of the session key (session key).

In Brazil, the company responsible for maintaining the entire physical infrastructure of the LoRaWAN network is American Tower do Brasil (ATC). ATC installs and maintains LoRaWAN gateways nationwide [10]. However, ATC does not directly market LoRaWAN connectivity; instead, it is handled by authorized distributors. These distributors sell LoRaWAN connectivity to end customers, each offering its own connectivity plans [11]. The main distributors of LoRaWAN connectivity in Brazil are Everynet, Algar Telecom, TCTEC Telecom, NLT, and KORE.

III. Related Work

In recent years, several papers have analyzed the coverage and performance of LoRaWAN networks in urban environments [12].The author in [13] studied the coverage of a LoRaWAN network in the city of *Bydgoszcz*, Poland, using machine learning techniques and radio propagation models. In this study, varying the number of end devices and gateways helped determine the optimal network coverage factor. The best results were achieved with 4-5 gateways, covering over 96% of the studied area.

In the work [4], the reliability and coverage of the LoRaWAN public network deployed in the city of Caxias do Sul/RS were evaluated. The authors positioned devices in both indoor and outdoor environments and used three gateways from the public network during the tests. The coverage estimated by the gateways was exceeded; however, some messages sent by the devices were not received by any of the deployed gateways. Another significant contribution of this work was the finding that the transmission rate was 81.5% (considering all three gateways), indicating that this public network is suitable for applications that do not require highly reliable data transmission.

The paper [14] analyzed the signal coverage of the LoRaWAN network deployed at the Toledo Campus of the Federal Technological University of Paraná (UTFPR). To collect data on Received Signal Strength Indicator (RSSI) and SNR signals, they used one gateway and four end devices, which were attached to a car and driven along predefined routes throughout the campus. The study found that devices capable of varying the SF achieved better coverage results compared to those with a fixed SF.

In the study [12], performance tests were conducted on a LoRa network, and the results from real experiments were compared with those from simulation experiments. The study used only two devices (a receiver and a transmitter), which were positioned at various points of interest near the Federal University of Rio de Janeiro (UFRJ). The authors tested both direct LOS and obstructed line of sight (NLOS) scenarios. The results showed that the performance tests in both practical and simulated environments corresponded closely.

In [15] analyzed the accuracy of empirical propagation models for planning the deployment of LoRaWAN networks in an urban environment (Glasgow, UK). The study utilized both simulated and real-world data on coverage values (RSSI). In the real tests, they deployed three gateways and an end device, which followed specific routes in the city while transmitting messages to the gateways. For the simulated tests, the same urban scenario (NLOS) was replicated, and empirical radio propagation models were employed to predict the RSSI received by each gateway. The study concluded that the RSSI values predicted by the Okumura-Hata and Cost-231 Hata models were notably accurate.

Table I presents the main components of the works listed and highlights the main contributions of this research. Most of the articles consider real scenarios in their study of LoRaWAN network coverage and performance, where they analyze coverage signal quality data (e.g., RSSI, SNR) and network metrics (e.g., Packet Delivery Ratio (PDR), Packet Loss Ratio (PLR) and latency). Some articles use network simulations to plan the future deployment of the technology and/or to estimate the behavior of the real network. This type of approach allows for greater flexibility in stress tests, such as significantly increasing the number of nodes and gateways and intensifying information traffic [12][13][15][16].

TABLE I
COMPARISON OF RELATED WORK AND PROPOSED STUDY

Papers	Scenarios	Env.	Sight	Deployed Network	GW number	Freq. (MHz)
[16]	Simulation	*Outdoor*	NLOS	×	1-3	915
[13]	Real Simulation	*Outdoor*	NLOS	×	1-5	868
[4]	Real	*Outdoor Indoor*	NLOS LOS	✓	3	902-928
[14]	Real	*Outdoor*	NLOS LOS	×	1	915
[15]	Real Simulation	*Outdoor*	NLOS	×	3	915
[12]	Real Simulation	*Outdoor*	NLOS LOS	×	1	868
This paper	**Real**	***Outdoor***	**NLOS**	✓	**11**	**915**

Concerning the environment studied, most of the studies focus on *Outdoor* environments (NLOS and/or LOS). Concerning the use of private ATC networks, the papers study controlled outdoor environments with few gateways, which are not part of the infrastructure deployed in the respective cities.

Finally, concerning the operator's frequency, the studies use the respective frequencies of Europe (868 MHz) and Australia (915 MHz). In this context, this study stands apart from other articles in this section by analyzing coverage and performance within a private LoRaWAN network in an urban environment (Manaus city). This contrasts with the controlled environments typically described in previous articles. Additionally, this study employs a larger number of gateways compared to previous research. Another significant scientific contribution is the availability of datasets generated from the Manaus LoRaWAN testbeds in a public repository.

IV. TESTBED METHODOLOGY

We adopted the methodology illustrated in Fig. 1 to study and analyze LoRaWAN coverage in Manaus city. First, routes were planned for coverage assessment. Subsequently, a LoRaWAN device was installed on a vehicle to collect coverage data while traversing these predefined routes. The end device transmitted LoRaWAN messages to gateways, which forwarded them to the Network Server via TCP/IP backhaul protocols. The server's role was to store the data received from the gateways. Duplicate packets were identified by comparing the frame counter (FCnt) and payload content of each uplink message. If identical FCnt values and payloads were received from different gateways, only one instance was retained for analysis. Packet loss was inferred based on missing FCnt values in the expected sequence, which may result from interference, coverage limitations, or network congestion. The stored data was accessed via HTTP requests to the respective API, facilitating analysis of the data collected during the routes. Finally, to measure the quality of the LoRaWAN signal at the points along the route, the following signal and network quality metrics were used:

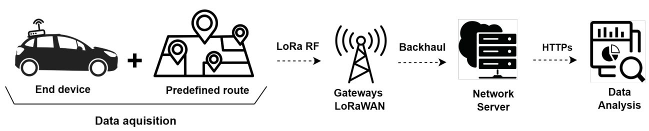


Fig. 1. Lorawan coverage analysis system architecture.

- **RSSI**: measure the quality and power of the connection signal received by a given device, considering possible losses, whether from propagation, antenna, or cable. For LoRaWAN technology, its typical values range from -30 to -120 dBm, and the closer the value is to 0, the stronger the signal [17];
- **SNR**: measure the quality of a signal in a meaningful way, by subtracting the noise identified by RSSI. For LoRaWAN technology, its typical values range from -20 to +10 dB, where +10 dB is considered optimal, close to 0 dB is considered good and below -4 dB is considered poorer quality [17];
- **PDR**: is the ratio of packets received to packets sent during the total communication period. The higher the PDR value, the better the network performance [18];

V. EXPERIMENTS AND RESULTS

This section details the prototype used, the end device parameters selected, the route taken, and the results.

A. Testbeds Planning

Four testbeds were planned to evaluate the performance and coverage range of the LoRaWAN network deployed in Manaus. The testbeds were intended to cover some of the main neighborhoods in the metropolitan area of Manaus, such as Adrianópolis, Japiim, Aleixo, São José, Raiz, São Lázaro, Betânia, and Distrito Industrial I, comprising the South, Central-South and part of the North and East zones of the city. In addition, some testbed routes were conducted in Manaus border regions, allowing us to note how far the LoRaWAN coverage can reach. The planned testbeds were:

- **Testbed I** (Planalto to São José do Operário): starts at the Planalto neighborhood, goes through Alvorada, and Flores areas, and ends in the São José Operário neighborhood. The entire route was 16 km;
- **Testbed II** (Parque 10 to Planalto): starts at Torres Avenue, located in the neighborhood of Parque 10 de Novembro, goes through the region of São José, District I, ending the journey in the neighborhood of Planalto. The entire route was 34 km;
- **Testbed III** (Lagoa Azul to Flores): starts at the entrance to Manaus, goes through the region of Lagoa Azul, Colônia Terra Nova, and ends in the neighborhood of Flores. The entire route was 18 km.
- **Testbed IV** (Planalto to Iranduba): starts at the Planalto, goes through Santo Agostinho, Compensa, crosses the Rio Negro bridge, and ends in the town next to Manaus, called Iranduba. The total distance was 29.7 km.

B. End Device

The end devices used for the experiments can be seen in Fig. 2a. It consists of a prototype whose circuit is made up of a transceiver module (RAK3172) for LoRa and LoRaWAN applications based on the STM32WLE5CC chip; a satellite data modem (M138), which is, in this study, responsible for acquiring and making available geolocation data to STM32WLE5CC; and an acetal case. The purpose of this device is to periodically send messages via LoRaWAN whose payload consists of geolocation and timestamp data.

Table II details the configuration of the end device for the LoRaWAN communication testbeds, highlighting the main parameters configured such as sending intervals, frequency, and payload size. Concerning the messages sent by the device, two sending intervals were considered: one message every 10 seconds and one message every 1 minute. These sent period intervals aimed to stress the LoRaWAN network and achieve a high number of radio frequency data samples (RSSI and SNR) that represented the regions studied since their variation in urban environments is high [12]. In addition, these short time intervals were configured to subject the city's public network to conditions of intense message traffic.

Concerning the LoRa transceiver antenna, a flexible antenna with a gain of 1.7 dBi was used. The LoRa operating frequency used was AU915 MHz, as this is the standard frequency in Brazil for this technology. The bandwidth was set to 125 KHz to achieve greater packet delivery. In addition, the Adaptive Data Rate (ADR) function was enabled. While ADR is typically designed to provide the end device with greater adaptability to interference in varying environmental conditions and contribute to a higher PDR, its effectiveness can be limited in mobile scenarios due to rapidly changing channel conditions [8]. Finally, the size of the *payload* of the LoRaWAN message sent was 17 bytes and the join mode used to activate the device on the LoRAWAN network was Over-the-Air Activation (OTAA), as it guarantees greater security than Activation by Personalization (ABP) mode [9].

TABLE II
END DEVICE LORA/LORAWAN PARAMETERS

Parameters	**End device values**
LoRa chip	SX1276
Antenna type	Flexible
Antenna gain	1.7 dBi
Antenna height	1 m
TX power	20 dBm
Carrier Frequency	915 MHz
Bandwith	125 kHz
ADR	ON
Payload Size	17 bytes
Packet Interval	10 s, 1 min
Activation mode	OTAA

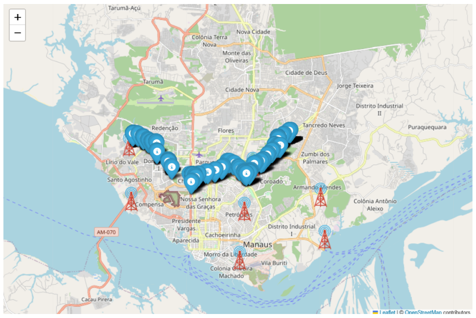
C. Testbeds Execution and Results Discussion

The duration of the testbeds' journeys ranged from 36 minutes to 2 hours at a speed $\sim$ 50 km/h. The photos in Fig. 2 show moments from the testbed routes, such as the end device with the case closed on the vehicle and a LoRaWAN GW up close (2c).

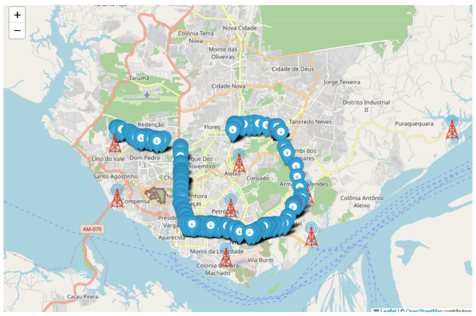
(a) Case open. (b) End device. (c) GW Tower.

Fig. 2. Hardware system during testbeds.

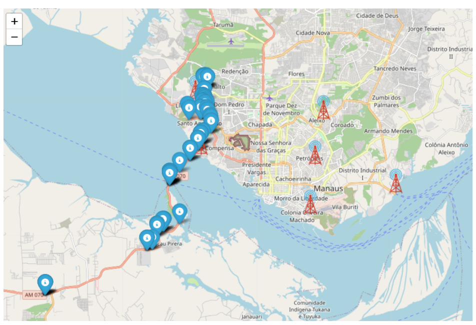
After communication tests in the field, the *datasets* of LoRaWAN messages stored on the LoRaWAN Network Server was accessed. The data obtained during the routes was analyzed regarding signal quality and packet delivery. The routes taken in all testbeds can be seen in Fig. 3, where the blue icons represent the locations sent in the *payload* message from the end device; and the tower icons in red represent the positioning of the *gateways* on the city's towers that receiving messages during testbed. The following subsections evaluate the LoRaWAN testbeds in terms of signal quality and packet delivery.



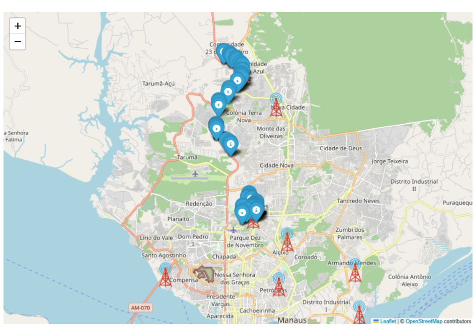
(a) Testbed I.



(b) Testbed II.



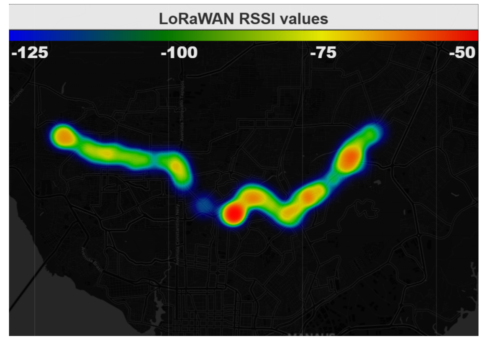
(c) Testbed III.



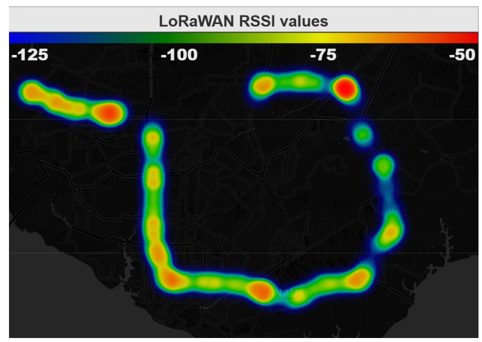
(d) Testbed IV.

Fig. 3. Routes generated during testbeds in Manaus.

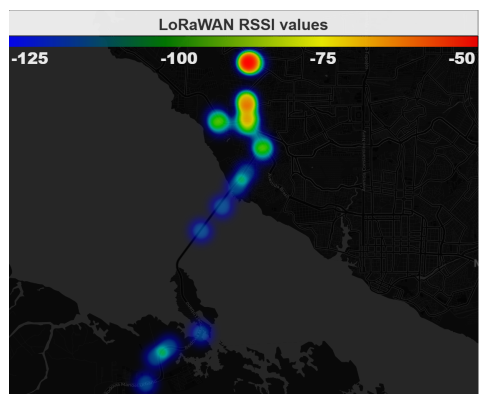
1) Signal Quality Evaluation: Fig. 4 shows the heat maps generated from the RSSI data received by the GWs for each packet sent by the end device across all testbeds. In these visualizations, red indicates better signal quality ($\geq$ -40 dBm), while blue indicates poorer signal quality ($<$ -120 dBm). The maps also reveal that shorter sending intervals in the testbeds allowed for more detailed observations of RSSI behavior at various points along the routes, providing a larger sample of the signal quality.



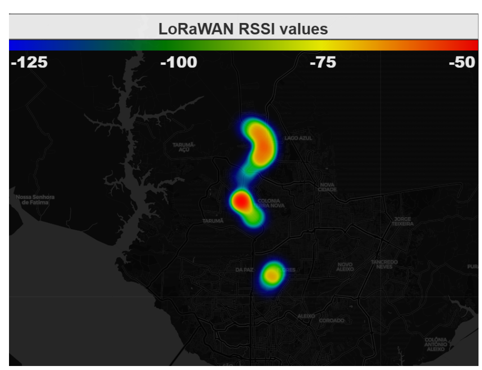
(a) Testbed I.



(b) Testbed II.



(c) Testbed III.



(d) Testbed IV.

Fig. 4. Heat maps generated from the RSSI data received.

The graphs in Fig. 5 show the RSSI and SNR metrics for each testbed. In all testbeds, the RSSI values mostly ranged between -100 and -120 dBm, indicating that the device's messages were within the LoRaWAN operating range despite environmental challenges. In Testbeds I and II (Figs. 5a and 5b), the shorter sending intervals provided a more detailed view of RSSI behavior at various points along the route. In contrast, Testbeds III (Fig. 5c) had fewer samples due to being conducted in the border regions of Manaus, which had lower coverage quality. Additionally, Testbed IV (Fig. 5d) had a longer sending interval of 1 minute compared to the 10-second interval in Testbed III.

The SNR values in the testbeds remained within the LoRaWAN operating range, generally between 10 and -20 dB for most of the experiment duration, with peaks reaching approximately 13.3 dB and -19.8 dB. However, this range suggests that the route experienced external environmental noise, which influenced the quality of the received signal. The higher SNR values, close to 13 dB, occurred when the end device was near the GW and/or experienced less interference from external noise compared to other regions covered.

Table III summarizes the RSSI and SNR results from the testbeds. The maximum and minimum RSSI values ranged from approximately -43 to -78 dBm and -117 to -123 dBm, respectively. The mean RSSI values and standard deviations reflect the significant variation in RSSI observed along the routes. Notably, there were some peaks with very good signal quality, close to -40 dBm. These peaks were recorded in regions very close to the gateways, where the signal quality improved as expected.

Therefore, these results suggest that the signal quality received by the gateways was significantly impacted by urban environmental interference, such as obstacles (e.g., buildings, trees, vehicles) and reflection and multipath phenomena common in cities. Given that the ADR function was enabled and end devices were mobile (traveling at approximately 50 km/h along defined routes), it is crucial to note that ADR's dynamic adjustments to transmit power and Spreading Factor also played a role in the observed RSSI and SNR values and subsequent packet losses. ADR's effectiveness in rapidly changing mobile environments is often limited, meaning it may not have optimally adapted to all instantaneous channel variations. Additionally, the end device was inside the car during the experiments, which further contributed to signal attenuation and resulted in a NLOS condition concerning the gateways.

TABLE III
SUMMARY OF RSSI AND SNR METRIC RESULTS

Testbed	RSSI (dBm)				SNR (dB)			
	Max.	Min.	Mean	Std.	Max.	Min.	Mean	Std.
I	-50	-120	-105	17.49	13.3	-14.0	-1.33	6.99
II	-43	-123	-109	11.29	11.5	-19.8	-5.34	6.67
III	-78	-120	-109	10.01	6.2	-16.5	-6.24	6.59
IV	-50	-117	-104	17.21	9.5	-15.5	-2.45	7.24

2) Package Delivery Evaluation: Regarding the PDR metric, Table IV provides a summary of the results obtained. The highest PDRs were achieved in Testbed IV (75%), followed by Testbed I (70.96%) and Testbed II (68.96%). Testbed III recorded a lower PDR of 43.66% due to reduced LoRaWAN coverage in the chosen route (Manaus border region). These results underscore the impact of environmental interference in outdoor settings, leading to packet loss in some instances. Furthermore, considering the mobility of the end devices and the enabled ADR function, it is plausible that instances of packet loss were also influenced by the end devices sending packets with suboptimal Transmit Power (TP) and SF due to ADR's inherent limitations in rapidly adapting to dynamic channel conditions.

TABLE IV
SUMMARY OF PDR RESULTS

Testbed	Period	Interval	Uplink			PDR
			Total	Unique	Duplicate	
I	1h 47 min	10 s	651	457	194	70.96 %
II	2h 31 min	10 s	999	630	369	68.93 %
III	23 min	10 s	91	62	29	43.66 %
IV	36 min	1 min	40	27	13	75.00 %

Furthermore, Table V presents the PDR for each gateway and the corresponding neighborhoods where they are installed. In Testbeds I and II, the GWs located in the Aleixo (Central-South Zone) and Petrópolis (South Zone) neighborhoods received the highest concentration of messages from the end device (37.6% and 28.6%). Testbed III showed the best results in the GWs deployed in the Lago Azul and Santa Etelvina (41.8% and 39.6%) neighborhoods (North Zone). In Testbed IV, the GWs in Compensa (West Zone) and São Lázaro (South Zone) exhibited the best performance (42.5% and 25.0%).

TABLE V
GW NEIGHBORHOOD PER PDR RESULTS

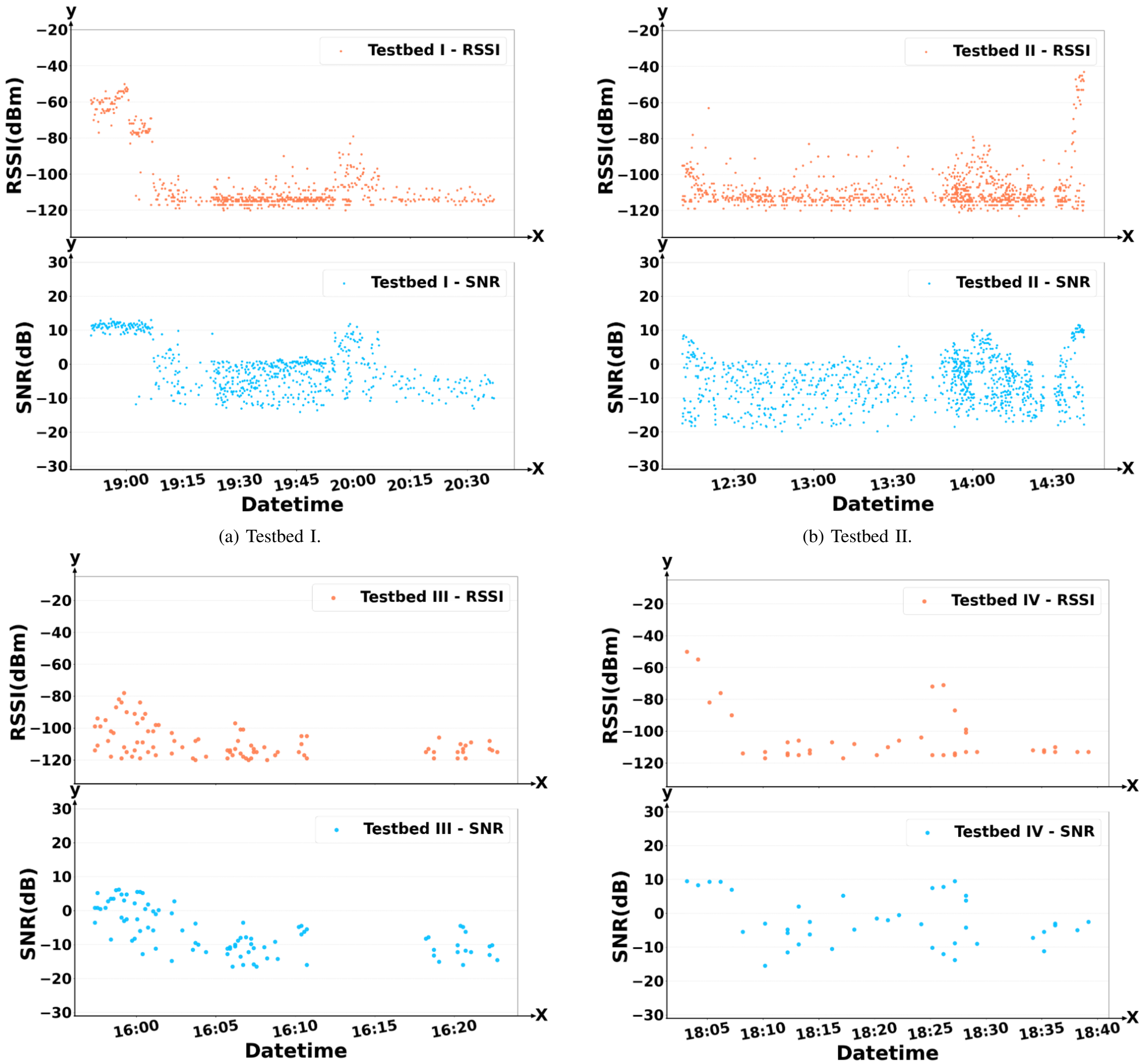
GW Neighborhood	Testbed PDRs (%)			
	I	II	III	IV
Aleixo	37.6	41.9	11.0	7.5
Compensa	11.1	12.9	2.2	42.5
Mauzinho	1.2	9.1	-	7.5
Petrópolis	28.6	15.7	-	2.5
Planalto	15.4	3.2	-	15.0
São Lázaro	5.4	13.8	1.1	25.0
Flores	-	-	4.3	-
Lago Azul	-	-	41.8	-
Santa Etelvina	-	-	39.6	-
Armando Mendes	0.7	3.2	-	-
Puraquequara	-	0.2	-	-

Finally, in addition to the analyses presented in this section, another interesting scientific contribution of this article is the availability of data collected in this **public link** to contribute to future research and discussions on the deployment of LoRaWAN technology and the study of coverage analysis of this technology in urban environments.

VI. CONCLUSIONS AND FUTURE WORKS

This research set out to analyze data from the LoRaWAN private network deployed in the city of Manaus, evaluating it concerning signal quality and packet delivery, standing out from recent works in the literature that focus on controlled environments and those simulated by software tools.

The proposed methodology was successfully applied and four Testbeds were carried out. The best results of the PDR metric were 70.96% and 75%. Given these PDRs obtained



(a) Testbed I.

(b) Testbed II.

(c) Testbed III.

(d) Testbed IV.

Fig. 5. The RSSI and SNR metrics results for each testbed.

with mobile end devices, the network's reliability in such dynamic scenarios suggests its suitability for applications where extremely high data transmission reliability is not a critical requirement. In terms of signal quality metrics, both Testbeds remained in the LoRaWAN operating range. The RSSI values during the execution of the experiments were around -100 to -120 dBm, with maximum and minimum peaks of approximately -40 and -123 dBm, respectively. The SNR metric values during the execution of the experiments were between 10 and -20 dB, with maximum and minimum peaks of approximately 13.3 and -19.8 dB.

It can be concluded that in all testbeds, the results obtained by means of the signal quality and packet delivery metrics reflect the complex interplay between urban environmental interference and the dynamic behavior of the ADR function with mobile end devices. While environmental phenomena presented significant challenges, ADR's continuous adjustments to SF and TP, alongside its inherent limitations in adapting to rapidly changing channel conditions in mobile scenarios, also significantly influenced the observed variations in signal quality and packet delivery. Finally, another significant contribution of this article was to make the data collected available in a public repository. This dataset, specifically detailing LoRaWAN performance with mobile end devices and an enabled ADR function in an urban environment, provides valuable insights into the complexities and challenges of such deployments. It can thus contribute to future research on the behavior of ADR in mobility, channel modeling in dynamic urban settings, and the development of more robust LoRaWAN mobility solutions.

As the next steps, coverage studies in regions close to the borders of Manaus will be conducted. They will include: stopping points on the route considered, repositioning the end node in the vehicle, relocating it to the outside, and changing the end node antenna to an antenna with a higher gain (> 1.7 dBi). At the end of these future tests, the authors aim to understand better the quality of LoRaWAN signal coverage in the city of Manaus and the % of packet delivery that can be achieved using the private infrastructure deployed.

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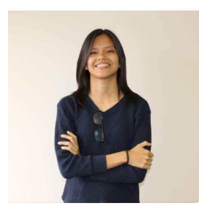

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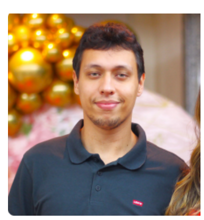

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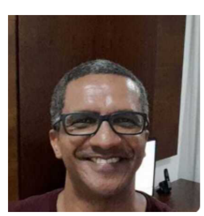

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