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Empowering IoT Development with LPWAN Technology: A Case Study at the National University of Misiones

Potenciando el Desarrollo de IoT con Tecnología LPWAN: Caso de Estudio en la Universidad Nacional de Misiones

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Abstract

This document underscores the vital role of Low Power Wide Area Network (LPWAN) technology in advancing the Internet of Things (IoT) and enabling connectivity for low-power devices, prioritizing factors like range, durability, and cost-efficiency. It explores the influences on LPWAN performance, including Ultra Narrow Band (UNB) and Spread Spectrum (SS) modulations, offering in-depth insights into their technical characteristics, pros, and cons across licensed and unlicensed operational spectrums. Notable challenges encompass battery life, quality of service, coverage, and expenditure. The city of Posadas, Argentina, is showcased as a successful LoRaWAN testbed, illustrating the system's commendable performance and functionality.

Keywords: LPWAN, Internet of Things, LoRaWAN, TTN, TTNMapper.

Resumen

Este documento analiza la importancia de las redes de área amplia y baja potencia (LPWAN) en la expansión del Internet de las Cosas (IoT) y en la conectividad de dispositivos de bajo consumo. Se centra en las tecnologías LPWAN con modulaciones Ultra Narrow Band (UNB) y Spread Spectrum (SS), evaluando sus características técnicas, ventajas y desventajas en función de su espectro operativo, ya sea licenciado o no licenciado. Los principales desafíos abordados son la duración de la batería, la calidad de servicio, la cobertura y los costos. Se destaca el éxito del sistema LoRaWAN en la ciudad de Posadas, Argentina, como un ejemplo de aplicación exitosa de estas tecnologías en la práctica.

Palabras clave: LPWAN, Internet de las cosas, LoRaWAN, TTN, TTNMapper.

Introduction

The fourth industrial revolution is the era of wireless communication that enables widespread connectivity between machines and objects. Over the years, communication systems have evolved and are now capable of supporting an exponentially growing number of interconnected devices. (Figure 1)

IoT applications demand technologies that are energy-efficient, cost-effective, and, above all, of low complexity. As a rule, their usage profiles must be carefully considered to extend the lifespan of nodes to the maximum.

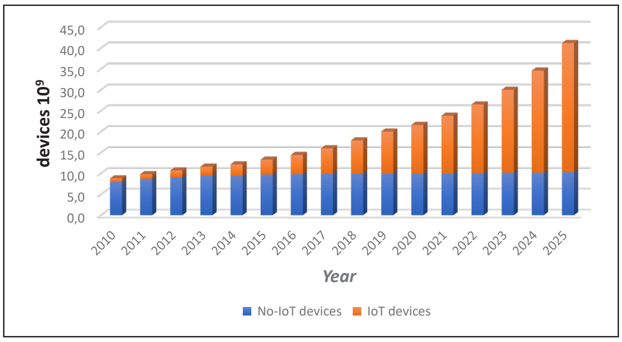

Figure 1: Prospective evolution of interconnected devices [1].

The Internet of Things (IoT) demonstrates steady growth, forming a series of networks with different design objectives and coverage. Some are intended solely for local area coverage, while others offer broader coverage, interconnecting sensors, actuators, meters (for water, gas, electricity, or parking), vehicles, appliances, and more.

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If we add the inherent requirements of IoT projects to the need for wireless communication over considerable distances (for security, motion control, agriculture, smart measurement, smart cities, and smart homes), the demand for specific technologies becomes even more relevant [2]. Short-range technologies (such as Bluetooth, Wi-Fi, 6LowPAN, industrial, scientific, and medical radio bands - ISM -, IEEE, etc.) are not the most suitable, whereas those based on cellular communications (3G, 4G, and 5G) can provide broader coverage but with excessive power consumption. These fundamental requirements in IoT have driven the adoption of Low Power Wide Area (LPWA) communication technologies.

LPWA enables communications over distances ranging from 10 to 40 km in rural areas and 1 to 5 km in urban areas as highly energy-efficient and cost-effective. The radio chip can be obtained for less than €2, and the operational cost is estimated at €1 per device per year [3], This has driven its use in both outdoor and indoor environments [4]a long-range data transmission is required in numerous Internet of Things (IoT, [5]Science, Medical. Therefore, the utilization of LPWA is justified when there is a need to transmit limited information over a distance greater than what is typically considered in other known wireless networks . LPWA has emerged not only in exclusive frequency bands where a single user is assigned one or more frequencies for a period of time but also in shared frequency bands where multiple users share the same frequencies [6]. This allows radio communication devices to operate without the need for individual authorization from authorities for each station.

LPWAN technologies employ two main techniques in the physical communication layer: Ultra Narrow Band (UNB) and Spread Spectrum (SS), making the selection of the most appropriate technique paramount.

Among the trending technologies, we can mention Sigfox UNB [7], a reliable wireless signal for IoT devices through an intelligent and adaptable network; LoRa (Long Range) [8] a low-power technology designed specifically for long-range communication between IoT devices; and NB-IoT [9] (*Narrowband-IoT*) also known as Narrowband Internet of Things, which is a cellular technology operating within licensed spectrum, allowing it to leverage existing cellular infrastructure for IoT connectivity. These three technologies exhibit significant technical differences, as observed in Table 1.

Table 1: LPWAN Technologies Contrast.

	LoRaWAN	**Sigfox UNB**	**NB-IoT**
Frequency band	Open use	Open use	license
Reach (urban)	5 Km	10 Km	1 Km
Reach (rural)	20 Km	40 Km	10 Km
Maximum data rate	50 Kbps	0,1 Kbps	200 Kbps
Maximum messages/day	Unlimited	140 up/4 down	unlimited
Modulation	CSS	BPSK	QPSK
Encryption	Yes (AES 128b)	No	Yes (LTE)
Adaptive data rate (ADR)	Yes	No	No
Private Networks	Yes	No	No
Access by	Any	Operator	Operator
Localization	RSSI y TDOA	RSSI	No

Sigfox and LoRa both originated from startup projects. Sigfox operates and commercializes its own IoT solution in over 75 countries and is continually expanding by partnering with network operators worldwide [7]. LoRa was acquired by Semtech in 2015 [10] and its standardization has been overseen by LoRa Alliance [8]. LoRaWAN is an open-source protocol that runs over the LoRa physical layer, enabling a medium access control mechanism for communication among multiple devices and network gateways. Unlike Sigfox and NB-IoT, LoRaWAN offers the ability to implement private networks and easy integration with various network platforms worldwide (e.g., The Things Network [11]). Because of this and its open-access specifications, LoRaWAN has attracted attention from the research community since its inception.

NB-IoT is developed by the Third Generation Partnership Project (3GPP) [12], and is based on narrowband radio technology using the same frequencies as LTE (Long Term Evolution) and QPSK (Quadrature Phase Shift Keying) modulation. To simplify it as much as possible and thereby reduce costs and consumption, NB-IoT eliminates many functions of LTE, including handover, channel quality monitoring, carrier aggregation, and dual connectivity. Some authors consider NB-IoT as a new wireless interface [13].

Technology

Sigfox deploys proprietary base stations equipped with software-defined cognitive radios and connects them to backend servers through an Internet Protocol (IP) network. End devices use binary phase shift modulation (BPSK) on an ultra-narrowband ISM sub-GHz (100 Hz) carrier. ISM bands do not require licenses, with frequencies of 868 MHz in Europe, 915 MHz in the Americas and Oceania, and 433 MHz in Asia. By utilizing the ultra-narrowband, Sigfox efficiently utilizes bandwidth and experiences very low levels of noise and energy consumption [14], along with high receiver sensitivity and a simple antenna design, transmitting at a rate of only 100 bps. The number of messages through the uplink is limited to 140 messages per day, with a maximum length of 12 bytes. However, the number of messages through the downlink is limited to four messages per day with a maximum payload length of eight bytes, which does not support acknowledgment of all uplink messages. Without proper acknowledgment support, the reliability of uplink communication is ensured using time and frequency diversity, as well as transmission duplication. Each end-device message is transmitted three times by default on different frequency channels: 400 orthogonal channels of 100 Hz (including 40 reserved and unused channels) [15]. Since base stations can receive messages simultaneously on all channels, the end device can randomly choose a frequency channel to transmit its messages, simplifying the end device design and reducing its cost.

LoRa is a physical layer technology that modulates signals in the ISM sub-GHz band using a patented spread spectrum technique. Bidirectional communication is provided by chirp spread spectrum (CSS) modulation. The resulting signal has low noise levels, giving it high resistance to interference, making it difficult to detect or block [16]. LoRa uses six spreading factors (SF7 to SF12). A higher spreading factor allows for greater range at the expense of a lower data rate (ranging from 0.3 to 50 kbps), and vice versa. The maximum payload length for each message is 243 bytes.

The LoRaWAN specification is a protocol designed to wirelessly connect “things” to the Internet through regional, national, or global networks. It focuses on key IoT requirements: bidirectional communication, security, mobility, and localization [17]. LoRaWAN is implemented in a star-of-stars topology, where gateways transmit messages between end devices and a central network server. These gateways are connected to the network server through standard IP connections and act as transparent bridges, converting radio frequency packets from end nodes into IP packets and vice versa. Wireless communication takes advantage of the long-range characteristics of the LoRa physical layer, enabling a single-hop link between the end device and one or multiple gateways. All nodes are capable of bidirectional communication, and there is support for multicast addressing groups to efficiently use the spectrum during tasks such as over-the-air firmware updates (FOTA) or other mass distribution messages.

Using LoRaWAN, every message transmitted by an end device is received by all gateways within range. LoRaWAN’s redundant reception quality improves the proportion of successfully received messages. However, achieving this feature requires multiple gateways, which can increase the cost of network deployment. The resulting duplicate receptions are filtered at the backend system, which also has the intelligence to verify security, send acknowledgments to the end device, and forward the message to the corresponding application server. For locating end devices, it uses the Time Difference of Arrival (TDOA) technique supported by highly accurate time synchronization among multiple gateways [18].

NB-IoT is a narrowband IoT technology that can coexist with the Global System for Mobile Communications (GSM) and LTE systems under licensed frequency bands. NB-IoT occupies a frequency bandwidth of 200 KHz, corresponding to a resource block in GSM and LTE transmissions [9]. The NB-IoT communication protocol is based on the LTE protocol, minimizing its functionalities and enhancing them as needed for IoT applications [19]. NB-IoT allows connectivity for up to 105 end devices per cell, with the possibility of expanding capacity by simply adding more NB-IoT carriers. It employs Frequency Division Multiple Access (FDMA) in the uplink and Orthogonal Frequency Division Multiple Access (OFDMA) in the downlink, using Quadrature Phase Shift Keying (QPSK) modulation. The data rate is limited to 200 kbps for the downlink and 20 kbps for the uplink, with a maximum message size of 1600 bytes.

LPWAN selection for IoT, key criteria

When selecting a Low-Power Wide-Area Network (LPWAN) technology for IoT applications, there are several key criteria to consider.

Coverage and Range: The wide area indicates the coverage that can be directly achieved without the need for another mesh network to extend the range [20]including wireless sensor networks, wireless mesh networks, and mobile ad hoc networks, is discussed in this paper. Wireless devices link to one another directly in an ad hoc network without the use of a central Wireless Access Point (WAP. Two techniques can be used to achieve long distances: Sub-GHz and special modulation schemes. Sub-GHz is used by most LPWA technologies due to its reliability, robust communication, and low power consumption [21]. Compared to 2.4 GHz, Sub-GHz experiences less frequency attenuation, less congestion, and fewer multipath fading effects caused by obstacles and dense surfaces. Due to its robustness and reliability, Sub-GHz enables extended communication range and low power consumption. LoRa can provide coverage for a city, whereas NB-IoT coverage is limited to LTE coverage areas, making NB-IoT less suitable for suburban and rural areas where LTE coverage networks are often absent. In such cases, LoRa and Sigfox are more appropriate options [22].

Data Rate: Low-Power Wide-Area Network (LPWAN) technologies are designed for applications that prioritize long-range communication and low power consumption over high data rates. They strike a balance between energy efficiency, long-range communication, and moderate data throughput, making them a popular choice for connecting IoT devices in scenarios where low power consumption is critical, and data transmission is intermittent or sporadic. However, when high data rates or real-time communication are essential, alternative wireless technologies may be necessary. The choice of LPWAN or other wireless standards depends on the specific needs of the IoT application.

Power Efficiency: LPWAN is known for its low power consumption, making it suitable for battery-operated devices typically provide lower data rates compared to cellular networks. The battery life of an IoT device primarily depends on the network topology and the duty cycle. LPWAN connects devices directly to the base station, bypassing the energy consumption associated with packet transmission through multi-hop networks [23]. The duty cycle of LPWA adapts to the application, power source, and traffic.

Scalability: LPWAN scalability encompasses device, coverage, traffic, application, service provider, interoperability, cloud, and security scalability. This scalability enables IoT deployments to expand and adapt to changing requirements, making LPWANs a versatile choice for a wide range of IoT applications.

Deployment Costs: hardware, network access fees, and operational expenses, need to be considered. It is important to conduct a thorough cost analysis based on the specific IoT project scope, scale, and requirements. This analysis should consider both upfront deployment costs and ongoing operational expenses to create a comprehensive budget. Some LPWAN technologies may be more cost-effective for specific use cases. The total cost of LoRa and Sigfox is lower than that of NB-IoT, primarily due to the cost of spectrum (licensing). Sigfox nodes can be produced for less than €2, LoRa nodes range from €3 to €5, while an NB-IoT end device can cost more than €20. Regarding implementation costs, a Sigfox base station costs around €4,000, an NB-IoT base station costs €15,000, while a LoRa gateway costs less than €100 [24]. It is evident that Sigfox and LoRa are more cost-effective when compared to NB-IoT.

Security: LPWAN offers unique benefits for IoT applications, but they also come with specific security challenges as: Limited Security Features, Device Authentication, Data Encryption, Key Management, Device Tampering, DoS Attacks, Firmware and Software Updates, Physical Security of Gateways, Regulatory Compliance and Interoperability. To mitigate these security issues in LPWAN, the following best practices need to be considered: strong authentication mechanisms for device onboarding, end-to-end encryption, update firmware and software, intrusion detection systems, secure physical access to gateways.

Interoperability: is crucial for hassle-free deployment. Sigfox and LoRa have reached a certain level of maturity and are applied in various countries, while NB-IoT lags behind in implementations. The significant advantage of the LoRa ecosystem is its flexibility. Unlike Sigfox and NB-IoT, LoRa offers the implementation of local networks.

Latency: While LPWAN offers good coverage, they may have higher latency compared to cellular networks. For applications that are not sensitive to latency and involve transferring a small amount of information, Sigfox and LoRa are excellent choices. When low latency is required, NB-IoT and LoRa are the best options [25].

Regulatory Compliance: is a crucial aspect of deploying LPWAN technologies for IoT applications. Some key considerations for LPWAN regulatory compliance are: spectrum Regulations, licensing Requirements, duty Cycle Limits, transmission Power, data privacy, firmware updates, local regulations, certifications, interference mitigation, geographical restrictions (Sigfox).

Reliability and Redundancy: LPWAN offers reliability advantages for IoT applications that prioritize long-range communication and power efficiency. However, to ensure reliable operation, it is essential to assess the specific requirements of applications, plan for network design and redundancy, and implement best practices for device placement, security, and maintenance. Redundancy is critical for maintaining connectivity in case of network failures.

Data Volume and Storage: LPWAN is typically designed for applications that involve transmitting small amounts of data over long distances with low power consumption. As a result, the data volume generated by LPWAN devices is relatively low. However, LPWAN deployments can accumulate significant amounts of data over time, and it is important to consider data volume and storage requirements.

Longevity: In Sigfox, LoRa, and NB-IoT, end devices are in low-power mode most of the time, thereby improving their battery life. The NB-IoT end device consumes additional energy due to the need for synchronous communication, QoS management, and its OFDM/FDMA access modes, which require higher maximum current [26]. This reduces the lifespan of the NB-IoT end device compared to Sigfox and LoRa.

Materials and methods

A methodological approach for implementing a Low-Power Wide-Area Network (LPWAN) and evaluating coverage and connectivity for IoT support services like The Thing Network (TTN) is presented. This work is part of project 16/Q1306-PI "*Internet de las Cosas y Redes LPWAN at the Universidad Nacional de Misiones*", which is being carried on at the Faculty of Exact, Chemical and Natural Sciences (FCEQyN) of the National University of Misiones (UNaM), whose general objective is to establish modern and updated methods usable in the field of the Internet of Things (IoT), addressing application development support as well as objects localization.

Although LoRaWAN was originally designed to operate across the frequency band defined by the International Telecommunication Union (ITU) from 902 MHz to 928 MHz; in Argentina, there was a deviation from the international definition. Instead, a segment of the Industrial, Scientific, and Medical (ISM) band ranging from 905 MHz to 915 MHz was allocated for Advanced Mobile Communications Service (SCMA) [27]. As a result, Argentina uses the frequency band known as AU915 instead of the originally planned US915 band. One disadvantage is that LoRa transceivers must operate in half-duplex mode.

Considering the criteria for selecting LPWAN technology, although conducting a quantitative cost analysis is challenging given the current situation in our country, we have defined commercial requirements, technological performance, and market availability to choose the appropriate LPWAN solution.

Figure 2: Gateway installed at main building of FCEQyN.

Figure 3: Deployment of a gateway at the Biochemistry building, FCEQyN.

Hence, the implementation of a LoRaWAN network has been defined to provide service to devices in the downtown area of the city of Posadas. The gateways have been deployed on Raspberry Pi 3 Model A+ devices (featuring a quad-core 1.4 GHz 64-bit processor, dual-band wireless LAN, and Bluetooth 4.2/BLE) [28], and a LoRaWAN concentrator board, the RAK831_915 [29]. This concentrator board has the capability to simultaneously receive packets using different spreading factors across multiple channels, making it a complete RF front-end (see Figures 2 and 3). The RAK831 includes the SX1301 digital baseband chip from Semtech, specifically designed for providing gateway capabilities in ISM bands. The external RAK LoRaWAN antennas operate in the 860-930MHz range and have a gain of 5.8dBi. IP network connectivity is provided by the National University of Misiones.

In Posadas city, different mobile nodes have been used for normal operation control and coverage testing. The nodes assembled at FCEQyN consist of an Arduino Pro Mini (ATMEGA328P) board serving as the processing unit, interconnected with an RFM85W 915 MHz chip functioning as the radio interface (Fig. 4). Additionally, a commercial LoRa node, Lopy v1.1[30] equipped with a Semtex 1272 transceiver mounted on a Pycom expansion board v2.1 [31], has also been employed (Fig. 5).

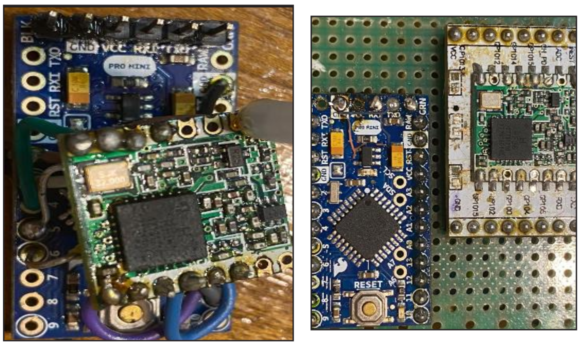

Figure 4: Nodes assembled at FCEQyN (Arduino Pro Mini + RFM95).

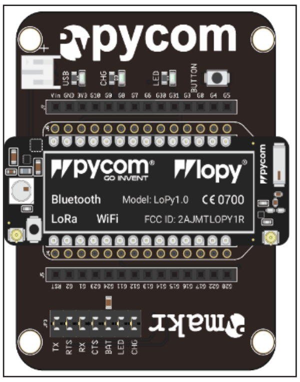

Figure 5: Lopy v1.1 Pycom Expansion Board v2.1.

The LoRaWAN network transmits data between sensor nodes and base stations installed in FCEQyN buildings, where the information is forwarded to The Things Network's backend services. The mission of The Things Network is to create and maintain an open, global, and decentralized Internet of Things (IoT) infrastructure that enables the connectivity of low-power IoT devices. The primary function of The Things Network is to provide a LoRaWAN-based network infrastructure that allows IoT devices to connect wirelessly over long distances while consuming minimal power. It achieves this by deploying and maintaining a network of LoRaWAN gateways and by developing and maintaining open-source network software for efficient device management, security, and routing. Additionally, TTN is an open platform for device registration, implementing all the necessary backend services for the operation of LoRaWAN base stations, where it collects, formats, and transparently forwards the information generated by different, making IoT technology more affordable and accessible for various applications.

Results

From the SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis of the technology considered appropriate for the project, certain conclusions have been drawn:

- LoRaWAN offers cost-effective end devices and the possibility of implementing private networks without the need for subscriptions.
- These features eliminate the need for subscriptions, provide extensive coverage, and offer low power consumption.
- Security concerns have been addressed through new versions of LoRaWAN, improving its overall security posture.
- Scalability can be optimized by synchronizing low-power transmission with low-cost, more intelligent Medium Access Control (MAC) solutions.
- The primary threat will continue to be external interference, as LoRaWAN operates in unlicensed bands. This is a matter to consider for future technologies to be developed in the near future.

Using mobile nodes, the streets of Posadas city have been traversed to verify the functionality of the deployed network, ensuring its normal operation and enabling access for users duly authenticated by TTN. This aims to prevent functional errors in the deployed network, which occur when it does not conform to the requirements defined and validated by the standards. The measurement of network coverage and RSSI have been carried out using the TTNMapper tool [32]. TTNMapper is a tool commonly used to map and analyze the coverage and performance of TTN's LoRaWAN networks. It allows users to collect data from LoRaWAN nodes as they move around a specific area, typically a city or region, and record information about the network's signal strength and coverage. The data collected by TTNMapper helps to visualize the network's performance, identify areas with weak or strong coverage, and make informed decisions about optimizing their LoRaWAN deployments. In fact, it is a very valuable tool for planning and improving the efficiency of LoRaWAN networks.

For a better differentiation and visualization of the results obtained in this work, the receptions at each of the gateways have been indicated in Figures 6 and 7.

As part TTN's global IoT network, the area of coverage shown by the gateways installed at UNaM has extended beyond the downtown area which is defined as the potential customer zone for the prospective LoRaWAN network.

In NLOS (non-line of sight) areas due to the presence of buildings, the covered radius has reached up to 4.5 kilometers from the gateways. This suggests that the network can penetrate obstacles to some extent, allowing devices to communicate even when there is no direct line of sight. In LOS (line of sight) situations, where most of the signal propagation occurs over the Paraná River or in open fields, the maximum distance reported by TTNMapper has been 13 kilometers.

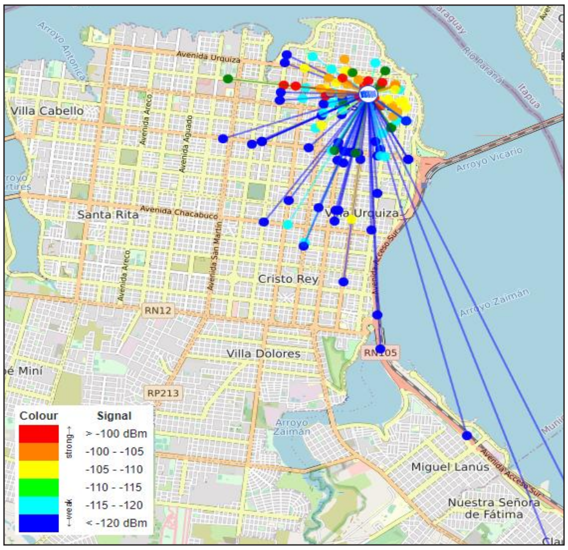

Figure 6: TTNMapper Report of Linked Nodes (FCEQyN Central).

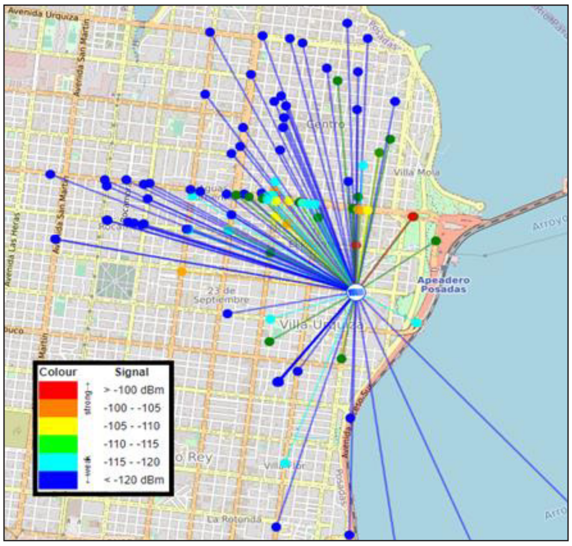

Figure 7: TTNMapper Report of Linked Nodes (Biochemistry building).

Conclusion and Future Work

In this article, we have thoroughly explored the Sigfox, NB-IoT, and LoRaWAN technologies, providing insights into their advantages and challenges. Following a comprehensive SWOT analysis that took into account economic and situational factors, we successfully deployed two TTN Gateways within the facilities of the FCEQyN. This LoRaWAN network has been in continuous operation since early 2017, serving both the wider community and IoT solution developers.

The LoRa nodes developed within the FCEQyN have demonstrated remarkable efficiency, offering extensive coverage and a prolonged lifespan at a reasonable cost compared to parallel commercial solutions that we have tested. Leveraging two gateways connected to UNaM's IP network, along with mobile nodes, we have achieved impressive coverage, reaching up to a 4.5 km radius in non-line of sight (NLOS) conditions and up to 13 km in line of sight (LOS) conditions.

TTNMapper graphics have illustrated that link performance tends to decrease as distance increases, particularly in the presence of obstacles like buildings and large trees.

Regarding scalability, the results indicate that a single LoRaWAN cell holds the potential to serve numerous clients transmitting small data payloads per day. Nevertheless, devices with higher data traffic requirements should be located closer to the base station, while fewer devices can operate effectively at greater distances. This scenario necessitates more efficient management of data rates employed by end nodes, as only a limited number of nodes operating at low data rates can be accommodated. Additionally, the use of message acknowledgments (ACKs) represents a factor limiting the scalability of the LoRaWAN cell.

LoRaWAN has indeed evolved into a crucial enabling technology for IoT (Internet of Things) projects at the National University of Misiones. Its distinctive ability to offer long-range, low-power connectivity has played a pivotal role in fostering the development and implementation of IoT applications across various domains within the city of Posadas. Moreover, this technology has paved the way for exciting opportunities in research, innovation, and real-world applications, effectively turning IoT into a tangible reality within our academic setting.

In addition to its practical advantages, LoRaWAN has also sparked a wave of academic and industrial interest. Our university has witnessed a surge in research activities related to IoT, with students and faculty members exploring innovative applications and solutions. This technology has facilitated collaboration with local businesses and government agencies, as they also recognize its potential to address real-world challenges.

In conclusion, LoRaWAN has become an integral part of our IoT ecosystem, driving advancements in technology, research, and practical applications. Its long-range, low-power connectivity has empowered us to address diverse challenges and opportunities within our academic environment and the broader community of Posadas. As we continue to harness the potential of this technology, we look forward to further innovation and transformative impacts on our region's IoT landscape.

Looking ahead, we have identified a future task: the necessity to install a gateway to the west of the city of Posadas. This step aims to validate the importance of redundancy in projects of this nature, further enhancing the robustness and reliability of our IoT network infrastructure.

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References

1. **«State of the IoT 2020: 12 billion IoT connections, surpassing non-IoT for the first time»**, IoT Analytics, 19 de noviembre de 2020. https://t.ly/ZTJWF (accedido 17 de agosto de 2023).
2. **«Overview of LTE enhancements for cellular IoT»**. https://t.ly/fqmWP (accedido 6 de junio de 2023).
3. **U. Raza, P. Kulkarni, y M. Sooriyabandara,** *«Low Power Wide Area Networks: An Overview»,* IEEE Commun. Surv. Tutor., vol. 19, n.o 2, pp. 855-873, 2017, doi: 10.1109/COMST.2017.2652320.
4. **A. M. Baharudin y W. Yan,** *«Long-range wireless sensor networks for geo-location tracking: Design and evaluation»*, en 2016 International Electronics Symposium (IES), sep. 2016, pp. 76-80. doi: 10.1109/ELECSYM.2016.7860979.
5. **O. Vondrouš, Z. Kocur, T. Hégr, y O. Slavíček,** *«Performance evaluation of IoT mesh networking technology in ISM frequency band»,* **en** 2016 17th International Conference on Mechatronics - Mechatronika (ME), dic. 2016, pp. 1-8.
6. **«Generalidades sobre las asignaciones de frecuencia»**. https://t.ly/kjzXm (accedido 8 de junio de 2023).
7. **«Coverage»**, *Sigfox 0G Technology*. https://t.ly/HrHkP (accedido 6 de junio de 2023).
8. **«Homepage - LoRa Alliance®»**. https://lora-alliance.org/ (accedido 6 de junio de 2023).
9. **Y.-P. E. Wang et al.**, *«A Primer on 3GPP Narrowband Internet of Things (NB-IoT)»*. arXiv, 13 de junio de 2016. doi: 10.48550/arXiv.1606.04171.
10. **«Semtech Semiconductor, IoT Systems and Cloud Connectivity | Semtech»**. https://www.semtech.com (accedido 8 de junio de 2023).
11. **«The Things Network»**. https://t.ly/QTjoH (accedido 16 de mayo de 2022).
12. **«Standardization of NB-IOT completed»**. https://t.ly/slPyq (accedido 6 de junio de 2023).
13. **R. & S. International, «Internet de las cosas en banda estrecha»**. https://t.ly/jHTkb (accedido 6 de junio de 2023).
14. **F. A. Aoudia, M. Gautier, M. Magno, M. L. Gentil, O. Berder, y L. Benini, «Long-short range communication network leveraging LoRa™ and wake-up receiver»**, Microprocess. Microsyst., vol. 56, pp. 184-192, feb. 2018, doi: 10.1016/j.micpro.2017.12.004.
15. **A. Ikpehai et al.**, *«Low-Power Wide Area Network Technologies for Internet-of-Things: A Comparative Review»*, IEEE Internet Things J., vol. 6, n.o 2, pp. 2225-2240, abr. 2019, doi: 10.1109/JIOT.2018.2883728.
16. **M. A. A. Khan, H. Ma, S. M. Aamir, y C. A. Baris,** *«Experimental Comparison of SNR and RSSI for LoRa-ESL Based on Machine Clustering and Arithmetic Distribution»*, 2022.
17. **«What is LoRaWAN® Specification»**, *LoRa Alliance®*. https://t.ly/ImS5_ (accedido 25 de febrero de 2022).
18. **R. Trüb, R. Da Forno, T. Gsell, J. Beutel, y L. Thiele,** *«Demo Abstract: A Testbed for Long-Range LoRa Communication»*, **en** *2019 18th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN)*, abr. 2019, pp. 342-343.
19. **B. Błaszczyszyn y P. Mühlethaler,** *«Analyzing LoRa long-range, low-power, wide-area networks using stochastic geometry»*, **en** *Proceedings of the 12th EAI International Conference on Performance Evaluation Methodologies and Tools*, mar. 2019, pp. 119-126. doi: 10.1145/3306309.3306327.
20. **R. Agrawal et al.**, *«Classification and comparison of ad hoc networks: A review», Egypt. Inform*. J., vol. 24, n.o 1, pp. 1-25, mar. 2023, doi: 10.1016/j.eij.2022.10.004.
21. **T. Miyamoto, S. Narieda, T. Fujii, y H. Naruse,** *«Measurement of Sub-GHz Band LPWA Radiowave Propagation on Each Floor in Indoor Environment»*, en 2023 International Conference on Information Networking (ICOIN), ene. 2023, pp. 85-88. doi: 10.1109/ICOIN56518.2023.10048939.
22. **A. Malik y R. Kushwah,** *«A Survey on Next Generation IoT Networks from Green IoT Perspective», Int. J. Wirel. Inf. Netw*., vol. 29, pp. 1-22, mar. 2022, doi: 10.1007/s10776-021-00549-0.
23. **J. C. Liando,** *«Experience of LoRa low power wide area network»*, Nanyang Technological University, 2019. doi: 10.32657/10220/47662.
24. **K. Mekki, E. Bajic, F. Chaxel, y F. Meyer,** *«A comparative study of LPWAN technologies for large-scale IoT deployment», ICT Express*, vol. 5, n.o 1, pp. 1-7, mar. 2019, doi: 10.1016/j.icte.2017.12.005.
25. **Rasveen, S. Agrawal, K. Chopra, y S. Kumar,** *«Coverage and Latency Analysis for NB-IoT in Uplink Transmission»*, en 2022 International Conference on Decision Aid Sciences and Applications (DASA), mar. 2022, pp. 330-334. doi: 10.1109/DASA54658.2022.9765226.
26. **S.-M. Oh y J. Shin,** *«An Efficient Small Data Transmission Scheme in the 3GPP NB-IoT System»,* IEEE Commun. *Lett.*, vol. 21, n.o 3, pp. 660-663, 2017, doi: 10.1109/LCOMM.2016.2632128.
27. **«Informe_consulta_publica_de_espectro_02.pdf»**, *informe consulta publica de espectro*. https://t.ly/WJD8f (accedido 3 de agosto de 2023).
28. **R. P. Ltd, «Buy a Raspberry Pi 3 Model B»**, *Raspberry Pi*. https://t.ly/qNAxY (accedido 27 de julio de 2023).

29. **«RAK831 WisLink LPWAN Concentrator Datasheet | RAKwireless Documentation Center»**. https://t.ly/cNINM (accedido 27 de julio de 2023).
30. **«LoPy»**. https://t.ly/aARTM (accedido 15 de agosto de 2023).
31. **«Expansion Board 2»**. https://t.ly/b-F2R (accedido 15 de agosto de 2023).
32. **«TTN Coverage»**. https://t.ly/0qwCx (accedido 16 de agosto de 2023).