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*Article*

# Implementation of LoRa Technology to Improve Data Transmission Reliability in Energy Monitoring Applications

# Implementación de tecnología LoRa para mejorar la fiabilidad de la transmisión de datos en aplicaciones de monitoreo energético

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**Abstract:** Intelligent energy monitoring using IoT systems has become increasingly important in both industrial and domestic environments due to its ability to optimize energy consumption and generate significant savings. This paper presents the design and development of a technology based on IoT and LoRa communication, aimed at measuring and transmitting energy consumption data for the company e2 Energía Eficiente. A low-power wide-area network (LPWAN) communication system was implemented, evaluating its performance under different environmental and operating conditions. Key variables such as energy consumption, transmission speed and stability, and data security were analyzed. Tests carried out in real environments, with various obstacles and distances, validated the effectiveness of the system in terms of coverage, reliability, and usefulness for the collection and analysis of energy data.

**Keywords:** Data transmission; Communication; Energy monitoring; Internet of Things; LPWAN

**Resumen:** El monitoreo inteligente de energía mediante sistemas IoT ha adquirido creciente relevancia tanto en entornos industriales como domésticos, debido a su capacidad para optimizar el consumo energético y generar ahorros significativos. En este trabajo se presenta el diseño y desarrollo de una tecnología basada en IoT y comunicación LoRa, orientada a la medición y transmisión de datos de consumo energético para la empresa e2 Energía Eficiente. Se implementó un sistema de comunicación de red de área amplia y baja potencia (LPWAN), evaluando su desempeño bajo diferentes condiciones ambientales y operativas. Se analizaron variables clave como el consumo energético, la velocidad y estabilidad en la transmisión, así como la seguridad de los datos. Las pruebas realizadas en entornos reales, con diversos obstáculos y distancias, permitieron validar la efectividad del sistema en términos de cobertura, fiabilidad y utilidad para la recolección y análisis de datos energéticos.

**Palabras clave:** Transmisión de datos; comunicación; Monitoreo de energía; Internet de las cosas; LPWAN

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## 1. Introdution

In a context of accelerated technological progress and growing environmental awareness, energy efficiency has become a fundamental pillar for the sustainability and competitiveness of industrial systems. The ability to monitor and manage energy consumption in real time, particularly in remote settings, enables resource optimization, cost reduction, and mitigation of environmental impacts. Solutions based on the Internet of Things (IoT) and wireless communications have emerged as key tools to address these challenges; however, their implementation faces limitations in environments characterized by physical obstacles, interference, and long transmission distances.

LoRa (Long Range) technology offers an efficient alternative for wireless data transmission in energy monitoring applications due to its low power consumption and extended communication range. This study focuses on the design and implementation of an IoT-based monitoring system using LoRa communication, applied to a Chiller-type air conditioning system in an industrial facility. The main objective is to ensure reliable data transmission between the Chiller room and the control room, separated by a distance of 120 meters, under real operating conditions.

The work includes experimental tests to evaluate system performance under different scenarios, ranging from line-of-sight transmissions to environments with significant physical obstacles. Key variables such as data transmission rate, packet loss, latency, and link stability are analyzed, along with the integration of environmental sensors to enrich the transmitted data payload. The results make it possible to determine the optimal configuration of LoRa modules to ensure efficient and continuous monitoring, thereby laying the groundwork for more effective energy management.

Real-time wireless data transmission in industrial environments presents significant challenges due to the physical and operational conditions of production facilities. Factors such as electromagnetic interference, physical obstacles, adverse atmospheric conditions, and long distances between transmitters and receivers can degrade the reliability of wireless links [6]. As a result, the lack of critical real-time information may affect system status monitoring, thereby compromising decision-making processes and operational efficiency.

In an industrial plant, multiple sensors monitor variables such as temperature, pressure, humidity, flow, and liquid levels. However, the transmission of these data to a centralized system faces barriers related to physical infrastructure, distance, and climatic factors [2]. The selection of an appropriate wireless technology is therefore crucial to ensure efficient communication. Technologies such as Wi-Fi, ZigBee, Bluetooth, and LoRa offer different advantages and limitations in terms of communication range, energy consumption, cost, security, and resistance to interference [14].

Long-distance wireless communication also poses challenges related to energy consumption, particularly for low-power wide-area network (LPWAN) devices, which must operate autonomously for extended periods in remote locations without access to a constant power supply [4]. Therefore, it is essential to identify solutions that maximize energy efficiency without compromising communication quality.

In the context of the company e2 Energía Eficiente, one of the main challenges identified is the inconsistency in data acquisition from energy monitoring systems and environmental sensors. These shortcomings hinder robust and continuous data analysis, affecting the generation of statistical reports, energy consumption assessments, and preventive and corrective maintenance recommendations. The lack of reliable data transmission reduces the system's ability to detect anomalies, optimize energy usage, and validate energy savings over different time periods.

For this reason, the present research focuses on minimizing data loss through a wireless communication infrastructure based on LoRa technology, characterized by its low power consumption and long communication range. The objective is to ensure continuous and reliable transmission of energy-related data, enabling more accurate analysis, faster responses to operational events, and a substantial improvement in energy management.

## 2. Contributions

This paper presents the following main contributions:

- The design and characterization of an IoT-based LoRa communication architecture aimed at improving the reliability of data transmission in energy monitoring applications.

- The implementation of a low-power wireless monitoring system tailored to real industrial operating conditions, integrating environmental and energy-related sensors.
- An experimental evaluation of the proposed architecture under both line-of-sight and non-line-of-sight scenarios, analyzing key communication metrics such as packet loss, transmission rate, latency, and link stability.
- The identification of optimal LoRa configuration parameters that balance energy efficiency and communication reliability in industrial environments.

## 3. Related Works

The implementation of low-power wireless technologies for data monitoring in industrial environments has been addressed from multiple perspectives. A LoRa-based smart lighting system has been developed to improve energy efficiency through automatic adjustment of lighting intensity [11]. Additionally, the scalability and effectiveness of LoRaWAN for multiple IoT applications have been demonstrated, highlighting its long-range transmission capabilities [12].

Sigfox technology has also been employed in remote monitoring systems. Its implementation has proven effective for capturing pressure and humidity data in tailings dams, emphasizing its low energy consumption [3]. Furthermore, an ESP32-based system has been designed to evaluate solar collectors, underscoring accessible and efficient solutions for renewable energy environments [8].

In industrial contexts, a hybrid LoRa and NB-IoT system has been proposed for vibration synchronization in critical machinery [5]. Conversely, energy optimization strategies in Wi-Fi–based IoT devices have also been analyzed [13].

Specific applications in rural or remote sectors have likewise adopted these technologies, such as the implementation of LoRaWAN for wind turbine monitoring [10] and the integration of LoRa in unmanned aerial vehicles (UAVs) for data acquisition in inaccessible areas [2]. Moreover, the performance of LoRaWAN in smart agriculture has been evaluated, highlighting its reliability in scenarios with limited connectivity [7].

Finally, improvements in communication protocols for low-power devices have been proposed, prioritizing energy efficiency, data compression, and scalability—critical aspects in LPWAN networks such as Sigfox and LoRaWAN [9], [1].

## 4. Justification

The increase in energy costs and the growing demand for sustainability have driven the adoption of technological solutions that enable efficient energy consumption management, particularly in industrial environments. Air conditioning systems, which are essential to ensure optimal production and storage conditions, represent one of the largest sources of energy consumption. The absence of real-time monitoring limits the ability to respond promptly to failures or inefficiencies, thereby hindering performance optimization and energy savings.

In this context, the implementation of an IoT-based monitoring system using LoRa technology constitutes a low-power, long-range solution capable of overcoming the physical and connectivity barriers commonly found in industrial facilities. This project is oriented toward the design of a prototype that enables real-time acquisition, transmission, and visualization of energy-related data, thereby supporting informed decision-making and continuous improvement of the monitored systems.

Moreover, the proposed approach offers flexibility and scalability, making it applicable not only to industrial environments but also to residential settings. The adaptable system architecture allows replication and expansion for future applications focused on sustainability and energy resource optimization, establishing it as a key tool for modern energy management strategies.

## 5. Methodology

This study is framed as applied research focused on technological development, with the objective of implementing a long-range wireless communication network for monitoring energy consumption in an industrial Chiller-type air conditioning system. To this end, low-cost devices based on LoRa technology are employed, enabling an accessible, replicable, and scalable solution for future projects.

The study seeks to establish the relationship between the characteristics of the industrial environment and the performance of the wireless communication in terms of communication range, latency, packet loss, and energy consumption. The project is structured into sequential phases, including system design, hardware and firmware implementation, transmission testing under controlled and real operating conditions, and analysis of the collected data to validate the effectiveness of the proposed system.

### *5.1. System Architecture*

The design of the proposed system follows a structured architecture in which different functional blocks are integrated to enable efficient and continuous data transmission for subsequent monitoring and analysis. This architecture is described in Table 1 and illustrated in Figure 1.

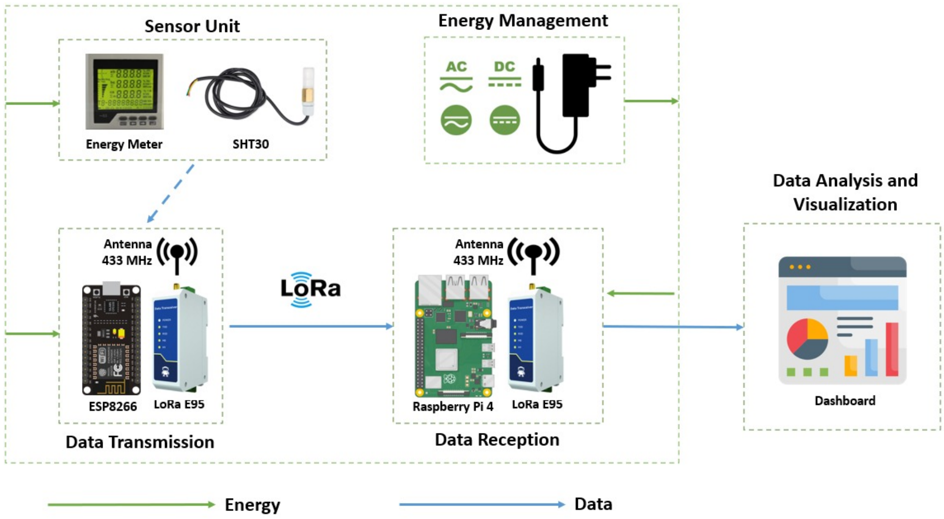


**Figure 1.** System structure.
**Source:** Author's own elaboration.

**Table 1.** System architecture blocks and their corresponding descriptions.

| Block | Description |
|---|---|
| Sensor unit | This block is mainly composed of measurement and data acquisition instruments. Temperature and humidity sensors are used for the air conditioning system. In addition, an energy meter is incorporated to obtain system power values, enabling comprehensive energy monitoring. |
| Data transmission | This block includes the data transmission device (transmitter node), which uses an ESP8266 microcontroller for the sequential execution, storage, and packaging of data obtained from the sensor unit. It also integrates a LoRa module responsible for transmitting data packets over long distances to the receiver device. |
| Data reception | This block corresponds to the device responsible for receiving the data packets sent by the transmitter. The receiver node consists of a Raspberry Pi, which processes the received data and uploads them to a cloud-based database. An additional LoRa module is used to receive the transmitted packets, configured identically to the transmitter module to establish a direct communication link. |
| Data analysis and visualization | At this stage, the received data stored in the database are visualized through a monitoring platform hosted on the Raspberry Pi, configured to operate as a server. This setup enables real-time monitoring as well as historical data analysis, allowing comprehensive system monitoring. |
| Energy management | This block is essential for the operation of all other system components. It is responsible for supplying the required voltage to each device, as energy consumption is necessary for transmitting and receiving data packets over long distances, even when using low-power wide-area network (LPWAN) devices. |

### *5.2. Experimental Procedures*

To evaluate the performance of the LoRa-based communication system, a set of experimental tests was developed to analyze data transmission rate, packet loss, effective communication range, and energy consumption. These tests were conducted prior to the final installation of the system and included the optimization of LoRa module parameters at both the transmitter and receiver nodes.

The experimental evaluation was structured into three sequential phases:

- Phase 1: The performance of data transmission was evaluated under ideal conditions, with direct line-of-sight and no physical obstacles, in order to determine the maximum communication range between the nodes.
- Phase 2: Tests were carried out within the real application environment, varying the distance between devices and exposing the communication link to electromagnetic interference and materials that affect signal propagation.
- Phase 3: The total packet transmission was measured at the final installation site, an industrial warehouse with multiple physical obstacles, simulating the system's final operational scenario.

### 5.2.1. Maximum Distance Test Between Transmitter and Receiver Nodes

The first experimental phase evaluated the maximum communication range between the LoRa modules under ideal line-of-sight conditions, with no physical obstacles and outside the application environment. The test was conducted along a section of the Malecón del Río (Barranquilla), covering a progressive distance from 0 to 1120 meters, increased in intervals of 160 meters, as illustrated in Figure 2. Beyond this distance, visual obstructions were detected that affected the communication link.


**Figure 2.** Location of each interval separated every 160 meters of distance.
**Source:** Google Earth.

The slave node transmitted periodic signals consisting of LED activation commands to the master node, which confirmed successful reception through synchronized activation of its own LED. For each evaluated distance, 30 packets were transmitted using different transmission rate (AirRate) configurations, ranging from 1.2 kbps to 19.2 kbps, while maintaining a fixed transmission power of 30 dBm.

For each distance and configuration combination, the number of successfully received packets was recorded, allowing the calculation of the packet loss percentage. The test locations were georeferenced using GPS coordinates, which are summarized in table 2.

**Table 2.** Parameters of the maximum distance test between transmitter and receiver nodes under line-of-sight conditions.

| Test No. | Latitude | Longitude | Distance (m) | No. of Packets |
|---|---|---|---|---|
| 1 | 11.0111188 | -74.7834366 | 0 | 30 |
| 2 | 11.0100551 | -74.7824335 | 160 | 30 |
| 3 | 11.0090652 | -74.7813659 | 320 | 30 |
| 4 | 11.0080818 | -74.7802944 | 480 | 30 |
| 5 | 11.0070761 | -74.7792591 | 640 | 30 |
| 6 | 11.0060598 | -74.7782130 | 800 | 30 |
| 7 | 11.0050119 | -74.7772045 | 960 | 30 |
| 8 | 11.0040272 | 11.0040272 | 1120 | 30 |

### 5.2.2. Data Transmission Test Within the Application Environment with Distance Variation

The second experimental phase focused on evaluating the performance of the transmission system within the real application environment, specifically inside the company's facilities where the Chiller-type air conditioning system is in operation. Unlike the first phase, this test was conducted under non-line-of-sight conditions between the nodes, exposing the LoRa link to physical obstacles, electromagnetic interference, and human activity (Figure 3).

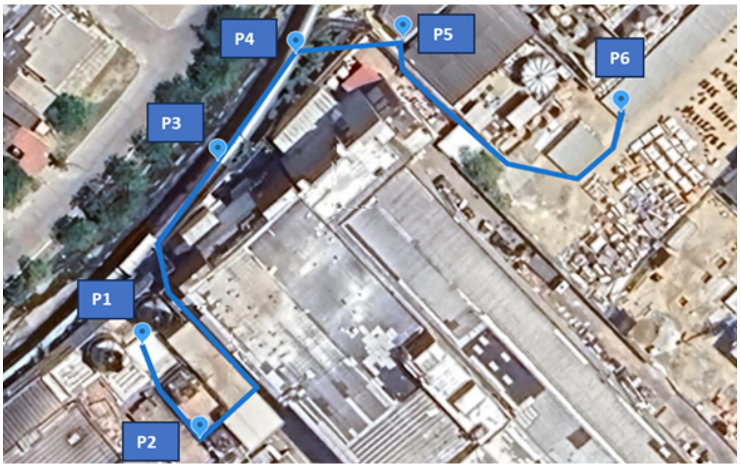


**Figure 3.** Location of the receiving node at different points within the company environment.
**Source:** Google Earth.

An SHT30 sensor was used to transmit temperature and humidity data, thereby increasing the size of the transmission packet. The tests began in the Chiller room (0 m) and progressed in intervals of 20 meters up to a maximum distance of 100 meters, which was limited by the dimensions of the industrial facility (Figure 4).

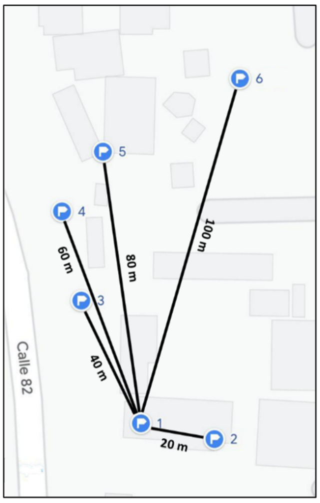


**Figure 4.** Distance between each location point of the receiving node within the company environment.
**Source:** Google Maps.

The initial configuration of the LoRa modules consisted of a transmission power of 24 dBm and a data rate (AirRate) of 9.6 kbps, selected based on the results obtained in Phase 1 and the trade-off between energy consumption and transmission speed. However, when packet loss exceeded 10%, the transmission parameters were adjusted by increasing the transmission power or reducing the data rate as required.

During this phase, the packet loss percentage was quantified, and the transmission delay between packet emission and reception was measured. For the calculation of the average latency, lost packets were excluded, allowing for a more accurate assessment of the link performance (Table 3).

**Table 3.** Initial parameters of the transmission test with distance variation within the application environment.

| Test No. | Latitude | Longitude | DNRT (m) | IP (dBm) | IR (kbps) |
|---|---|---|---|---|---|
| 1 | 11.022655 | -74.802791 | 0 | 24 | 9.6 |
| 2 | 11.022498 | -74.802696 | 20 | 24 | 9.6 |
| 3 | 11.022965 | -74.802668 | 40 | 24 | 9.6 |
| 4 | 11.023147 | -74.802539 | 60 | 24 | 9.6 |
| 5 | 11.023173 | -74.802361 | 80 | 24 | 9.6 |
| 6 | 11.023049 | -74.801997 | 100 | 24 | 9.6 |

**Note:** DNRT = Distance between receiver and transmitter nodes; IP = Initial transmission power; IR = Initial data rate.

#### 5.2.3. Total Data Transmission Test at the Node Installation Site

The third and final phase consisted of evaluating the system in its definitive operational environment. The LoRa devices were installed at the locations defined in the project: the transmitter node in the Chiller room, responsible for acquiring energy system data, and the receiver node in the control room, separated by approximately 120 meters and characterized by multiple physical obstacles typical of an industrial environment (Figure 5).

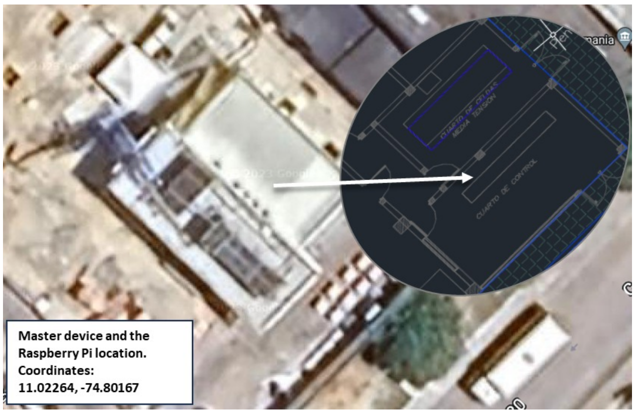


**Figure 5.** Location of the receiver node within the control room.
**Source:** Author's own elaboration.

This test focused on determining the optimal configuration of transmission parameters, such as transmission power and data rate (AirRate), in order to achieve a balance between energy efficiency and communication quality. The average packet loss percentage and transmission delay were monitored, considering a fixed data transmission interval of 20 seconds, which is suitable for continuous energy monitoring.

The final selected configuration was required to ensure low energy consumption, minimal packet loss, and low latency. The results obtained from this evaluation are presented in detail in the following section.

## 6. Results

### *6.1. Development of PCB Boards for Data Acquisition and Transmission*

As part of the development of the LoRa-based energy monitoring system, dedicated printed circuit boards (PCBs) were designed and implemented to integrate the microcontroller with the communication modules and data acquisition sensors. This approach ensured an organized, efficient, and reliable interconnection among components, avoiding the use of temporary wired connections that could compromise system stability.

The PCB design process was carried out using EasyEDA Pro software, which facilitated circuit routing and verification. Two types of boards were developed:

- Interface board for the LoRa E32 module: Designed to enable communication between the LoRa module and the microcontroller, ensuring electrical compatibility and appropriate physical connectivity for data transmission and reception (see Figure 6).
- Data acquisition and transmission board: Responsible for managing the acquisition of temperature and humidity data from the SHT30 sensor and transmitting data packets to the receiver node. This board includes the necessary connections for power supply, I2C communication with the sensor, and integration with the LoRa module (see Figure 7).

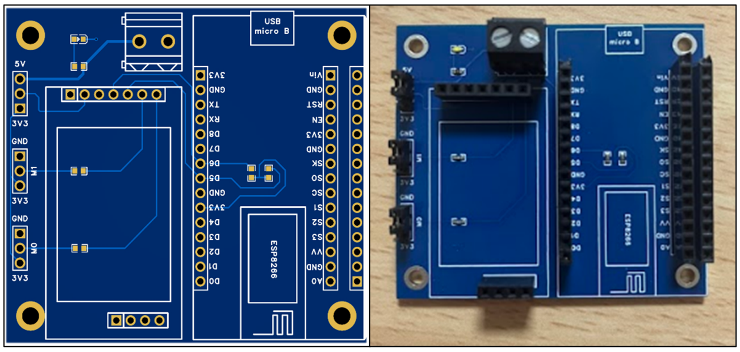


**Figure 6.** PCB design and actual image of the LoRa module board.
**Source:** Author's own elaboration.

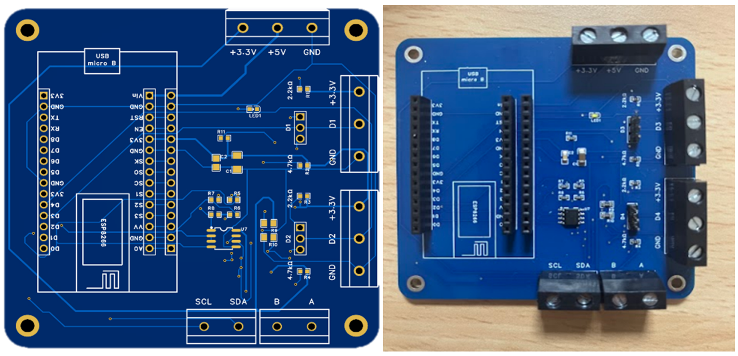


**Figure 7.** PCB design and actual image of the sensor and data acquisition card.
**Source:** Author's own elaboration.

6.1.1. LoRa Module Configuration

For wireless communication between the transmitter and receiver nodes, the LoRa E32 module was used and configured according to the parameters permitted for operation in Colombia. The selected operating frequency was 433 MHz, in compliance with the regulations of the Agencia Nacional del Espectro (ANE), within the range established by the LoRa Alliance (433–434.79 MHz for the region).

The communication channel configuration was kept constant between both nodes to ensure synchronization and to avoid interference from external devices. Additionally, unique addresses were assigned to each module within the same channel to enable clear and unidirectional identification during transmission, ensuring that messages were delivered exclusively to the intended destination node (Figure 8).

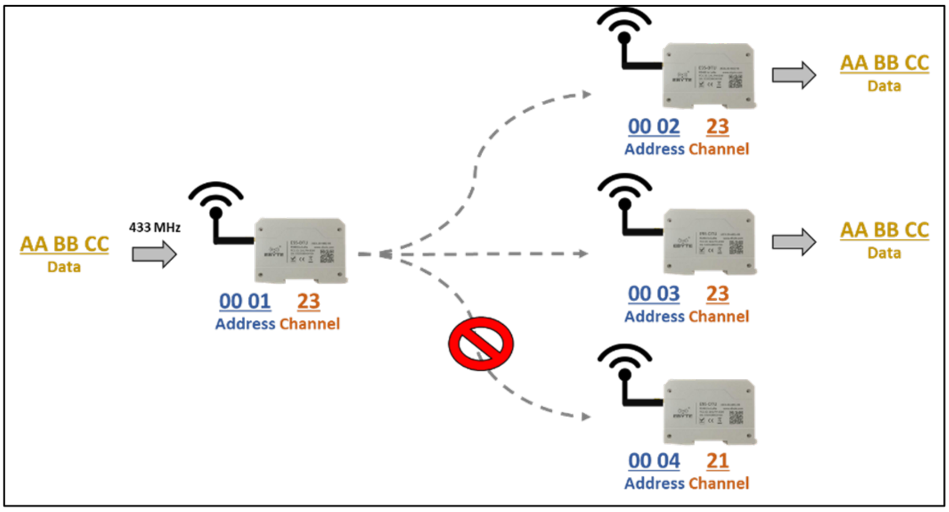


**Figure 8.** Configuration diagram for the transmitter and receiver nodes.
**Source:** Author's own elaboration.

### *6.2. Results of the Maximum Distance Test Between Nodes*

### *6.3. Analysis of Transmitted and Received Packets*

In the evaluation of communication under direct line-of-sight conditions, it was observed that the link between the transmitter and receiver nodes maintained acceptable performance up to a distance of 640 meters, as shown in Figure 9, provided that the transmission rate did not exceed 9.6 kbps. Beyond this distance, and particularly under configurations with higher data rates, a significant increase in packet loss was observed. This behavior indicates that, to ensure link reliability at longer distances, it is necessary to reduce the transmission rate, thereby enabling a more robust modulation that is more tolerant to signal attenuation.

Figure 9 illustrates the behavior of the packet loss percentage as a function of distance and the different transmission rate configurations, allowing the identification of optimal parameters for efficient communication under ideal conditions.

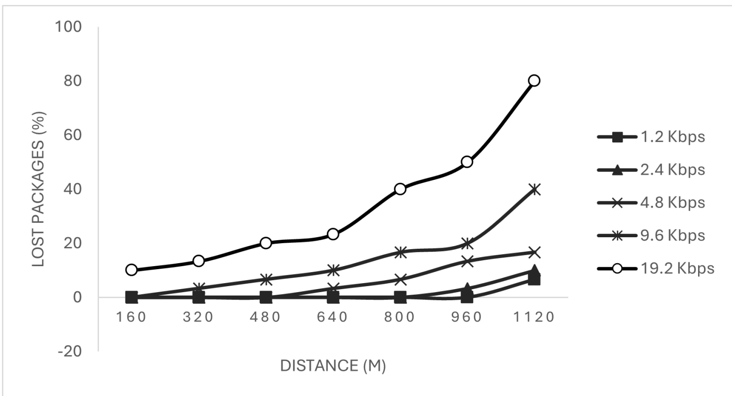


**Figure 9.** Percentage of packets lost by distance in meters and transmission rate configuration of the LoRa modules.
**Source:** Author's own elaboration.

Based on the previous figure, it can be observed that the lower the transmission rate, the lower the packet loss percentage. Therefore, for the proposed monitoring system, it is necessary to establish a moderately high transmission rate that does not significantly increase packet losses, since each received data packet is critical for accurate real-time monitoring.

It is important to note that a packet loss percentage of 10% or lower was considered acceptable, given the high frequency of data transmission. Based on this criterion, an analysis of the effective communication range as a function of the transmission rate was performed for both modules.

#### 6.3.1. Effective Range by Transmission Rate

The maximum distance between nodes with a packet loss percentage equal to or lower than 10% is considered the effective communication range, taking into account the transmission rate suitable for line-of-sight communication between both points.

Considering the results presented in table **??**, it can be determined that at shorter distances between nodes, significantly higher transmission rates can be achieved. Consequently, this parameter was taken into account for the development of subsequent experimental tests.

**Table 4.** Effective communication range by transmission rate in the test area.

| AirRate (kbps) | Effective Range (m) | SP | RP | PL (%) |
|---|---|---|---|---|
| 19.2 | 160 | 30 | 27 | 10 |
| 9.6 | 640 | 30 | 27 | 10 |
| 4.8 | 800 | 30 | 28 | 7 |
| 2.4 | 1120 | 30 | 27 | 10 |
| 1.2 | 1200 | 30 | 28 | 7 |

**Note:** AirRate = Transmission rate; SP = Sent packets; RP = Received packets; PL = Packet loss.

### *6.4. Results of the Transmission Test in the Application Environment*

#### 6.4.1. Packet Loss as a Function of Transmission Distance

The LoRa link was initially configured with a transmission rate of 9.6 kbps and a transmission power of 24 dBm. Under these conditions, tests were conducted at fixed time intervals of 20 seconds, collecting a total of 30 data samples for each evaluated distance.

The analysis focused on determining the packet loss percentage as a function of the transmission distance. The obtained results show a gradual increase in data loss as the separation between nodes increases, highlighting the limitations of the initial configuration in non-line-of-sight environments. Figure 10 presents the detailed behavior of the packet loss percentage for each tested distance.

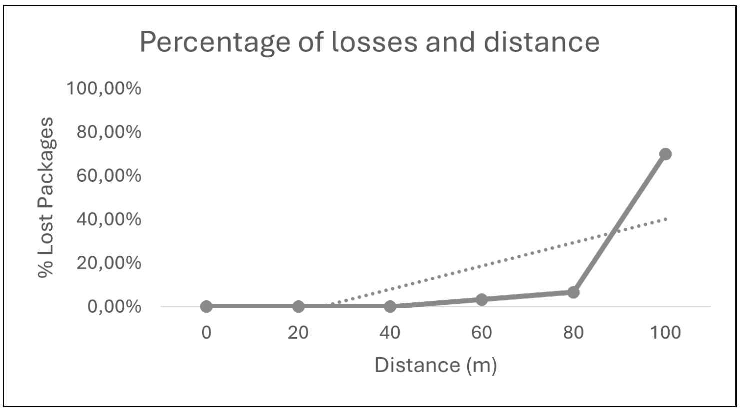


**Figure 10.** Percentage of packet loss by transmission distance, with initial configuration of 24 dBm at 9.6 kbps of the LoRa module.
**Source:** Author's own elaboration.

The figure 10 indicates that the packet loss percentage remains below 10% up to a distance of 80 meters between both nodes under non-line-of-sight conditions. At a distance of 100 meters, a significant increase in packet loss is observed, reaching approximately 70%

of data not received. The successfully received data under these conditions are shown in figure 11.

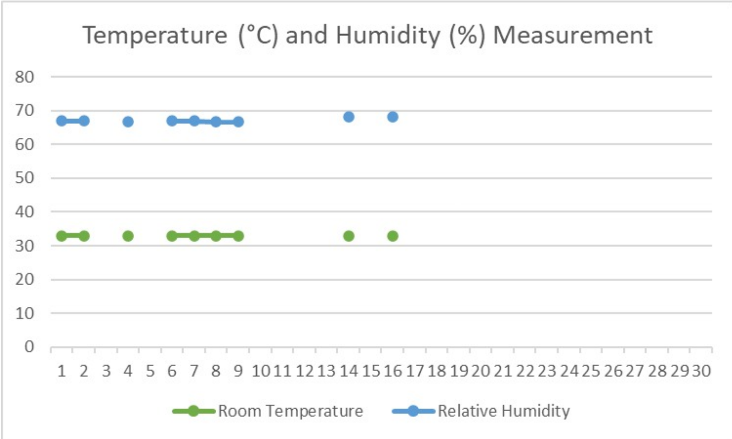


**Figure 11.** Percentage of packet loss by transmission distance, with initial configuration of 24 dBm at 9.6 kbps of the LoRa module.
**Source:** Author's own elaboration.

One of the strategies proposed to improve the packet loss percentage at a node separation distance of 100 meters involved testing different configurations of the LoRa modules, with the aim of analyzing the effectiveness of data transmission.

### 6.4.2. Transmission Effectiveness

By increasing the transmission power and reducing the data rate, the effective communication range was significantly extended, even in the presence of environmental obstacles. Based on this approach, the results of transmitted and received packets under this optimized configuration were obtained, maintaining minimal changes with respect to the initial parameter values used in this test. These results are presented in Figure 12.

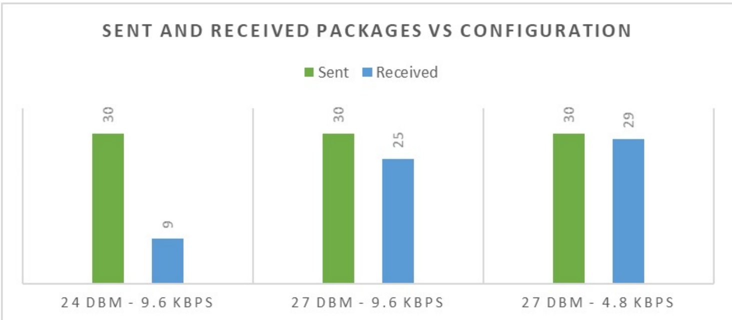


**Figure 12.** Number of packets sent and received for each configuration made to the LoRa modules with transmission distance of 100 meters.
**Source:** Author's own elaboration.

From the aforementioned figure, the number of received packets for each configuration applied to the LoRa modules can be determined. Consequently, the transmission effectiveness percentage for each configuration was calculated, as shown in table 5.

**Table 5.** Transmission effectiveness percentage by configuration of the LoRa modules.

| Distance (m) | Sent Packets | Received Packets | TE (%) | Configuration |
|---|---|---|---|---|
| 100 | 30 | 9 | 30.00 | 24 dBm / 9.6 kbps |
| 100 | 30 | 25 | 83.33 | 27 dBm / 9.6 kbps |
| 100 | 30 | 29 | 96.67 | 27 dBm / 4.8 kbps |

Ultimately, a high transmission effectiveness was achieved using a transmission power of 27 dBm and a data rate of 4.8 kbps on both LoRa modules.

### 6.4.3. Packet Transmission Delay

Although reducing the transmission rate to 4.8 kbps improves signal penetration in environments with physical obstacles, it also results in an increase in the response time between nodes. This effect was observed when comparing data reception times at the Raspberry Pi, which were higher than those obtained with a transmission rate of 9.6 kbps.

To quantify this difference, a comparative analysis of transmission delay was conducted for each configured data rate, while keeping the transmission power and the distance between nodes constant. For this purpose, 30 packets were transmitted per data rate, with a fixed interval of 20 seconds between packets, and the average delay was calculated for each case. The results of this analysis are presented in Figure 13, where the relationship between reduced transmission speed and increased latency is clearly illustrated.

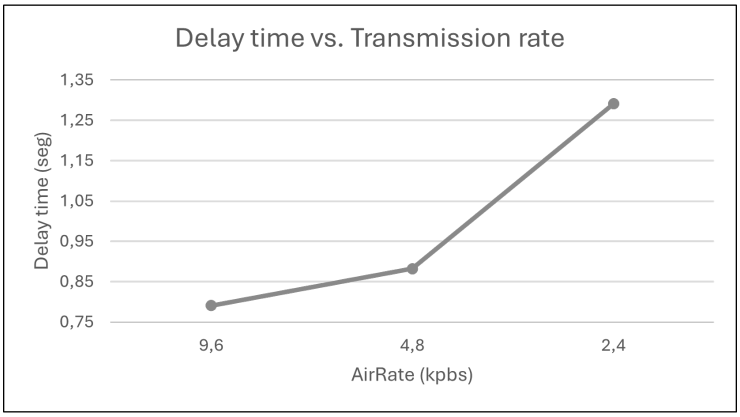


**Figure 13.** Delay time per transmission rate in the module configuration.
**Source:** Author's own elaboration.

Based on the figure 13, a transmission power of 27 dBm combined with a data rate of 4.8 kbps was selected as the optimal configuration for the LoRa modules. This configuration maintains an acceptable delay for real-time data monitoring.

The temperature and humidity data obtained using this configuration are shown in the figure 14.

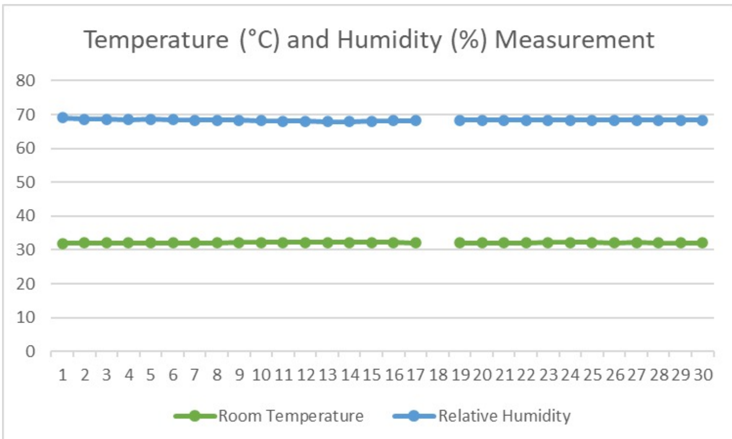


**Figure 14.** Capture of ambient temperature and humidity data, with a total of 29 packets received out of 30 transmitted. Transmission effectiveness of 96.67%.
**Source:** Author's own elaboration.

### *6.5. Results of the Transmission Test at the Node Installation Location*

In the final test, the receiver node was installed in the control room, located 120 meters from the transmitter node, which remained in the Chiller room. Under this scenario, system performance was evaluated by transmitting environmental data (temperature and humidity) from the transmitter node to the receiver using the optimal configuration obtained from previous tests.

During the test, a total of 30 packets were transmitted, of which 26 were successfully received, representing a packet loss of 13.33%. This result provides a realistic reference for the performance of LoRa communication under industrial operating conditions, where multiple physical obstacles and sources of interference are present. Figure 15 summarizes the data collected during this phase and illustrates the system behavior in the final installation environment.

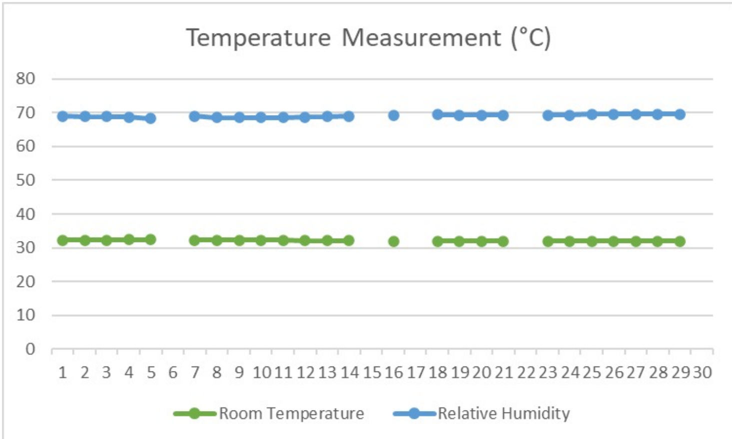


**Figure 15.** Captures temperature and humidity data at a distance of 120 meters within the application environment. Transmission effectiveness of 86.67%.
**Source:** Author's own elaboration.

Due to the relatively low transmission effectiveness observed during the initial communication between the Chiller room and the control room, the transmission rate was reduced to 2.4 kbps. Although this adjustment increased the transmission delay, the increase did not significantly affect the 20-second sampling interval established for continuous monitoring. On the contrary, this change substantially improved link performance, achieving 100% effectiveness in packet reception.

This result highlights the advantage of dynamically adapting the transmission rate to optimize communication in environments with physical obstacles and electromagnetic noise. Figure 16 presents the data collected under this configuration.

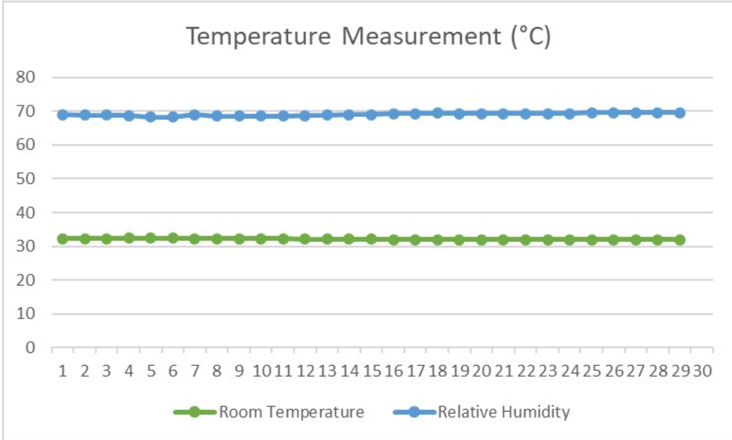


**Figure 16.** Captures temperature and humidity data up to 120 meters away within the application environment. 100% transmission effectiveness.
**Source:** Author's own elaboration.

## 7. Conclusions

Based on the results obtained from the experimental tests conducted in each phase and the implementation of the LoRa modules, it can be concluded that high reliability was achieved in data transmission for real-time energy monitoring applications. This performance is attributed to the appropriate configuration and efficient operation of the LoRa modules, which resulted in high transmission effectiveness and a nearly negligible packet loss rate. Additionally, successful data acquisition was achieved through the integration of sensors and energy measurement equipment, with the collected data packaged and transmitted to the receiver node for storage and visualization within the monitoring system.

The initial experimental tests made it possible to determine the maximum effective communication range under line-of-sight conditions as a function of the configured transmission rate for each LoRa device. These results demonstrate that reliable data transmission can be achieved over long distances in open environments, while also confirming that data transmission in non-line-of-sight scenarios is feasible when appropriate transmission rate configurations are applied to the LoRa modules.

In addition to effective communication range, key performance metrics such as transmission effectiveness and packet loss percentages were obtained based on a defined number of transmitted packets, supported by instrumentation and sensors that provide quantitative values for data analysis within specific time intervals. These metrics offer a comprehensive assessment of the communication link performance under varying environmental conditions.

The results also indicate that antenna placement plays a critical role in communication quality. Locating node antennas at elevated positions and in open spaces can significantly reduce transmission interference caused by environmental factors such as the presence of other antennas or concrete structures, thereby improving overall system performance.

The design of the data acquisition board combined with the ESP8266 microcontroller enables the integration of digital sensors for various monitoring applications, particularly those requiring temperature measurements. However, the system architecture allows for further enhancements, such as the development of acquisition boards capable of supporting additional sensor types and extended functionalities.

Regarding data management, the use of a database enables real-time visualization and analysis of the monitored variables, as well as historical data analysis of system behavior. Furthermore, this architecture allows access to the monitoring platform from any device connected to the same local area network as the Raspberry Pi hosting the database.

Finally, this development provides a flexible foundation for future improvements, including remote access to the database through cloud-based servers to enable monitoring from any location, the implementation of local data storage with automatic synchronization in the event of network failures, the expansion of the system to support a larger number of sensors and measurement devices through enhanced acquisition hardware, and the incorporation of control variables and automated alert mechanisms to enable a more comprehensive system analysis and improved operational performance.

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The author has read and agreed to the published version of the manuscript. Please refer to the CRediT taxonomy for the definitions of the terms.

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## Authors' Biography

**Andrés Lowis Torregroza** Electronic Engineer with a professional focus on engineering applications and data analysis. I am recognized for strong communication skills, teamwork, problem-solving abilities, adaptability, creativity, and effective time management. I have approximately four years of experience in data analysis roles, working primarily with technologies such as Python, SQL, and Power BI, as well as machine learning models, DevOps practices, process automation and optimization, and PCB circuit design and development.