LoRaWAN Technique for Identifying Electrical Failures and Increasing Reliability in Distribution Systems in Unconnected Areas of Colombia

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Abstract: This research examines the current issues facing the national interconnected system (SIN) in Colombia, focusing on the implementation of smart connection alternatives to improve interconnectivity and service quality in unconnected areas (ZNI). An analysis based on the "Roadmap for the Implementation of Smart Grids in Colombia" is conducted, highlighting challenges in coverage, service quality, and tariffs in rural areas. This research proposes a detailed analysis of the latest techniques for detecting electrical failures using technologies such as sensors, advanced algorithms, and neural networks, evaluating their potential application in the Colombian context. The implementation of early failure detection systems could significantly improve the quality of electricity supply, reducing interruption times and increasing service reliability. Additionally, a reference framework is sought to enable professionals and engineering students to develop skills in areas such as artificial intelligence and programming.

Key–Words: LoRaWAN, Electrical Failures, Distribution Systems, Rural Electrification, Smart Grids, IoT

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1 Introduction

In recent years, global energy demand has increased significantly, with an acceleration in consumption starting in 2023, where a 2.2% increase was reported, compared to an average growth rate of +1.5% per year reported between 2010 and 2019, according to statistics published by Enerdata (2024). Regarding electricity, Enerdata reported that global electricity consumption grew by 2.6% in 2023, primarily driven by countries such as China and India, highlighting a considerable increase in global electricity demand.

Mathematically, the growth in electricity demand can be represented as follows:

$$D(2023) = D(2022) \times (1 + r) \tag{1}$$

where $D(2023)$ is the demand in 2023, $D(2022)$ is the demand in 2022, and r is the growth rate.

In Colombia, statistics and projections made by UPME also revealed substantial annual increases, generating demand projections from 2024 to 2038, considering various coverage scenarios (Coverage Index IC) and different actors such as the National Interconnected System (SIN), large special consumers (GCE), electric mobility (ME), and distributed generation (GD). The statistics reported by UPME forecast demand increases ranging from 0.03% as a minimum to 5.93% as a maximum, considering all scenarios. Moreover, significant increases of 46.43% are noted for the medium coverage scenario, 66.15% for an IC greater than 95%, 26.52% for an IC less than 95%, 57.46% for an IC greater than 68%, and 35.45% for an IC less than 68%; which illustrates a considerable increase in electricity demand (UPME, 2024).

The statistics reported forecast demand increases ranging from (0.03%) to (5.93%). Furthermore, notable increases of (46.43%) are indicated for a medium coverage scenario, while other categories show:

- (66.15%) for (IC $>$ 95%)
- (26.52%) for (IC $<$ 95%)
- (57.46%) for (IC $>$ 68%)
- (35.45%) for (IC $<$ 68%)

This highlights a considerable increase in electricity demand.

In addition to the increased demand, Colombia has unconnected areas to the SIN (ZNI) and areas with a low coverage index (UPME, 2024), corresponding to approximately 52% of the Colombian territory with an estimated population of 1,900,000 inhabitants. These populations are consistently affected by electricity service interruption issues, according to the indicators SAIDI (System Average Interruption Duration Index) and SAIFI (System Average Interruption Frequency Index) determined by the Superintendence of Public Services (Superservicios, 2023). Therefore, considering that the constitutional regulatory framework guarantees an electricity supply contributing to a dignified housing (Constitutional Court, Sent. T-367, 2020; Constitutional Court, Sent. T-337, 2023), there is a pressing need to improve accessibility to energy services in rural areas, where topographical conditions hinder access to continuous and quality service.

In response to this problem, some service providers in ZNI, such as Electrocaquetá, have implemented various measures ranging from building new electrification projects to enhancing the use of information technologies (ElectroCaquetá, 2024). Despite these advances, distribution systems still require improvements to optimize their use and enhance service quality. For this reason, this research outlines the necessary workflow for implementing new technologies such as LoRaWAN as a viable solution to address connectivity and quality of electricity service issues in these areas.

Thus, this paper evaluates the use of the LoRaWAN technique to identify electrical failures in distribution systems in unconnected zones, thereby improving the reliability of electricity supply. The feasibility of using LoRaWAN in rural electricity distribution contexts is also analyzed, and an architectural design for the integration of LoRaWAN with existing systems is proposed.

2 Characterization of the Colombian Rural Electrical System

The Colombian electrical system is characterized by a high dependence on hydroelectric generation, with 75% of energy produced coming from this source. However, there is a marked difference in service quality offered in urban versus rural areas. Statistics from IPSE and UPME show a complex landscape concerning coverage and supply quality (UPME, 2016).

As seen, 75% of energy in Colombia is generated from hydroelectric and thermal plants, highlighting the necessity for a system that can couple the different technologies for energy distribution that Colombia possesses. Furthermore, the Colombian electrical network has a wide variety of operators at the national level (UPME, 2016), with installations in rural scenarios characterized by a line that hangs from SSU1 (where SSU1 refers to a substation) of radial typology, with transformers approximately 30 km apart and a nominal voltage level of 34.5 kV in MT (Medium Voltage) and 0.44 kV in BT (Low Voltage). All these systems are regulated by the Technical Regulations for Electrical Installations - (RETIE) (Ministry of Mines and Energy, 2024).

The implementation of smart grid technologies and microgrids is essential to address current limitations. Emerging technologies, such as LoRaWAN, offer an innovative approach for monitoring and improving electrical service.

3 LoRaWAN in Detecting Electrical Failures

LoRaWAN (Long Range Wide Area Network) is a low-power, long-range wireless communication technology designed specifically for Internet of Things (IoT) applications (Adelantado, et al. 2017). This system features operational characteristics that make it an optimal alternative for rural and low-resource areas. However, despite its advantages, it also has limitations that must be considered for maximizing its efficiency and implementation in electrical infrastructure projects (Centenaro et al., 2019).

Advantages:

- *Extensive Coverage:* LoRaWAN allows long-range communications, ideal for rural areas (up to 10 km).
- *Low Energy Consumption:* This reduces operational costs, as devices can operate on solar energy.
- *Ease of Deployment:* Requires less infrastructure compared to traditional systems.
- *Scalability:* Easy integration of new nodes into the network.

Challenges:

- *Data Capacity Limitations:* LoRaWAN manages small packets, which may be insufficient for applications requiring continuous data flows.
- *Latency:* Slower information transmission can affect the detection of critical failures.
- *Dependence on Local Infrastructure:* The effectiveness of the system depends on the installation and maintenance of base stations (gateways).

A study by Augustin et al. (2016) demonstrated that LoRaWAN is suitable for rural applications due to its ability to operate in low-density population areas with limited coverage; working optimally in low-power, low-performance, long-range networks. Field tests were conducted in urban and rural environments to measure range and signal quality, evaluating the energy consumption of LoRa devices in various operating modes (transmission, reception, and sleep mode) and analyzing network scalability through simulations of multiple devices connected to the same gateway.

From the most relevant findings, it was demonstrated that, in rural areas, LoRa achieved distances of up to 15 km with line of sight, and approximately 2-5 km in urban environments with obstacles. Regarding energy consumption, LoRa devices consume less than 50 mA during transmission and less than 1 μA in sleep mode, allowing battery life for several years. In terms of scalability, it was shown that the network can support up to 1,000 devices per gateway, depending on transmission frequency and packet size.

In another study by Petäjäjärvi et al. (2017), optimal results were obtained by evaluating LoRaWAN performance in rural areas, where simulations studied network scalability with up to 10,000 connected devices. Among the results, robustness and capacity to maintain reliable communications even under adverse conditions were highlighted, demonstrating that the network can handle a large number of devices, with slight performance drops when exceeding 5,000 devices per gateway due to spectrum congestion.

Additionally, a practical case in Africa implemented a LoRaWAN network to monitor soil moisture, temperature, and water quality on a rural farm. The sensors used, powered by solar energy, operated continuously throughout the study period (6 months), and the LoRaWAN network covered an area of 12 km^2 with a single gateway. This illustrates that LoRaWAN is an effective and economical solution that can be satisfactorily used to monitor crops and water resources in areas without electrical coverage, demonstrating high feasibility and efficacy in these types of systems and applications.

Finally, another example of LoRaWAN implementation is presented in a practical case conducted in Africa, demonstrating the effectiveness of using LoRaWAN systems along with Internet of Things (IoT) platforms. In the study, Odongo et al. (2022) developed a deployment of a LoRaWAN-IoT platform in an electrical network using six transformers, where it was determined that the proposed method can significantly reduce the time elapsed between the occurrence of a failure and the receipt of information about the incident at the monitoring and control center, reducing notification time to the Control Monitoring Center by a factor of 100,000. Additionally, it minimized the time spent by operational technicians in locating the defective site, as the GPS location of the electrical distribution defect was also transmitted.

3.1 Proposed Architecture for a LoRaWAN System (Methodology)

The approach of this research is theoretical and is based on secondary research, which will compile recent information about LoRaWAN (Long Range Wide Area Network) systems as an alternative solution to the problems identified in fault detection in rural areas of Colombia. For this analysis, the methodology proposed by Odongo et al. (2022), which achieved significant progress in adapting LoRaWAN-IoT as a solution to improve fault detection in electrical networks, was reviewed. This article also describes the technical characteristics of LoRaWAN, the costs and benefits of implementing LoRaWAN, and a pilot proposal based on the findings.

An architecture is proposed that includes self-powered IoT nodes, LoRaWAN gateways, and a central server. Nodes should be capable of monitoring key variables (voltage, current, temperature) and reporting abnormalities to the central server, which will process the data and generate alerts for operators. To analyze the feasibility of implementing the system, the methodology proposed by Odongo et al. (2022) is followed. However, with a differential approach to the research conducted by the authors, a different algorithm is proposed to achieve a reduction in energy consumption, greater precision, and better scalability.

3.2 Implemented Algorithm

In their research, Odongo et al. (2022) propose an algorithm based on a deep sleep state. However, this research proposes a variation of the algorithm that allows optimizing the processes carried out by the microcontroller. The proposed algorithm, like that of Odongo et al., is based on the operational states of the microcontroller, which are:

- *Deep Sleep State:* The microcontroller consumes minimal energy.
- *Light Monitoring State:* The microcontroller periodically wakes to check the status of the sensors.
- *Active Mode State:* The microcontroller processes data and sends alerts in the case of anomalies.

Subsequently, the pseudocode of the proposed algorithm for fault detection in the electricity distribution network is presented. This algorithm uses interrupts and low-power techniques to optimize system energy efficiency.

The proposed code uses the `LowPower` library to manage the low-power mode of the microcontroller. When an anomaly is detected, the microcontroller wakes up, reads data from the sensors, and sends an alert via LoRaWAN. If no anomalies are detected, the system returns to deep sleep mode to conserve energy.

In addition to the optimization made with the algorithm, additional improvements such as machine learning for fault detection can be included, implementing a machine learning model on the network server to analyze the data sent by the sensors and detect fault patterns, allowing for more accurate detection and reducing false positives (Vivek, Teja, Mallala, & Srinitha, 2024). Communication can also be adaptive, adjusting the frequency of data transmission according to the criticality of the situation. For example, data may be sent every 5 minutes during a fault and every hour under normal conditions (Agrawal, Gelles, & Sahai, 2016). Other improvements could include using hybrid energy by combining solar panels with supercapacitors to ensure a constant power supply (Nordin et al., 2021), even in low light conditions and redundancy in the network by using multiple LoRaWAN gateways to ensure coverage in critical areas and avoid data loss.

The comparison, shown in Table 1, illustrates how the proposed algorithm improves the efficiency of the microprocessor compared to the algorithm in the article by Odongo et al.

The proposed algorithm improves energy efficiency and fault detection accuracy by combining interrupts, light monitoring, and low-power techniques. Additionally, it is scalable and can adapt to different network conditions.

3.3 Components of the Architecture

As described in "LoRa and LoRaWAN for IoT: A Practical Guide" (Hersent, Boswarthick, & Elloumi, 2020), the LoRaWAN architecture consists of four main components: end devices, gateways, network servers, and application servers. According to Magrin et al. (2020), LoRaWAN is suitable for IoT applications due to its long range, low power consumption, and scalability.

Based on the architecture detailed by Hersent et al. (2020), a system is proposed that uses LoRaWAN gateways to cover rural areas with low connectivity. In addition to the basic components, it is important to consider the materials used by Odongo et al., for the fault detection platform. These materials are detailed in Table 2.

4 Applicability in Colombia

Given the versatility of LoRaWAN, its effectiveness, low cost, and ease of implementation and integration with electrical networks in rural or urban areas (Almuhaya et al., 2022), LoRaWAN presents a viable alternative for modernizing Colombian electrical networks. However, prior to making a pilot proposal, it is important to consider LoRaWAN's limitations, such as its limited capacity to transmit small data packets, making it less suitable for systems requiring large volumes of information, like real-time control of electrical parameters. Furthermore, it exhibits higher latency compared to other systems, which affects performance in situations demanding quick responses, and it relies on a local infrastructure of gateways, complicating implementation in its absence. Integration with standardized systems such as DNP 3.0 or SCADA may require additional development to ensure interoperability (Gallardo, 2022).

In addition to the aforementioned issues, factors like topography could significantly influence not only installation costs but also the effectiveness of LoRa communications, with as much as a 58.63% decrease in the number of successfully received packets compared to a flat environment (Torres-Sanz et al., 2023). Therefore, for a pilot proposal, the installation of two gateways on transformers in the population of Uribia in La Guajira is considered, as this area is part of the country's unconnected regions (UPME, 2024) and features flat topography, which favors LoRa network performance (Table 3).

Selected Area:

- *Region:* Municipality of Uribia, La Guajira department. It is primarily rural, has low network coverage, and seeks to optimize energy resources.

Network Design:

- *Gateways:* 2 strategically placed gateways to cover an area of 20 km^2.
- *Sensors:* 30 sensors to measure temperature, electrical current, energy flow.
- *Connectivity:* Gateways will connect to the Internet via cellular networks (3G/4G).

Applications: The applications of the system include timely detection of any abnormalities in the electrical network and communication of data to the central server for effective decision-making. Other applications that could be integrated into the system to generate a broader social impact include integrating soil moisture, temperature, and water quality sensors, focusing on real-time crop monitoring and optimizing irrigation based on data while generating early alerts to prevent agricultural losses.

Operational Conditions (Estimated Installation Time): To implement a LoRaWAN system in unconnected areas, it is recommended to follow these steps:

1. *Site Preparation (1 - 2 hours):* Site Inspection, Review of Existing Infrastructure, Assessment of

Table 1: Comparison of the proposed algorithm with the algorithm of Odongo et al. (2022)

Characteristic	**Algorithm from Article**	**Proposed Algorithm**
Energy Consumption	Low (Interrupts)	Very low (Duty)
Fault Detection	Based on interrupts	Confirmation
Scalability	Limited	High
Complexity	Medium	Medium-High
Flexibility	Low	High (adaptive)

Table 2: List of materials for the fault detection platform. Adapted from Odongo et al. (2022)

Component	**Function**
Arduino MEGA 2560	Microcontroller Unit
Dragino LoRa Shield	LoRa transceiver
GSM/GPRS SIM900	GPS location info
RAK7258 Micro Gateway	LoRaWAN Gateway
DS3231 RTC	Real-time clock
Solar Panel (5V, 3.5W)	Energy harvesting
SCT-013 100A:5mA	Current sensing
TP 4056 Module	Charge controller

Table 3: Expected results for optimal algorithm operation.

Parameter	**Expected Value**
Deep Sleep Cons.	$< 1\ \mu$A
Active State Cons.	20-50 mA
Response Time	$<$ 1 second
LoRa Coverage	10-15 km (line of sight)
Data Delivery Rate	$>$ 95%

Interferences.

2. *Installation of the LoRaWAN Gateway (2 - 4 hours):* Physical Installation, Connection to Power Supply, Antenna Installation.

3. *Configuration and Testing (2 - 3 hours):* Network Connection, LoRaWAN Configuration, Connectivity and Data Transmission Testing.

Total Estimated Time: 5 - 9 hours.

Additional Considerations:

- *Job Complexity:* The installation of a LoRaWAN gateway on a transformer is a specialized task that may require additional skills, potentially resulting in higher costs than standard electrical installations.
- *Geographical Location:* Costs may vary depending on the region in Colombia where the work is conducted.

Costs Associated with Equipment: Based on the methodology proposed by Odongo et al. (2022), the costs of components are estimated as shown in Table 5.

Table 4: Costs associated with equipment (COP/USD)

Component	**Price**
Arduino MEGA 2560	150,000 COP
Dragino LoRa Shield	120-250k COP
GSM/GPRS SIM900	95,000 COP
RAK7258 Micro Gateway	200 USD
DS3231 RTC	25,000 COP
Solar Panel	42,000 COP
SCT-013	35-50k COP
TP 4056 charge module	5-20k COP

In cases where there are difficulties in acquiring the elements established by Odongo et al.'s methodology, alternative gateways with different specifications can be considered. The approximate cost of these devices may vary, typically around (5,000) USD for gateways and (50) USD for sensors.

5 Conclusion

LoRaWAN presents an economical communication technology compared to other solutions such as cellular or satellite networks. LoRaWAN devices are relatively inexpensive, and the necessary infrastructure (gateways and servers) is accessible, especially when compared to the benefits they offer. Furthermore, the low energy consumption of LoRaWAN devices reduces operational costs since frequent maintenance and battery replacements are not required.

The installation of LoRaWAN devices is straightforward and quick. The sensors are compact, do not require complex wiring, and can be strategically placed in locations such as transformers, distribution lines, or poles. Additionally, LoRaWAN gateways have a broad range (up to 15-20 km in rural areas), meaning fewer gateways are needed to cover large areas, simplifying installation further.

LoRaWAN is also ideal for electrical networks that span rural or hard-to-reach areas, where other communication technologies may not be viable or are too expensive. Its ability to operate over long distances ensures that even the most remote points of the network can be monitored. Furthermore, LoRaWAN devices are designed to consume very little energy, allowing them to operate on batteries for years without replacement—especially useful in areas with limited or no access to electrical grids.

In summary, the benefits of implementing LoRaWAN include improved efficiency in monitoring and fault detection in electrical distribution systems, reduced operational costs, and enhanced reliability of service delivery in rural Colombian electrical networks.

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