RECyT
Year 26 / Nº 41 / 2024 / 45–53
DOI: https://doi.org/10.36995/j.recyt.2024.41.006

Harnessing Low-Power IoT Sensor Potential: The Synergy of LoRaWAN, Energy Harvesting and Supercapacitors

Sensores Autónomos de Bajo Consumo para IoT: La Sinergia de LoRaWAN, Acopio de Energía y Supercapacitores

Milton E. Sosa[1], Marcelo E. Romeo[2], Eduardo O. Sosa[1]

1- Faculty of Exact, Chemical and Natural Sciences. National University of Misiones. Argentina.
2- School of Science and Technology. National University of San Martín. Argentina.
* E-mail: milton.eduardo.sosa@gmail.com

Received: 22/11/2023; Accepted: 28/05/2024

Abstract

This article delves into the potential of low-power IoT sensors by harnessing the synergy of three essential technologies: LoRaWAN, energy harvesting techniques, and supercapacitors. It emphasizes the pivotal role these technologies play in the ever-expanding realm of IoT and their contribution to sustainable, low-power solutions. The study presents the development and implementation of a system designed for rapid issue reporting within low-voltage metropolitan systems. It introduces cost-effective hardware solutions that incorporate unconventional energy storage methods, such as supercapacitors instead of traditional batteries. The collected information is transmitted to a network operations center via a publicly accessible LoRaWAN network. This system offers comprehensive insights into the condition of electrical networks, enabling the identification of both sporadic and recurring events. It empowers the formulation of corrective and preventive measures aimed at enhancing the quality of service provision.

Keywords: LoRaWAN; Energy harvesting; Supercapacitor; IoT; Sensors.

Resumen

Este artículo profundiza en el potencial de los sensores IoT de bajo consumo al aprovechar la sinergia de tres tecnologías esenciales: LoRaWAN, técnicas de recolección de energía y supercapacitores, enfatizando el papel fundamental que desempeñan estas tecnologías en el siempre creciente ámbito de IoT y su contribución a soluciones sustentables de bajo consumo de energía. Se presenta el desarrollo e implementación de un sistema diseñado para informar rápidamente sobre problemas en sistemas metropolitanos de baja tensión. Introduce soluciones de hardware rentables que incorporan métodos no convencionales de almacenamiento de energía, como supercapacitores en lugar de baterías tradicionales. La información recopilada se transmite a un centro de operaciones de red a través de una red LoRaWAN de acceso público. Este sistema ofrece una visión integral del estado de las redes eléctricas, lo que permite la identificación de eventos esporádicos y recurrentes, facilitando la formulación de medidas correctivas y preventivas destinadas a mejorar la calidad de la prestación de servicios.

Palabras clave: LoRaWAN; Captación de energía; Supercapacitor; IoT; Sensores.

Introduction

This project was undertaken as part of the Specialization Program in Embedded Systems (CESE), offered by the Laboratory of Embedded Systems at the University of Buenos Aires. In broad terms, a smart infrastructure is characterized by its integration of digital technology and intelligent sensors to enable self-control, efficient resource management, and informed decision-making. These networks promote efficiency, cost savings, reliability, security, resilience, user interaction and empowerment, and sustainability, all of which contribute to an enhancement in service quality.

Smart infrastructure is purpose-built to offer adaptability, data acquisition and analysis capabilities, and the continual refinement of the feedback loop through technology, ultimately improving outcomes, well-being, and overall quality of life. Currently, sensors utilizing microprocessors and integrated transceivers are fundamentally altering the way we control, monitor, and maintain civil infrastructure. Although sensors and smart technology are not novel concepts, their large-scale integration is still in its nascent stages[1].

The term “palliative maintenance,” generally defined as any delayed repair that can pose safety risks and other costs, is a significant challenge in any enterprise. Limited funding, coupled with customer demand, has led to prioritizing only the most urgent maintenance and postponing other critical maintenance activities until more funding is available or until the asset itself is at risk of total failure [2]. Unfortunately, this “fix-what-fails” approach to critical infrastructure is costlier and less efficient in the long run.

Electric energy conversion is essential for its use in various applications and sectors. Depending on the operating voltage, there are transformer stations (greater than 66 kV) and Distribution Substations (less than 66 kV) [3]. For distribution to end consumers, so-called Overhead Distribution Substations (S.E.T.A.) are used to convert the transport voltage from medium to low voltage (220V or 110V).

Smart electrical distribution networks, also known as Smart Grids (SG), are networks that use digital technologies, sensors, and software to better match electricity supply and demand in real-time, minimizing costs while maintaining network stability and reliability. They cover the more traditional domains of bulk generation, transmission, distribution, consumption, markets, and power electronics, with the growing penetration of relatively newer domains such as renewable energy, electric vehicles, and demand response-compatible charging systems. SG control allows prescriptions for interconnections and interactions between these traditional and emerging domains at the right moments, in the right locations, and in the right way [4] (see Figure 1).

The distribution networks of energy are considered critical infrastructure, so distribution system operators have developed sophisticated engineering practices to enhance their resilience. In recent years, due to the evolution of Smart Grids, this infrastructure has become a distributed system where prosumers (consumers who produce and share excess energy through the network) can connect distributed energy resources and manage a bidirectional electrical grid through advanced control infrastructure [6].

SG is a comprehensive and ubiquitous closed-loop system where control is central in the network landscape. The underlying physical layer, interconnection topologies, and dynamic interactions among various domains shape the control algorithms and architectures.

SG is a multidisciplinary concept related to the modernization and improvement of the electrical system, involving real-time information with specific communication requirements, where the reliability of the system depends on the ability to control the network. There are three main challenges for this: having an adequate number of real-time measurement units, the capability to manage large datasets, and low-latency bidirectional communications [7], aimed at more efficient, effective, and resilient control solutions.

Generally, low-voltage distribution networks at 380/220V typically lack the capacity to provide additional services. In contrast, medium and high-voltage

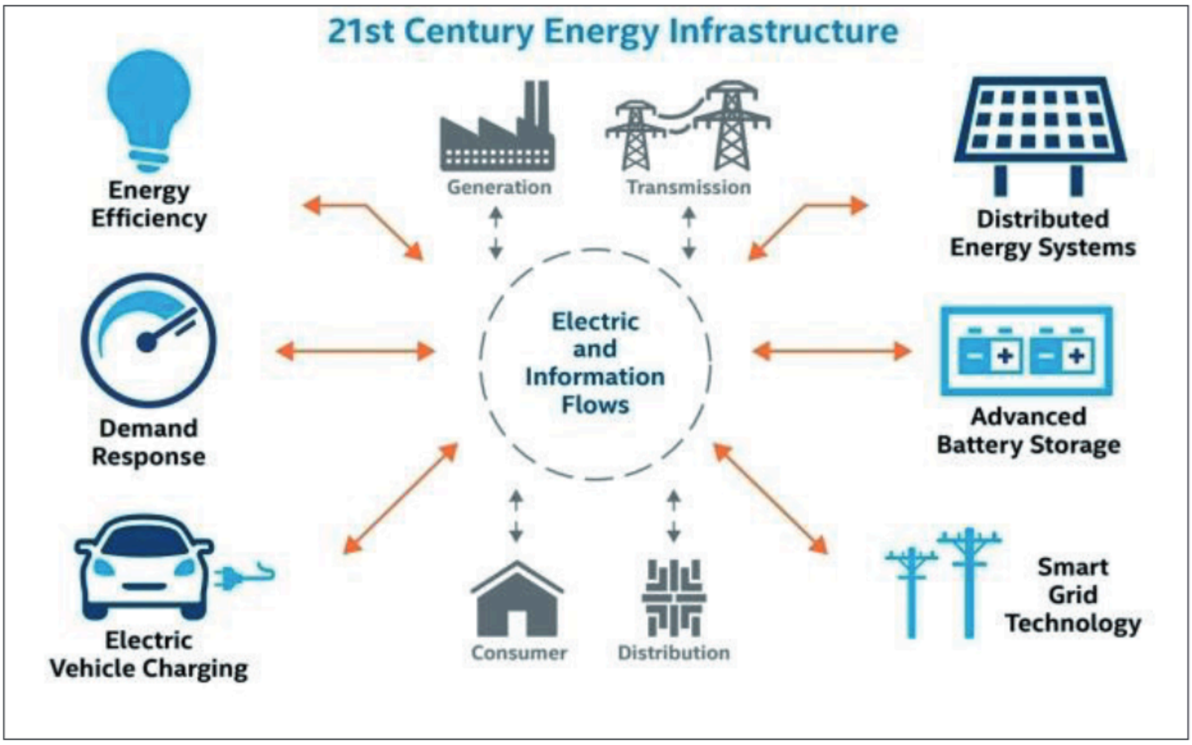


Figure 1: Smart Grid infrastructure [5].

transmission networks (33 kV and 132 kV) incorporate an optical ground wire (OPGW)[8] combining grounding and communication functions.

Optical fibers are used for data transmission, either for their own use in the protection and control of the transmission line or for data transmission, either for their own use or for third parties. In certain circumstances, when facing extreme weather conditions, these installations exhibit some vulnerability, resulting in high maintenance costs [9].

Most energy distribution companies, in the event of service interruptions, typically respond by directly engaging with end-users through complaints. Afterward, a task force is being sent to try to determine the cause of the incident. This approach is inadequate and ineffective, especially when considering the duration of service downtime. Customers often perceive this service interruption time as poor quality of service.

Emerging IoT technologies, such as Low Power Wide Area Network (LPWAN) [10] and mesh networks, are considered available and viable technologies to provide a communication infrastructure for metropolitan power distribution networks [11]. Other authors present autonomous systems using thermoelectric and electromagnetic transducers for energy conversion, which can be saved for later use, or to power the electronics involved in monitoring and control at the same time [12], [13].

Internet of Things (IoT) devices are deployed in large numbers worldwide, primarily powered by conventional batteries with limited capacity and lifespan. However, batteries pose several challenges in terms durability, size and environmental impact, as their manufacture involves environmentally aggressive chemicals.

Additionally, it is known that battery components tend to degrade above 30ºC. Adapting new energy storage variants, such as supercapacitors, offers a sustainable alternative for the IoT environment, reducing the billions of depleted batteries produced annually[14], simply by introducing a new energy storage alternative: the supercapacitor.

Over the past two decades, more than 75 international manufacturers have introduced various families of supercapacitors to the market, reflecting significant growth in the availability and diversity of supercapacitor options for various applications.

Supercapacitors can be charged and discharged rapidly, making them ideal for applications that require a quick release of energy. Moreover, their longevity and ability to withstand frequent charge and discharge cycles make them a practical choice for IoT devices that may be “deployed and forgotten” for extended periods.

Some supercapacitors have achieved energy density levels comparable to lead-acid batteries, and in some cases, they surpass the energy density of rechargeable lithium batteries by several orders of magnitude [15].

This improvement in energy density makes them attractive for applications that require an efficient and compact power source, where their versatility and advantages in terms of durability and fast charging make them suitable for many IoT applications, especially when a quick response and energy efficiency are essential.

Among the advantages of supercapacitors are their high energy storage capacity, high power density, and straightforward charging method.

Supercapacitors allow rapid charge and discharge without the risk of overcharging and can surpass 500,000 cycles. Furthermore, they are not subject to chemical reactions, ensuring environmental safety, and their lifespan extends from 10 to 12 years [16].

Several LPWAN (Low Power Wide Area Network) technologies are available in the market: SigFox[17], NB-IoT[18] and LoRaWAN[19]. SigFox provides coverage through a single operator network, with deployments in different countries facilitated by various member companies. Telecommunications companies offer NB-IoT as an IoT communication alternative to sub-GHz LPWAN technologies operating in the 868 MHz or 915 MHz bands, depending on the country in question. Since NB-IoT operates in licensed spectrum, it offers higher traffic reliability compared to other sub-GHz technologies. Unlike SigFox and NB-IoT, LoRaWAN offers the possibility of private network implementations and easy integration with various global network platforms (e.g. TTN - The Things Network)[20]). Private network implementations are crucial for safeguarding sensitive data, maintaining confidentiality, and ensuring that only authorized users can access the organization’s resources.

LoRaWAN (Long Range Wide Area Network) is a wireless communication technology specifically designed for Internet of Things (IoT) applications and specifically tailored for low-power connected devices. The reasons for using this technology include long-range capability, low power consumption, low transfer speed, wide indoor and outdoor coverage, scalability, relatively low implementation cost, unlicensed frequency of operation, security, and compatibility with open standards. In the context of IoT and other technologies, compatibility with open standards is important because it allows devices and systems from different manufacturers to work together seamlessly, facilitating technology expansion and adoption, as well as the creation of broader and more diverse ecosystems. It also promotes transparency and innovation by enabling multiple stakeholders to contribute to the ongoing development and improvement of standards.

Hypothesis and Objectives

The main objective of this work is to develop a system capable of determining the effective RMS values of alternating current in metropolitan low-voltage electrical energy distribution systems and reporting their status to an operations center through a public LoRaWAN network.

In particular, we aim to assess the use of a supercapacitor as a replacement for a conventional battery in conjunction with an energy harvesting circuit, and develop low-power electronics to maximize autonomy.

As a hypothesis, it is expected that the implementation of the system will have a positive impact on the operation of metropolitan low-voltage electrical networks. This hypothesis implies that the ability to monitor and report in almost real-time states will enable operators to make more effective decisions and act upon considering some network events or issues, which, in turn, could enhance the reliability and quality of electrical energy supply services.

The specific objectives to address different critical aspects of system development and implementation are as follows:

a) Evaluate the applicability of supercapacitors as an energy accumulator.

b) Develop Ultra low power (ULP) electronics to maximize autonomy.

c) Design and build a high-precision measurement module for effective alternating current values.

d) Implement communication through the public LoRaWAN network.

e) Conduct tests for resilience and durability.

These specific objectives are related to key aspects of the system development, from the choice of the energy source to the implementation of communication and the evaluation of its performance.

Materials and methods

Figure 2 displays the block diagram of the hardware developed in the project: I) Mode selection circuit: a relay and control circuit connected to the current transformer. II) Rectification, energy storage, and voltage boosting. III) RMS current value measurement stage. IV) Microcontroller governing the node behavior, digitizing measurements, and transmitting data to the LoRaWAN network.

In addition to the hardware components, it has been necessary to implement a set of backend services to retrieve information from the LoRaWAN network, store it, and present it in a graphical interface.

Figure 3 depicts the architecture established to use the LoRaWAN network as a data transmission tool and its interaction with the business logic running on the microcontroller.

Figure 3 shows the architecture set up to use the LoRaWAN network as a data transmission tool and its interaction with the business logic running on the microcontroller.

The main components of the hardware developed and implemented are as follows:

- Current Transformer (CT): Relevant for handling high current values. For operational reasons, a split-core CT has been used, allowing easy installation and removal of the hardware without the need to cut the wire for setting up.
- CTSCM40-200/5 CTs made by Howard-Butler have been installed [21].
- Selection Circuit: The selection circuit consists of a non-latching double-pole double-throw relay responsible for switching the operating mode. The coil can be energized with 5V or less. It is capable of handling a current of up to 5A. The selected relay for this purpose was the Hongfa model HF115F/005-2ZS4A [22].
- Full-Wave Rectifier: This stage is based on a MOSFET-based full wave rectifiers [23]a low-voltage and low-power dynamic threshold voltage Metal Oxide Semiconductor Field Effect Transistor (DTMOS.

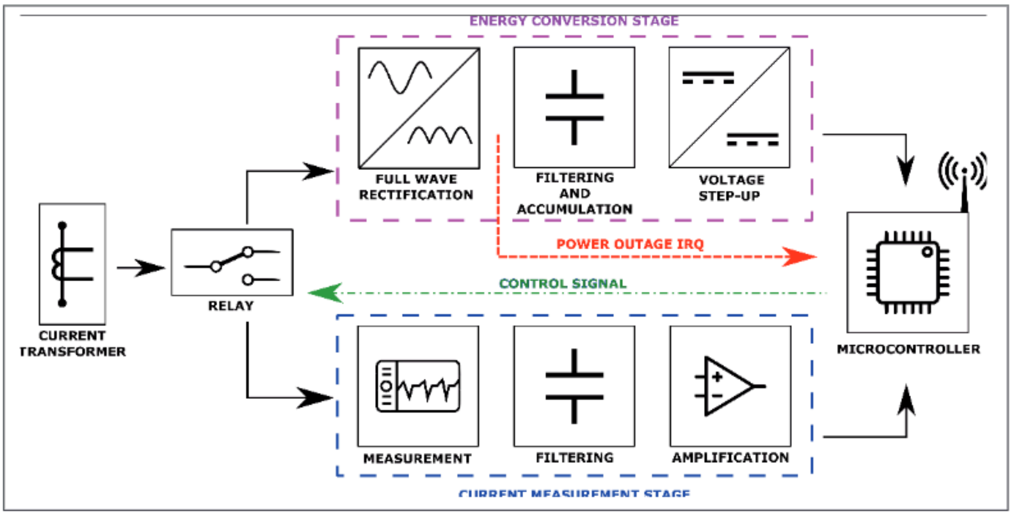


Figure 2: Hardware block diagram.

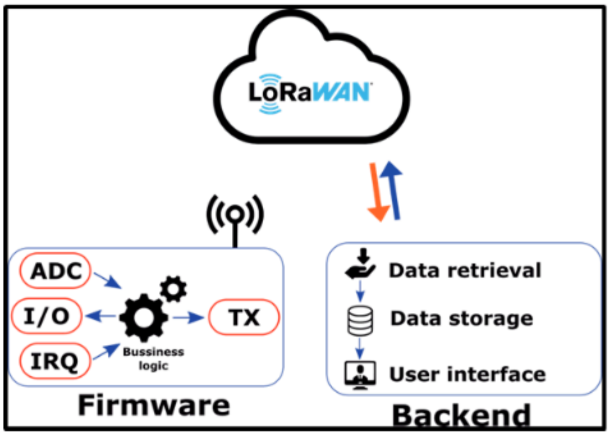


Figure 3: Firmware and its interaction with the LoRaWAN network and backend services.

This project seems to be suitable for using a non-relational database, as it only stores records of a single type and does not require creating complex relationships between different data tables.

Initially, an open-source text search server based on JSON documents, Elasticsearch [24], has been implemented, which integrates with the selected tool for developing the graphical interface, Grafana [25].

Due to the resource demands of the database engine and considering the performance of the implemented hardware (Raspberry Pi [26]), a more architecture-friendly open-source tool, MariaDB [27], was chosen.

The graphical interface is responsible for presenting the acquired data from each node to the end user.

A simple change in the node color on the screen indicates issues with the node, which are represented using the Worldmap panel plugin, a tiled map of the planet where circles represent responses to specific queries.

A simple change in the screen indicates problems with the node, which are represented using the Worldmap panel plugin, a mosaic map of the planet where circles represent answers to specific queries.

Why use supercapacitors instead of batteries? It has been taken into account that in the project development area (Misiones, Argentina), temperatures are above 30°C for at least 7 months of the year, which can be detrimental to batteries, causing premature component deterioration [28].

A bank of two supercapacitors is used to store energy to keep the electronics operational in case of a power conversion interruption, each one with a capacitance of 500 F x 2.7 V in series (Figure 4), resulting in an equivalent capacitance of 250 F x 5.4 V, connected to the output of the full wave rectifier.

These capacitors are mounted on a board with a protection circuit responsible for limiting the voltage across their terminals to 2.5 V and dissipating excess power.

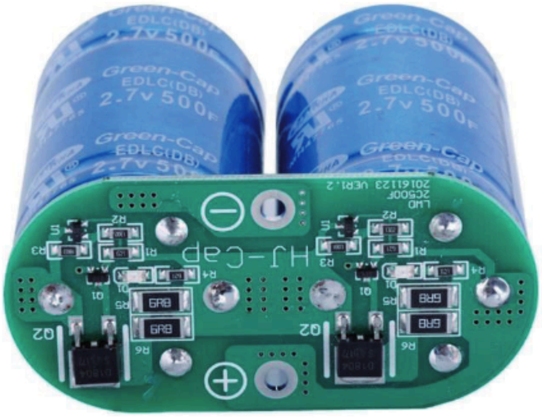


Figure 4: Array of 500F x 2.7V supercapacitors used as an accumulator.

To provide a fixed DC voltage to the microcontroller and the associated electronics, a commercially available boost or step-up topology DC/DC converter module has been used.

The converter takes the variable voltage from the supercapacitor connected to its input and outputs a fixed (voltage of)* 5 V with a current limit of up to 500 mA.

A wide range of development boards from different manufacturers is available in the market.

For this project, a LoPy4 board produced by Pycom [29] has been chosen. It is based on an ESP32 microcontroller, it has 8 Megabytes of flash memory, LoRa and 802.11 radio transceivers, and an internal voltage regulator. The LoPy4 is programmed using the MicroPython [30] programming language.

The current transformer terminals are, by default, connected to the energy conversion and accumulation stage. Once the voltage across the accumulator terminals reaches the minimum value for the DC/DC converter to start operating, the electronics also power up without the need for external intervention.

One of the relevant functionalities of the hardware is to detect power outages in the metropolitan network. The proposed power outage detector circuit is based on a TLV3691 comparator from Texas Instruments [31]. This comparator generates a 3.3 V signal that wakes up the microcontroller through a hardware interrupt. The output of the full wave rectifier is connected to the detector via a diode, filtering the ripple present in the signal with a pair of capacitors, resulting in a DC signal at the non-inverting input of the comparator. In the event of a power outage, the current through the diode is zero, and the capacitors discharge through a resistor. Once a certain low voltage threshold is reached, the hardware interrupt will be triggered and serviced by the microcontroller (see Figure 5).

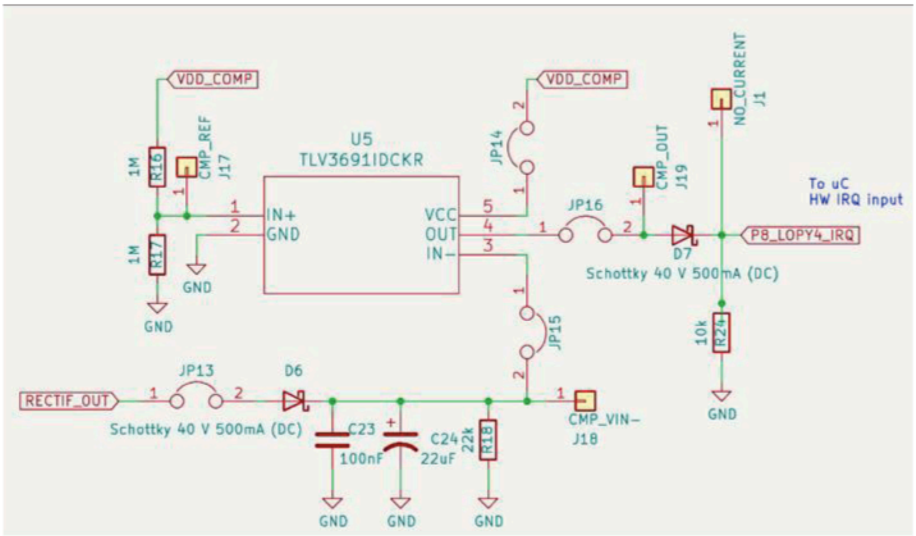


Figure 5: Outage detection circuit based on the TLV3691.

To measure current intensity using a current transformer, it is first necessary to convert the intensity into an equivalent voltage signal, and from this, calculate its RMS value.

A TO-220-2 encapsulated 0.1 Ω shunt resistor was adopted to convert the current from the secondary of the current transformer into a voltage signal suitable for RMS measurement.

Dedicated integrated circuits for RMS measurement of signals provide a DC voltage output that is proportional to the RMS value of the input voltage. For this project, the LTC1966 integrated circuit from Linear Technologies has been used [32].

Whenever current measurement is required, the microcontroller activates the relay coil and disconnects the current transformer from the energy conversion stage and connects the current transformer to the RMS value measurement stage.

To minimize power consumption in an idle state, it is necessary to de-energize all electronics associated with the hardware, except for the microcontroller and the detection circuit. Two independent power buses based on an ON Semiconductor FPF2104 load switch have been adopted for this purpose. [29]. In this way, the various stages of 3.3 V and 5 V are powered on only when the microcontroller enables the load switches.

The voltage across the supercapacitor terminals and the RMS value of the current intensity are analog signals. For this reason, it is necessary to digitalize these signals in order to be transmitted by the communication module. The ADS1015 chip from Texas Instruments [33], was adopted for the digitalization of these signals. This integrated circuit features a 12-bit resolution analog-to-digital converter, a 3.3 V power supply, I2C communication interface, 4 input channels, internal reference voltage, and a programmable gain amplifier.

The business logic of the implemented firmware is a reactive system and a power-saving loop (see Figure 6).

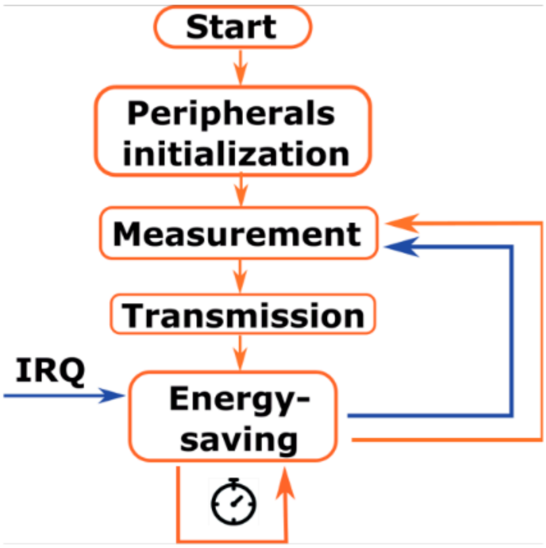


Figure 6: Firmware business logic architecture.

The peripheral initialization is executed each time a reset occurs on the microcontroller. When the power-saving period is completed or in case of an interruption, the 3.3 V and 5 V load switches are activated, configuring the hardware in measurement mode. The relay changes its state, connecting the current transformer to the shunt resistor. Communication with the converter is performed through the I2C communication bus. A freely accessible library ready to interact with the ADS1015 [35], is used to take 10 consecutive values of the signal of interest and store them in an array to calculate their arithmetic mean. The same method is invoked to digitalize the voltage corresponding to the supercapacitor.

To optimize data transmission time to the LoRaWAN network, readings need to be compressed as a consecutive stream of 48 bits. After assembling the payload, it is transmitted to the LoRaWAN network. A library provided by Pycom manages the interaction with the higher layers of the LoRaWAN protocol for authentication and network access.

Before configuring the power-saving mode, the firmware enables the hardware interruption of the LoPy4. Before setting the power saving mode, the firmware activates the LoPy4 hardware interrupt. The measurement and transmission action lasts only a few seconds, an interval that is negligible compared to the time the microcontroller remains in energy-saving mode.

In the absence of interruption, the microcontroller remains in energy-saving mode for a specific period and "wakes up" due to an internal timeout. However, if a power failure occurs, the detector circuit generates an interrupt signal, and the cycle starts again with measurement and transmission.

Results

Figure 7 displays the final operational prototype.

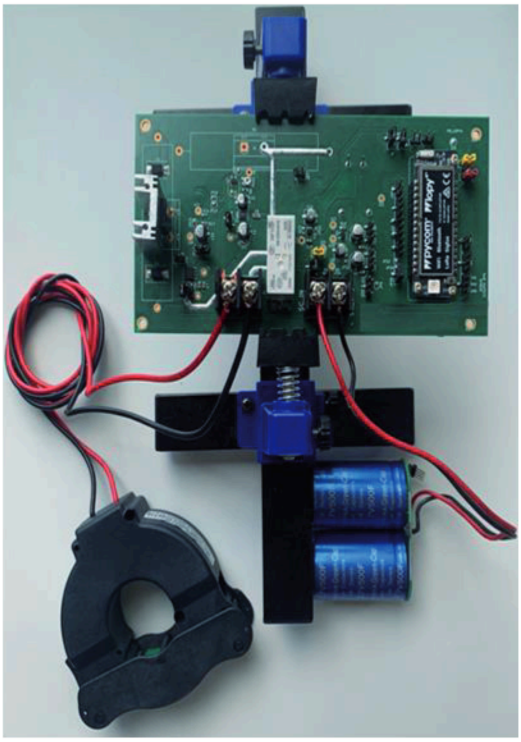


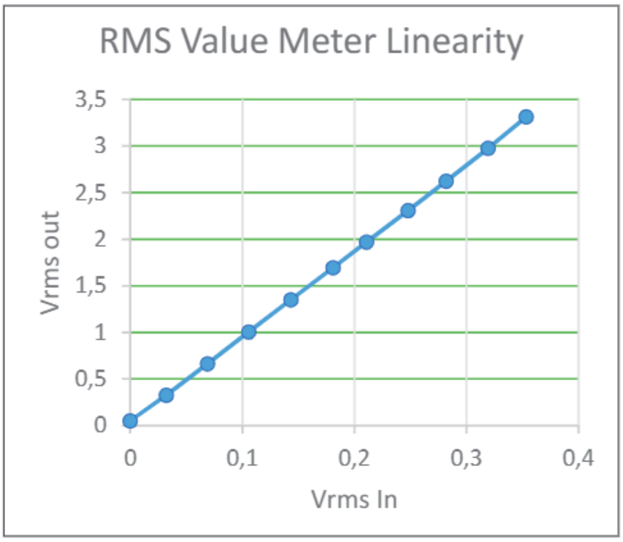
Figure 7: Deliverable prototype.

A Hold Peak multimeter, model HP-770d [34] and a signal generator from Feel Tech, model FY6900 [35] were used to inject a 1 Vpp (peak to peak voltage) signal that has simulated the voltage signal generated across the shunt. The maximum power consumption, taken as the average of 20 measurements, was 62 µA during deep sleep mode and 127 mA during transmission.

To determine the autonomy of the supercapacitor, it was charged with an external power source unit to a voltage of 4.67V and, with a 5-minute power-saving interval (Deep sleep) at the end of each transmission, the achieved autonomy was 19 hours.

This value could be increased by disabling the LED indicator for the relay activation or proposing a mode selection circuit based on an array of transistors.

A 10-step sweep was conducted on the amplitude of the sine wave at the output of the generator. Simultaneously, RMS voltages were recorded at the input of the LTC1966 and at the output of the amplification stage using the multimeter. The recorded values are presented in Figure 8, which shows linearity across the entire measurement range of the amplitude.



Vrms	Vout	Vout expected	Difference
(mV)	(mV)	(mV)	(mV)
0	0,052	0	0,052
0,032	0,326	0,3034	0,0226
0,069	0,665	0,6476	0,0174
0,106	1,005	0,9945	0,0105
0,143	1,35	1,3467	0,0033
0,181	1,696	1,7007	0,0047
0,211	1,969	1,9806	0,0116
0,248	2,309	2,328	0,019
0,282	2,622	2,6473	0,0253
0,319	2,974	2,9985	0,0245
0,354	3,313	3,3197	0,0067

Figure 8: RMS Meter Linearity.

To simulate different current values through the current transformer, the number of turns on the primary winding was increased, proportionally increasing the magnetic flux without increasing the load to which the test bench's electrical network was put under.

The results demonstrated that a current below 50A in the primary generated a hardware interrupt. The microcontroller exited power-saving mode and correctly sent a status via LoRaWAN to the backend services.

The results of the accumulator autonomy test, as shown in Figure 9, illustrate the historical evolution of the voltage across the supercapacitor terminals.

Figure 9: End to end autonomy test.

Conclusions

The conclusions that can be drawn from this development are as follows:

- The developed tool is a cost-effective solution for energy service providers, as it effectively connects hardware, firmware, and backend services and integrates with the LoRaWAN network.
- The system provides a higher level of information granularity about the state of distribution networks without requiring significant changes to the existing infrastructure. This is valuable for improving service quality by identifying recurring events and their possible causes, enabling corrective and preventive measures.
- The results support the idea that the combination of energy harvesting circuits and alternative energy accumulation technologies, such as supercapacitors, could be a feasible replacement for lithium batteries in autonomous applications. This is important to reduce costs and reduce the current dependence on batteries.
  The energy saving loop pattern implemented in the microcontroller proved to be effective in optimizing the node energy management, contributing to increase its operational autonomy.
- The total data propagation time from the on-site node to presentation on the graphical interface is 5 ± 1 seconds, which is an exceptional record for reporting issues in the low-voltage network.
- The use of LAMPP (Linux, Apache, MySQL, PHP, Perl) streamlined the setup of backend services and their integration with the LoRaWAN network through its REST API.
- The choice of Python as the programming language for both the firmware and mockups facilitated the integration of LoRaWAN and backend services, contributing to the project's success.

In summary, this development represents a valuable solution for energy service companies, offering increased visibility and efficiency in distribution network management, along with the possibility of replacing lithium batteries with more sustainable technologies. Additionally, improved energy management efficiency and faster data propagation enhance the quality of services provided.

Acknowledgements

This article would not have been possible without the generous assistance of the colleagues at the electronics laboratory of the Facultad de Ingeniería Oberá (Argentina). We are indebted to Germán Andrés Xander for his unwavering commitment to granting the access to the laboratory's physical resources and for his exceptional contributions to the implementation, measurement, and control aspects of our work.

References

1. **S. Goldsmith, B. Gardner, and J. Jamieson**, *"Toward a Smarter Future: Building Back Better with Intelligent Civil Infrastructure."* Accessed: Sep. 11, 2023. [Online]. Available: https://t.ly/FPbd1
2. **Aging Water Infrastructure.** Accessed: Sep. 13, 2023. [Online]. Available: https://t.ly/SO9n7
3. **"Reglamentación Lineas eléctricas exteriores."** Accessed: Sep. 11, 2023. [Online]. Available: https:// t.ly/rtAYc
4. **"IEEE Vision for Smart Grid Controls: 2030 and Beyond Reference Model,"** *IEEE Vision for Smart Grid Control: 2030 and Beyond Reference Model,* pp. 1–10, Sep. 2013, doi: 10.1109/IEEESTD.2013.6598993.
5. **HelioEsfera,** *"¿Qué son los Smart Grids?,"* HelioEsfera. Accessed: Sep. 12, 2023. [Online]. Available: https://t.

ly/Ew6WM

6. **H. Aranha, M. Masi, T. Pavleska, and G. P. Sellitto,** *"Enabling Security-by-Design in Smart Grids: An Architecture-Based Approach,"* in 2019 15th European Dependable Computing Conference (EDCC), Sep. 2019, pp. 177–179. doi: 10.1109/EDCC.2019.00042.
7. **A. E. Labrador Rivas and T. Abrão,** *"Faults in smart grid systems: Monitoring, detection and classification,"* Electric Power Systems Research, vol. 189, p. 106602, Dec. 2020, doi: 10.1016/j.epsr.2020.106602.
8. **"Cable de guarda con fibra óptica,"** *Sector Electricidad | Profesionales en Ingeniería Eléctrica*. Accessed: Sep. 11, 2023. [Online]. Available: https://t.ly/Jccx8
9. **P. Xin, J. Zou, S. Zhang, Q. Xiao, J. Lu, and Y. Wei,** *"OPGW Cable Risk Identification Method Based on K-means Clustering,"* in 2022 IEEE 22nd International Conference on Communication Technology (ICCT), Nov. 2022, pp. 1452–1457. doi: 10.1109/ICCT56141.2022.10072782.
10. **"Future Wireless Communication Technologies for Smart Grids: A LPWAN Prospective - IEEE Smart Grid."** Accessed: Sep. 11, 2023. [Online]. Available: https://t.ly/oY7pj
11. **T. Durand and M. J. Booysen,** *"Performance Evaluation of a Mesh-Topology Lora Network."* Rochester, NY, Feb. 15, 2023. doi: 10.2139/ssrn.4359315.
12. **H. Klaina et al.,** *"Analysis of low power wide area network wireless technologies in smart agriculture for large-scale farm monitoring and tractor communications,"* Measurement, vol. 187, p. 110231, Jan. 2022, doi: 10.1016/j.measurement.2021.110231.
13. **Di Li, C. Wang, X. Cui, D. Chen, C. Fei, and Y. Yang,** *"Recent progress and development of interface integrated circuits for piezoelectric energy harvesting,"* Nano Energy, vol. 94, p. 106938, Apr. 2022, doi: 10.1016/j.nanoen.2022.106938.
14. **D. Van Leemput, A. Sabovic, K. Hammoud, J. Famaey, S. Pollin, and E. De Poorter,** *"Energy Harvesting for Wireless IoT Use Cases: A Generic Feasibility Model and Tradeoff Study,"* IEEE Internet of Things Journal, vol. 10, no. 17, pp. 15025–15043, Sep. 2023, doi: 10.1109/JIOT.2023.3263543.
15. **D. Kularatna-Abeywardana and N. Kularatna,** *"Supercapacitor energy storage for battery-less, greener IoT networks,"* in 2023 IEEE Green Technologies Conference (GreenTech), Apr. 2023, pp. 160–163. doi: 10.1109/GreenTech56823.2023.10173835.
16. **E. Yu. Abramov, A. A. Shtang, and M. V. Rozhkova,** *"Effective Use of Supercapacitor Batteries for Urban Electric Transport,"* in 2018 XIV International Scientific-Technical Conference on Actual Problems of Electronics Instrument Engineering (APEIE), Oct. 2018, pp. 16–18. doi: 10.1109/APEIE.2018.8545937.
17. **"Home,"** Sigfox 0G Technology. Accessed: Oct. 10, 2023. [Online]. Available: https://www.sigfox.com/
18. **"Standardization of NB-IOT completed."** Accessed: Oct. 10, 2023. [Online]. Available: https://www.3gpp.org/news-events/3gpp-news/nb-iot-complete
19. **"What is LoRaWAN® Specification,"** LoRa Alliance®. Accessed: Oct. 10, 2023. [Online]. Available: https://hz1.37b.myftpupload.com/about-lorawan/
20. **T. T. Network,** *"The Things Network,"* The Things Network. Accessed: Oct. 02, 2023. [Online]. Available: https://www.thethingsnetwork.org/
21. **"Split Core Current Transformers Range - Hobut Ltd."** Accessed: Sep. 18, 2023. [Online]. Available: https://t.ly/-0Pdj
22. **"HF115F | Industrial Relay | HONGFA."** Accessed: Sep. 18, 2023. [Online]. Available: https://t.ly/pWw4B
23. **A. Yesil, M. Konal, and F. Kacar,** *"A Low-Voltage Low-Power Full-Wave Rectifier Based on Dynamic Threshold Voltage MOSFET,"* Journal of Nanoelectronics and Optoelectronics, vol. 14, no. 9, pp. 1326–1330, Sep. 2019, doi: 10.1166/jno.2019.2634.
24. **"Elasticsearch: Motor de búsqueda y analítica distribuido oficial,"** Elastic. Accessed: Sep. 25, 2023. [Online]. Available: https://www.elastic.co/es/elasticsearch
25. **"Grafana: The open observability platform,"** Grafana Labs. Accessed: Sep. 25, 2023. [Online]. Available: https://grafana.com/
26. **R. P. Ltd,** "Buy a Raspberry Pi 4 Model B," Raspberry Pi. Accessed: Sep. 25, 2023. [Online]. Available: https://t.ly/QEJqq
27. **"MariaDB Foundation,"** MariaDB.org. Accessed: Sep. 25, 2023. [Online]. Available: https://mariadb.org/
28. **G. Zhang et al.,** *"Research on the impact of high-temperature aging on the thermal safety of lithium-ion batteries,"* Journal of Energy Chemistry, vol. 87, pp. 378–389, Dec. 2023, doi: 10.1016/j.jechem.2023.08.040.
29. **"LoPy 4." Accessed: Sep. 25, 2023. [Online]. Available: https://t.ly/JJHMT**
30. **"MicroPython - Python for microcontrollers."** Accessed: Sep. 25, 2023. [Online]. Available: http://micropython.org/
31. **"tlv3691.pdf."** Accessed: Sep. 25, 2023. [Online]. Available: https:// t.ly/znzdO
32. **"1966fb.pdf."** Accessed: Sep. 25, 2023. [Online]. Available: https:// t.ly/XO-j0
33. **"ads1015.pdf."** Accessed: Oct. 02, 2023. [Online]. Available: https:// t.ly/yHM-X
34. **"Proveedores y fabricantes de multímetros personalizados de alta precisión de 40000 conteos de China - Venta al por mayor directa de fábrica - HOLDPEAK."** Accessed: Oct. 02, 2023. [Online]. Available: http://t.ly/UIKJR
35. **"FY6900."** Accessed: Oct. 02, 2023. [Online]. Available: http://t.ly/KOIu_