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Energy Harvesting for Powering the Wireless Sensor Network Nodes

SUMMARY

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CONTENTS

1 Introduction 1

1.1 Justification, Relevance, and Timeliness of the Research Topic 1

1.2 PhD thesis structure 3

2 State-of-the-Art Analysis 6

2.1 PRISMA Statement Framework 6

2.2 EH technologies and mechanisms 7

2.2.1 Cases of studies and applications 8

2.2.2 Energy obtained from the harvester 9

2.3 Energy Storage in BF-WSN 9

2.3.1 Supercapacitors (SCs) 10

2.4 Power Management Stage (PMS) 11

2.4.1 Energy Cycle in EH-WSN 12

2.4.2 SC Solutions 13

2.5 Partial Conclusions 14

3 Technological Framework 16

3.1 Device's Behaviour 16

3.1.1 System Architecture 17

3.2 Simulation Model for the Mote 17

3.3 Partial Conclusions 21

4 System Implementation and Validation 23

4.1 System Architecture 23
4.2 The IoT Platform 24
4.3 The Sink 26
4.4 Mote Prototype 27
4.5 Field Deployment 30
4.5.1 Operational behaviour for the entire year 31
4.6 Security considerations 34
4.6.1 Between mote and sink 34
4.6.2 Between sink and platform 36
4.6.3 Application layer 36
4.7 Partial Conclusion 37
5 Final Conclusions. Original contributions, and future research directions 40
5.1 Original Contributions 42
5.2 Future Research Directions 43
Bibliography 46

1 INTRODUCTION

Wireless Sensor Networks (WSNs) are a key enabling technology for a wide range of applications. This network typically is composed of spatially distributed sensor nodes (also referred to as motes, in line with IoT terminology) capable of sensing, processing, and wirelessly transmitting data where energy is the dominant limiting factor. As a result, mote design cannot be addressed in isolation: sensing, processing, communication, and power management must be co-optimized to minimize energy consumption and extend operational lifetime. Traditionally, this challenge has been addressed through battery-powered motes; however, this approach fundamentally limits long-term autonomy and scalability.

Energy harvesting (EH) has emerged as a promising approach to overcome these constraints [1] by enabling motes to extract energy from ambient sources such as solar, thermal, mechanical, or radio-frequency energy [2]. Among these, solar EH is particularly attractive due to its widespread availability and relatively high energy density. Despite extensive research on individual harvesting technologies, substantial challenges remain in the design, optimization, and real-world validation of fully Battery-Free WSN (BF-WSN) systems, especially regarding energy storage, power management, and long-term autonomous operation.

This thesis addresses the design and analysis of BF-WSN motes, with a particular focus on EH, energy storage, and power management strategies that enable long-term, energy-neutral operation. Rather than treating energy as an isolated subsystem, this work adopts a system-level perspective in which harvesting sources, storage elements, power management circuits, and mote operation are jointly considered.

1.1 JUSTIFICATION, RELEVANCE, AND TIMELINESS OF THE RESEARCH TOPIC

The shift towards BF-WSN motes powered by EH presents numerous advantages, including extended operational lifetimes, reduced maintenance requirements, and minimal environmental impact. However, despite the evident benefits, the practical implementation and optimization of such systems remain a complex area of research. The inherent variability of ambient energy sources, coupled with the need for efficient energy storage and power

management, presents significant technical challenges that must be addressed to realize the full potential of BF-WSNs.

This thesis aims to develop a methodological framework and experimental architecture for the design and validation of WSN motes capable of operating without batteries through collection and management of ambient energy, mainly natural light, in order to advance the understanding and optimization of autonomous distributed sensing systems.

Through a combination of theoretical modelling, simulation, and experimental validation, the research focuses on achieving sustainable energy management, efficient power utilization, and reliable operation in dynamic environmental conditions. By addressing these objectives, the work seeks to contribute to the advancement of EH technologies and promote the deployment of environmentally friendly and long-lasting WSN solutions.

Research objectives include:

- **RO1:** To conduct a systematic and critical review of the state of the art on energy harvesting, storage and management in ultra-low power embedded systems, in order to identify the main trends, technological limitations and scientific gaps in battery-free wireless sensor node research.
- **RO2:** Analyse and model the energy balance of a battery-free node, considering the temporal dynamics of harvested energy, the behaviour of storage devices, and the consumption profiles of electronic components.
- **RO3:** Design a modular hardware and firmware architecture that allows for the experimental validation of different energy management and storage approaches, ensuring the reproducibility of experiments and the comparability of results.
- **RO4:** Implement an experimental test bench for evaluation in the laboratory and under real-world operating conditions, measuring energy performance, communication reliability, and the node's functional stability.

By addressing these objectives, the research aims to contribute to the advancement of sustainable and autonomous WSN technologies, paving the way for their widespread adoption in diverse applications. The outcomes of this study are expected to provide significant insights

and practical solutions for the deployment of environmentally friendly and long-lasting WSN systems, thereby enhancing their impact and utility in various domains.

The research was conducted during the following stages:

- **Literature Review and Problem Identification:** The initial stage involved a comprehensive review of existing literature on WSNs, EH technologies, and power management strategies. This review will cover current advancements and state-of-the-art methods in these fields.
- **Establish the behaviour of the WSN device:** This encompasses the advancement of a multitasking operative system (OS) as a malleable abstraction layer between user applications that run as protothreads and the Arduino framework.
- **Simulation and Analysis:** We utilized the SPICE simulation framework to simulate the behaviour of the designed EH systems and power management circuits.
- **Prototyping and Experimental Validation:** Based on the optimized designs, prototypes of battery-free motes incorporating the developed EH and Power Management Stage (PMS) were developed. Laboratory experiments were conducted to validate the prototypes' performance under controlled conditions.
- **Field Testing and Performance Evaluation:** Prototypes were deployed in real-world environments to assess their practical performance.

All these steps are focused on optimizing the EH and PMS to improve performance and efficiency. Additional simulations and experiments may be performed as needed to validate these improvements.

1.2 PhD thesis structure

Including the Introduction and this section, the thesis is organized as follows:

Chapter 2 — State-of-the-Art Analysis

This chapter presents a comprehensive state-of-the-art analysis of EH and energy management, including PMS, in BF-WSN. The chapter is grounded on a systematic literature review (SLR) and complementary survey studies previously conducted by the author. It

provides a structured overview of harvesting technologies, power management architectures, and energy storage solutions reported in the literature.

It first introduces the methodological framework adopted for literature analysis, followed by a classification of EH mechanisms and representative application scenarios. The SLR studio reveals how BF-WSN gains attention, with particular emphasis on supercapacitors (SC) as energy storage. Furthermore, analyses PMS and energy cycles commonly employed in EH nodes. Finally, the chapter synthesizes the main findings and design trends, establishing the basis for the subsequent chapters of the thesis.

Chapter 3 — Technological Framework

This chapter describes the proposed device architecture and the simulation framework used to analyse its behaviour. The chapter introduces SPICE-based simulation models for the discrete elements involved in EH and storage, including photovoltaic (PV) panels, thermoelectric generators (TEG), batteries, and SCs. These models are then integrated to study the energy behaviour of the complete device.

Subsequently, the hardware and firmware architecture of the mote is presented, covering the process model, scheduling, energy management strategy, timers, and networking stack. A simulation model of the device is developed and validated against a simplified experimental testbed based on an Arduino platform, allowing the comparison between simulated and real behaviour. The chapter concludes with a partial discussion summarizing the observed system behaviour and the validity of the proposed models.

Chapter 4 — System implementation and validation

This chapter presents the design, implementation, and long-term evaluation of the proposed battery-free sensing system. The chapter describes the complete prototype, including the hardware architecture of the mote, the firmware framework and scheduling model (idOS), energy consumption modelling, and simulation of the energy subsystem based on PV harvesting and SC storage. Simulation results are contrasted with experimental observations, and the operational behaviour of the system is further analysed through a year-long field deployment, including data logging and performance characterization. In addition, the chapter

introduces the system platform developed to collect, manage, and visualize the data generated by the prototype, covering the sink architecture, backend infrastructure, data model, and visualization tools. In addition, the chapter includes brief methodological remarks on the development process, highlighting the use of custom laboratory tools for early prototyping and the role of AI-assisted coding techniques in the evolution of the platform.

Chapter 5 — Final Conclusions. Original contributions. Published work and future research directions

Contains the conclusions, a precise list of original contributions, recommended future research directions, and a list of published works.

Following the main body, the thesis includes the Bibliography, List of publications, and the Statement of authenticity.

2 STATE-OF-THE-ART ANALYSIS

This chapter is based on the article "*Energy Harvesting Techniques for Wireless Sensor Networks: A Systematic Literature Review*", published in the journal "Energy Strategy Reviews", 2025 [3].

2.1 PRISMA STATEMENT FRAMEWORK

The present study was conducted in accordance with the PRISMA Statement framework for SLR [4]. The RQs aim to answer were formulated based on the CIMO scheme (Context, Intervention, Mechanisms, Outcomes) [5].

- **RQ1**: What methods or technologies are implemented for *harvesting energy* from the environment to power *WSN nodes*?
- **RQ2:** What are the conditions and contexts in which *EH methods and technologies* have been utilized to power nodes within *WSNs*?
- **RQ3:** What are the documented outcomes or results of implementing *EH* methods and technologies to ensure an indefinite power supply to *WSN nodes*?

An adaptation of the PICO (Population, Intervention, Comparison, Outcome) framework in software engineering [6], is presented for identifying keywords and formulating search strings from RQ. The identified keywords are *EH* and *WSN*; each becomes a set of keywords for search. In each set, the primary keyword is paired with its synonyms as follows:

- **Set 1:** energy harvesting; energy scavenging; energy harvester; harvester; harvesting.
- **Set 2:** wireless sensor network; wsn; sensor node; iot device.

Starting with the search statements, the initial search retrieved **1,491** publications from three electronic databases, limited to the interval **from 2014 to 2025** (the last 11 years). Specifically, Web of Science yields **197** publications, IEEE Xplore yields **574**, and ScienceDirect yields **720**. Using Zotero as a bibliographic manager, **32** duplicate references were detected.

In the first screening, the title and abstract were reviewed. Papers that potentially met the eligibility criteria for this research were selected. After this process, **306** records remain. In the second and final screening, which consisted of reading and analysing the documents, **91** were eliminated, considering that they did not include all the elements for this investigation. Ultimately, **215** articles were eligible for review.

2.2 EH TECHNOLOGIES AND MECHANISMS

This subsection addresses RQ1 by exploring the various methods and technologies employed to harvest energy from environmental sources to power WSN nodes. To enhance the precision of the classification, these concepts have been distinctly separated and stated:

- **Energy source:** An entity that creates energy, for example, wind, sea waves, sun, antenna, electricity in a wire, etc.
- **Energy type:** Type of energy produced by a source, for example, light, heat, electromagnetic (EM) wave, mechanical vibration, etc.
- **Transducer type:** A device that, based on a physical principle, transforms ambient energy into usable electricity.

Figure 1 summarizes the distribution of papers based on transducer type. Here, piezoelectric (PZ) transducers emerge as the most referenced, followed by triboelectric nanogenerator (TENG) and EM variants.

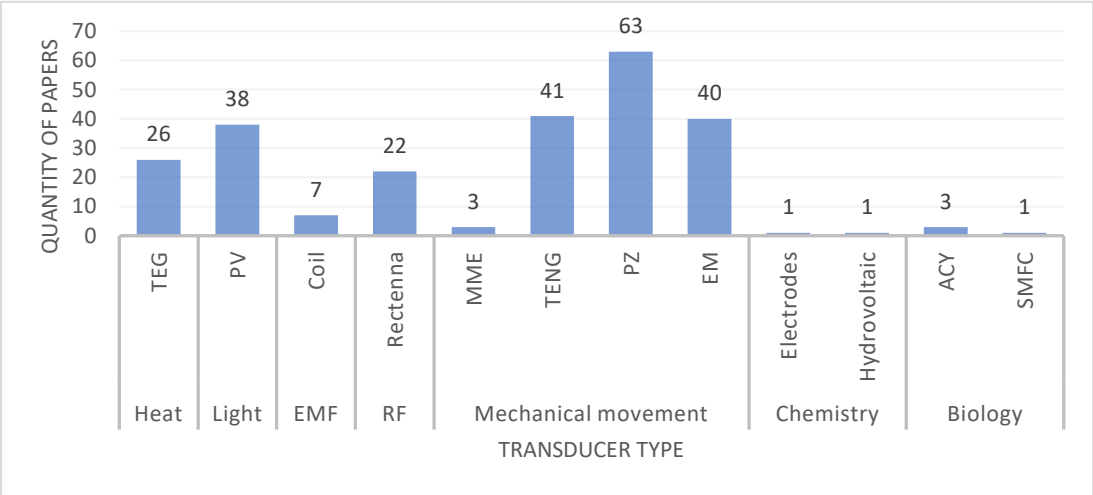

Figure 1: Distribution of papers based on transducer type

Both the article and the thesis contain an extensive explanation of the energy harvesting mechanisms from different sources. Here, we will only briefly refer to the most relevant findings:

- **Mechanical transducers dominate** the literature, accounting for over 50% of the reviewed papers, with **piezoelectric (PZ)** being the most cited, followed by **triboelectric (TENG)** and **electromagnetic (EM)** variants.
- **PV systems** are surprisingly underrepresented in SC-based BF-WSN studies; most PV implementations use batteries as storage.
- **Hybrid systems** (combining multiple transduction methods or energy types) are emerging but remain complex.

2.2.1 Cases of studies and applications

A critical examination of these papers reveals that many solutions can be utilized or adapted for other contexts. In numerous instances, authors do not specify a particular working environment, leading to the use of the category "Not Referenced/Not Clear":

- **Agriculture:** Include environmental and soil variables in crop fields and agricultural machinery.
- **Smart home/building/city:** Encompasses applications ranging from monitoring indoor environments to city infrastructure, local weather, and air quality.
- **Water/Sea/Marine environments:** Refers to a system that collects energy from water bodies, primarily utilizing wave energy.
- **Transportation:** Apply to applications that harvest energy from modes of transportation, including trains, trucks, and cars. In this context, energy is primarily collected from vibrations generated by the movement of cargo vehicles.
- **Wearables/healthcare**: Encompasses wearable devices, implants, and other health monitoring devices, including pets.
- **Environmental outdoor:** This category can be viewed as a specific instance of "Not referred/Not clear," where authors imply that energy is harvested from outdoor environments, primarily sourced from the sunlight, wind, or water currents.

- **Industry:** While the industrial environment is known for its aggressive nature, it also represents a considerable amount of untapped energy resources that are often wasted in the operation of machinery, mainly heat, vibration, and EM fields.
- **Not referred/not clear:** This category encompasses papers that lack information about application scenarios or provide only broad and general suggestions for potential applications.

2.2.2 Energy obtained from the harvester

Power density is commonly employed in review papers as a metric to evaluate the potential of different energy sources for harvesting applications. It serves as a quantitative measure of the available energy per unit area or volume, providing valuable insight into the feasibility and efficiency of EH systems. The heat map in Table 1 shown energy sources in the columns, and ranges of power along the rows using a natural logarithmic scale. Each number within the rows serves as a multiplier, indicating the number of solutions that fall within a specific range of power values, as indicated in each cell.

Table 1: Power generation heat map.

P (W)	Heat	Light	EMF	Rectenna	Mech(TENG)	Mech(PZ)	Mech(EM)	Chem	Bio
1 uW	1	1	1	2	3	2	0	0	0
10 uW	1	2	1	2	4	9	3	0	2
100 uW	2	3	1	0	4	8	2	0	0
1 mW	9	2	1	4	6	18	8	1	0
10 mW	2	6	1	0	5	5	6	0	0
100 mW	5	5	0	0	2	5	2	0	0
1W	0	3	0	0	0	1	3	0	0
10 W	0	1	0	0	0	0	1	0	0

Table 1 visualizes the distribution and density of solutions based on their power across different energy sources, providing valuable insights into the characteristics and performance of each source within a broad context.

2.3 Energy Storage in BF-WSN

The reviewed literature addresses several energy storage solutions used in EH systems for WSNs, with the primary objective of ensuring continuous operation under fluctuating energy

availability. The identified storage approaches include batteries, SC, and hybrid configurations combining multiple technologies. However, the suitability of each solution depends on parameters such as energy density, charge–discharge dynamics, lifespan, and maintenance requirements. Figure 2 presents the distribution of the analysed papers according to the energy storage element employed. In the Figure 2 capacitors and SC are grouped into a single category, shown as C-SC.

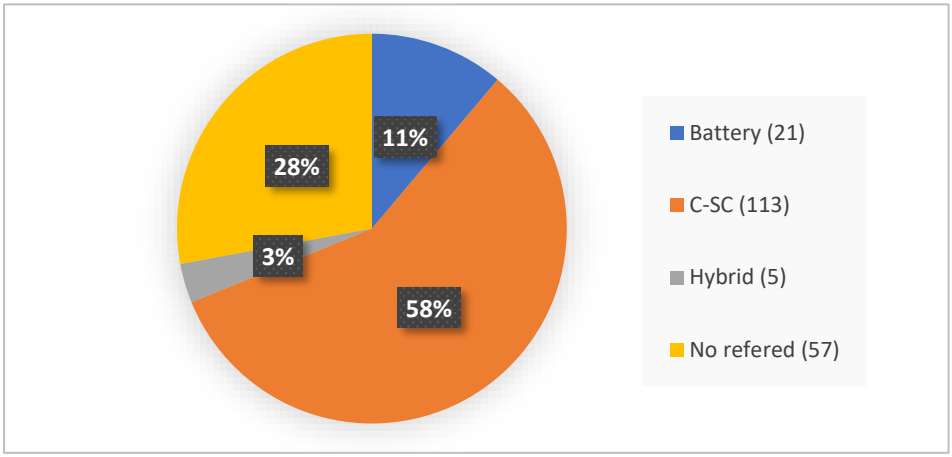

Figure 2: Distribution of energy storage elements.

We can observe that solutions based on capacitors or SC dominate the literature, likely due to their lower cost, extended cycle life, maintenance-free operation, and reduced environmental impact, all of which are particularly advantageous for long-term and unattended WSN deployments.

2.3.1 Supercapacitors (SCs)

From this section, the contents are adapted from the conference proceedings "*Energy Storage and Management in Battery-free Wireless Sensor Networks*", presented orally at the international congress "*14th International Conference on Renewable Energy Research and Applications, ICRERA 2025*" in the city of Vienna, Austria [7].

SC can be systematically classified into three primary categories based on their assembly configuration, charge storage mechanism, and the materials utilized for the electrodes and electrolytes [8] in **Electric double-layer capacitors (EDLCs), Pseudocapacitors (PCs) and Hybrid SCs (HSCs).** The most representative devices in the market are EDLCs, with a significant

growth forecast until 2033. In contrast, hybrid pseudocapacitors and SCs are growing rapidly, but still represent a smaller portion of the overall market [9].

Among the hybrid SC on the market, lithium-ion capacitors (LICs) stand out. This technology has been promoted as uniquely bridging the gap between conventional lithium-ion batteries and SCs [10].

SC models span from simple RC networks to multi-branch equivalents, capturing transient and slow dynamics. This survey focuses on **EDLCs** as the primary BF-WSN storage. Under constant current, EDLCs exhibit quasi-linear voltage decay between 80% and 40% of rated voltage, justifying treating capacitors and SCs similarly in typical operating scenarios:

- Equivalent Series Resistance (ESR): ESR is temperature-dependent, decreasing with moderate heat but accelerating degradation under excessive temperatures.
- Self-discharge: is influenced by temperature, initial voltage, charge duration, and technology.
- Degradation: SC end-of-life is reached when capacitance drops to 80% or ESR doubles. Factors accelerating aging include overvoltage, high temperature, humidity, and mechanical stress.

Our temperature tests on a 5F SC under low current (90 mA) showed no clear monotonic relationship between temperature and charge/discharge duration. This non-monotonic behavior is attributed to competing thermal effects: while heat improves ionic mobility and reduces ESR, it exponentially increases leakage current and self-discharge (Arrhenius law), with capacitance varying only ~6% across -40°C to 70°C. These coupled mechanisms mask any simple trend.

2.4 Power Management Stage (PMS)

Electrical interface between the energy harvester and the load typically includes power conditioning, impedance matching, regulation, and energy storage management stages. Depending on the implementation of the functions, different electrical behaviours can be observed in the PMS. Based on these functional differences, PMS architectures can be grouped into four main categories [11]:

- Direct coupling: the harvester is connected to the storage element or the load with minimal conditioning circuitry.
- Regulated: Incorporate DC–DC converters or linear regulators to provide a controlled output voltage.
- MPPT-based: Basically, impedance matching
- Storage-threshold-controlled PMS: typically used in ultra-low-power energy harvesting nodes where the instantaneous power available from the harvester is insufficient to sustain continuous operation.

This classification reflects the increasing level of circuit complexity and control required to ensure efficient and reliable operation in energy harvesting wireless sensor nodes.

2.4.1 Energy Cycle in EH-WSN

In EH-WSN, ambient energy is collected as the main power source, but it's typically intermittent and unpredictable. In the field, the PMS continuously regulates energy input from the harvester and stored reserves to guarantee that the device and its subsystems always receive sufficient power. Figure 3 shows the PMS architecture and depicts the storage cycle.

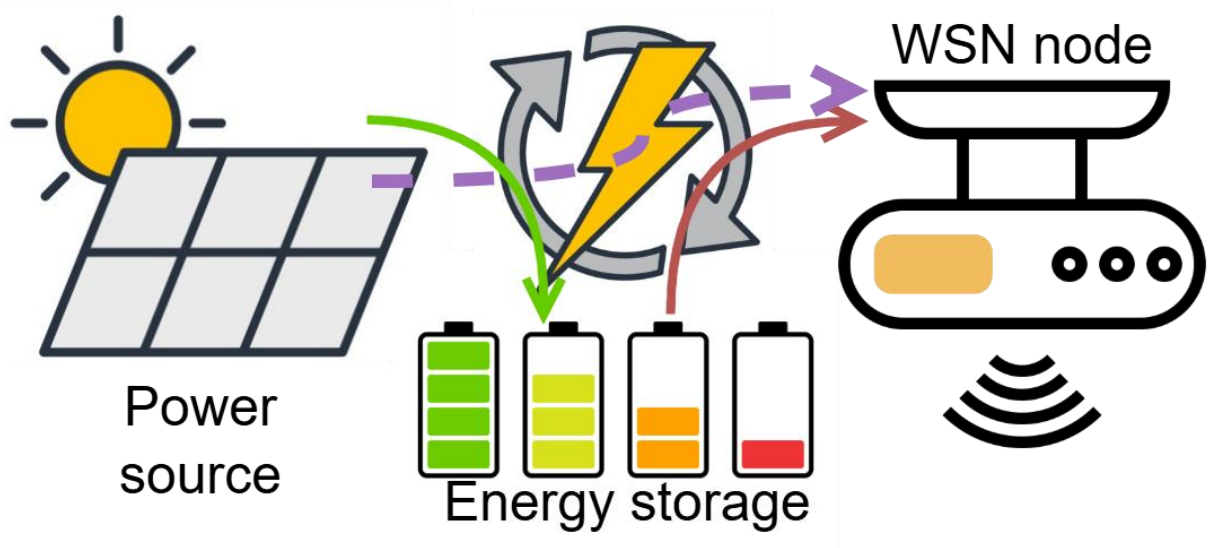

Figure 3: Overview of the PMS operation in a WSN device

It's possible to identify three scenarios:

- The energy produced by the harvester is sufficient to operate the mote.

- The energy produced by the harvester will never be enough to sustain the mote.
- The monitored event is the energy source itself or coincides with it.

Relying solely on intermittent EH limits system robustness to variations in source availability. Moreover, the typical charge–discharge profile of SCs poses an additional challenge, and incorrect sizing of the SC can be the difference between system success and failure.

2.4.2 SC Solutions

An adaptive charging circuit for harvesting systems is crucial because the load seen must be continuously adjusted for the PMS to match the maximum power point (MPP) [12]. Table 2 summarizes the circuits reported in the literature, including solutions based on discrete components that go beyond a simple rectifier bridge or a single capacitor.

Table 2 Summary of reported EH interface circuits

Type	Papers
discrete elements	[13–21]
LTC3388/LTC2935	[22]
LTC3588-1	[23–39]
LTC3105	[40]
LTC3106	[41]
LTC3108	[42–47]
LTC3330	[48]
LTC4071	[49]
LTC4071/LTC3108	[42]
ADP5090	[50]
AEM10941	[51]
AEM30940	[52]
BQ25570	[53–57]
BQ25570/LTC3106	[41]
LM2575	[58]
BQ25504	[59–61]
BQ25505	[62–64]
MB39C811	[65]

It is to be noted that while the IC LTC3588 is intended by the manufacturer only for capacitor or SC, the rest of the IC presented can also handle Li-Po and Li-ion batteries. It is necessary to

highlight the IC, the P1110 from Power-Cast, specifically designed for RF harvesting in the 902-928 MHz band, used by Tran and Chung, 2014 [66].

2.5 Partial Conclusions

The investigation of EH-WSN's mechanisms reflects both the significant innovation achieved in this field and the persistent technical challenges that remain. A wide range of mechanical and non-mechanical harvesting techniques, spanning from simple architectures to highly complex systems, demonstrates the diversity of approaches proposed to meet the energy demands of WSNs operating in heterogeneous environments. However, a substantial portion of these solutions have been validated primarily under laboratory or controlled conditions, highlighting the need for extensive real-world experimentation to assess long-term reliability and practical feasibility.

Recent research has also explored emerging and unconventional EH technologies, including rectennas, OPV cells, thermal resonators, hydrovoltaic devices, and bio-harvesters based on living microorganisms. While these approaches broaden the conceptual landscape of sustainable power generation for WSNs, their practical adoption must be carefully weighed against more established technologies, which often provide simpler, more cost-effective, and more predictable performance in real deployments.

Efficiency remains a central concern in EH-WSNs. Current strategies focus on increasing the number and diversity of transducers or introducing intermediate energy conversion stages to improve overall harvesting performance. Despite these efforts, achieving fully BF-WSN operation continues to pose significant challenges, underscoring the need for further research in both system integration and energy management.

The literature shows a clear predominance of mechanical energy sources, particularly vibration-based harvesting, which explains the dominance of PZ transducers. EM and TENG solutions have also attracted growing interest. In contrast, PV harvesting is comparatively underrepresented in studies that rely exclusively on SCs for energy storage, as noted in works such as [51]. This imbalance may be attributed to the technological maturity of PV systems, which reduces their perceived novelty, as well as to the inherent intermittency of solar energy.

Daily and indoor light cycles often impose prolonged low-illumination periods, preferring storage solutions with high energy density and motivating continued research into solar harvesting architectures. This observation aligns with prior studies on battery-free systems that rely on persistent artificial lighting [67] or on very large capacitance values to bridge sunlight cycles [68].

Within this context, capacitor-based storage, particularly electric EDLCs, is emerging as a key enabler of BF-WSNs. EDLCs combine high power density, long cycle life, and maintenance-free operation, making them well-suited for intermittent EH scenarios. They can effectively buffer energy during low-power sleep phases and deliver short, high-power bursts during active operation. Nevertheless, a critical design trade-off lies in the optimal sizing of the SC. While larger capacitance increases stored energy, it also extends the voltage ramp-up time due to the RC constant, potentially delaying or even preventing the node from reaching its minimum operational voltage.

Finally, beyond the choice of harvesting and storage components, the PMS plays a decisive role in enabling sustainable operation. It must adapt to fluctuating energy inputs, efficiently manage charge and discharge processes, regulate supply voltage, and schedule node activities to maintain long-term energy-neutral operation. Continued advances in both hardware design and system-level energy management will therefore be essential to fully realize the potential of BF-WSNs in practical deployments.

3 TECHNOLOGICAL FRAMEWORK

This chapter introduces the technological framework underlying the proposed BF-WSN mote. It begins by describing the SPICE simulation models developed for the discrete elements used in the analysis and simulations. These models, implemented in the LTspice® environment, are required because the corresponding components are not available in the standard libraries.

The chapter then presents the overall system architecture, including the mote firmware framework, scheduling model, and energy management strategy adopted to support energy-neutral operation. Finally, it describes the modelling and simulation approach used to analyse the energy behaviour of the system, encompassing EH, storage, and power consumption aspects, and establishes the technical foundation for the subsequent prototype implementation and validation.

The thesis contains a complete description of the SPICE models for PV, TEG, SC, and Li-ion batteries, based on models described in the literature. This summary will only present the mote model, which is one of the contributions of this research.

3.1 DEVICE'S BEHAVIOUR

This section is based on the conference proceeding "*Protothread and Cooperative Multitasking Scheduler on the Arduino Framework*", presented orally in the *2024 International Conference on Applied and Theoretical Electricity (ICATE)* [69]. This section presents idOS, an operating system (OS) implemented within the Arduino framework. As part of this research, idOS has been adapted by its authors to operate in periodic intervals, aiming to minimize energy consumption and thus better suit the energy-constrained conditions typical of WSNs. The following sections describe idOS in detail, including its architecture and subsystems.

IdOS is motivated by the necessity to simplify the approach to these systems for a more extensible audience, primarily Arduino users, and to facilitate the construction of applications directly from the Internet of Things (IoT), particularly for Low-Power and Lossy Networks (LLNs).

3.1.1 System Architecture

IdOS functions as a partial abstraction layer between applications and the Arduino framework, allowing direct access to Arduino and third-party libraries based on the specific requirements of the application. The structure of idOS includes the *kernel* and system libraries (*sys*), with an added abstraction layer (*arch*) between *sys* and hardware, which enhances hardware management within the framework.

Figure 4 provides a visual representation of the idOS structure.

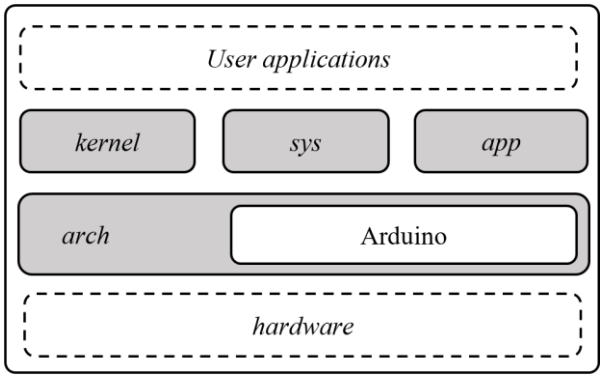

Figure 4: Structural elements of idOS.

IdOS components are loaded at compilation time, and memory is statically allocated to keep the code compact. Despite its functionality, the code footprint remains remarkably small, about 4 Kbytes, with only about 250 Bytes of RAM usage without the network stack, a significantly low impact. Even with the inclusion of the TCP/IP stack, the RAM and flash (code) footprint only increases to about 1.5 Kbytes, leaving plenty of space for applications to run alongside idOS. The thesis document and associated article offer an extensive description of idOS. The idOS source code is publicly available in a GitHub repository.

3.2 Simulation Model for the Mote

This section builds upon the article "*Comprehensive electrical models for a wireless sensor network device*", 2024, published in the *Heliyon* journal [70].

A mote acts as a load for the power source, as illustrated in Figure 3. Estimating the highest power consumption of a WSN node by simply summing the worst-case values provided by the

component manufacturers would be unrealistic. The electrical characteristics of key components in a WSN mote are crucial for understanding and modelling its power consumption and overall performance. The mote operates in various states, each influenced by different components with distinct properties. The main components are [71] the **Microcontroller (MCU)**, **Sensors and Radio Interface (Transceiver)**. Depending on the application, a WSN mote may include additional peripherals such as memory modules or actuators.

Each component contributes as a load that alternates between two states periodically. These loads are represented as current sources. Each current source simulates the states of each component as a pulse function, resulting in a composite function representing the sum of all current functions. This composite function can be expressed as a superposition of periodic two-level rectangular waveforms with constant duty cycle TLW, with amplitude A_i, frequency f_i and phase ϕ_i.

$$y(t) = \sum_{i=0}^{N} TLW(A_i, \quad f_i, \quad \phi_i) \qquad [1]$$

The model will be completed with a source representing the mote in the lowest consumption mode, an aleatoric signal simulating noise, and an RLC network. In the model, shown in the Figure 5, the current source uses a pulse function where I_{on} and I_{off} are the consumption states, T_{on} the time in a high consumption state into a period T_{period} and T_{delay} define the phase as a delay.

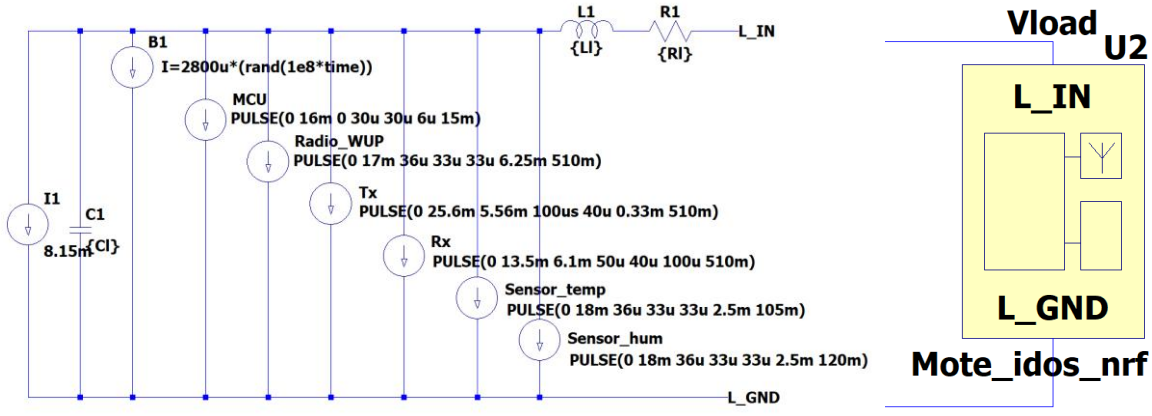

Figure 5: WSN node model at left. On the right, the symbol for LTspice®

The Figure 6 presents, in the first plot, the LTspice® simulation of the mote's energy consumption and, in the second, a screenshot of the NI Elvis III datalogger web interface.

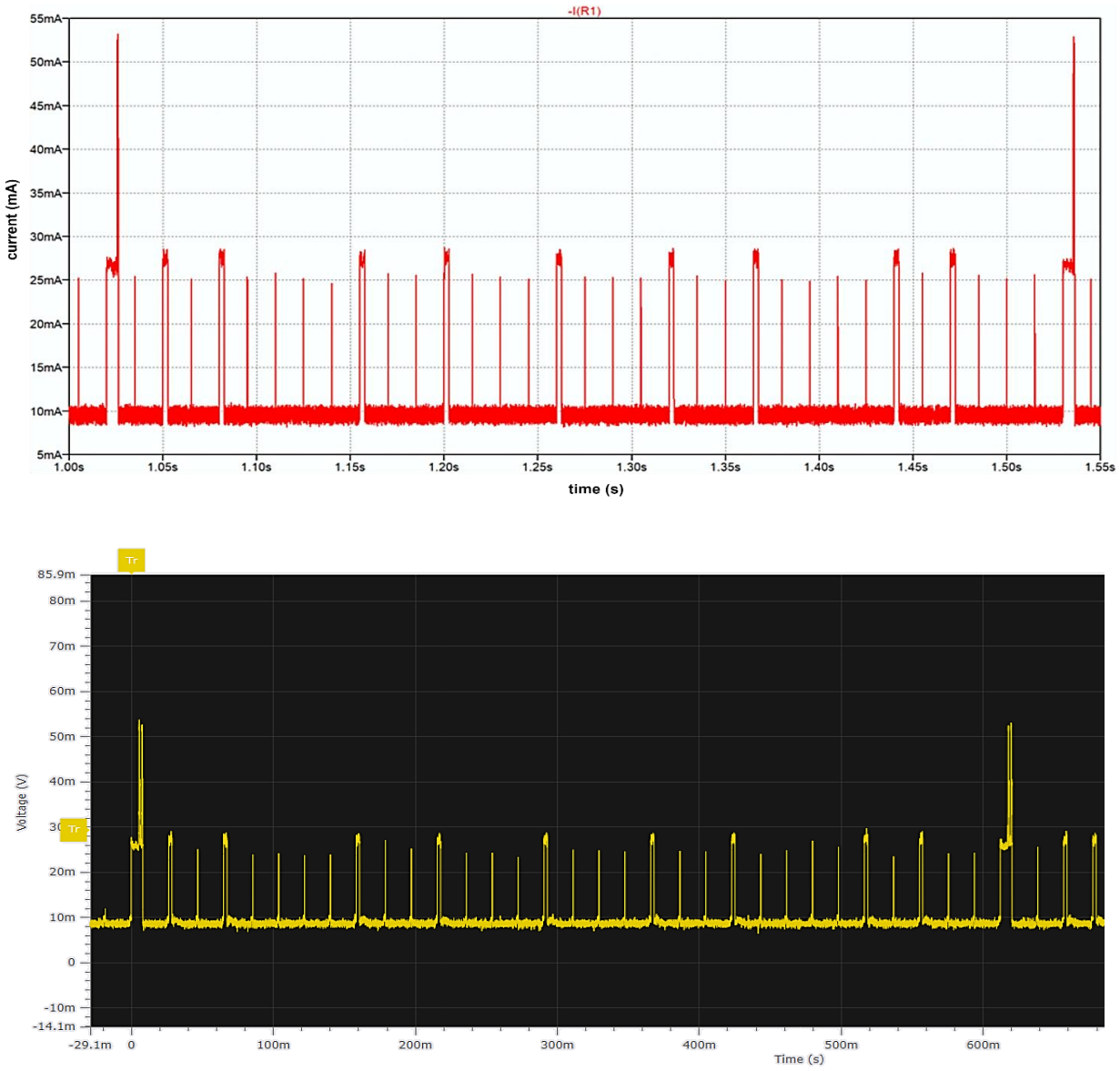

Figure 6: Entire cycle between radio interface activities in LTspice® simulation (on top) vs the real mote in NI Elvis III web interface (at the button).

To examine in greater detail the correspondence between the simulated and measured behaviour of the mote, two Tx/Rx intervals were extracted: one from the LTspice® simulation and the other from data acquired using the NI Elvis III. These intervals were temporally aligned using MS Excel to enable direct comparison. The resulting overlap is shown in Figure 7.

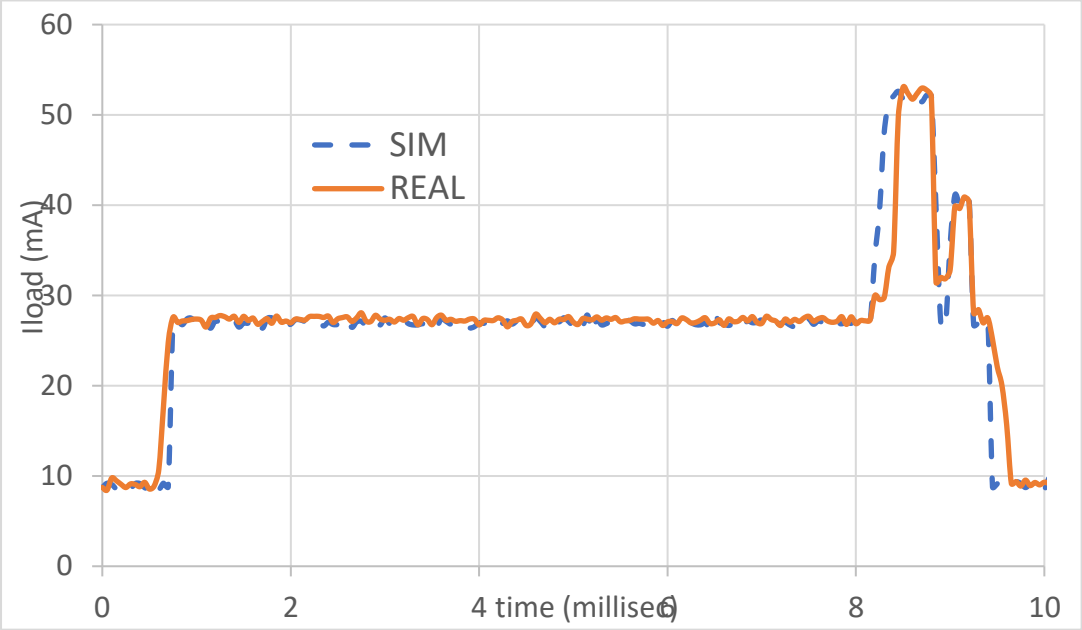

Figure 7 a Tx/Rx event in simulation vs. a mote on the same graph

To assess the model accuracy from an energy consumption perspective, measurements obtained from the physical prototype were compared against simulation results.

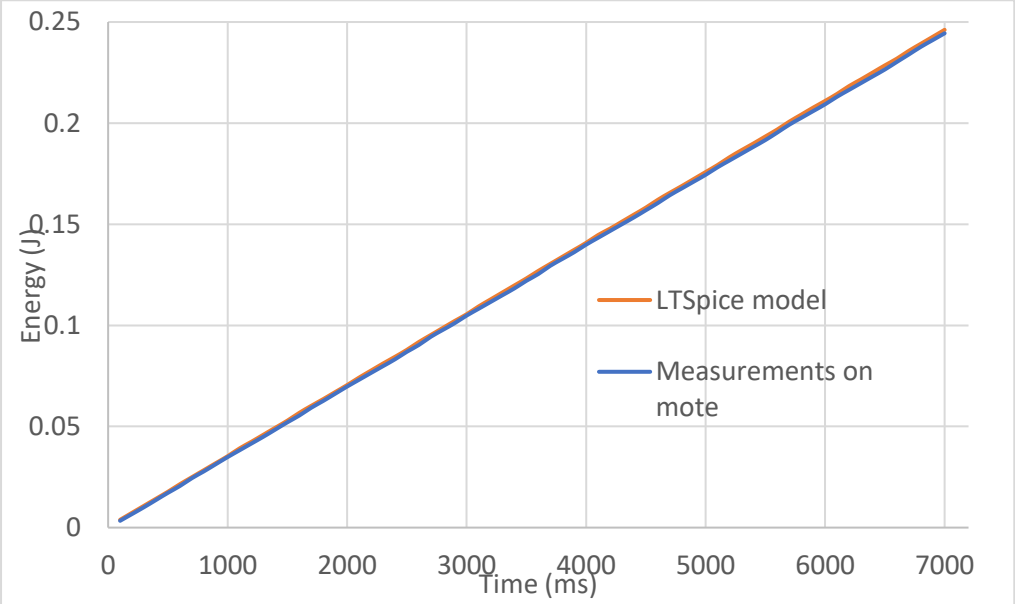

Figure 8: Progress of energy consumption measured on real mote versus model running in LTspice.

Figure 8 presents the power consumption profile over a 7-second interval for both the simulation and the real prototype, showing a nearly identical temporal behaviour. To obtain the values presented in the graph in Figure 8, energy was calculated every 100 milliseconds.

3.3 PARTIAL CONCLUSIONS

This chapter has presented a comprehensive technological framework for the design, implementation, and analysis of BF-WSN motes. The framework integrates firmware architecture, hardware modelling, and circuit-level simulation, establishing a solid foundation for subsequent prototype implementation and experimental validation.

Leveraging the simplicity and widespread adoption of the Arduino framework, idOS is introduced as a lightweight, event-driven operating system tailored for resource-constrained IoT devices. Based on a cooperative scheduling model inspired by protothreads, idOS enables efficient discrete multitasking while maintaining low memory and energy overhead. Core services such as timers, power management primitives, and a lightweight TCP/IP networking stack demonstrate its suitability for constrained environments.

The analysis of the nRF24 transceiver highlights its advantages in terms of simplicity, low power consumption, and cost, making it an attractive option for energy-constrained nodes. However, its limited payload size and lack of robust medium access control mechanisms impose constraints on protocol design and network scalability. While these limitations do not preclude its use, they necessitate additional mechanisms for packet aggregation and gateway-based IP integration, which are identified as directions for future work.

From a hardware and energy perspective, this chapter has introduced a SPICE-based electrical modelling framework for EH components, including PV panels, TEGs, lithium batteries, and SCs, together with a detailed circuit-level model of a WSN mote. The proposed model accurately reproduces the duty-cycled behaviour of a real device by incorporating the electrical characteristics of the microcontroller, sensors, radio transceiver, and power management circuitry.

Although the model abstracts away network-level dynamics and assumes ideal communication conditions, experimental validation against a physical prototype demonstrates a close correspondence between simulated and measured energy consumption. This confirms the model's effectiveness for circuit-level analysis and for

evaluating power management strategies and EH subsystems within a SPICE simulation environment. As such, the model provides a valuable tool for optimizing power consumption and supporting the design of energy-efficient, long-lived WSN nodes.

Future work will focus on refining idOS with synchronization primitives to prevent race conditions, enhancing low-power operating modes, and exploring tighter integration between EH techniques and adaptive power management strategies. These extensions are expected to further improve the sustainability and robustness of BF-WSN deployments.

4 System Implementation and Validation

This chapter focuses on the implementation and experimental validation of the proposed system. It details the construction of the prototype, the integration of hardware and firmware components, and the deployment setup used for long-term evaluation. Simulation results are contrasted with experimental observations, and the operational behaviour of the system is assessed through real-world measurements, providing insights into performance, robustness, and practical limitations.

4.1 System Architecture

This section is based on a conference proceeding, *"Integration of a Sink Node and Django Platform for Solar-Powered BF-WSNs: Enabling IP Connectivity and Cloud Data Management"*, 31st International Symposium for Design and Technology in Electronic Packaging (SIITME), 2025 [72].

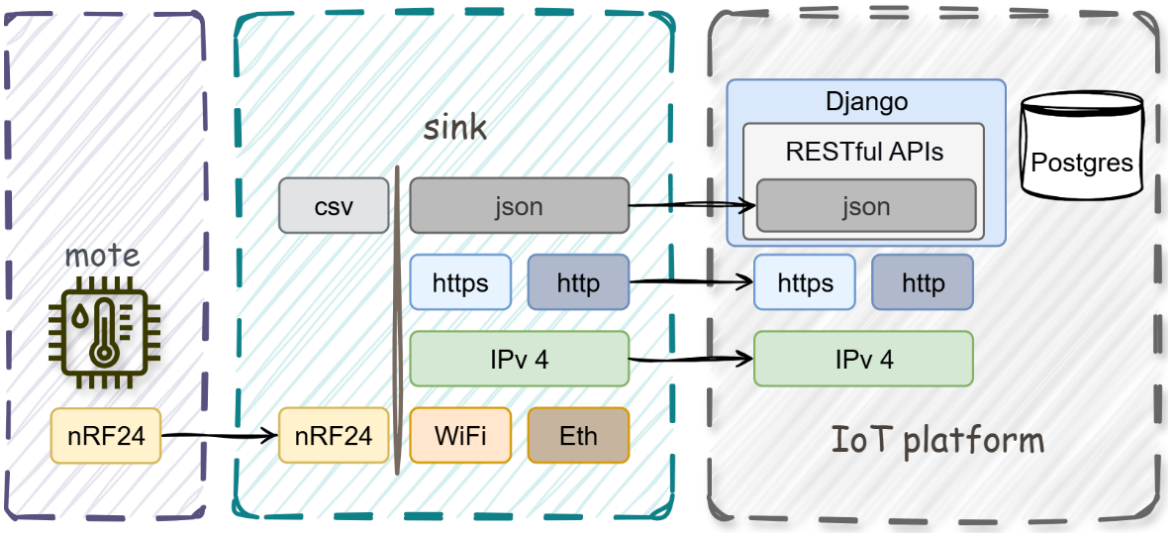

Figure 9: System architecture: protocol stack decomposition

The proposed system architecture implements a three-tier approach that bridges the gap between BF-WSN devices and standard IP network infrastructures. The architecture consists of the mote (BF-WSN node tier), the sink (gateway tier), and IoT platform (application tier), each addressing specific technical challenges while maintaining interoperability and scalability requirements. Figure 9 illustrates the complete system architecture.

4.2 THE IOT PLATFORM

The platform is implemented as a modular web application using Django framework [73], and it integrates database structures, geospatial tracking, and real-time visualization features, enabling both the long-term management of motes and the validation of battery-free behaviour.

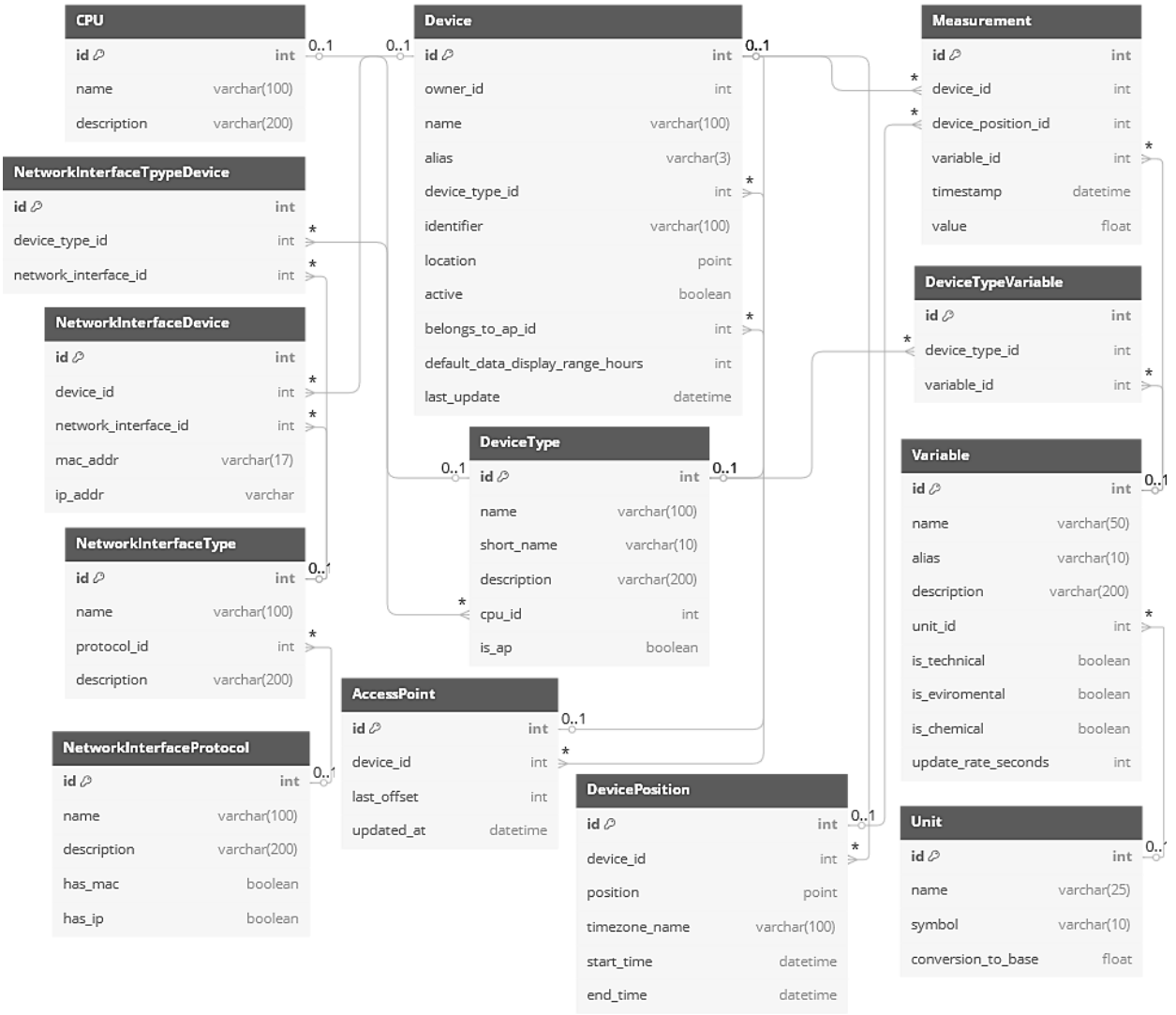

Figure 10: physical database diagram of the Device application

The deployment of the IoT platform leveraged Django's framework, necessitating a shift from the initial CSV-based storage to a relational database model. Figure 10 presents the physical database diagram that describes the core data structures of the system. Data persistence is implemented via Django's object-relational mapper (ORM) using conventional relational models, appropriate given the low sensor update frequency (order of minutes).

The data model centres on Device, linked to *DeviceType* (CPU, access point capability, network interfaces). *DevicePosition* tracks mobility over time, avoiding redundancy. *Measurement* records sensor data, linking devices to Variable (metadata: units, aliases, classification) via *Unit*. Network interfaces are abstracted through *NetworkInterfaceType*, *NetworkInterfaceProtocol*, and *NetworkInterfaceDevice* to support heterogeneous hardware. *CPU* facilitates code reuse. *AccessPoint* distinguishes sinks from sensors. *DeviceTypeVariable* defines measurable variables per device type.



Figure 11: Detail view for technical motes´ variables

The interface provides a summary panel (metadata, geolocation via Leaflet.js, filters) and time-series visualization (*Plotly*) for key variables (PV voltage, SC voltage, temperature, humidity).

The interface provides both real-time and historical insights into the operational state of deployed devices. Figure 11 shows the technical monitoring panel for one of the field motes (Senspire_Mote_2), automatically generated from the backend database.

The time-series chart, rendered using Plotly, presents historical measurements over selectable intervals and supports interactive features such as zooming, panning, tooltips, and dynamic series selection.

The integrated map widget provides essential spatial context by displaying the last recorded device position stored in the *DevicePosition* table, facilitating the management of multiple motes distributed across the deployment area.

4.3 The Sink

The sink's architecture implements a tri-interface design that enables seamless communication between the nRF24-based sensor network and standard IP networks. The system utilizes an ESP8266 microcontroller as the primary processing unit, selected for its integrated Wi-Fi capabilities, sufficient computational resources, and compatibility with both nRF24L01 modules and ENC28J60 Ethernet controller through serial peripheral interface (SPI) interface communication. The sink incorporates a DS3231 RTC and SD card adapter alongside its core functionality. To ensure continuous operation, we implemented an uninterruptable power supply (UPS) subsystem using commercial modules, a TP4056 charger for the 18650 Li-ion battery, an HT7333 LDO regulator maintaining 3.3V system voltage, and an IRLM6402 MOSFET-based protection circuit against battery overload.

As shown in Figure 12, the sink integrates an OLED display to provide local user feedback and basic control. In addition, the sink incorporates a CN3791 PWM switch-mode Li-ion battery charger with built-in MPPT, allowing it to be powered directly from a PV source. The unit can operate from either a conventional 5 V supply or a solar panel, using a rechargeable battery as a backup energy source to ensure uninterrupted operation.

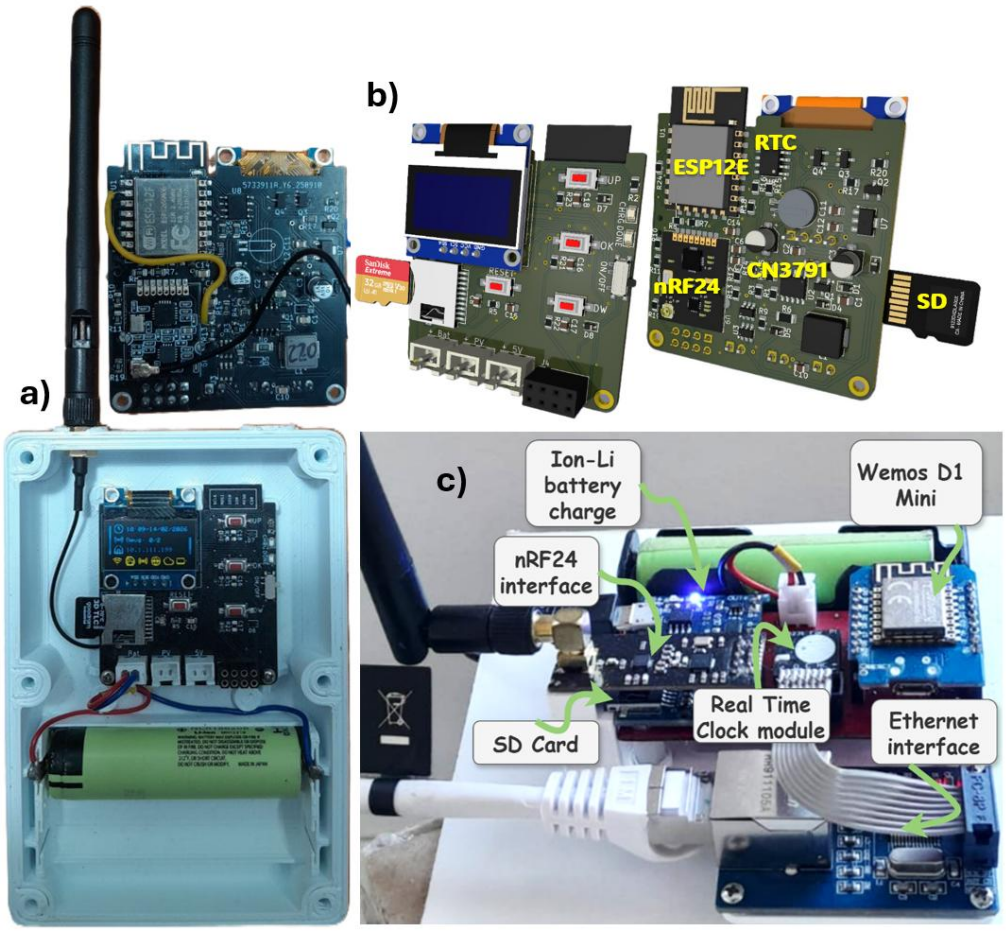

Figure 12: The sink

The firmware, developed directly on the Arduino framework (unlike the mote's implementation), operates in persistent listening mode across all network interfaces.

4.4 Mote Prototype

The objective of the mote's design was to achieve simplicity, intending to minimize power consumption, cost, and circuit complexity. As illustrated in Figure 13, the device was manufactured using a low-cost, handmade CNC machine, following the technique described by León Ávila et al. [74].

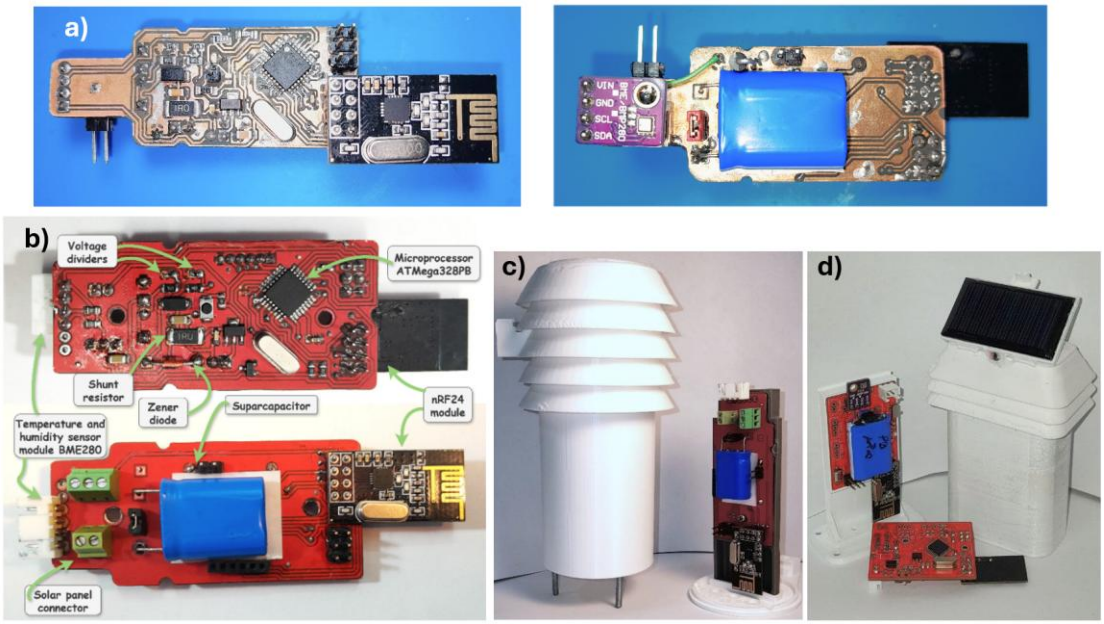

Figure 13: View the three versions of the mote´s prototype, including the case

Figure 13 shows the three version that have developed from the mote. Figure 13 a) and b) show both sides of two early hardware variants manufactured using a quasi-handmade process, following the techniques described in León Ávila et al. [74]; the first variant does not include a solder mask. Figure 13 c) presents a masked prototype housed in a custom 3D-printed polypropylene (PP) enclosure. Figure 13 d) shows the latest revision, featuring a PCB fabricated by JLCPCB and manually assembled, together with the most recent enclosure design incorporating an integrated PV panel. There are no significant changes in the electronics between the different prototypes, only adjustments to the PCB.

Figure 14 represents the general schematic of the motto that was developed. Note how the PV output is routed through an SS14 Schottky diode to charge the SC. The stored energy is then supplied to the system via an HT7333 linear regulator, which provides up to 3.3 V to the mote. The microcontroller operates reliably within the 2.7–3.3 V range, and the regulator's ability to function below 3.3V allows continuous operation until the brown-out detection (BOD) threshold (2.7 V) is reached.

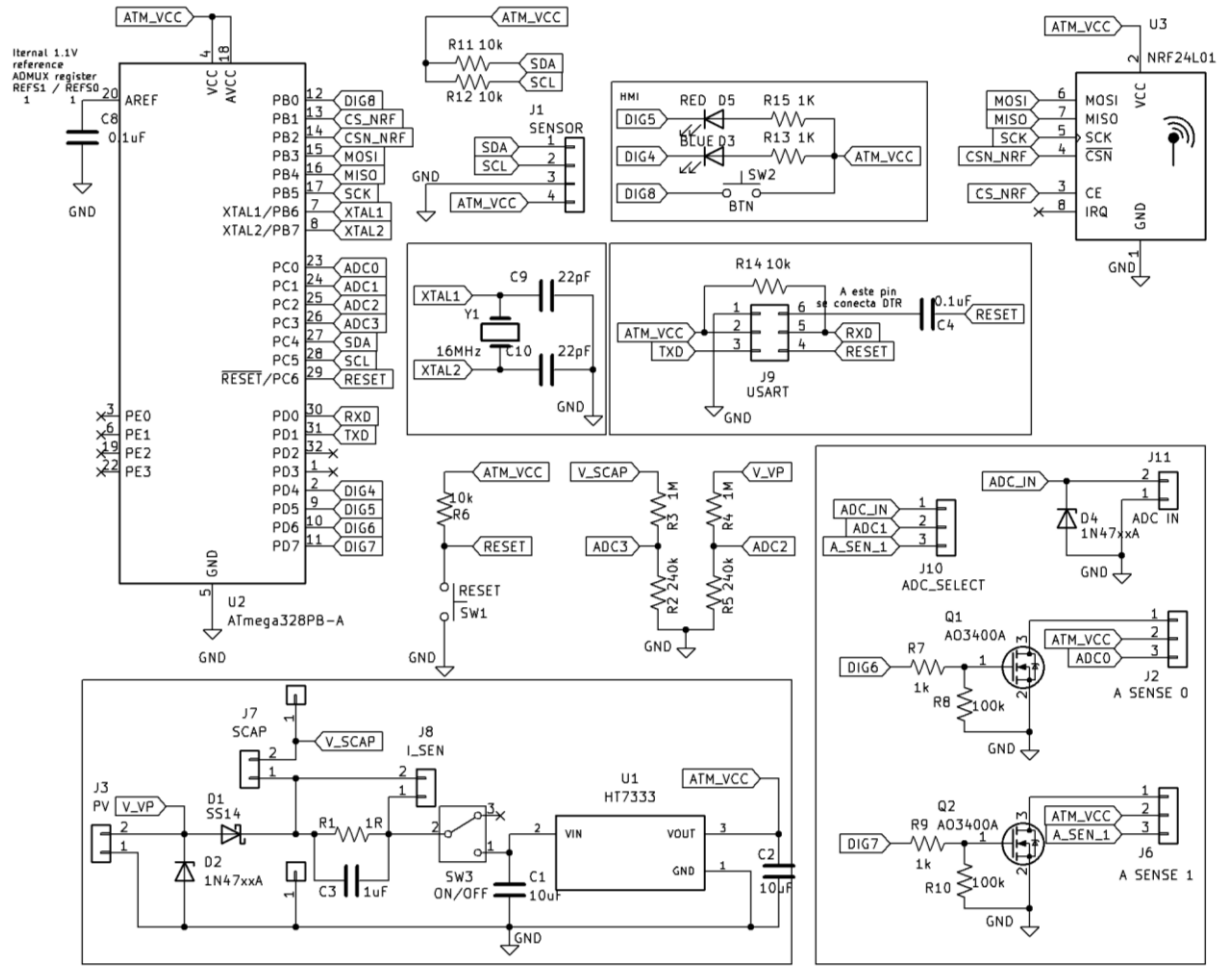

Figure 14: General schematic of the mote

A commercial polycrystalline micro-PV panel (53 × 30mm) was selected as the energy source. According to the manufacturer, it delivers up to 5.1V at 32mA under STC, although the operating point is not explicitly specified.

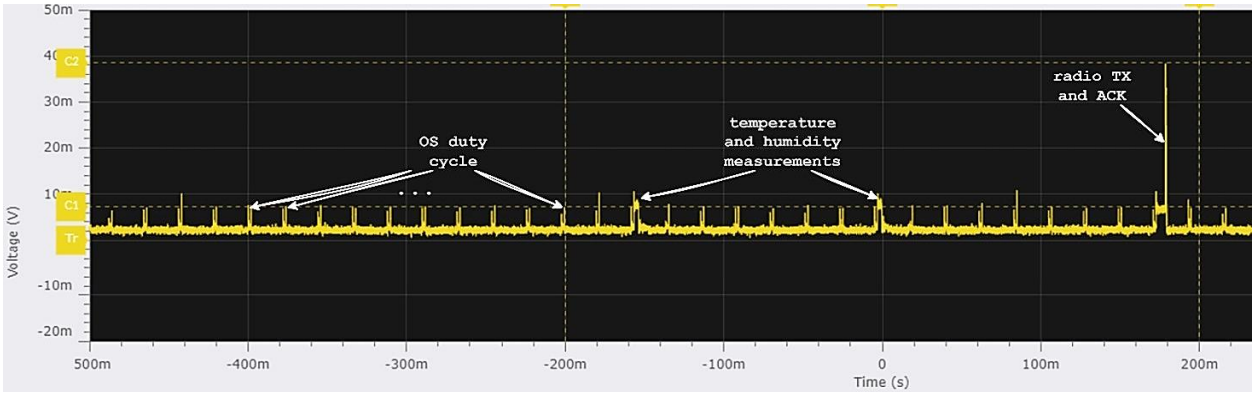

Figure 15: Energy profile obtained by measuring the voltage drop across a 1Ω shunt resistor inserted in the VCC line

Figure 15 illustrates the consumption profile of the developed mote. In the Figure 15, the operation of the mote can be observed at regular intervals (*system ticks*), between which its energy consumption is practically negligible.

4.5 Field Deployment

Two distinct environments were chosen, a tropical savanna climate 'Aw/As' (Sancti Spiritus, Cuba), and Romania with a humid continental climate 'Dfb' (Brașov, Romania), according to the Köppen-Geiger classification [75]. In this sense, Brașov has a significantly more variable and seasonal climate than the tropical Caribbean, with temperature extremes, snow, persistent winter cloudiness, and complex rainfall patterns, making it an excellent testing ground for these systems. Figure 16 shows a deployment of one mote on the roof of the Colina Universității, Romania.



Figure 16: Mote deployed in Romania

Applying the same principles as in our simulations and acknowledging that the monitored events evolve slowly and are non-critical, the motes use a semi-adaptive transmission scheme: data is sampled every 5 minutes, but it only transmits when it detects a change of ±0.1 °C in temperature or ±1% in relative humidity. If 5 consecutive sampling intervals yield no change, a *keep-alive* transmission is sent to confirm mote activity, transmitting at intervals between 5 and 25 minutes.

4.5.1 Operational behaviour for the entire year

To validate the self-sustainability of a mote in the different previously deployed environments during the year 2025 will be serializing the voltage of SC (V_{sc}) using MS Excel based on the irradiance series provided by Copernicus [76]. These include 15-minute global irradiation on the horizontal plane (GHI) at ground level in Wh/m^2, including the impact of clouds. To match the mote measurements, the value will be converted to *irradiance averages* in the panel as $G = GHI \times 4$.

In order to obtain the series, we calculated *the open circuit voltage* (V_{oc}) and *short circuit current* (I_{sc}) in function of G, adjusted by linear empirical coefficient (k_G), and including the effects of the temperature T in Celsius degrees according to translation equations in IEC 60891 [77].

$$I_{sc}(G) = I_{sc_stc} \times G \times 10^{-3}\,(1 + \alpha(T - 25)) \quad [2]$$

$$V_{oc}(G) = V_{oc_stc} + k_G \times \ln(G \times 10^{-3}) + \beta(T - 25) \quad [3]$$

The temperature was taken from Open-Meteo one-hour time series [78] and incremented in an empirical factor (ΔT), due the differences between the environmental temperature and PV-surface temperature resulting in $T = T_{env} + \Delta T$.

The PV voltage (V_{pv}) depends on V_{oc}, and will be limited to the breakdown voltage of the Zener diode (V_z), and once it breaks the conduction threshold of the Schottky diode (V_{stk}), it will be modulated by the SC voltage (V_{scap}). Algorithmically, we represent it in the following way:

$$V_{pv} = MIN\big(V_z,\quad MIN\big(V_{oc},\quad (V_{scap} + V_{stk})\big)\big) \quad [4]$$

From these equations, the voltage increase/decrease in the SC (ΔV_{sc}), with capacitance C, will be recalculated every 5 minutes (Δt) from an initial value of V_{sc}, as a starting point for both the Excel's model calculations and the series values taken by the real mote, where:

$$V_{scap} = V_{sc_previus} + \Delta V \quad [5]$$

$$\Delta V = \frac{I_{net} \times \Delta t}{C} \quad [6]$$

I_{net} is the SC's charge/discharge current. Since there is a Schottky diode with a dropout voltage V_{stk}, this current contribution from the panel will only be made if $V_{oc} \geq V_{scap} + V_{stk}$, otherwise, the SC discharges into the load ($-\Delta V$). Algorithmically, we can express it as:

$$I_{net} = IF\left(\left(V_{oc} \geq V_{scap} + V_{stk}\right), \left(I_{chg}\right), \left(-I_{dischg}\right)\right) \quad [7]$$

When:

$$I_{dischg} = I_L - I_{leak} \quad [8]$$

$$I_{chg} = I_{pv} - I_L - I_{leak} \quad [9]$$

While I_L and I_{leak} are constants, I_{pv} represents a specific operating point on the PV cell's nonlinear $I_{pv}(V_{pv})$ characteristic, curve that differs depending on irradiance. This graph can be divided into 3 sections:

- From $0V$ to voltage of maximum power point V_{mpp},
- From V_{mpp} to open circuit voltage V_{oc}
- Greater than V_{oc}

where V_{mpp} is the voltage at the maximum power point, expressed as 80% of V_{oc}. The first one is defined by $(V_{scap} + V_{stk}) \leq V_{mpp}$ and as an approximation, we can define I_{pv} as the current of the maximum power point (I_{mpp}), expressed as 90% of I_{sc}.

The second section is defined in the interval $V_{mpp} \leq (V_{scap} + V_{stk}) \leq V_{oc}$ which, although it does not have a linear behavior, we believe that the approximation is feasible, taking as points (V_{mpp}, I_{mpp}) and $(V_{oc}, 0)$:

$$m = \frac{0 - I_{mpp}}{V_{oc} - V_{mpp}} = \frac{-I_{mpp}}{V_{oc} - V_{oc} \times 0.8} = \frac{-I_{mpp}}{V_{oc} \times 0.2} \quad [10]$$

$$n = -mV_{oc} \quad [11]$$

$$I_{pv} = m \times (V_{scap} + V_{stk} - V_{oc}) \quad [12]$$

The third section is when $V_{oc} \leq (V_{scap} + V_{stk})$ and should never occur, but for safety, we will take it into account just to express that in this case $I_{pv} = 0$ or directly $\Delta V = 0$

The last consideration is that, as we have already seen in V_{pv}, the voltage in the SC is also limited by the Zener diode, and this is not taken into account in the previous calculation that works with the theoretical values, so this must also be expressly cut in the Excel equation as:

$$\Delta V = IF(V_{oc} > V_z, 0, (\Delta V)) \quad [13]$$

Based on comparisons with actual measurements in October 2025, the error metrics shown in Table 3 were obtained.

Table 3: Error metrics between simulated and measured supercapacitor voltage

Metric	Value
Mean Absolute Error (MAE)	0.134 V
Root Mean Square Error (RMSE)	0.366 V
Normalized RMSE (nRMSE)	8.30%
Mean Absolute Percentage Error (MAPE)	5.74%
Coefficient of Determination R^2	0.54

The values obtained fall within the ranges typically accepted in the literature for this type of model:

- The MAPE of 5.74% is particularly low, indicating high relative accuracy in the prediction.
- The nRMSE of 8.3% is also low, suggesting that the model does not exhibit significant systematic deviations.
- The MAE of 0.134 V represents a small absolute deviation, less than 6% of the measured voltage's dynamic range.
- The moderate R^2 value of 0.54 is almost at the lower limit considered acceptable. R^2 should not be used as a sole metric; it should be accompanied by MAE/RMSE. In our case this value can be mainly attributed to high-frequency fluctuations in irradiance (due, for example, to cloud cover), which are not captured by the 15-minute temporal resolution of the Copernicus data, and to the simplified nature of the photovoltaic panel model. For the main purpose of this study, which is to assess daily energy feasibility and predict energy starvation events, this level of accuracy is considered more than sufficient.

This strong alignment enables us to reconstruct system behaviour using historical irradiance time series reliably. Once the models have been validated, we apply them over a full calendar year, specifically, the most recent complete year, 2025.

In Figure 17, each marker on the “min” and “max” curves corresponds to the lowest and highest daily values, respectively, computed for each day of the calendar year 2025. As shown in the figure, the mote’s voltage dips below BOD threshold and ceasing operation in only 3 days in isolated events.

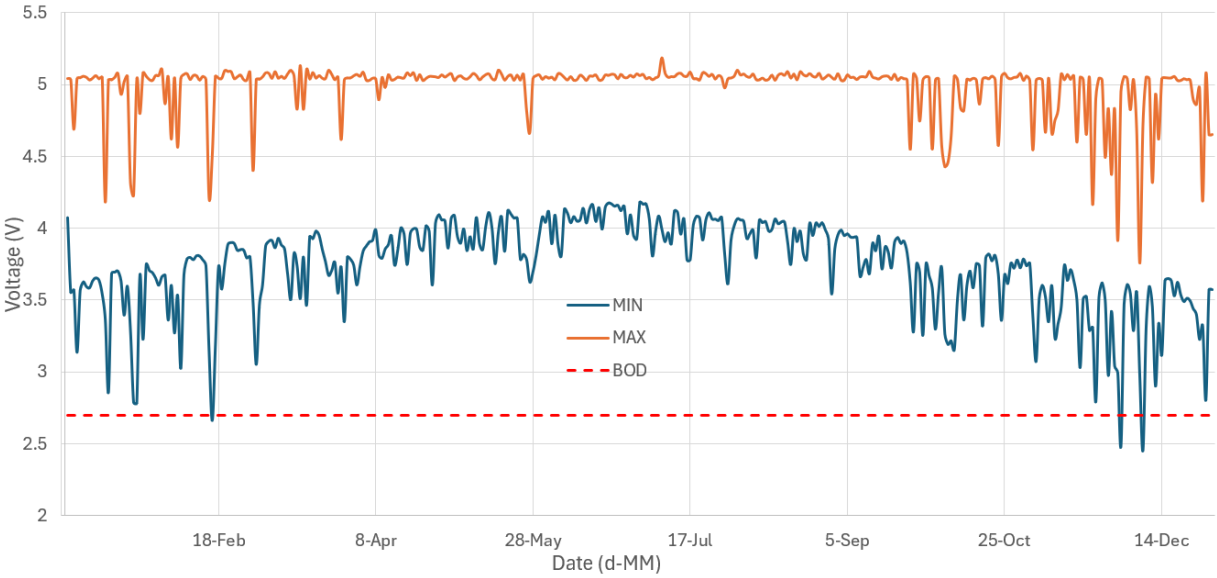

Figure 17: Daily minimum and maximum V_{scap} values throughout 2025

Depending on the application, this temporary drop could be mitigated entirely through adaptive mechanisms or may even be irrelevant in less critical scenarios [79]. Given the node's deliberately simple architecture (lacking maximum power point tracking (MPPT) mechanisms or DC–DC buck converters), the results emphasise the feasibility of battery-free systems in a variety of WSN deployments.

4.6 SECURITY CONSIDERATIONS

The deployment of systems with such limited resources introduces unique cybersecurity challenges. As identified in the final stages of this research, discussing security policies for these nodes is imperative.

If we look at the whole system, there is three layers from the security point of view, mote-sink, sink-platform and application. Therefore, we will issue some separate assessments of policies and mechanisms.

4.6.1 Between mote and sink

It is possibly the most vulnerable precisely because it is the most restricted. In architectures with standardized LLNs such as BLE, Zigbee, or LoRa, there are established mechanisms for

protection, mitigation, and recovery from threats, but in the one presented in this thesis, none of these mechanisms exist.

The main challenges in this layer are:

- **The Energy-Security Trade-off:** In BF-WSN, energy is the dominant limiting factor. Implementing any cryptographic protocol introduces a computational overhead that can quickly deplete the limited energy stored in a 5F SC. There is a critical need for **lightweight authentication mechanisms** that are compatible with the strict energy budgets of SC-powered motes.
- **Resilience to Intermittent Operation:** Intermittent computing, where nodes lose power and reboot frequently, creates vulnerabilities in maintaining a "secure state."
- **Very limited payloads:** The nRF24 only has 32 bytes. Adding cryptographic headers, message authentication codes, or nonces to each packet reduces the available payload for sensor data and increases the number of packets required for a given volume of data and quickly saturates the available payload space and would force frames to be split into bursts, with the resulting energy cost potentially becoming unsustainable.
- **Physically exposed devices:** Since their function in most cases is performed in open, isolated, and unattended and even publicly accessible locations. It must be assumed that they may be victims of vandalism, impersonation, physical tampering, radio channel saturation, and all kinds of interference given their low power, as well as inevitable passive eavesdropping by unauthorized or directly hostile persons or entities.

In this sense the security of this layer is only a first line of defense that in a serious approach must always be assumed to be breached and mitigation and containment measures adopted at higher levels.

Looking at it, one might wonder; is it worth protecting this layer? When it comes to security, the answer will always be YES, but not for obvious reasons and not in the traditional way. In these networks, data is not usually the most important thing, so malicious interventions usually aim to denial of service (DoS) attacks on the nodes or their impersonation.

In particular, these networks introduce a new vector of attack: energy. If there is access to the physical environment of the network, in general:

- **Physically:** An attacker, even without physical access to the mote, could manipulate the ambient power source.
- **Resource Exhaustion:** Non-legitimate nodes can flood the network with various types of traffic depleting the energy reserves.

You can also spoof the mote or even the sink to receive as much traffic as possible and then either significantly increase its latency, degrading the service, or directly drop it without rerouting it, directly interrupting the service.

The protocol under development includes:

- Fixed and universal identification numbers for devices.
- Light CRC plus character count sent to detect corrupt or deliberately modified data.
- Protection against replay attacks using a hash consisting of a sequence number and a nonce generated by the sink.
- Sink-managed whitelist that identifies the node by its unique and universal physical ID.
- Energy anomaly detection, where the node constantly monitors its energy sources and reports to the platform.

4.6.2 Between sink and platform

The security of this layer is based on standard network security mechanisms and will depend primarily on the last-mile link on the sink side and the implementation of the REST API on the platform side. The current implementation mechanisms at the application layer include HTTPS and Django session management. These are all part of specific framework standards and implementations, so we won't go into detail here.

4.6.3 Application layer

This layer is the last and most important line of defence. However, the security architecture is specific to the application managing the platform, so it's outside the scope of this work.

In addition to well-known security policies and mechanisms, it's possible to offer some empirical considerations based on experience handling data:

- **Total distrust:** Each data string originating from a mote may be modified or contain erroneous data. Any anomalous or unexpected behaviour must be suspicious.
- **Distrust and continue distrusting:** Even if current data does not appear compromised, historical data should be checked and cross-referenced periodically for anomalies and inconsistencies.
- **Forcing the sink to authenticate each node individually**, even though the sink is actually managing the node sessions.
- **It should also distrust of the sink**, because this one can also be compromised or directly impersonated.

In general, we think that, due to the resource limitations of these systems, the best way to design a security architecture is to assume that guaranteeing the security and integrity of the data we receive from the nodes of an LLN is impossible, so a good security policy involves actively trying to detect and mitigate malicious activities in the application level.

4.7 Partial Conclusion

By combining a compact PV panel, a small 5F SC, and a custom ultra-low-power device supported by a lightweight OS, this chapter demonstrates uninterrupted daily operation of BF-WSN motes in both tropical and temperate climates. Energy autonomy is achieved by ensuring that the SC reliably completes at least one recharge cycle per day, despite variations in solar irradiance, confirming the practical feasibility of BF-WSN operation.

The proposed strategy prioritizes the daily recharge cycle rather than maximizing long-term energy storage, distinguishing it from conventional PV system designs. This design choice enables the use of smaller, lower-cost components while maintaining functionality under modest irradiance conditions. As a result, low device cost allows redundancy to be introduced at the network level, supporting resilient BF-WSN deployments through topology-control mechanisms and energy-aware adaptive sensing strategies that reduce unnecessary communication and conserve power.

Nevertheless, environmental constraints remain a limiting factor, particularly in temperate regions during periods of reduced sunlight. Seasonal variations, dust accumulation, snow

coverage, and temperature fluctuations can disrupt the daily charge cycle, highlighting the importance of environment-aware mote design and energy margin considerations to ensure reliable long-term operation across diverse deployment scenarios.

Beyond the energy subsystem, this work also demonstrates a complete end-to-end BF-WSN ecosystem through the integrated development of a custom sink and a Django-based IoT platform. The sink bridges ultra-low-power nRF24L01-based networks to standard IP infrastructures using lightweight protocol translation, while a non-blocking, event-driven architecture ensures continuous monitoring of communication channels alongside periodic system tasks. The synchronization mechanism minimizes network usage through incremental data transfer, offset-based data positioning, and chunked transmission, enabling reliable handling of large datasets under tight memory constraints.

In addition to the core system architecture, two methodological aspects proved instrumental during implementation and validation. First, the adoption of an in-lab PCB fabrication workflow enabled rapid hardware iteration and close hardware–software co-design during early prototyping stages. Although limited compared to industrial fabrication processes, this approach facilitated fast design–test cycles and reproducible experimental hardware. Second, the systematic use of AI-assisted programming tools supported firmware, simulation, and platform development by accelerating routine coding tasks and exploratory implementations under human supervision. These methodologies did not replace conventional engineering practices but acted as enablers that reduced development overhead and supported multidisciplinary integration.

The comparative analysis between the LDO and the most commonly used PMICs in the literature shows that the high additional cost (at least 10 times more) plus the increased complexity of the PMS, which raises testing costs and potential points of failure, does not translate significantly into extra hours of autonomy in the evaluated scenarios. The use of a PMIC that implements MPPT, such as the BQ25570, is only justified in scenarios with adverse energy harvesting conditions.

Looking forward, future work will focus on building annual energy profiles using deployed devices, refining maintenance and calibration strategies, integrating more dynamic energy management policies, and further optimizing PV and SC sizing. At the system level, extending the communication stack toward robust bidirectional operation with standardized protocol abstractions will enhance scalability and deployment flexibility, strengthening the applicability of BF-WSN solutions in large-scale, real-world scenarios.

Regarding the security, in general, given the resource constraints of LLN nodes, the best way to design a security architecture is to assume that guaranteeing the security and integrity of the data we receive from the nodes of an LLN is impossible, so a good security policy involves actively trying to detect and mitigate malicious activities in the application level.

5 FINAL CONCLUSIONS. ORIGINAL CONTRIBUTIONS, AND FUTURE RESEARCH DIRECTIONS

This doctoral thesis provides an integrated and experimentally validated framework for the design, modelling, deployment, and evaluation of **BF-WSN devices**. The work advances the state of the art by bridging four domains that traditionally appear in isolation:

- EH technologies and characterization,
- energy storage and power-management architectures,
- software and firmware design for intermittent computing, and
- system-level integration with real IoT infrastructures.

The most relevant findings and conclusions, according to the research objectives, are mentioned below.

Chapter 2 in its entirety answers the **RO1.** As first step, a taxonomic framework for classifying renewable energies was proposed, distinguishing between energy type (e.g., light, heat, or mechanical energy), energy source (e.g., sun, industrial activity, or ocean waves), and transducer (e.g., PV cells, TEGs, or PZs)A SLR was conducted based on the PRISMA framework analysing a decade of research (2014-2025) on EH-WSNs resulted in the identification and categorization of 215 articles. From this review it was possible to discern that:

- It was identified that mechanical energy sources have received the most attention in the literature, and within this category, PZ transducers are the most studied (Section 2.3).
- It was observed that, although solar energy harvesting is technologically mature, it is underrepresented in studies that exclusively use solar cells (SCs) for storage, with a lack of experimental validation under real-world field conditions for battery-free solar systems (Section 2.3.1).
- This contrasts with storage trends, as 89% of cutting-edge studies in energy-efficient power systems (EH-WSN) have abandoned batteries in favour of capacitors and SCs due to their longer lifespan and low maintenance (Section 2.4).

RO2 was addressed in section 2.5 as part of the SLR. It was observed that the energy cycle for battery-less systems is fairly homogeneous, based on short cycles (no more than a day) of energy collection and temporary storage for a limited number of device activities, which must include data collection and transmission. This is because their design is based on the premise of intermittent energy availability, but always with the expectation that the source will be available at some point. Based on this observation, was developed a complete modelling framework, including SPICE models for SCs, PV panels, TEGs and complete mote (Chapter 3). This modelling effort demonstrated that the behaviour of BF-WSN motes can be predicted with high fidelity when both the harvesting subsystem and the consumption profile are represented jointly. The results provided a replicable methodology to dimension energy storage elements, determine feasible duty cycles, and estimate long-term operational viability.

A fully functional prototype of a battery-free mote was designed answering the **RO3**, manufactured, and experimentally validated. The firmware, based on the custom idOS operating system, demonstrated that cooperative multitasking, lightweight networking, and energy-aware scheduling can all be executed on low-end microcontrollers while maintaining strict energy budgets (Section 3.2). We evaluate he prototype in laboratory conditions and through long-term field deployment, confirming that daily autonomous operation is feasible using only solar energy and SC storage.

The Chapter 4 address the **RO4**, where was described the developed an integration of the BF-WSN system with an IP-enabled sink node and a Django-based IoT platform demonstrated end-to-end interoperability. The platform enables continuous monitoring, data synchronization, geospatial visualization, and long-term analysis of device behaviour. This system validates that battery-free motes can form part of complete, production-grade IoT infrastructures.

Section 4.7.2 shows the estimated behaviour for a whole year based on historical satellite data, demonstrating the validity of the models presented as well as the feasibility of deploying extremely simple and very low-cost PMS nodes with capacitances below 5F and PV panels of less than 15 cm^2.

These deployed networks are particularly insecure because they lack security mechanisms beyond mote identification against the sink and active integrity verification. However, in general, these networks are not entirely secure due to their limitations. Therefore, it can be concluded that the best security policy is attack detection, containment, and damage mitigation.

Overall, the thesis demonstrates that BF-WSNs can be realistically deployed, modelled, and managed using low-cost hardware, SC-based storage, and lightweight software stacks, provided that the system is carefully dimensioned and designed as a whole. The findings contribute methodological clarity, experimental evidence, and practical tools that advance the long-term feasibility of sustainable sensing systems.

5.1 Original Contributions

The main original contributions of this doctoral research are the following:

- **A taxonomic framework** for classifying renewable energies in energy types, energy source and transductor.
- **A comprehensive SLR specifically focused on EH for WSNs.** Unlike previous reviews, this SLR introduces a structured methodology, identifies research trends, quantifies power ranges across harvesting mechanisms, and highlights gaps in SC-based designs and realistic environmental validation.
- **A unified modelling framework for BF-WSN nodes (motes).** The framework enables reproducible energy-budget analysis and accurate forecasting of mote behaviour under intermittent energy availability. This includes SPICE models for:
    - PV panels,
    - TEGs,
    - SCs (including ESR, self-discharge, ageing),
    - and the complete mote consumption profile.

- **The rigorous adaptation and test of idOS, a lightweight operating system, in intermittent and energy-aware motes**. idOS integrates:
    - cooperative multitasking via protothreads,

    - network stack based on uIP,
    - energy-aware scheduling and sleep/wake cycles,
    - timer and IPC mechanisms optimized for battery-free operation. This provides a functional system abstraction layer for resource-limited microcontrollers.
- **Development and validation of a complete SPICE-based simulation methodology for BF-WSNs.** The methodology couples harvesting models, storage behaviours, and mote energy consumption to simulate realistic daily operational cycles. It provides a new tool for system sizing and design-space exploration.
- **Full integration of a BF-WSN ecosystem with an IP-enabled sink and a Django-based IoT platform.** This demonstrates end-to-end system viability. Including:
    - protocol translation from nRF24L01 to IP,
    - incremental synchronization protocol,
    - geospatial device tracking,
    - dashboard and energy-profile visualization.
- **Real-world deployment and year-long evaluation of battery-free motes powered exclusively by solar energy and SCs.** This constitutes one of the few field-validated studies of BF-WSN behaviour over extended periods, providing empirical evidence for daily operation without batteries and extremely limited resources to obtain, store, and manage energy.

5.2 Future Research Directions

Future work can extend the findings of this thesis in several promising directions:

- **Advanced EH integration and hybrid systems.** The research is limited to commercial solar panels. Other energy sources and transducers should be evaluated, such as:
    - Combine PV, thermal, and mechanical sources under unified power-management schemes.
    - Investigate emerging technologies such as OPV, TENG and bio-harvesters under realistic environmental conditions.

- **Enhanced storage materials and high-cycle SCs.** The market offers other forms of energy storage that should be evaluated, as well as mechanisms to preserve and extend the useful life of these elements.
    - Characterize new SC chemistries, hybrid Li-ion/SC systems, or solid-state capacitors.
    - Explore aging models and accelerated-life testing for long-term deployments.
- **Prediction-free energy-aware networking for BF-WSNs.** The research deliberately avoided making any predictions about energy availability, beyond duty cycle mechanisms for energy saving in mote. This showed excellent results with the simplest methods that force the device to work in conditions far from optimal points. The integration of network-specific mechanisms with highly restrictive devices can:
    - adaptive duty-cycling with and without forecasting,
    - opportunistic communication protocols for intermittent devices,
    - link-layer mechanisms optimized for highly variable power budgets.
- **Expansion of idOS into a fully modular intermittent-computing platform.** IdOS is currently running on a relatively resource-constrained microprocessor, the ATMega328PB. Expanding the mote's processing capabilities using more powerful hardware should be evaluated:
    - Support for additional MCUs and radio interfaces;
    - automated power-trace analysis to adapt scheduling in real time;
    - integration with intermittent-safe data structures.
- **Long-term field deployments at scale.** Data was collected from 5 motes over a period of about 5 months. To evaluate a year's performance, a simulation was performed using satellite data and assuming that all motes would continue to function in the same way under different conditions. Large-scale studies can more accurately validate this model and offer better assessments for the industry. Some proposed activities are:
    - Study environmental variability across seasons, crops, indoor and outdoor contexts;
    - evaluate network behaviours with tens or hundreds of motes;
    - quantify reliability, maintenance cost, and total cost of ownership.

- **Toward standardized BF-WSN architecture.** The mechanisms and protocols used were developed specifically to validate the proposed case studies. It is necessary to describe standards that can be reviewed and adopted by the industry.
    - develop open specifications for energy-aware motes, sinks, and platforms;
    - define reference interfaces for power-management ICs and storage modules.
- **Security and resilience in intermittent, ultra-low-power systems.** It is evident that this research fails to consider a fundamental aspect related to security. The establishment of policies and mechanisms for network security is imperative. The following tasks must be completed:
    - lightweight authentication compatible with SC-powered motes;
    - resilience to partial-state execution and communication interruptions.

As this work demonstrates, it is part of the long journey of IoT. It is our contribution to building a new generation of simpler, more economical, sustainable, and environmentally friendly sensor network devices.

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