Transilvania University of Brasov
Faculty of Electrical Engineering and Computer Science
Department of Electronics and Computers

SCIENTIFIC REPORT

on the doctoral thesis entitled

"Energy Harvesting for Powering the Wireless Sensor Network Nodes"

prepared by PhD candidate Eng. Bernardo Yaser LEÓN ÁVILA

The undersigned, Prof. Dr. Cotfas Petru Adrian, professor at the Department of Electronics and Computers, Faculty of Electrical Engineering and Computer Science, Transilvania University of Brasov, in the capacity of scientific supervisor, and Prof. Dr. Quintero Domínguez Luis Alberto, professor at the Computer Engineering Department, University of Sancti Spíritus "José Martí Pérez", Cuba, in the capacity of scientific supervisor under the joint supervision (cotutelle) agreement, of the doctoral thesis entitled "Energy Harvesting for Powering the Wireless Sensor Network Nodes", prepared by the doctoral student Eng. León Ávila Bernardo Yaser, based on our knowledge of the scientific activities carried out by the doctoral student and on a careful analysis of the content of the doctoral thesis, formulate the following assessments:

- The topic addressed fits within current scientific research and development activities in the field of electronics engineering, telecommunications and information technologies. It concerns the design, modelling and experimental validation of battery-free wireless sensor network (BF-WSN) nodes capable of long-term autonomous operation. This is achieved through ambient energy harvesting (mainly solar), supercapacitor energy storage, and simplified energy management, all integrated into a complete IoT architecture spanning from the node to the data management and visualization platform.
- The doctoral thesis has a logical and coherent structure, being organized in five chapters, in a format based on scientific publications. The thesis comprises 175 pages and contains 13 tables, 45 figures and a list of 389 bibliographic references.
- The studies carried out and the text of the doctoral thesis are original, bringing valuable contributions from both the theoretical and the applied points of view.
- The first chapter presents the context, problem statement and motivation for the doctoral research, justifying the need for battery-free nodes in WSN and IoT applications. Four research objectives are formulated: analyzing the state of the art, modelling of the node's energy balance, designing a modular hardware and firmware architecture, and developing an experimental test bench for both laboratory and field validation. Additionally, this chapter outlines the stages followed in the research. The

adopted methodology treats the system as a whole, jointly considering the energy source, storage, energy management circuits and operation of the node.

- The second chapter is dedicated to the analysis of the state of the art, carried out through a systematic literature review following the PRISMA framework and the CIMO scheme. Based on this analysis, a taxonomy of renewable energies (energy type, source, transducer) is proposed, and harvesting technologies, storage solutions with an emphasis on supercapacitors, and energy management stages are analysed. The analysis highlights the predominance of mechanical sources (especially piezoelectric transducers), while solutions based on PV cells and TEGs dominate the harvesting of energy from light and heat sources, respectively, and rectennas have emerged as a basis for battery-free systems. A lack of validation under real field conditions for battery-free solar systems was also highlighted.
- The third chapter presents the technological framework: the SPICE models for the photovoltaic panel, the thermoelectric generator, the Li-ion battery and the supercapacitor; the software architecture of the node based on idOS (a lightweight operating system based on protothreads and cooperative multitasking, with a uIP network stack, energy-aware scheduling, timers and inter-process communication); and the SPICE model of the complete node, built from the measured consumption profile. The model is validated by comparison with an experimental test bench, showing good agreement between the simulated and the measured supercapacitor voltage.
- The fourth chapter deals with the implementation and validation of the system: the end-to-end architecture, the Django-based IoT platform (incremental synchronization mechanism, data model, geospatial and energy-profile visualization), the sink node performing protocol translation from nRF24L01 to IP, the node prototype and resource dimensioning through simulation, the evaluation of the thermoelectric generator, as well as the aspects of in-lab PCB fabrication and the use of artificial intelligence as a programming tool. Field validation was carried out through deployments in Cuba and Romania, and, based on the validated models and historical irradiance data, the operational behaviour for a full calendar year was reconstructed. The results show that a daily recharge strategy, with photovoltaic panels smaller than 15 cm^2 and 5 F supercapacitors, ensures continuous operation even under winter conditions.
- The conclusions, the original contributions and the future research directions are presented in the last chapter. The main contributions include the taxonomy of energy sources and transducers, a systematic literature review dedicated to energy harvesting in WSNs, a unified SPICE modelling framework for BF-WSN nodes, the adaptation and testing of the idOS operating system on resource-constrained microcontrollers, the complete integration of the BF-WSN ecosystem with an IP sink and an IoT platform, and the year-long field evaluation of exclusively solar-powered nodes. The limitations of the study and the future work directions are also presented.
- The results obtained during the doctoral studies were disseminated through scientific publications in ISI-indexed journals and in IEEE Xplore-indexed conferences. Directly

on the topic of the thesis, the doctoral student is first author of two articles published in Q1 Elsevier journals ("Energy Strategy Reviews", 2025 and "Heliyon", 2024) and of four papers presented at international IEEE Xplore-indexed conferences (ECAI 2024, ICATE 2024, SIITME 2025 and ICRERA 2025). In addition, during the doctoral period, the doctoral student contributed as a co-author to four articles in ISI-indexed journals (including IEEE Access and Energy), five papers at IEEE Xplore conferences and one book chapter (Springer). All these publications certify the value and recognition of the results of the research activity carried out by the student. The minimum standards of the commission for electronics engineering, telecommunications and information technologies have been successfully met.

Based on the above, we consider that the thesis prepared by Eng. Bernardo Yaser León Ávila is a relevant scientific work, with original contributions in the doctoral field of Electronics Engineering, Telecommunications and Information Technologies, appropriately written and presented, meeting the technical and practical requirements imposed on a doctoral thesis, and we express our agreement for the public defence of the thesis in order to obtain the scientific title of Doctor of Engineering.

Date:
18.11.2026

Scientific supervisor
Prof. Dr. Cotfas Petru Adrian



Scientific supervisor under joint supervision (cotutelle)
Prof. Dr. Luis Alberto Quintero Domínguez

