a) Project title

Multi-layer approach for energy neutral communications in 6G Systems

b) Proponent

Roberto Alesii

c) Academic position

RTD-A at DISIM.

d) Curriculum vitae

Current role
Roberto is an *assistant professor* (RTD-A) at the University of L'Aquila, working on on analytical modelling, optimization, and standardization of next-generation wireless systems, wireless protocols for IoT, design of radio-frequency identification (RFID) systems and implementation wireless testbed using Software defined radio approach.

Previous Positions

- Permanent Technical-Scientific and Data Processing Area staff member, University of L'Aquila, Center of Excellence DEWS (dews.univaq.it), 2008-2024
- Research and technology transfer scholarship, Project title: Development of mobile gateways, in collaboration with Selex Communications S.p.A., Chieti Scalo - University of L'Aquila, Center of Excellence DEWS
- Project Manager and project development in the field of Wireless Sensor Networks, Embedded Systems, Software Defined Radio, WEST Aquila S.r.l., Spin-Off University of L'Aquila, www.westaquila.com

Academic Appointments

- *Ph.D. degree in* Electrical and Information Engineering, University of L'Aquila, 2008
    - Thesis: Development of design methodologies for wireless sensor networks.
- Degree in Electronic Engineering, University of L'Aquila ,2004
    - Design of communication protocols for a short-to-medium range radio interconnection system, 110/110 cum laude.

Project responsibility

- WP Leader for WP "THz wireless channel measurements - Channel Modeling", TWIN MODEL: Terahertz WIreless seNsing and coMmunication through cOmprehensive channel analysis and harDwarE modeLing for Graphene-Based Devices, 2024
- Responsable of DEWS Research line: Wireless technologies applications - Medical applications, 2023 –
- WP Leader of WP4 and WP6 in the project PNT Center for Automated Road-Transport" P-CAR, Coordinated by Radiolabs, 2023-24

Teaching responsibility

- Master level course at the University of L'Aquila: Laboratory of SDR and IoT, 60 CFU - 2016—ongoing

PhD supervision

- A. L. Zuriarraín Sosa, "*Accurate and reliable positioning solutions through multi-constellation and multi-sensor approaches*," Information and Communication Technology - DISIM – University of L'Aquila, Supervisor: F. Santucci, R. Alesii, PhD thesis, 2024.
- A. Piccioni, "*Software-Dened Radio for Spectral Analysis and Integrated Sensing and Communications*," Information and Communication Technology - DISIM - University of L'Aquila, Supervisor: F. Graziosi, R. Alesii, PhD thesis, Jul. 2024.

Patents and Publications

- 44 peer-reviewed publications (4 international journals, 2 book chapter, 38 international conference papers).

Significant publications relative to the project (2021-2025)

[1] R. Alesii, P. Di Marco, F. Santucci, "A Virtual Framework for the Cross-Layer Analysis of BackCom Systems in umMTC Scenarios", IEEE Computing and Communication Workshop and Conference (CCWC), Nevada. January 2026 (To appear)
[2] U. Spagnolini et al., "High Frequency Wireless RESTART Spoke3 Laboratories: From Devices to Networks," 2025 AEIT International Annual Conference (AEIT), Amantea (CS), Italy, 2025, pp. 1-6.
[3] G. Pettanice, F. Loreto, D. Romano, F. Santucci, P. Di Marco, G. Antonini, and R. Alesii: *Time-domain Characterization of Reconfigurable Intelligent Surfaces for Wireless Communications.* EMC Europe. Sweden. September 2022
[4] R. Valentini, P. Di Marco, R. Alesii, and F. Santucci: *Cross-layer analysis of multi-static RFID systems exploiting capture diversity.* IEEE Transactions on Communications. 69(10):6620-6632. October 2021

e) Co-authors of the proposal

- Prof. Piergiuseppe Di Marco, Associate Professor at DISIM (S.S.D ING-INF/03), University of L'Aquila
- Prof. Alessandro D'Innocenzo, Associate Professor at DISIM (S.S.D ING-INF/04), University of L'Aquila
- Prof. Roberto Valentini, RTD-A at DISIM (S.S.D ING-INF/03), University of L'Aquila
- Dott. Daniele Romano, Co.Co.Co. (until 31/12/25 RTD-A) at DIIIE (S.S.D ING-IND/31) University of L'Aquila, ASN for Associate professor

f) ERC sectors

- PE7_6 Communication systems, wireless technology, high-frequency technology
- PE7_7 Signal processing
- PE7_3 Simulation engineering and modelling
- PE7_1 Control engineering

g) Abstract

The requirements of 6G extend beyond enhanced 5G capabilities to include new objectives such as sustainability in terms of cost, maintenance, and environmental impact. Energy-neutral systems

represent a promising solution, especially for ultra-massive Machine Type Communication (umMTC) scenarios with densities up to 10^8 devices/km². This has motivated the investigation of novel physical-layer and radio access techniques, including Non-Orthogonal Multiple Access (NOMA) for both active and passive devices, such as backscatter communication (BackCom). In this context, we recently developed a virtual cross-layer framework [Ar26] to analyze and optimize BackCom networks, supporting adaptive protocol design and proactive collision mitigation. To further enhance energy efficiency, Intelligent Reflecting Surfaces (IRSs) are increasingly considered. This project aims to establish an SDR-based laboratory to validate IRS-enabled NOMA-BackCom scenarios in real-world conditions, addressing a gap in the literature. Experimental data will support the development of ML-based optimization strategies, enabling a multi-level approach that balances performance and sustainability and paves the way for Digital Twin and integrated sensing and communication applications.

h) Project description

State of the art

The rapid proliferation of the Internet of Things (IoT) has led to a dramatic increase in electronic devices, many of which rely on conventional battery-based power supplies. This paradigm is inherently unsustainable due to frequent battery replacements, high maintenance costs, and the accumulation of electronic waste. Energy-autonomous devices capable of harvesting ambient energy—such as light, heat, mechanical vibrations, radio-frequency signals, or via wireless power transfer—offer a promising solution. By reducing energy consumption and battery dependence, these systems can extend operational lifetimes from several years to decades. Additional sustainability gains are achieved through ultra-low-power hardware, intelligent energy management with adaptive algorithms, reduced maintenance requirements, and scalable architectures for large-scale sensor networks, enabling efficient and environmentally sustainable digital systems.

In wireless communication systems, sustainability is closely tied to energy efficiency and energy-neutral operation, where the energy required for transmission is fully supplied by harvested energy. Communication techniques are central to this objective. Backscatter communication (BackCom) allows devices to transmit data without generating active RF signals, by modulating and reflecting existing ambient signals, and is a key enabler for ultra-low-power IoT scenarios [Va21], [Vl21]. In contrast, active radio communication provides higher data rates, reliability, and flexibility at the cost of increased energy consumption. The joint and adaptive use of BackCom and active communication enables a trade-off between performance and energy efficiency, dynamically adapting transmission modes to energy availability.

To support the design and optimization of BackCom networks, we recently introduced a virtual cross-layer analysis framework [Ar26]. This framework enables the design of adaptive protocols, evaluation of proactive collision mitigation and recovery mechanisms, and contributes to addressing key 6G communication requirements. A major focus is on medium access and its integration with the physical layer, particularly the capture effect, which allows a receiver to decode a stronger signal despite interference. Exploiting this effect, Non-Orthogonal Multiple Access (NOMA) schemes intentionally superimpose signals over shared time-frequency resources, distinguishing users by received power and enabling successive interference cancellation (SIC) at the receiver [Va22], [Di22].

Intelligent and Reconfigurable Surfaces (IRSs) have recently emerged as a promising solution to enhance coverage, reliability, and spectral efficiency in future wireless networks. Fundamental principles, opportunities, and signal processing aspects of IRSs have been extensively investigated

[Bj22], [Li21]. Accurate IRS-assisted link modeling requires electromagnetic-consistent formulations to capture propagation phenomena, path loss, and mutual coupling effects [Da21], [Gr21]. Experimental and time-domain characterizations further highlight the importance of realistic modeling for performance evaluation [Pe22]. Addressing computational challenges, we evaluated the Partial Elements Equivalent Circuit (PEEC) method for IRS electromagnetic analysis, explicitly accounting for mutual coupling [Pe23]. For large-scale time-domain simulations, standard convolution-based techniques are computationally expensive; the Segment Fast Convolution (SFC) method with Piecewise Constant (PWC) approximations provides efficiency, while our enhanced Piecewise Linear (PWL) approach significantly improves accuracy and extends to time-varying electromagnetic scenarios [Pe25], [Pe25x].

From an implementation perspective, we developed an open-source high-performance software framework bridging electromagnetic simulations at the physical layer with network-layer communication analysis for IRS-assisted systems. This framework enables robust cross-layer investigations, supporting adaptive protocol design, energy-efficient communication, and the evaluation of complex scenarios combining BackCom, NOMA, and IRS elements [Pe25c]. By integrating electromagnetic modeling, communication-theoretic analysis, and adaptive algorithm support, this approach facilitates sustainable and high-performance wireless network design, paving the way for Digital Twin approaches, integrated sensing and communication, and real-world validation of next-generation 6G scenarios.

Scenario

The project aims to complete the simulation-based development of backscattering communication aspects in an environment where key technologies for 6G are present, in support of the creation of a network that focuses on sustainability. The use of backscattering communication technology, the appropriate use of IRS elements and the vision of a cross-layer approach to network MAC management allows for the optimisation of device consumption and the reduction of real collisions.

Figure 1 highlights the elements belonging to the scenario as well as the interactions between them. The transmitter signal will arrive both directly and reflected by the IRSs, just as the signal reflected by the tag will arrive at the listener both directly and via the reflective elements, IRS, radio channel and tags themselves. While assumptions can be made on the simulation side, the complexity of managing the scenario can be better assessed in a Proof of Concept validation. The laboratory is intended to be a tool for validating theoretical aspects with performance measurements in real contexts where many of the simplifying assumptions no longer apply.

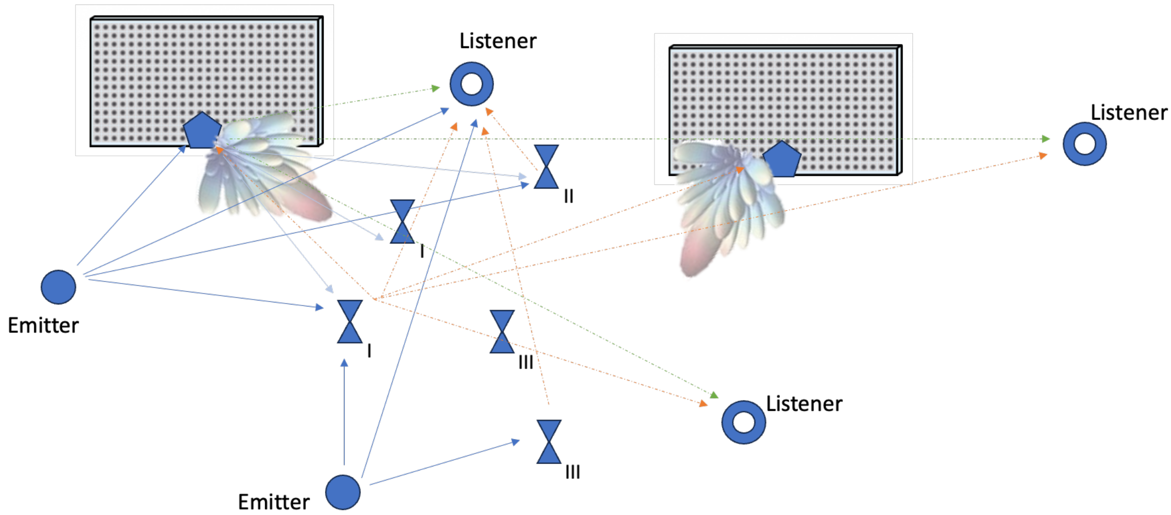


Figure 1 Representation of scenario elements with emitters, listeners, IRSs and IoT devices

Objectives

The main aspects of the project's development can be divided into two phases: the first phase involves the development of the test laboratory, and the second phase involves its use for the evaluation of MAC protocols.
The objectives of the project are summarized in the following.

- **Objective 1a**. Laboratory design with the development of listeners, emitters and implementation of the database for storing information for the study of the scenario (figure 2).
- **Objective 1b**. Integration of IRS into the laboratory in the scenario (figure 2): this will require verification of the consistency between the simulation of the actual characteristics of the RIS and the characterisation in a controlled environment such as an anechoic chamber.
- **Objective 2a**. Development of the communication protocol for the validation and verification of analytical/simulation expectations (figure 2).
- **Objective 2b**. Evaluation and verification of the IRSs component with respect to the case study.

However, the defined objectives are only a vision that can be achieved in the short term. The laboratory will have to be designed so that it can be reused as effectively as possible when it is developed for the evaluation of future protocols, within the limits of the SDR platforms that will be used.

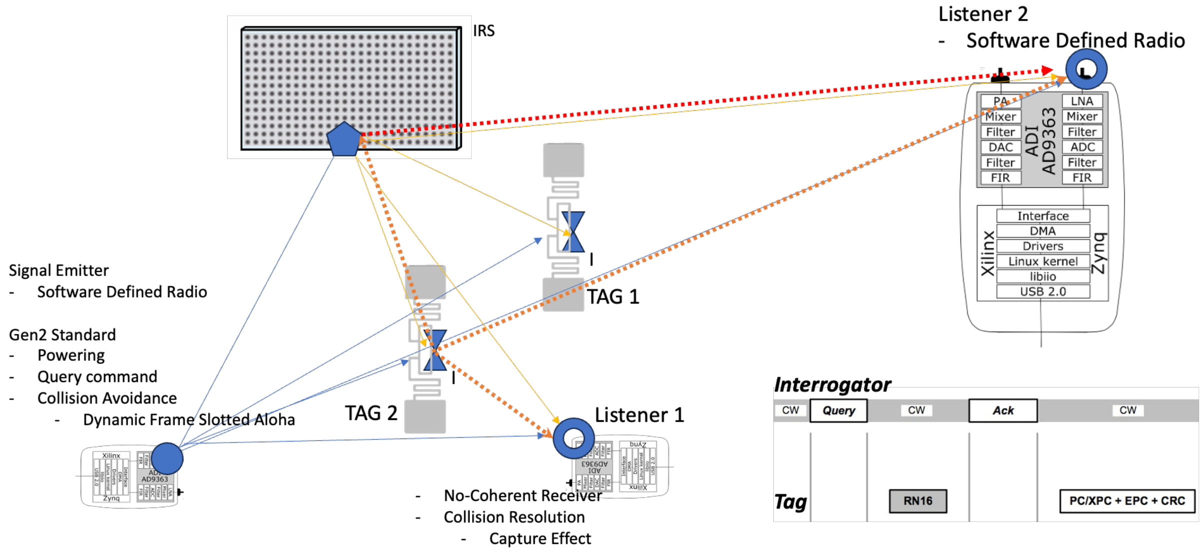


Figure 2 Representation of the possible solution for the laboratory, highlighting emitters and listeners developed using SDR technology, remotely managed IRS, and IoT tag devices that use backscattering technology to communicate. Obviously, the communication protocol under evaluation will need to be implemented. The figure shows the basic assumption of a standard Gen2 UHF RFID protocol.

Methodology

This project aims to provide support for the development of 6G technologies based on the paradigm of energy-neutral communication in order to meet sustainability objectives.

Taking its cue from the latest research on optimising collision management approaches, such as the capture effect concept and the NOMA approach, the aim is to create an environment in which analytical and simulation studies can be completed. The characterisation of the elements that make up the laboratory is fundamental; information on backscattering-based devices, the relative antenna efficiency and the behaviour of the IRS considering the position of the signal generator and receiver depending on the configuration set. The characterisation of the IRS element is very complex, both due to the high number of elements, the influence between the IRS elements themselves and the distance between the signal source antenna and the receiving antenna; the distances could be such that the classic simplifications of the radio propagation condition for long distances cannot be considered. The assessment must be completed by an analysis in a controlled environment to validate its characteristics and then consider the inclusion of IRSs in the laboratory.

The laboratory will be developed using a software-defined radio approach so that radio protocols and signal waveforms can be developed for signal sources and radio signals can be acquired. The backscattering devices will be developed ad hoc or commercial products will be used according to the necessary assessments. In the case of autonomous systems, it is necessary to consider whether the energy required for operation is extracted from signals in the same band in which the device communicates; in this case, knowledge of the characteristics of the device and how the ratio between the energising signal and other signals in the band can compromise the extraction of energy itself. Therefore, the use of signal source and listening elements allows the behaviour of the individual device to be characterised. This information will be useful for analysing how to develop efficient algorithms.

The creation of datasets from experimental data will enable the future development of ML algorithms to optimise the settings of controllable elements such as IRSs.

Activities and planned tasks

The project will be developed over 10 months and carried out in three activities.

- *Activity 1 "Characterisation of real IRS"*

Simulation modelling of a real IRS and verification/comparison in a controlled environment such as an anechoic chamber: given the size of the IRS object in relation to the distances in the scan, there will be situations in which propagation can be approximated as a plane wave, far field condition, but also conditions in which approximation is not possible, i.e. a near field condition.

- *Activity 2 "Laboratory Design"*

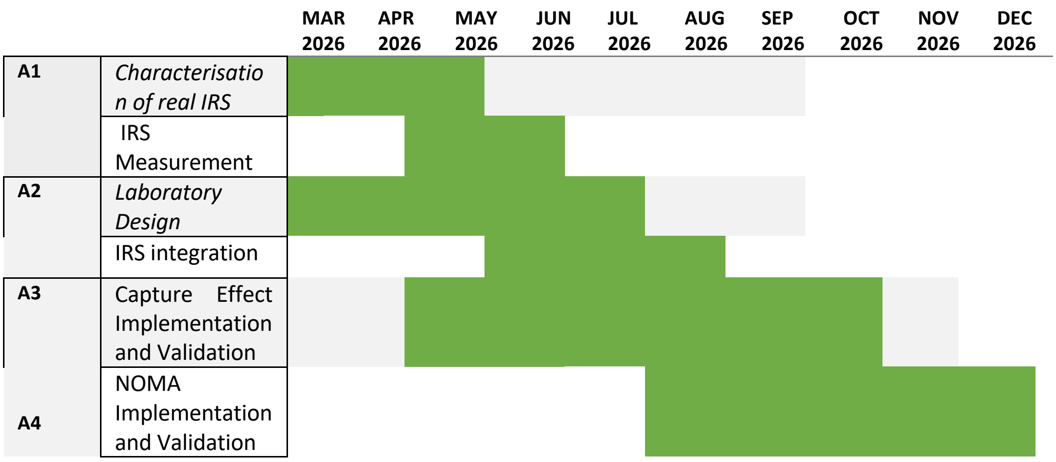
Design of a laboratory of sufficient dimension for testing with SW development as far as possible with SDR platforms of the elements, for remote control of the IRSs and data collection for subsequent analysis using Machine Learning algorithms.

- *Activity 3 "Capture Effect Analysis"*

Implementation and validation of the Capture Effect, as a preliminary building block of NOMA, for backscattering in the presence of IRSs.

- *Activity 4 "NOMA Analysis"*

Implementation and validation of NOMA.



It is important to remark that the project will take advantage of a collaboration between the DISIM and the DIIIE department at the University of L'Aquila.

i) Elements of originality

The proposal aims to support the transition from theoretical analysis and simulation-based model development to practical implementation and experimental validation. As outlined in the objectives, two complementary research lines converge toward the realization not only of a proof of concept, but also of a dedicated laboratory environment. The proposed design, based on a Software-Defined Radio (SDR) approach, provides high versatility in terms of signal modeling and operating frequency, enabling flexible experimentation across different scenarios.
The systematic collection of data from multiple experimental tests and deployment conditions into a structured database will form the basis for the development of machine learning algorithms. These algorithms will support both the analysis of protocol-level aspects and the study of dynamic behaviors introduced by the presence of Intelligent Reflecting Surfaces (IRSs), whose configuration and

interaction with the environment are inherently dynamic. To this end, the characteristics of all laboratory components will be carefully measured, recorded, and analyzed within a complex and realistic experimental scenario.

Within the research line focused on the study, experimentation, and validation of energy-neutral communication paradigms, the laboratory will enable the development and integration of the system's key components. In particular, by considering communication between devices, as well as between devices and passive listeners through backscatter communication, the presence of IRSs will play a dual role. On the one hand, IRSs will enable communication even in the absence of direct radio visibility; on the other hand, they will modify the electromagnetic field experienced by different devices, thereby increasing spatial diversity. This spatial diversity represents a fundamental enabler for capture-effect-based techniques and, subsequently, for non-orthogonal multiple access (NOMA) solutions. Efficient IRS management strategies will be essential to limit device complexity and, consequently, reduce energy consumption.

The project will thus support the experimental validation of simulation results, enabling not only the performance evaluation and optimization of design choices, but also a comprehensive assessment of their impact in terms of energy consumption. In the near future, the integration of the simulator with the Hardware-in-the-Loop (HIL) laboratory will enable the implementation of a Digital Twin framework. Moreover, in the context of backscatter communication and leveraging the waveform generation capabilities of SDR technology, the laboratory will allow the experimental evaluation of integrated sensing and communication (ISAC) scenarios.

Expense plan

Expense type	**Amount (euro)**
Co-financing research grants	5000
Consumables	500
Equipment, instruments, software	7000
Travel costs	1000
Books, digital libraries	500
Publications	2000
TOTAL	**15000**

References

[Bj22] E. Björnson, *et al*,: Reconfigurable Intelligent Surfaces: A signal processing perspective with wireless applications, in IEEE Signal Processing Magazine, 39(2):135-158, Mar. 2022

[Da21] F. H. Danufane, *et al*, On the Path-Loss of Reconfigurable Intelligent Surfaces: An Approach Based on Green's Theorem Applied to Vector Fields, in IEEE Trans. On Comm., 69(8):5573-5592, 2021

[Di22] P. Di Marco, *et al.*: Boosting NOMA systems through smart metasurfaces. Frontiers in Communications and Networks. October 2022.

[Gr21] G. Gradoni and M. Di Renzo, End-to-End Mutual Coupling Aware Communication Model for Reconfigurable Intelligent Surfaces: An Electromagnetic-Compliant Approach Based on Mutual Impedances," in IEEE Wireless Communications Letters, 10(5):938-942, May 2021

[Li21] Y. Liu, *et al*. Reconfigurable intelligent surfaces: Principles and opportunities. IEEE Commun. Surv. Tutorials 23, 1546–1577 2021.

[Pe22] G. Pettanice, *et al*: "Time-domain Characterization of Reconfigurable Intelligent Surfaces for Wireless Communications." EMC Europe, Sweden. Sept. 2022.

[Va21] R. Valentini, P. Di Marco, and F. Santucci: “Exploiting capture diversity for performance enhancement of ALOHA-based multi-static backscattering systems in the 6G perspective”, Sensors. 21(15):5070. July 2021

[Va22] R. Valentini, P. Di Marco, and F. Santucci: *A NOMA Scheme for IoT Enabled by Selective Powering of Passive Backscattering Nodes*. IEEE Comm. Letters. 26(9):2195-2199. September 2022

[Vl21] R. Valentini, P. Di Marco, R. Alesii, and F. Santucci: “Cross-layer analysis of multi-static RFID systems exploiting capture diversity”, IEEE Transactions on Communications. 69(10):6620-6632. Oct. 2021

[Pe25c] G. Pettanice et al., “A Software Tool for Robust and Reliable Electromagnetic Models: the case of Reconfigurable Intelligent Surfaces”, IEEE CAMAD 2025, (To appear)

[Ar26] R. Alesii, P. Di Marco, F. Santucci, “A Virtual Framework for the Cross-Layer Analysis of BackCom Systems in umMTC Scenarios”, IEEE Computing and Communication Workshop and Conference (CCWC), Nevada. January 2026 (To appear)

[Pe23] Giuseppe Pettanice, Roberto Valentini, Piergiuseppe Di Marco, Fabrizio Loreto, Daniele Romano, Fortunato Santucci, Domenico Spina and Giulio Antonini: *Mutual Coupling Aware Time-Domain Characterization and Performance Analysis of Reconfigurable Intelligent Surfaces Through the Partial Element Equivalent Circuit Method.* IEEE Transactions on Electromagnetic Compatibility. 65(6):1006-1020. December 2023.

[Pe25] Giuseppe Pettanice, Roberto Valentini, Piergiuseppe Di Marco, Fortunato Santucci, Giulio Antonini: *Fast Convolution Schemes for Piecewise Approximation of Large-Scale Electromagnetic Systems in Emerging Applications.* IEEE Transactions on Circuits and Systems. 72(7):3498-3511. July 2025.

[Pe25x] Daniele Romano, Giuseppe Pettanice, Martin Stumpf, Ioan E. Lager, Jonas Ekman, Ondrej Franek, Roberto Valentini, Piergiuseppe Di Marco, Fortunato Santucci, and Giulio Antonini: *Partial Elements Equivalent Circuit Modeling of Distributed and Lumped Time-Varying Dielectric Phenomena.* Nature Scientific Reports, vol. 15, 44166. November 2025.