Wireless Identification and Sensing Systems for Harsh and Severe Environments

Edited By

Smail Tedjini • Valentina Palazzi

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Wireless Identification and Sensing Systems for Harsh and Severe Environments

Edited by

Smail Tedjini
Grenoble INP/LCIS
University Grenoble Alpes
Valence
France

Valentina Palazzi
Department of Engineering
University of Perugia
Perugia
Italy

IEEE Press

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Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

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Library of Congress Cataloging-in-Publication Data is applied for

Hardback ISBN 9781394169078

Cover Design: Wiley
Cover Images: © Longhua Liao/Getty Images, © Weiquan Lin/Getty Images

Set in 9.5/12.5pt STIXTwoText by Straive, Pondicherry, India

To our families and to all the colleagues and mentors who inspired our research.

Contents

List of Contributors

Sara Amendola
RADIO6ENSE S.r.L.
Roma
Italy

Thierry Aubert
Université de Lorraine, CNRS, IJL
Nancy
France

Rahul Bhattacharyya
Auto-ID Labs, Massachusetts Institute of Technology
Boston, MA
USA

Francesca Benassi
DEI "Guglielmo Marconi"
University of Bologna
Bologna
Italy

Martí Boada
Department of Electronic, Electric and Automatic Engineering
Universitat Rovira i Virgili
Tarragona
Spain

Michele Borgese
Research and Development Department, SIAE Microelettronica
Milan
Italy

Mathieu Le Breton
Géolithe Company
Crolles
France

ISTerre, Université Grenoble Alpes
Grenoble
France

Mathieu Cassel
ENS, Université de Lyon
Lyon
France

Valérie Guillard
JRU IATE 1208, Univ Montpellier
CIRAD, Montpellier SupAgro
Montpellier
France

Filippo Costa
Dipartimento Ingegneria dell'Informazione, Università di Pisa
Pisa
Italy

Alessandra Costanzo
DEI "Guglielmo Marconi"
University of Bologna
Bologna
Italy

Francesco Alessio Dicandia
Istituto di Elettronica e di Ingegneria dell'Informazione e delle Telecomunicazioni, Consiglio Nazionale delle Ricerche (CNR)
Torino
Italy

Yvan Duroc
Univ Lyon, Université Claude Bernard Lyon 1, INSA Lyon, Ecole Centrale de Lyon, CNRS
Villeurbanne
France

Omar Elmazria
Université de Lorraine, CNRS, IJL
Nancy
France

Cécile Floer
Université de Lorraine, CNRS, IJL
Nancy
France

Simone Genovesi
Dipartimento Ingegneria dell'Informazione, Università di Pisa
Pisa
Italy

David Girbau
Department of Electronic, Electric and Automatic Engineering
Universitat Rovira i Virgili
Tarragona
Spain

Jasmin Grosinger
Institute of Microwave and Photonic Engineering, Graz University of Technology
Graz
Austria

Sami Hage-Ali
Université de Lorraine, CNRS, IJL
Nancy
France

Amirhossein Karami-Horestani
CIMITEC, Departament d'Enginyeria Electrònica, Universitat Autònoma de Barcelona
Bellaterra
Spain

Antonio Lázaro
Department of Electronic, Electric and Automatic Engineering
Universitat Rovira i Virgili
Tarragona
Spain

Giuliano Manara
Dipartimento Ingegneria dell'Informazione, Università di Pisa
Italy

Gaetano Marrocco
Tor Vergata University of Roma and RADIO6ENSE S.r.L.
Roma
Italy

Ferran Martín
CIMITEC, Departament d'Enginyeria Electrònica, Universitat Autònoma de Barcelona
Bellaterra
Spain

Diego Masotti
DEI "Guglielmo Marconi"
University of Bologna
Bologna
Italy

Alicja Michalowska-Forsyth
Institute of Electronics, Graz University of Technology
Graz
Austria

Carolina Miozzi
RADIO6ENSE S.r.L.
Roma
Italy

Manuel Monedero
NXP Semiconductors GmbH
Munich
Germany

Cecilia Occhiuzzi
Tor Vergata University of Roma and RADIO6ENSE S.r.L.
Roma
Italy

Giacomo Paolini
DEI "Guglielmo Marconi", University of Bologna
Bologna
Italy

Valentina Palazzi
Department of Engineering
University of Perugia
Perugia
Italy

Ferran Paredes
CIMITEC, Departament d'Enginyeria Electrònica, Universitat Autònoma de Barcelona
Bellaterra
Spain

Camille Ramade
Tageos
Montpellier
France

Benjamin Saggin
IES, Univ Montpellier, CNRS
Montpellier
France

Brice Sorli
IES, Univ Montpellier, CNRS
Montpellier
France

Robert Staraj
Université Côte d'Azur, LEAT
Laboratoire Electronique Antennes et Télécommunications
Sophia Antipolis
France

Smail Tedjini
LCIS, University of Grenoble-Alpes
50 Rue Barthelemy de Laffemas
Valence
France

Philippe Le Thuc
Université Côte d'Azur, LEAT
Laboratoire Electronique Antennes
et Télécommunications
Sophia Antipolis
France

Arnaud Vena
IES, Univ Montpellier, CNRS
Montpellier
France

Ramón Villarino
Department of Electronic, Electric
and Automatic Engineering
Universitat Rovira i Virgili
Tarragona
Spain

Konstantinos Zannas
LCIS, University of Grenoble-Alpes
50 Rue Barthelemy de Laffemas
Valence
France

About the Editors

Smail Tedjini, Life Fellow IEEE, URSI Fellow; Doctor d'Etat in Physics 1985 Grenoble University; senior researcher of CNRS 1986–1993; University full professor since 1993, now with Grenoble Institute of Technology. His main topics for both research and teaching, concern Applied Electromagnetism, RF, Optoelectronics, RFID, and Wireless Systems. He served as coordinator and staff member in numerous academic programs both for education and research. He was coordinator for PhD program, master and bachelor programs for the Universities at Grenoble, some of these programs are under collaboration with international universities from Europe, Canada, Brazil, Vietnam, Egypt, and Maghreb. He served as the director of Esisar, Department of Grenoble-INP. He is involved in academic research supervision since 1982. His main topics in research are applied electromagnetism, modeling of devices and circuits at both RF and optoelectronic domains. Current research focuses on wireless systems with special attention to RFID technology and its applications. He is the founder in 1996 and past director of the LCIS Lab. Now, he is within ORSYS group that he leaded until 2014 and founded in 2002. He supervised tens of research contracts with public administrations and industries. He supervised 50 PhD, co-authored 350 publications, 3 books, 7 patents, 10 book chapters, and book: Wiley "Non-linearities in Passive RFID Systems" and served as reviewer/opponent for tens of PhD worldwide.

TPC-Cochair of IEEE-RFID2011 TPC Member for several editions of IEEE-RFID, TPC member or cochair for RFID-TA since 2010. General Chair IEEE RFID-TA 2012. Organizer of IEEE-RFID-TA 2012 in France. Organizer/co-organizer of RFID special sessions in numerous conferences in particular: IEEE-MTTs, IEEE-APs, IEEE-RFID-TA, EuMW, EuCAP, URSI-GASS, URSI-ATRASC, local conferences in France, Brazil, Vietnam, Tunisia. Organizer of RFID summer school in France, Brazil, Vietnam, and Maghreb. Organizer of (3) Student Design Competitions at IEEE-IMS. Editor of special issue on RFID at IEEE-microwave magazine, and Annales des telecom. Vice-chair IEEE MTT-TC

24 (2017–2019). Chair IEEE MTT-TC-26 (2020–2021), since 2024 he is the chair of French Chapter of IEEE-Antenna and Propagation. Since October 2022 he is nominated as Emeritus professor at University Grenoble Alpes. Since 2024 he is Distinguish Lecturer of the IEEE Council on RFID.

Valentina Palazzi received the MS degree in electrical engineering and the PhD degree in industrial and information engineering from the University of Perugia, Italy, in 2014 and 2018, respectively. During her PhD, she was visiting PhD student at the Tyndall National Institute, Cork, Ireland, at the Centre Tecnològic de Telecomunicacions de Catalunya, Barcelona, Spain, and at the Georgia Institute of Technology, Atlanta, GA, USA. Currently, she is a researcher with the High Frequency Electronics Laboratory at the University of Perugia, Perugia, Italy. She has been the scientific coordinator for the University of Perugia of the European projects CHARM - Challenging environments tolerant Smart systems for IoT and AI (G.A. n. 876362) and OPEVA - Optimization of Electric Vehicle autonomy (G.A. n. 101097267).

She wrote more than 80 scientific papers (both journal and conference proceedings), and a book chapter, and she holds three patents. Her current research interests include the design of RF components, wireless sensors, radar front ends, wireless power transfer technologies, additive manufacturing, and conformal electronics.

Dr. Palazzi is an elected member of the IEEE Microwave Theory and Technology Society (MTT-S) Administrative Committee from 2024 to 2026. She is a member of IEEE MTT-S Technical Committees 16 "Microwave and Millimeter Wave Packaging Interconnect and Integration," 17 "Microwave Materials and Processing Technologies," and 26 "RFID, Wireless Sensor and IoT." She was the Chair of the Technical Committee 26 from 2022 to 2023. She has been an Early Career Representative of the URSI Commission D "Electronics and Photonics" of the International Union of Radio Science (URSI) from 2021 to 2026. She won a number of international prizes, including the IEEE Graduate Fellowship in 2017, 2017 MTT-S Prize–Italy Chapter Central and Southern Italy, and the International Union of Radio Science (URSI) Young Scientist Best Paper Award conferred at the 2019 URSI Italian National Meeting. Since November 2024, she has served as an Associate Editor for IEEE Microwave and Wireless Technology Letters.

Preface

In the continuously evolving digital landscape, wireless systems are experiencing considerable developments. Emerging concepts such as digital twins, Industrial IoT, telemedicine, precision agriculture, and fail-operational systems are changing the approach toward the design of electronics and telecommunication systems, opening the way to new markets and applications that were unimaginable only a few decades ago. The urgence for pervasive real-time monitoring systems is pushing technology beyond its current limits, raising new challenges for both academic and industrial R&D labs.

In this context, wireless sensors and RFID technologies can offer very effective solutions provided that their design and implementation take into account the characteristics and constraints imposed by the envisioned applications. For both wireless sensors and RFID devices the use of radiofrequency (RF) technologies is pivotal not only for enabling the data transfer but also for sensing and energy scavenging. While the simplicity and the high performance of RF devices in free space and line-of-sight (LOS) are well known, the situation is quite different for real applications that can include the presence of lossy materials, non-LOS communication, metallic elements, and so forth. Therefore, in most applications the real environment is very different compared to free space and introduces severe propagation conditions from an electromagnetic point of view. Additionally, harsh environmental conditions, such as high temperatures or humidity, can challenge electronics operation, calling for new materials and design approaches.

This book is aimed at both doctoral students and engineers developing R&D projects about wireless and RFID technologies. It provides a unique source of examples of successful wireless system solutions leveraging RFID technologies and similar energy-efficient wireless approaches, enabling the implementation of advanced concepts such as Internet of Things (IoT) in severe and harsh environments. Indeed, while several literatures on wireless technologies and RFID systems are available and can be considered for the design of basic systems mostly in controlled environments (i.e. anechoic chambers) and academic labs, only a few focus on the actual implementation of advanced and effective solutions in real environments. In real applications wireless sensors and RFIDs have to communicate their information by means of RF signals which propagate in heterogeneous and complex environments. The presence of metal, liquids, biological tissues, plants, and so forth cause significant degradation, distortion or even cancellation of the RF signals, not to mention the detuning effects on the antenna and on the other RF signal components that are generated by the presence of heterogeneous objects in the application environment. Real environment exhibits severe behavior for electromagnetic signals and RF devices. The same characteristics are encountered in harsh environment where high temperatures, strong radiation, and corrosive materials are present. Last but not least, wireless systems that operate in real applications have to comply with the constraints imposed by standards and regulations which are rarely considered in controlled environments.

The book covers the recent advances in wireless and RFID systems where severe electromagnetic behavior and harsh conditions are taken into consideration, while complying with RF standard and regulations. So, this book provides the reader with the design rules and methodologies to obtain satisfactory performance and possibly avoid the typical oversights and mistakes that can be made when first approaching to this topic.

The book is organized in 12 independent chapters grouped in 3 sections. The first section is dedicated to RFID design approaches to implement passive wireless sensors able to operate in harsh and severe environments. This section includes 6 chapters concerning different use cases, which are briefly described herein below:

Chapter 1 entitled "UHF RFID Identification and Sensing for the Industrial Internet of Things (I-IoT)." This chapter analyzes the challenges for the successful integration of RFID sensor networks within the industrial and consumer IoT contexts. The challenges in RFID sensor networks encompass robust communication links and accurate sensing measurements. Industrial applications confront additional difficulties due to wireless powering in presence of lossy mediums and metallic objects, compounded by high temperatures and sensor placement on fast-moving mechanical parts. Temperature impacts sensing ICs, reducing communication ranges, and affecting performance. External probes connected via analog front ends experience stronger temperature sensitivity, causing nonlinear drift. Monitoring high-speed components introduces further issues, including backscattering link robustness and data transmission/decoding issues, exacerbated by electromagnetic noise from high-power motors. Ensuring data integrity across the IoT platform necessitates comprehensive security assessments. Adopting new-generation of microchips with sensing capabilities and low-power encryption algorithms for data security requires careful evaluation, considering implications for power consumption and data rates. All these challenges are carefully described in the chapter, and possible countermeasures are highlighted.

Chapter 2 entitled "RFID Sensing In Power-Plant Generators and Power Transformers." The harsh environment in this chapter is predominately represented by the dense metallic parts which need to be monitored wirelessly. Such environments hinder the antenna performance. In addition, fast rotating parts cause mechanical stress on potential sensors, and the high electric/magnetic field needs to be taken into consideration when selecting the antenna. To tackle the aforementioned harsh environment impact, there are specific choices to be made: the antenna structure should offer good performance when positioned on metallic surfaces, the weight of a potential sensor should be minimized to avoid adding extra strain to the rotating system and loop antenna types must be avoided since they can be current generated by the movement inside of a high magnetic field. Overall, solutions are shown, which are dictated by the expected environment of operation.

Chapter 3 entitled "Design of Passive UHF RFID Sensors Meeting Food Industry Regulations." RFID tags transformed into sensors sensitive to certain parameters of their environment must be produced in large quantities and at low cost. These requirements can affect measurement reliability, especially in harsh environment conditions. The solutions presented in this chapter aim to avoid this lack of reliability and could therefore be considered for a variety of applications. So by using a simple RFID antenna and a suitable RFID chip, the described systems are easy to duplicate and can be used in groups. Food products are delivered as batches and are separated at the very end in the delivery to the consumer. Although monitoring until the purchase is of interest, it is essential during the first few hours/days of transport, because if the repeated exchanges between the various logistics partners and the exponential growth of micro-organisms. Furthermore, unlike many RFID systems, the described solutions are independent of external databases. This is an advantage, especially in crowded electromagnetic or severe environments.

Chapter 4 entitled "Challenges of Using RFID for Outdoor Environmental Monitoring." The deployment of RFID tags outdoors brings a new spectrum of technical difficulties that must be overcome. The presence of water rain, dew, snow, or frost on tags usually decreases signal strength and modify phase difference of arrival, by coupling with the tag antenna. In the far field, propagation through non-air mediums such as soil, water, snowpack, snowy terrains, or vegetation increases loss, phase delay and multipath interferences. These conditions make it challenging to reliably use passive tags outdoors for localization, sensing but also identification. In this chapter all these challeges are accurately described, with the aim to provide an estimate of the performance loss.

Chapter 5 entitled "Harmonic Transponders for Tracking and Sensing." This chapter is dedicated to a special category of backscatter radios, called harmonic transponders. Harmonic transponders can operate in environments characterized by strong reflections and metal parts, which are particularly severe for signal propagation, as the contribution from the tags can be easily separated from the rest of the reflections. Additionally, due to their simple circuitry (they are usually based on single diodes), they are particularly robust, which makes them good candidates to operate in environments characterized by harsh conditions (such as low or high temperature, high humidity, and so forth), thereby expanding the possible fields of application of wireless sensors.

Chapter 6 entitled "Passive Wireless Sensors in Radiation Environments." This chapter examines the radiation environment and its impact on passive/batteryless wireless sensors using the ultrahigh frequency (UHF) radiofrequency identification (RFID), specifically the ramifications of radiation on electronic devices. The chapter explores the use of RFID sensors in radiation environments, including potential radiation effects on RFID tags and methods for protecting these tags against radiation damage. In particular, the discussion links the fundamentals of radiation effects in CMOS circuits with the architectural characteristics and operation features of the RFID tag chip frontends, going down to the circuit block level. Although RFID sensor tags are not yet widely used in radiation environments, there is promising potential demonstrated by existing sensor tag prototypes. These prototypes have successfully addressed major issues, such as tight power constraints resulting from batteryless operation and harsh radiation environments caused by ionizing radiation. Signal-pattern-based sensor tag systems have proven particularly successful in areas such as wireless power transfer, setup independence, and robustness in moderate static multipath environments. Additionally, using scaled CMOS for RFID chips and their passive operation is a promising trend that offers a certain degree of radiation hardness.

The second section entitled chipless includes four chapters, dedicated to wireless sensors based on both surface acoustic wave (SAW) and RF resonators, as reported hereafter:

Chapter 7 entitled "SAW Devices Combining RFID and Sensor Functionalities for Harsh Environments." This chapter is dedicated to provide an introduction to the surface acoustic wave (SAW) sensors. In our modern society, due to the development of the Internet of Things (IoT) or the industry 4.0, the continuous monitoring of physical data has become a real need. This is still a challenge in harsh environments such as high-temperature environments or difficult to access environments. Thanks to an electro-mechanical conversion, the surface acoustic wave (SAW) technology enables to overcome the limits of conventional sensors. Indeed, SAW sensors are passive systems and thus there is no embedded electronic and no need to regularly replace the battery. Thanks to their small size they can be placed in small and tight spots or even work as abandoned sensors (buried sensors for example). SAW sensors can also be remotely interrogated and can thus offer exciting perspectives for remote monitoring and control of moving parts.

Chapter 8 entitled "Wireless Sensing for Harsh and Severe Environments Based on SAW Sensors." Surface acoustic wave (SAW) sensors are able to measure various physical parameters like temperature, pressure, and stress without an external power supply. This type of sensors can withstand high temperatures (up to 600 °C), voltages up to 530 kV, currents up to 20 kA, as well harsh chemical environments (heavy fuel oil, SF6 gas, or mineral oil). Therefore, sensors based on SAW technology are used in specific harsh environments like ship engine room, medium- or high-voltage electrical equipment either air- or gas-insulated switchgears or oil-filled circuit-breakers. These environments contain many metallic parts where the sensors can be placed, which in some scenarios involve movement, as well as the presence of chemical. The proximity of metallic parts in motion or chemical in different states, with a temperature and age-dependent complex permittivity, in the vicinity of the antenna associated with the SAW sensor can modify its input impedance leading to a significant measurement error. Actual SAW transducers are described in this chapter, and their performance are toroughly discussed.

Chapter 9 entitled "Microwave Encoders for Motion Control and Chipless RFID Applications." This chapter presents microwave encoder systems for motion control. They represent an interesting option over optical (encoder) systems based on a similar principle, due to the fact that microwaves are more tolerant to the effects of dirtiness and pollution, as compared to optical radiation. Namely, if the apertures in optical encoders are clogged, the system cannot exhibit its functionality, contrary to microwave encoders, more robust against the effects of pollution and dirtiness. Such harsh and polluted environments are encountered in many industrial systems, and, for this reason, microwave encoders are especially suited in such applications.

Chapter 10 entitled "Chipless RFID Technology for Operations in Harsh Environments." There are two main relevant aspects of this chapter that deals with the benefit of using chipless RFID sensors. On the one hand, the chapter addresses the different wireless sensor paradigms, namely surface acoustic wave sensors, near-field ones as well as far-field radio frequency backscattering. Moreover, it puts in evidence the advantages with respect to solutions that resort to wired connection to recover the data at the sensor or solutions that require batteries. On the other hand, several application domains are addressed (space, oil and gas, automotive, industrial tools monitoring) and great attention is paid to the employed materials.

The third section is entitled systems. It includes two chapters and is dedicated to the impact of specific environments on system based on wireless and contactless devices. Chapter contents are briefly described herein after:

Chapter 11 entitled "Energy-Autonomous Wireless Architectures for Predictive Maintenance in Harsh Closed Applications". In the application described in this chapter, the sensor nodes are placed all around an electromagnetically harsh environment full of metal parts, and they are energized remotely by RF sources operating in the Industrial, Scientific and Medical (ISM) 2.4 GHz band; these sources act as "illuminators," and a multitude of wireless batteryless sensor nodes are placed in the key points of the bonnet, in contact with parts of the car that need to be monitored. These spaces are generally made of metallic parts, creating an environment that is hostile to the electromagnetic fields. Suitable solutions are described and their performance is discussed.

Chapter 12 entitled "Implanted NFC Tags: Study of Energy Harvesting and Reading by Means of Smartphones." This chapter describe an IoT solution for implanted electronics based on near-field communication (NFC). Information gathering from implanted electronics is hampered by a number of factors, including poor coupling due to the vastly different sizes of the reader and the tag antennas; the unknown position of the implanted device causing misalignment; the constrained quality factor of the communication bandwidth; the detuning of the antennas; and, most importantly, the effects of the body that increase the losses, degrading the quality factor of the antenna. The implanted electronics as well as its antenna must be properly protected to ensure proper operation for a sufficient amount of time. To avoid infections, these protections must also be biocompatible. Consequently, the electrical properties of the antenna are modified. Maximum power transfer to load design should be taken into consideration to effectively power the implanted electronics since the power source comes from the smartphone. Consequently, it is crucial to know the NFC IC input impedance. Hence, considering this type of design, the modeling of the IC presents another issue because of its non-linear behavior. Finally, the presence of ferrites in the smartphone, which allows its antenna to be electrically isolated from the battery and other metallic parts, affects the separation between the mobile and the implant, since they are directly linked to the coupling coefficient.

Smail Tedjini and Valentina Palazzi

Section 1

RFID