



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

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

Contents

List of Contributors xv

About the Editors xix

Preface xxi

Section 1 RFID 1

- 1 UHF RFID Identification and Sensing for the Industrial Internet of Things (IIoT) 3**
Carolina Miozzi, Sara Amendola, Cecilia Occhiuzzi, and Gaetano Marrocco
- 1.1 Introduction 3
- 1.2 I-IIoT Ecosystem: Architectures and Components 5
- 1.2.1 Data Generation 6
- 1.2.2 Data Transmission 10
- 1.2.3 Data Management and Analysis 14
- 1.3 RFID for Product Monitoring at Item-Level 15
- 1.3.1 Construction 16
- 1.3.2 Conveyor Belt 18
- 1.3.3 Pharmaceuticals 19
- 1.4 RFID for Plant and Processes Monitoring 20
- 1.4.1 Filter Press in Chemical Industry 20
- 1.4.2 Electrical Equipment and Renewable Energy Plants 24
- 1.4.3 Fruits Monitoring in Ripening Rooms 27
- 1.5 Challenges and Countermeasures 30
- 1.6 Conclusions 34
- References 35
- 2 RFID Sensing in Power-Plant Generators and Power Transformers 39**
Konstantinos Zannas, Yvan Duroc, and Smail Tedjini
- 2.1 Introduction 39
- 2.2 Harsh Environment 40

| | | |
|-------|---|----|
| 2.2.1 | Conductive Environment | 41 |
| 2.2.2 | Multipath Effects and Time-Variant Environment | 47 |
| 2.2.3 | High Electric and Magnetic Fields | 48 |
| 2.3 | Design and Measurement of RFID Sensor Tag | 49 |
| 2.3.1 | Design Considerations | 49 |
| 2.3.2 | Measurement of the Proposed UHF RFID Sensor Tag | 50 |
| 2.4 | RFID Sensors: Application in Power Transformers | 52 |
| 2.4.1 | Installation Procedure | 52 |
| 2.4.2 | Temperature Measurement with the RFID Sensor Tags | 55 |
| 2.5 | Conclusion | 60 |
| | References | 61 |

3 Design of Passive UHF RFID Sensors Meeting Food Industry Regulations 65

Benjamin Saggin, Arnaud Vena, Brice Sorli, Valérie Guillard, and Camille Ramade

| | | |
|---------|---|----|
| 3.1 | Introduction | 65 |
| 3.2 | RFID Sensors | 66 |
| 3.2.1 | Interest in RFID | 66 |
| 3.2.2 | Types of RAIN Sensors | 67 |
| 3.3 | Monitoring Food Spoilage | 68 |
| 3.3.1 | Food Spoilage Process | 68 |
| 3.3.2 | State of the Art on RFID-based Food Sensors | 69 |
| 3.4 | Food Spoilage Sensitive RFID Tag Design | 71 |
| 3.4.1 | Hardware Design | 71 |
| 3.4.1.1 | Position | 71 |
| 3.4.1.2 | Biopolymer Test Specimen | 72 |
| 3.4.1.3 | Interdigitated Capacitor | 74 |
| 3.4.1.4 | Sensing RFID Transponder | 75 |
| 3.4.2 | Measurement Reading | 78 |
| 3.4.2.1 | Common Software Framework | 78 |
| 3.4.2.2 | Turn-on Power Algorithm | 79 |
| 3.4.2.3 | Frequency Sweeps | 81 |
| 3.4.2.4 | Transponder-Embedded Calibration | 82 |
| 3.5 | Validation | 83 |
| 3.5.1 | In Simulated Conditions | 83 |
| 3.5.2 | In Real Conditions | 85 |
| 3.6 | Conclusion | 87 |
| | References | 87 |

4 Challenges of Using RFID for Outdoor Environmental Monitoring 91*Mathieu Le Breton, Rahul Bhattacharyya, and Mathieu Cassel*

- 4.1 Versatile Data Acquisition Approaches 91
- 4.2 Weather and Environment Influence 96
 - 4.2.1 Effect of Rainfall and Dew 96
 - 4.2.2 Effect of Snow 97
 - 4.2.3 Effect of Vegetation 99
 - 4.2.4 Effect of Mud and Tag Burial 100
- 4.3 Aquatic Environments 101
 - 4.3.1 Fish Population Estimation 101
 - 4.3.2 Driftwood Movement Monitoring 104
 - 4.3.3 Sediment Tracing 106
- 4.4 Landslide and Rockfall Detection 111
- 4.5 Agriculture 114
- 4.6 Infrastructure 116
- 4.7 Conclusion on the Main Challenges 118
- References 121

5 Harmonic Transponders for Tracking and Sensing 133*Valentina Palazzi*

- 5.1 Introduction 133
- 5.2 Harmonic Backscattering 135
- 5.3 Frequency Doubler for Harmonic Transponders 137
- 5.4 One-Bit Harmonic Transponders 141
- 5.5 Harmonic Tracking Systems 143
- 5.6 Multi-Bit Harmonic Transponders 144
- 5.7 Harmonic Tag for Rotation Sensing 147
- 5.8 Harmonic Tag for Temperature Sensing 148
- 5.9 Harmonic Tag for Vibration Sensing 150
- 5.10 Harmonic Tag for Crack Sensing 151
- 5.11 Harmonic Tags for Buried Items Localization 155
- 5.12 Conclusion 158
- References 158

6 Passive Wireless Sensors in Radiation Environments 163*Jasmin Grosinger and Alicja Michalowska-Forsyth*

- 6.1 Introduction 163
- 6.2 Passive Wireless RFID Sensors 165
 - 6.2.1 UHF RFID Systems 167

- 6.2.2 RFID Reader 168
 - 6.2.2.1 Reader Receiver 169
- 6.2.3 RFID Tags 172
 - 6.2.3.1 Tag Chip 172
 - 6.2.3.2 Tag Antenna 173
 - 6.2.3.3 Radar Cross Section 174
- 6.2.4 Antenna-based RFID Sensors 175
 - 6.2.4.1 Harsh Application Environments 177
- 6.3 Radiation Environments and Radiation Hardness 177
 - 6.3.1 Radiation Environments 178
 - 6.3.1.1 Space Radiation 178
 - 6.3.1.2 Manmade Radiation Sources 179
 - 6.3.2 Interactions with Materials 179
 - 6.3.3 Radiation Effects in Electronic Devices 180
 - 6.3.3.1 Total Ionizing Dose 181
 - 6.3.3.2 Total Non-ionizing Dose 181
 - 6.3.3.3 Single-event Effects 182
 - 6.3.4 Radiation Hardening Techniques 184
 - 6.3.4.1 Technology Level 185
 - 6.3.4.2 Physical Layout Level 185
 - 6.3.4.3 Architecture Level 187
 - 6.3.5 Radiation Assurance Testing 188
- 6.4 RFID Sensors in Radiation Environments 189
 - 6.4.1 RFID Tag Chip 190
 - 6.4.2 Radiation Effects in RFID Tags 191
 - 6.4.3 Radiation Hardening of RFID Tags 192
- 6.5 Conclusions 193
- 6.6 Biographies 194
- References 195

Section 2 Chipless 203

7 SAW Devices Combining RFID and Sensor Functionalities for Harsh Environments 205

Omar Elmazria, Cécile Floer, Thierry Aubert, and Sami Hage-Ali

- 7.1 Introduction 205
- 7.2 Saw Sensor Principle 206
- 7.3 Principle of Wireless Sensors Including RFID Code 208
- 7.4 Resonator 209
- 7.5 Reflective Delay Line (R-DL) 209

| | | |
|-------|--|-----|
| 7.5.1 | Conventional Configuration of R-DL | 209 |
| 7.5.2 | R-DL with Connected IDTS | 210 |
| 7.6 | Saw Sensor for Harsh and Severe Environments | 211 |
| 7.6.1 | Piezoelectric Material for High Temperature | 211 |
| 7.6.2 | Metallic Material for Electrodes | 217 |
| 7.7 | Antennas for Harsh Environments | 219 |
| 7.8 | Packaging for Harsh and Severe Environments | 220 |
| 7.8.1 | Packaging for Saw Devices | 220 |
| 7.8.2 | Packageless Solution | 220 |
| 7.9 | Conclusion and Outlooks | 223 |
| | References | 225 |

8 Wireless Sensing for Harsh and Severe Environments Based on Saw Sensors 233

Manuel Monedero, Robert Staraj, and Philippe Le Thuc

| | | |
|-------|--|-----|
| 8.1 | Introduction | 233 |
| 8.2 | State of the Art | 234 |
| 8.2.1 | Active Wireless Sensors | 234 |
| 8.2.2 | Passive Wireless Sensors | 234 |
| 8.3 | Surface Acoustic Wave Sensors | 235 |
| 8.3.1 | The Different Types of SAW Sensors | 236 |
| 8.3.2 | Resonator SAW Sensors | 236 |
| 8.3.3 | Delay Line SAW Sensors | 238 |
| 8.3.4 | Two Resonators-One-Port Sensors | 238 |
| 8.3.5 | Temperature Effect on the Resonance Frequencies | 239 |
| 8.4 | Remote Interrogation System for Surface Acoustic Wave Sensors Based on Differential Mode | 240 |
| 8.4.1 | Operation of the Interrogation System in Transmission Mode (T_x) | 240 |
| 8.4.2 | Operation of the Interrogation System in Reception Mode (R_x) | 242 |
| 8.5 | Miniature Antenna/Saw Sensors Characterization | 244 |
| 8.6 | Global Modelization of a Wireless Saw Sensor Interrogation System | 246 |
| 8.6.1 | Theoretical Sensor Models | 246 |
| 8.6.2 | Radio Link Modeling | 247 |
| 8.6.3 | Impedance Matrix [Z] | 247 |
| 8.6.4 | Equivalent Circuit | 248 |
| 8.6.5 | Mutual Coupling Between Antennas Modeling | 248 |
| 8.6.6 | Theoretical Aspects of the Model | 249 |
| 8.7 | Conclusion | 250 |
| | References | 251 |

| | | |
|-----------|---|------------|
| 9 | Microwave Encoders for Motion Control and Chipless-RFID Applications | 255 |
| | <i>Ferran Martín, Ferran Paredes, and Amirhossein Karami-Horestani</i> | |
| 9.1 | Introduction | 255 |
| 9.2 | Working Principle of Microwave Encoders and Case Example | 257 |
| 9.3 | Quasi-Absolute Synchronous Encoders | 265 |
| 9.4 | Chipless-RFID Application | 269 |
| 9.5 | Hybrid Approach | 274 |
| 9.6 | Conclusions | 277 |
| | References | 278 |
| 10 | Chipless RFID Technology for Operations in Harsh Environments | 283 |
| | <i>Simone Genovesi, Filippo Costa, Michele Borgese, Francesco Alessio Dicandia, and Giuliano Manara</i> | |
| 10.1 | Introduction | 283 |
| 10.2 | Wireless Sensor Paradigms | 286 |
| 10.2.1 | Surface Acoustic Wave Sensors | 286 |
| 10.2.2 | Near-Field Sensors | 288 |
| 10.2.3 | Far-Field Radio Frequency Backscattering | 288 |
| 10.3 | Sensors for Space | 289 |
| 10.3.1 | Temperature Sensors | 290 |
| 10.3.2 | Vehicle Health Monitoring Systems | 291 |
| 10.4 | Oil and Gas | 293 |
| 10.5 | Automotive | 295 |
| 10.5.1 | Tyre Monitoring | 295 |
| 10.5.2 | Torque Monitoring | 298 |
| 10.6 | Sensors for Industrial Tools Monitoring | 300 |
| 10.7 | Conclusion | 306 |
| | References | 306 |
| | Section 3 Systems | 313 |
| 11 | Energy-Autonomous Wireless Architectures for Predictive Maintenance in Harsh Closed Applications | 315 |
| | <i>Alessandra Costanzo, Diego Masotti, Francesca Benassi, and Giacomo Paolini</i> | |
| 11.1 | Introduction and State of the Art | 315 |
| 11.2 | Transmitter/Receiver Link Analysis and Illuminators Best Positioning Simulations | 317 |

| | | |
|-----------|---|------------|
| 11.3 | Design and Realization of the 2.45 GHz RF Power Source | 322 |
| 11.4 | Design of Low-Power Wireless Battery-Less Sensor Nodes | 323 |
| 11.5 | EH and Power Management: Rectification and WPT Performance Characterization | 327 |
| 11.6 | Case Study: Measurement Campaign in the Engine Compartment of a Car | 330 |
| 11.7 | Conclusions | 332 |
| | References | 333 |
| 12 | Implanted NFC Tags: Study of Energy Harvesting and Reading by Means of Smartphones | 337 |
| | <i>Antonio Lázaro, Martí Boada, Ramón Villarino, and David Girbau</i> | |
| 12.1 | Introduction | 337 |
| 12.2 | General Considerations on the Proposed Systems | 339 |
| 12.3 | Description of the Two Systems | 341 |
| 12.3.1 | Reader Modeling | 342 |
| 12.3.2 | NFC IC Tag Modeling | 344 |
| 12.3.3 | Effect of the Body on the Implant | 346 |
| 12.3.3.1 | Study of the Implanted Antenna | 347 |
| 12.3.3.2 | Considerations of the Relay Antenna in a Three-Coil System | 351 |
| 12.3.4 | Coupling Coefficient in Systems Based on Two- and Three-Coils | 352 |
| 12.3.5 | Simulation of the Coupling Coefficient and the Power Delivered to the Implant | 355 |
| 12.4 | Experimental Measurements of Implants Using a Commercial Smartphone with NFC | 361 |
| 12.4.1 | Efficiency Characterization | 361 |
| 12.4.2 | Wireless Power Transfer Using a Smartphone as Reader | 362 |
| | References | 368 |
| | Index | 373 |

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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 urgency 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 back-scattering 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 challenges 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 thoroughly 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) 2.4GHz 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.

Section 1

RFID

