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# Time-Domain Signature Barcodes for Chipless-RFID and Sensing Applications

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*To our families*
*Anna, Alba, and Arnau*
*Noe and Chloe*
*Maria, Roman, and Roger*
*Ana*
*and to many other people who have unconditionally, and sometimes imperceptibly, provided to us their strong and continuous support*

# Preface

Automatic identification and data capture (AIDC) systems have progressively increased their presence in our daily lives in recent years. Among them, radiofrequency identification (RFID) is probably the technology that has experienced a most significant growth and penetration in the market. RFID, a wireless technology that uses RF or microwaves for identification and tracking, cannot compete in terms of cost against optical identification systems. For this reason, the AIDC market is still dominated by optical barcodes and quick response (QR) codes. However, RFID exhibits advantages over optical systems, including higher data capacity, larger read ranges, and the possibility to read multiple tags simultaneously, among others. With these advantageous aspects, RFID systems are appropriate in a wide range of markets, where the cost of the tags can be sacrificed in favor of the high performance that RFID systems exhibit. Applications include automated data collection, identification and tracking of items, animals and persons, livestock identification, automated vehicle identification, wireless sensing, etc.

In most commercial RFID systems, the tags are equipped with an integrated circuit (IC), or chip (where data is stored), and with a planar antenna, necessary for communication with the reader. Such integrated circuits represent a huge portion of the cost of chip-based RFID tags and prevent from the further penetration of RFID technology in the market. For instance, the price of passive UHF-RFID tags (fed by the interrogation signal rather than by batteries) is in the range of several eurocents. This cost is small, but it may be prohibitive in many low-cost items.

Chipless-RFID technology emerged several years ago as a low-cost alternative to chipped-RFID, where the tag IC is replaced with a planar (printed or etched) encoder, with substantially lower cost. Despite the intensive research efforts carried out in the last fifteen years, the performance of state-of-the-art chipless-RFID systems, particularly the data storage capacity, is not comparable to the one of the chip-based systems. Most reported chipless-RFID systems store the information in the frequency domain. In such systems, the encoders consist of a set of printed, or etched, resonant elements tuned to different frequencies, and the identification (ID) code is given by the so-called spectral signature (with singularities in the amplitude or phase response of the tag at certain frequencies, depending on the specific ID code). The number of bits of spectral signature barcodes (the usual designation of frequency-domain tags) is limited by the required spectral bandwidth of the interrogation signal necessary for tag reading (proportional to the number of bits). Although several proposals of chipless-RFID systems where the information is stored in frequency and other domains simultaneously have been reported (hybrid systems), it is not possible to compete against the number of bits of chip-based tags for interrogation signals with reasonable bandwidths (increasing the bandwidth severely affects reader cost).

Time-domain chipless-RFID tags have been also reported. Most time-domain systems are based on time-domain reflectometry (TDR), where the ID code is inferred from the echoes of a narrow pulsed (wideband) signal generated by a delay line with reflectors. Commercial TDR systems based on surface acoustic wave (SAW) encoders exhibiting very high data capacity are indeed available. However, the cost of these SAW-based tags is very high. Low-cost TDR-based tags based on printed or etched delay lines of various types have been also reported, but extremely long delay lines or very narrow pulses are needed in order to implement TDR systems able to read tags with a moderate number of bits (still far from the data capacity of chipped tags).

In this book, an unconventional time-domain approach for chipless-RFID that combines low tag cost and high data storage capacity is reported. The tags consist of a set of identical metallic inclusions (the encoder) printed or etched on a dielectric substrate and arranged as a linear (or circular) chain. Tag reading in these systems proceeds by proximity, through near field coupling with the reader, and the bits are read sequentially (by displacing the tag over the reader) in a time-division multiplexing scheme. The reader contains a sensitive element, a resonator-loaded transmission line, able to detect the functional inclusions of the chain, thereby providing the tag ID code. For that purpose, the reader line is fed by a harmonic (single tone) interrogation signal, which is amplitude modulated (AM) at the output port of the line due to tag motion. Specifically, the functional inclusions, usually associated with the logic state '1', modify the transmission coefficient of the reader line, and consequently, the harmonic interrogation signal is AM modulated at the output port of the line. Since the ID code is contained in the envelope function of such AM signal and revealed as singularities (either peaks or dips) in time domain, it follows that such encoders can be designated as *time-domain signature barcodes*. This is the nomenclature adopted in this book for these time-domain chipless tags, in parallelism to the so-called spectral (or frequency domain) signature barcodes, where the ID code is contained in the frequency domain.

The book is organized as follows. In Chap. 1, the advantages and limitations of chipless-RFID versus chip-based RFID and optical barcodes are discussed, and the classification, as well as a comparative analysis, of the state-of-the-art chipless-RFID approaches is reported. Such analysis is mainly done based on the reported data capacity and density of the different systems. Despite the fact that the analysis does not include the time-domain signature barcodes subject of the present work (and left for future chapters), Chap. 1 concludes by pointing out the high achievable number of bits of these encoders, competitive against the data storage capacity of chipped tags (yet keeping relative small tag sizes).

In Chap. 2, the working principle of chipless-RFID systems based on time-domain signature barcodes is presented in detail. The advantages and limitations as compared to other chipless-RFID approaches are presented, with special emphasis on the data density and capacity (the key advantageous aspects of time-domain signature barcodes) and read range. Because tag reading proceeds through near field, proximity and proper alignment between the tag and the reader are required. Although this is a clear drawback in certain applications, where far-field tags are a due, reading by proximity provides a high level of confidence against eavesdropping or spying, and this may be of interest in other applications, e.g., secure paper or authentication, as discussed in Chap. 2. This chapter also discusses strategies to enhance the data density and provides several examples of chipless-RFID systems based on time-domain signature barcodes, including approaches based on encoders implemented by means of rectangular-shaped resonators and linear metallic inclusions. An exhaustive tolerance analysis, to study the effects of potential misalignments between the tag and the reader, as well as variations in their relative distance (e.g., caused by vibrations), is also included (for each specific approach) in the chapter.

System requirements for industrial scenarios and applications are the subject of Chap. 3. Tag programming and erasing, tag implementation in flexible substrates, including plastic and paper, and synchronous tag reading are discussed in this chapter. As it is highlighted, tag programming is a key factor to reduce tag fabrication costs, since thousands or even millions of all-identical tags can be massively manufactured through industrial processes (e.g., rotogravure, screen-printing, offset), and then programmed (i.e., equipped with the ID code) in a later stage (e.g., by means of low-cost process, such as inkjet printing). Since massive tag fabrication involves a single mask, it follows that the reported approach (where tag personalization is separated from the main industrial fabrication process) offers a low-cost solution for tag manufacturing, as reported in Chap. 3. Secure paper, proximity sensors, and motion control are the main relevant applications of the proposed chipless-RFID system. All these applications are included in Chap. 3.

In Chap. 4, a particular application of the reported time-domain signature barcodes is considered: electromagnetic rotary encoders. Such encoders are indeed angular displacement and velocity sensors and are therefore motion control systems. However, rotary encoders based on metallic inclusions deserve a specific chapter, since such encoders may represent an alternative to the well-established optical encoders in applications where cost and operation in harsh and hostile environments are a due. Strategies to enhance the number of pulses per revolution of the envelope function, the figure of merit in rotary encoders (with direct impact on angular resolution), are discussed in the chapter.

Finally, concluding remarks and future prospects are included in Chap. 5. Tag implementation with organic conductive inks (environmentally friendly and fully recyclable) and all-dielectric 3D-printed tags based on permittivity contrast (robust against mechanical wearing) may constitute two topics of research interest for near future, as revealed by the promising preliminary results already obtained.

This book reflects part of the recent research activity carried out by the authors within the topic of chipless-RFID (although in the review Chap. 1, the state of the art in chipless-RFID technology contributed by many authors worldwide is also included). It is the authors' hope that the present manuscript constitutes a significant contribution in the field of RFID and related topics and that the book can be of practical interest to engineers, professionals, and students working in this fascinating sub-area of wireless technologies.

Barcelona, Spain
August 2019

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# Acronyms

| | |
|---|---|
| AIDC | Automatic identification and data capture |
| AM | Amplitude modulation |
| BC-SRR | Broadside-coupled split-ring resonator |
| BC-S-SRR | Broadside-coupled S-shaped split-ring resonator |
| BER | Bit-error rate |
| CPW | Coplanar waveguide |
| CRLH | Composite right-left handed |
| CSR | Complementary spiral resonator |
| CSRR | Complementary split-ring resonator |
| DPF | Density per frequency |
| DPL | Density per length |
| DPS | Density per surface |
| EC-SRR | Edge-coupled split-ring resonator |
| ED | Envelope detector |
| ELC | Electric LC |
| EMI | Electromagnetic interference |
| EPC | Electronic product code |
| HF | High frequency |
| IC | Integrated circuit |
| ID | Identification |
| LF | Low frequency |
| MIW | Magneto-inductive wave |
| OCR | Optical character recognition |
| OOK | ON–OFF keying |
| PCB | Printed circuit board |
| PEN | Polyethylene naphthalate |
| PPM | Pulse-position modulation |
| PPR | Pulses per revolution |
| QR | Quick response |
| RCS | Radar cross section |

| | |
|---|---|
| REF | Reference |
| RF | Radio frequency |
| RFID | Radio frequency identification |
| SAW | Surface acoustic wave |
| SHF | Super high frequency |
| SMA | Sub-miniature version A |
| SMD | Surface-mount device |
| SRR | Split-ring resonator |
| S-SRR | S-shaped split-ring resonator |
| TDR | Time-domain reflectometry |
| UHF | Ultra-high frequency |
| USB | Universal serial bus |
| UWB | Ultra-wide band |
| VCO | Voltage-controlled oscillator |