Wiley Series in Microwave and Optical Engineering

Kai Chang, Series Editor

ADVANCED CHIPLESS RFID

MIMO-Based Imaging at 60 GHz – ML Detection

Nemai Chandra Karmakar

Mohammad Zomorrodi • Chamath Divarathne

WILEY

ADVANCED CHIPLESS RFID

MIMO-Based Imaging at 60 GHz–ML Detection

By

NEMAI CHANDRA KARMAKAR
MOHAMMAD ZOMORRODI
CHAMATH DIVARATHNE

WILEY

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

Library of Congress Cataloging-in-Publication Data

Names: Karmakar, Nemai Chandra, 1963– author. | Zomorrodi, Mohammad, 1973– author. | Divarathne, Chamath, 1983– author.
Title: Advanced chipless RFID : MIMO-Based Imaging at 60 GHz–ML Detection / by Nemai Chandra Karmakar, Mohammad Zomorrodi, Chamath Divarathne.
Description: Hoboken, New Jersey : John Wiley & Sons, Inc., [2016] | Series: Wiley series in microwave and optical engineering ; 1187 | Includes bibliographical references and index.
Identifiers: LCCN 2016014411 | ISBN 9781119227311 (cloth)
Subjects: LCSH: Radio frequency identification systems. | MIMO systems.
Classification: LCC TK6570.I34 K364 2016 | DDC 621.3841/92–dc23 LC record available at https://lccn.loc.gov/2016014411

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

The book is dedicated to our families.

Shipra, Antara, and Ananya Karmakar
Fathemeh Sajjadidokht, Mohammadkasra, and Zoha Zomorrodi
Navarathne Banda and Dayani Chandramali

PREFACE

The author's group has developed various chipless RFID tags and reader architectures at 2.45, 4–8, 24, and 60 GHz. These results were published extensively in the form of books, book chapters, refereed conference and journal articles, and finally, as patent applications. However, there is still room for improvement of chipless RFID systems. In this book, we proposed advanced techniques of chipless RFID systems that supersede their predecessors in signal processing, tag design, and reader architecture.

The book introduces a few novel and advanced-level high-capacity data encoding and throughput improvement techniques for fully printable multibit chipless RFID tags and reader systems, respectively. These techniques enhance data content capacity of tags and perform reliable tag detection for readers at the instrumentation, scientific, and medical (ISM) frequency bands 2.45, 24, and 60 GHz. First, a comprehensive review of existing chipless RFID tags provides the state of the art in the field and exposes impediments for commercial success. The limiting factors for commercialization of reported chipless RFID tags are (i) printing errors, (ii) degradation of tag performance on low-grade laminates, (iii) low data capacity, (iv) errors in tag reading in industrial environment, (v) reading reliability, and (vi) read range. This book addresses these limitations and provides solutions with an image-based tag design and advanced signal processing techniques.

The book provides the details of the new approaches – electromagnetic (EM) imaging, high-capacity data encoding, and robust tag detection techniques. In the introduction chapter first, a comprehensive review of the available and reported chipless RFID systems is presented. Then, their above-mentioned impediments for commercial success are analyzed. The analysis shows that the conventional techniques used for chipless RFID tag encoding and detection do not address the challenges imposed by commercial grade tags and reader systems. This encourages the researchers for new techniques and approaches in this field.

The book is divided into two main parts. Part I of the book, "EM Image-Based Chipless RFID System," introduces the novel EM imaging concept for data extraction from a 60-GHz chipless RFID tag. Part II "Advanced Tag Detection Techniques for Chipless RFID Systems" presents smart tag detection techniques for existing chipless RFID systems and an innovative MIMO-based tag detection technique for high content capacity and zero guard-band tag detection. These approaches have been fully developed and tested in Monash Microwave, Antenna RFID and Sensor Research Group (MMARS) at Monash University.

In Part I of the book, the fundamental of EM imaging at millimeter-wave band 60 GHz for data extraction is introduced followed by the EM imaging through synthetic aperture radar (SAR) technique. It is shown that the millimeter-wave EM imaging has significant potentials for commercialization of chipless RFID. The EM imaging technique exploits advantages of RFID systems including their flexible non-line-of-sight (NLoS) operation and high data capacity benefit. Moreover, the proposed EM imaging technique inherits low-cost advantages and fully printable features of the barcodes on low-grade packaging materials. The downside of the conventional SAR-based EM imaging technique, requirement for physical movement of the reader antenna, is addressed by the new idea of MIMO-SAR technique. With the proposed MIMO-based EM imaging, no relative movement of the reader and tag is required hence very fast tag imaging is achievable. Finally, the MIMO approach is optimized through global genetic approach for minimum hardware complexity and to introduce a complete solution for chipless RFID system. In this pursuit, the system elements and technical requirements are discussed in details. The proposed approach to the EM imaging technique enhances the content capacity of the chipless systems to a commercial level, for example, EPC Global Class 1 Generation 2 with 64 data bits.

The main emphasis for Part II of the book is to introduce a few new smart tag detection techniques for chipless RFID systems. Researchers were mainly focusing on improving the RFID reader architecture [1,2] and the chipless tag design in conventional approaches [3] and paying less attention to signal processing. As a result, most signal processing techniques being used in chipless RFID systems are primitive and should further be investigated. The first part of Part II focuses on advanced signal processing techniques that significantly improve the tag detection rate and tag reading range for the existing reader architecture [1] and tag design [4]. In addition, the proposed techniques allow removing the guard band presented in frequency-domain tags allowing the spectral efficiency to be improved. As a result, data capacity of the frequency-domain tags can be improved. Maximum-likelihood (ML)-based detection techniques have shown improved performances in communication systems compared to reported techniques such as threshold-based detection techniques [5]. The motivation for this work is to apply the ML detection techniques for chipless RFID tag detection so that the existing RFID system would perform better. One limitation of likelihood-based techniques is its exponential increase in computation complexity with higher number of data bits. Two computationally feasible tag detection techniques have been introduced to overcome this challenge. With these new tag detection techniques, computation complexity only increases linearly with the number of data bits. The second part of Part II presents a novel MIMO-based chipless RFID system and required tag detection techniques that can be used to improve the spectral efficiency, hence increasing data bit capacity.

We hope that the book will contribute significantly to the field of chipless RFID removing many practical barriers for commercialization of the technology.

Nemai Chandra Karmakar
Mohammad Zomorrodi
Chamath Divarathne
Melbourne
November 2015

REFERENCES

1. N.C. Karmakar, R. Koswatta, P. Kalansuriya and R. E-Azim, *Chipless RFID Reader Architecture*, Artech House Publishing, 2013.
2. R.V. Koswatta and N.C. Karmakar, "A Novel Reader Architecture Based on UWB Chirp Signal Interrogation for Multiresonator-Based Chipless RFID Tag Reading," *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 9, pp. 2925–2933, 2012.
3. R. Rezaiesarlak, and M. Manteghi, *Chipless RFID, Design Procedure and Detection Techniques*, Springer, USA, 2015.
4. S. Preradovic and N.C. Karmakar, *Multi-Resonator-Based Chipless RFID*, Springer, USA, 2012.
5. R. Koswatta and N.C. Karmakar, "Moving Average Filtering Technique for Signal Processing in Digital Section of UWB Chipless RFID Reader," *Proc. 2010 Asia Pacific Microwave Conference*, Yokohama, Japan, December 7–10, 2010.

ACKNOWLEDGMENT

The book is the outcome of two PhD level thesis works under the supervision of the first author. The PhD scholarship was supported by the Australian Research Council (ARC) Discovery Project grant DP110105606: Electronically Controlled Phased Array Antenna for Universal UHF RFID Applications. Therefore, the support from ARC is highly acknowledged. The editor-in-chief of Wiley Mr. Brett Kurzman, Editor, Global Research, Professional Practice and Learning, Wiley and Mr. Alex Castro, Senior Editorial Assistant of Wiley were very supportive from the inception of the book project to the end of production. Their support is highly acknowledged. The two student authors were cosupervised by Professors Jeff Walker and Jamie Evans of Monash University. Their valuable suggestions and technical assistance are also acknowledged. During the course of the research work, the team members of the authors' research group, Monash Microwave, Antenna, RFID, and Sensor (MMARS) Laboratory of Monash University, were very supportive to the PhD projects. The supports from the electronics and mechanical workshops of ECSE department of Monash University were instrumental for the research outcomes that are produced in the book.

The family members of the Authors had to endeavor their absence during this research. Their support and companionship are gratefully acknowledged.

NEMAI KARMAKAR
MOHAMMAD ZOMORRODI
CHAMATH DIVARATHNE
Melbourne
November 2015

CONTENTS

PART I

EM IMAGE-BASED CHIPLESS RFID SYSTEM

1

INTRODUCTION

The area of contactless identification systems is growing rapidly into a multi-billion dollar market. It covers a broad range of applications including supply chain management, manufacturing, and distribution services. Examples of these applications include consumer packaged goods, postal items, drugs, books, airbag management, animal tracking, pharmaceuticals, waste disposal, clothes, defense, smart tickets, people tracking such as prisoners, hospital patients, patients in care homes, and leisure visitors as shown in Figure 1.1. Tough trading conditions due to the global competition strive industries to attain more process efficiencies. Therefore, effective goods tracking systems are required to assist the implementation of the modern management system.

In general terms, any application that involves object identification, tracking, navigation, or surveillance would benefit from an identification system. Several hundred billion tags per year are required by this wide area of applications [1].

In this market, every application has its own technical and financial specifications. Main applications, those that need a huge number of tags, require high data encoding capacity and survive only with a very cheap tag solution. For others, secure identification and antitheft tagging is more important. In some cases, the tag size is a key factor and for some others proper identification of highly reflective items such as liquid containers or metal objects is of more importance. Reading range would be another imperative factor for many applications.

Advanced Chipless RFID: MIMO-Based Imaging at 60 GHz–ML Detection, First Edition.
Nemai Chandra Karmakar, Mohammad Zomorrodi, and Chamath Divarathne.

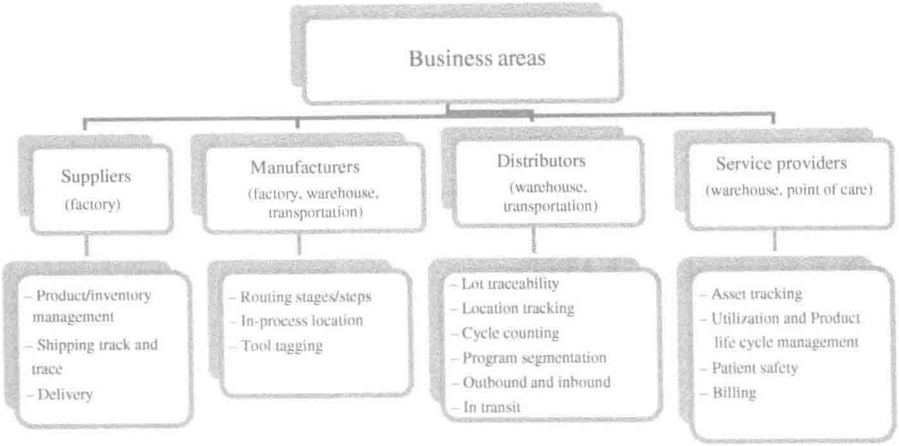

Figure 1.1 Application areas of identification systems.

Irrespective of all priorities, there are two main factors that significantly matter in all applications: the *data encoding capacity* and the *system cost*. For applications with millions of items for tagging, high data capacity of the identification system is a must. For applications with a limited number of objects, high data encoding capacity would be also beneficial to secure the identification process or provide higher reading reliability by sacrificing some of the available bits. The cost reduction is the main initiative for the usage of identification systems in industry; hence, the cost of the identification system and its tagging price must be low and competitive enough to initiate the request for the system. Otherwise, there would be no demand for such systems.

The cost of identification systems, like any other broadcasting service, has two parts: the reader and the tag. The reader cost is normally a fixed cost irrespective of the number of tags. However, the price of the tag attached to every individual item is the most costly part of the whole system. Specifically when the number of items is in the order of millions, the tag price plays a major role in the system's total cost. For such applications, a tag price of only \$1 would increase the total cost of the system to a level that restricts the usage of identification systems. Therefore, the tag price should be kept as small as possible to offer a reasonably low identification system cost.

1.1 BARCODES AS IDENTIFICATION TECHNOLOGY

Barcode is an optical-based, machine-readable technique for identification purposes. It has been established in various industries for many decades with proven applicability. Barcode provides an *extremely low-cost* solution for identification of items to which it attaches. Originally, barcode are comprised of many parallel printed dark lines. The tag's data are systematically represented by varying the widths and

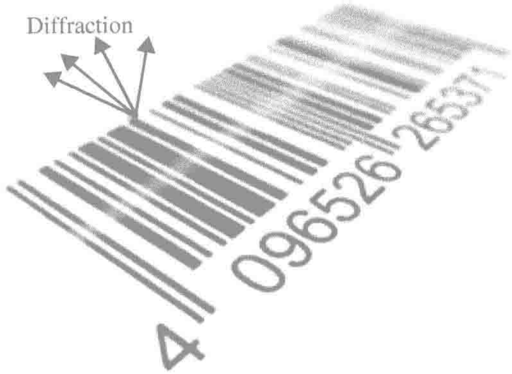

Figure 1.2 Data encoding limitation of a 1D barcode tag due to diffraction effect.

spacing of those parallel lines. This type of barcode, dominant in many applications, is normally referred to as linear or one-dimensional (1D) barcode. Data encoding capacity of the barcode tag is restricted by the diffraction of light through the edges of the lines, the reader sensitivity, and the reading distance, as shown in Figure 1.2. Diffraction restricts the minimum detectable line width as well as the minimum distance between two adjacent lines. This means that for increasing the data encoding capacity of the barcode, the only way is to increase the length of the tag. As the data encoding capacity of barcodes is proportional to the tag's size, it may result in an unreasonable tag size for many applications. This issue is considered as the main limitation of the barcode systems. The 1D barcodes have evolved into rectangles, circles, dots, hexagons and other two-dimensional (2D) geometric patterns to enhance the data encoding capacity. This has resulted in new machine-readable optical labels known as quick response (QR) code. QR codes use four standardized encoding modes to efficiently store data. The maximum storage capacity of QR codes can be up to 7000 characters, which is better than that of barcodes [2]. However, barcodes and QR have many operational limitations. They are very labor intensive as every tag needs to be read/scanned individually. Moreover, being an optical-based system, a clear line-of-sight (LoS), known as optical LoS, is also necessary for proper reading. This means that the tag shall be always printed and exposed on the products and the scanner requires clear optical LoS to read the barcodes or QR codes. Barcodes inside clear polyethylene bags cannot be read due to the light reflection of the bags. Any damage or dirt on the barcode results in improper reading. The reading distance between the optical scanner and the tag is also limited when considering the light dispersion/attenuation in free space and diffraction effect on the tag surface. Normal reading distance in optical systems is limited to few centimeters. Moreover, barcode is not a secure means of communication as tags can be easily reproduced by a cheap inkjet printer. The reading errors of barcodes depend on applications and many industries lose billions of dollars as compensations and damages each year. For example, optical barcode-based luggage handling has approximately 20%