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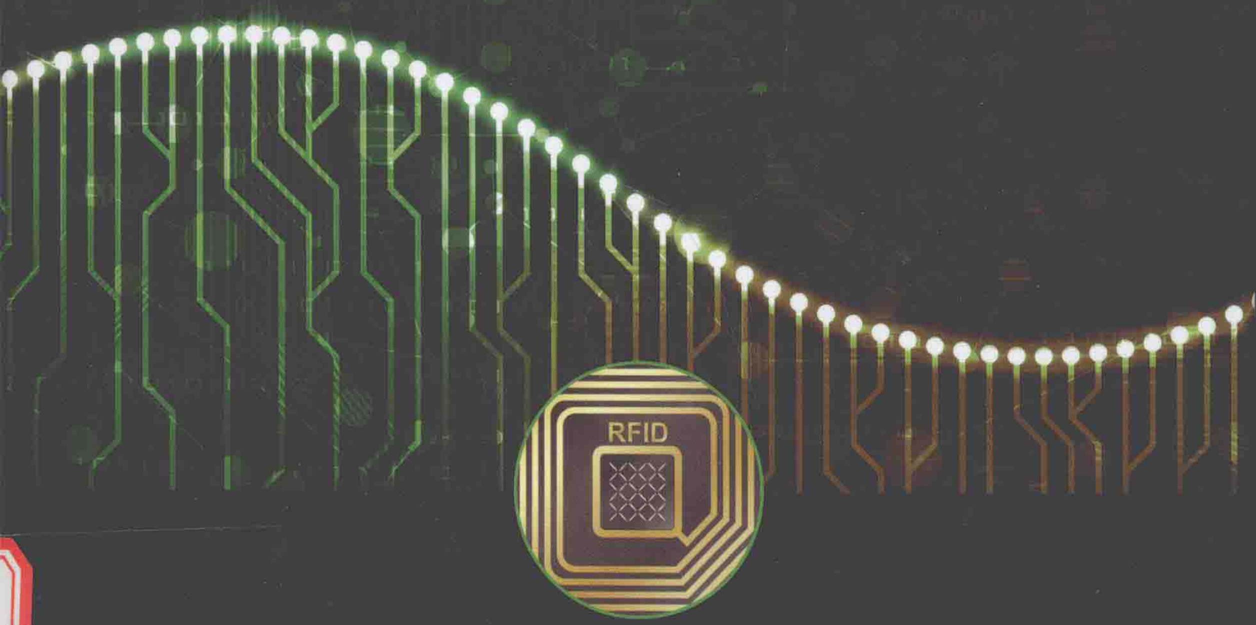
Digital Signal Processing for RFID



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DIGITAL SIGNAL PROCESSING FOR RFID

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to Zhiying and Anna Yuhan

Feng Zheng

to Petra and Hendrik

Thomas Kaiser

Preface

Identification is pervasive nowadays in daily life due to many complicated activities such as bank and library card reading, asset tracking, toll collecting, restricted access to sensitive data and procedures and target identification. This kind of task can be realized by passwords, biometric data such as fingerprints, barcode, optical character recognition, smart cards and radar. Radio frequency identification (RFID) is a technique to identify objects by using radio systems. It is a contactless, usually short distance, wireless data transmission and reception technique for identification of objects. An RFID system consists of two components: the tag (also called transponder) and the reader (also called interrogator).

Generally, signal processing is the core of a radio system. This claim also holds true for RFID. Several books are available now addressing other topics in RFID, such as the basics/fundamentals, smart antennas, security and privacy, but no book has appeared to address signal processing issues in RFID. We aim to complete this task in this book.

The book is organized as follows. Chapter 1 (Introduction) reviews some basic facts of RFID technology and gives an introduction about the scope of the book. In Chapter 2 (Fundamentals of RFID Systems), the operating principles and classification of RFID will be briefly introduced, some typical analogue circuits of RFID and their basic analysis will be addressed, channel models of RFID will be presented and RFID protocols will be briefly reviewed. In Chapter 3 (Basic Signal Processing for RFID), we will discuss some basic signal processing techniques and their applications in RFID. In Chapter 4 (RFID-oriented Modulation Schemes), we will address those modulation schemes that are suitable to RFID tags, which include binary amplitude shift keying and frequency/phase shift keying. The performance of these modulation schemes for RFID channels will be investigated. In Chapter 5 (MIMO for RFID), we examine the problems of transmit signal design and space-time coding at the tag for MIMO-RFID systems. In Chapter 6 (Blind Signal Processing for RFID), we will investigate the possibility of identifying multiple tags simultaneously from signal processing viewpoint in the PHY layer by using multiple antennas at readers and tags. In Chapter 7 (Anti-Collision of Multiple-Tag RFID Systems), we deal with the problem of identifying multiple tags from the viewpoint of networking. The basic tree-splitting and Aloha-based anti-collision algorithms for multi-tag RFID systems and their theoretical performance analysis will be examined. Some improvements for the corresponding algorithms will be discussed. Chapter 8 (Localization with RFID) is devoted to localization problems. Several localization algorithms/methods by using RFID systems will be described. In Chapter 9 (Some Future Perspectives for RFID), covert radio frequency identification by using ultra wideband and time reversal techniques, as an example of high-end RFID applications, and chipless tags, as an example of low-end RFID systems, will be presented.

This book is targeted at graduate students and high-level undergraduate students, researchers in academia and practicing engineers in the field of RFID. The book can be used as both a reference book for advanced research and a textbook for students. We try our best to make it self-contained, but some preliminary background on probability theory, matrix theory and wireless communications are helpful.

Acknowledgements

In July 2012, Professor T. Russell Hsing, a Co-Editor-in-Chief of the Wiley ICT Book Series, invited us to write a book proposal summarizing our recent research results. In the meantime, we were planning to deliver a lecture on RFID-related signal processing techniques. Therefore, the book idea for *Digital Signal Processing for RFID* came to us. Dr. Simone Taylor, Director of Editorial Development, and Diana Gialo, Senior Editorial Assistant at John Wiley, also supported this book idea. We received constant encouragement from Professor Hsing in writing and revising the detailed book proposal. Therefore, we wish to express our deep gratitude to Professor Hsing, Dr. Taylor, and Diana Gialo for their direct initiative of this book project.

We are grateful to the four anonymous reviewers for their constructive advice and comments on the initial book proposal. In particular, one reviewer suggested that we add a chapter addressing radar-embedded communications. This leads to the concept of coverting RFID, which forms the main part of Chapter 9. The reviewers also motivated us to add some sections on RFID protocols and MIMO principles. All these suggestions and comments helped improve the organization and quality of this book. In this regard, our thanks also go to Anna Smart, Acting Commissioning Editor at John Wiley & Sons, Ltd, for her coordinaton of the proposal reviewing.

We are particularly grateful to Liz Wingett, Clarissa Lim, Tiina Wigley, and Victoria Taylor, Project Editors at John Wiley & Sons, Ltd, for their superb support and coordination of the project.

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Abbreviations

ACK	acknowledgement signal
ACMA	analytical constant modulus algorithm
AEE	average estimation error
AM	amplitude modulation
AME	average modulus error
AoA	angle of arrival
ASK	amplitude-shift keying
ASTC	Alamouti space-time coding
ATT	average transmission time
AWGN	additive white Gaussian noise
BER	bit error rate
AFSA1	adaptive frame size Aloha 1
AFSA2	adaptive frame size Aloha 2
BFSK	binary frequency-shift keying
BLF	backscatter link frequency
BPSK	binary phase-shift keying
BSP	blind signal processing
BSS	blind signal (or source) separation
C1G2	Class 1, Gen 2
CDMA	code-division multiple access
CIR	channel impulse response
CLT	Central Limit Theorem
CM	constant modulus
CMA	constant modulus algorithm
CPFSK	continuous-phase frequency-shift keying
CRB	Cramer–Rao bound
CRC	cyclic redundancy check
CROD	companion of real orthogonal design
CSI	channel state information
CSMA	carrier sense multiple accesses
CSMA/CA	carrier sense multiple access with collision avoidance
DAS	distributed antenna system
DC	direct current
DCF	distributed coordination function

DoA	direction of arrival
DR	divide ratio
DS	direct sequence
DSB	double sideband
DSTC	differential space-time coding
EIRP	equivalent isotropically radiated power
EPC	Electronic Product Code
FD	frequency-domain
FHSS	frequency hopping spread spectrum
FM	frequency modulation
FSK	frequency-shift keying
GPS	global positioning system
IC	integrated circuit
ID	identity
IDT	interdigital transducer
IoT	Internet of things
IR	impulse radio
ISI	inter-symbol interference
ISO	International Organization for Standardization
k-NN	*k*-nearest neighbours
LCD	least common denominator
LLS	linear least square
LMMSE	linear minimum mean square error
LNA	low-noise amplifier
LoS	line of sight
LPF	lowpass filter
LS	least square
LWLS	linear weighted least square
MAC	media access control
MIMO	multiple-transmit and multiple-receive antennas, or multiple-input multiple-output
MISO	multiple-transmit and single-receive antenna, or multiple-input single-output
ML	maximum likelihood
MLE	maximum likelihood estimation
MMSE	minimum mean square error
MUSIC	multiple signal characterization
NLoS	non line of sight
NRZ	non-return-to-zero
NSI	numbering system identifier
PA	power amplifier
PAM	pulse amplitude modulation
PPM	pulse position modulation
PC	protocol control
pdf	probability density function
PDoA	phase difference of arrival

PDP	power delay profile
PHY	physical or physical layer
PIE	pules-interval encoding
PLL	phase-locked loop
PM	phase modulation
PR	phase-reversal
PSD	power spectral density
PSK	phase-shift keying
QAM	quadrature amplitude modulation
QPSK	quadrature phase-shift keying
QT	query tree
RF	radio frequency
RFID	radio frequency identification
ROD	real orthogonal design
RSS	received signal strength
RSSE	received signal strength error
SAW	surface acoustic wave
SD	spatial-domain
SER	symbol error rate
SIMO	single-transmit and multiple-receive antennas, or single-input multiple-output
SISO	single-transmit and single-receive antenna, or single-input single-output
SNR	signal-to-noise (power) ratio
SS	spread spectrum
SSB	single sideband
STC	space-time coding
STT	signal travelling time
S-V	Saleh–Valenzuela
TDoA	time difference of arrival
TDSTT	time difference in signal travelling time
TH	time hopping
TID	tag's ID
ToA	time of arrival
TR	time reversal
TS	tree-splitting
UHF	ultrahigh frequency band
UMI	user-memory indicator
UWB	ultra wideband
VCO	voltage-controlled oscillator
WLAN	wireless local area network
WLS	weighted least square
XPC	extended protocol control

Contents

1

Introduction

1.1 What is RFID?

Identification is pervasive nowadays in daily life due to many complicated activities such as bank and library card reading, asset tracking, toll collecting, restricted accessing to sensitive data and procedures and target identification. This kind of task can be realized by passwords biometric data such as fingerprints, barcode, optical character recognition, smart card and radar. Radio frequency identification (RFID) is a technique to achieve object identification by using radio systems. It is a contactless, usually short distance, wireless data transmission and reception technique for identification of objects. An RFID system consists of two components:

- tag (also called transponder) – is a microchip that carries the identity (ID) information of the object to be identified and is located on/in the object;
- reader (also called interrogator) – is a radio frequency module containing a transmitter, receiver, magnetic coupling element (to the transponder) and control unit.

A passive RFID system works in the following way: the reader transmits radio waves to power up the tag; once the power of the tag reaches a threshold, the circuits in the tag start to work and the radio waves from the reader are modulated by the ID data inside the tag and backscattered to the reader and finally, the backscattered signals are demodulated at the reader and ID information of the tag is obtained.

RFID technology is quite similar to the well-known radar and optical barcode technologies, but an RFID system is different from radar in that backscattered signals from the tag are actively modulated in the tag (even for a passive tag or chipless tag), while backscattered signals in a radar system are often passively modulated by the scatterers of the object to be detected. An RFID system is different from an optical barcode system in that the information carrying tools are different: the RFID system uses radio waves as the tool, while the barcode system uses light or laser as the tool.

Many applications of RFID or barcode techniques are somewhat exchangeable, i.e., many ID identification tasks can be implemented by either RFID technique or barcode technique. However, optical barcode technology has the following critical drawbacks: (i) the barcode cannot be read across non-line-of-sight (NLoS) objects, (ii) each barcode needs care taken in order

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to be read and (iii) the information-carrying ability of the barcode is quite limited. RFID technology, using radio waves instead of optical waves to carry signals, naturally overcomes these drawbacks. It is believed that RFID can substitute, in the not-too-distant future, the widely used barcode technology, when the cost issue for RFID is resolved.

1.2 A Brief History of RFID

Many people date the origin of RFID back to the 1940s when radar systems became practical. In World War II, German airplanes used a specific manoeuvering pattern to establish a secret handshake between the pilot of the airplane and the radar operator in the base. Indeed, this principle is the same as that of modern RFID: to modulate the backscattering signal to inform the identity of an object. The true RFID, in the concept of modern RFID, appeared in the 1970s when Mario Cardullo patented the first transponder system and Charles Walton patented a number of inductively coupled identification schemes based on resonant frequencies. The first functional passive RFID systems with a reading range of several metres appeared in early 1970s [4]. Even though RFID has significantly advanced and experienced tremendous growth since then [1, 2], the road from concept to commercial reality has been long and difficult due to the cost of tags and readers. A major push that brought RFID technology into the mass market came from the retailer giant Wal-Mart, which announced in 2003 that it would require its top 100 suppliers to supply RFID-enabled shipments by the beginning of 2005[1]. This event triggered the inevitable movement of inventory tracking and supply chain management towards the use of RFID. Up to now, RFID applications have been numerous and far reaching. The most interesting and widely used applications include those for supply chain management, security and tracking of important objects and personnel [3, 5, 6].

Similar to other kinds of radio systems, the development of RFID has also been stimulated by necessity. Even though the progress in the design and manufacturing of antennas and microchips has smoothly driven performance improvement and cost decrease of RFID, booming development for it has not appeared until recently, since optical barcode technology has dominated the market for the last few decades. In recent years, many new technologies, such as smart antennas, ultra wideband radios, advanced signal processing, state-of-art anti-collision algorithms and so on, have been applied to RFID. In the meantime, some new requirements to object identification and new application scenarios of RFID have been emerging, such as simultaneous multiple object identification, NLoS object identification and increasing demand on data-carrying capacity of tag ID. It is this kind of application that calls for the deployment of RFID systems.

1.3 Motivation and Scope of this Book

Generally, signal processing is the core of a radio system. This claim also holds true for RFID. Several books are available now coping with other topics in RFID, such as basics, fundamentals, smart antennas, security and privacy, but no book has appeared to address signal processing issues in RFID. We aim to complete this task in this book.

The main purpose of this book is two-fold: first, it will be a textbook for both undergraduate and graduate students in electrical engineering; second, it can be used as a reference book

[1] see 'Wal-Mart Draws Line in the Sand' (www.rfidjournal.com/articles/view?462) and also 'Wal-Mart Expands RFID Mandate' (www.rfidjournal.com/articles/view?539).

for practice engineers and academic researchers in the RFID field. Therefore, the contents of this book include both fundamentals of RFID and the state-of-the-art research results in signal processing for RFID. For the former, we will discuss the operating principles, modulation schemes and channel models of RFID. For the latter, we will highlight the following research fields: space-time coding for RFID, blind signal processing for RFID, anti-collision of multiple RFID tags and localization with RFID. Also, due to the two-fold purpose of the book, some attention will be paid to pedagogical methods. For example, some concrete examples on the analysis of transmission efficiency of tree-splitting algorithms will be illustrated in detail before presenting general results in Chapter 7.

The book consists of the following chapters, after this one.

Chapter 2 – Fundamentals of RFID Systems. In this chapter, we will discuss the following issues: (i) operating principles of RFID, (ii) classification of RFID, (iii) analogue circuits for RFID and their basic analysis, (iv) channel models of RFID, (v) a brief review of RFID protocols and (vi) challenges in RFID. This chapter provides a basis for Chapters 3 to 9.

Chapter 3 – Basic Signal Processing for RFID. In this chapter, we will discuss some basic signal processing techniques and their applications in RFID, which include analogue/digital filtering and optimal estimation.

Chapter 4 – RFID-oriented Modulation Schemes. Since a passive RFID tag does not have an 'active' transmitter, some complicated signal modulation schemes in general communication systems cannot be applied to RFID. Instead, only very simple modulation schemes, namely, binary amplitude-shift keying and frequency/phase-shift keying, are suitable for an RFID tag. In this chapter, these modulation schemes, tailored to RFID channels, will be described. The performance of these modulation schemes for RFID channels will be investigated.

Chapter 5 – MIMO for RFID. In this chapter, we will discuss the following issues: (i) channel models of RFID systems with multiple antennas at both readers and tags (MIMO); (ii) signal design at the reader for RFID-MIMO systems (iii) space-time coding at the tag for RFID-MIMO systems and (iv) differential space-time coding at the tag for RFID-MIMO systems. Using multiple antennas in radio systems (especially in communication systems) is a general trend. Actually, employing multiple antennas has been incorporated into many existing communication standards. It is also believed that RFID systems equipped with multiple antennas will be deployed in the near future. Therefore, this chapter will be dedicated to the combination of RFID with MIMO. We will show that, by proper design, the bit-error-rate performance of the system can be greatly improved by using multiple antennas at the reader and tag.

Chapter 6 – Blind Signal Processing for RFID. In practice, one often meets the situation where several or many transponders are present in the reading zone of a single reader at the same time. Therefore, it is important to study the techniques to identify multiple tags simultaneously. In principle, two approaches can be used to do this job. The first one is to use collision avoidance techniques such as Aloha from a networking viewpoint. The second one is to use source separation techniques from a signal processing viewpoint. In this chapter, the second approach will be investigated, while Chapter 7 will be devoted to the first approach. It will be shown that, under a moderate SNR and when the number of measurements to the multiple tags in one snapshot is sufficiently high, the overlapped signals coming from the multiple tags can