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Digital Signal Processing for RFID

Feng Zheng • Thomas Kaiser

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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

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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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We are happy to acknowledge fruitful cooperation with Dr Bernd Geck and Mr Eckhard Denicke at the Leibniz University of Hannover and Dr. Kiattisak Maichalernnukul at Rangsit University in RFID-related projects. We are grateful to Professor Qing Zheng at Gannon University, Mr. Yuan Gao and Mr. Marc Hoffmann at the University of Duisburg-Essen for their carefully proofreading the book and helpful comments.

Finally, we want to thank our families Zhiying, Anna Yuhan, Petra and Hendrik for their unwavering love, support and patience. Without their spiritual support and tolerance in time, this book could not have been finished. Without their love, our expedition in this exciting field could never succeed. Therefore, we would like to dedicate this book to them.

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

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 be separated at the reader receiver if the number of the tags is less than the number of receiving antennas at the reader.

Chapter 7 – Anti-Collision of Multiple-Tag RFID Systems. As already mentioned, there are two approaches to dealing with the multiple-tag identification problem. In this chapter, we will discuss this problem from the networking viewpoint. Basically, the traditional anti-collision algorithms in WLAN, such as tree splitting and slotted Aloha, can be applied to this problem. Since passive RFID systems are highly asymmetric, i.e., the reader is resource-rich, while tags have very limited storage and computing capabilities and are unable to hear the signal transmitted by other tags and to detect collisions, some advanced collision-avoidance algorithms in WLAN, such as carrier sense multiple access are difficult to implement in RFID tags. Therefore, basic tree-splitting and Aloha-based anti-collision algorithms for multi-tag RFID systems will be discussed in this chapter. The methods for the theoretical performance analysis of these algorithms will be addressed. It is found that the static Aloha yields very poor performance in both mean identification delay and transmission efficiency for multiple-tag RFID systems. Therefore, we propose two adaptive frame size Aloha algorithms, which have only a very light computational burden at the reader and no additional computational burden at the tag, but yield significant performance improvement.

Chapter 8 – Localization with RFID. In principle, the problem of localization with the help of RFID is similar to radar ranging problem. However, RFID ranging has its peculiar concerns. Since the distance between the reader and tag is usually short (typically of the order of less than 10 m), the round-trip signal delay is on the order of a few tens of nanoseconds. Because the available bandwidth of typical RFID signals is narrow, it is difficult to measure the time of arrival or time difference of arrival of the RFID signal. Thus baseband phase information is extremely useful for RFID localization problems. In this chapter, we will give an overview for RFID localization algorithms using various methods based on different kinds of information. To use the localization algorithms of the geometric approach, the range between readers and tags or angle of arrival (AoA) should be reliably measured or estimated from the measured information. Two approaches, namely frequency-domain phase difference of arrival (PDoA) approach and spatial-domain PDoA approach for measuring the range and AoA respectively, will be discussed. Finally, the challenging issue, that is, non-line-of-sight mitigation issue in RFID localization, will be addressed.

Chapter 9 – Some Future Perspectives for RFID. RFID systems discussed in preceding chapters belong to the middle class of RFID in the sense that IC chips are integrated inside the tags, but the power needed for signal transmission in the tags of this kind of RFID should be harvested from the reader's transmitted radio waves. This situation can be extended in two extreme ends: chipless tags and active tags. Using active tags, some advanced communication functionalities, such as covert radio frequency identification, can be realized. Using chipless tags, most tags can be printed by inkjet printers, thus greatly reducing the cost of manufacturing and packaging of tags. In this chapter, we will present a brief review for covert RFID and some chipless tags. For the first task, we need to use ultra wideband (UWB) technology and the time reversal (TR) technique. Therefore, some basics for UWB and TR will be also introduced. For the second task, two kinds of chipless tags, namely time-domain reflectometry-based chipless tags and frequency-domain spectral-signature-based chipless tags, will be discussed.

1.4 Notations

Throughout the book, we use $\mathbf{I}$ to denote an identity matrix, whose dimension is indicated by its subscript if necessary, $P_A(x)$ and $p_A(x)$ represent, respectively, the cumulative distribution function and probability density function (pdf) of a random variable A, $\mathbb{E}$ (or $\mathbb{E}_A$ if necessary) stands for the expectation of a random quantity with respect to the random variable A, $\mathbb{E}(\cdot|\cdot)$ denotes the conditional expectation, and $\mathrm{Var}(A)$ stands for the variance of A. The notation $\mathcal{N}(0, \sigma^2)$ stands for a Gaussian-distributed random variable with zero mean and variance σ^2. For a matrix or vector, the superscripts ^{T}, *, † denote the transpose, the element-wise conjugate (without transpose), and the Hermitian (conjugate) transpose, respectively, of the matrix or vector. The notations * and † also apply to a scalar. The symbol $\jmath$ is defined as $\jmath = \sqrt{-1}$. The function log is naturally based, if the base is not explicitly stated. We use `diag` to denote a diagonal matrix with the diagonal entries being specified by the corresponding arguments. The real part and imaginary part of a complex variable are denoted by `Re` and `Im`, respectively. We use $|\cdot|$ or $\det(\cdot)$ to denote the determinant of a matrix. Throughout the book, the symbols 0 or $\mathbf{0}$ denote scalar zero, vector zero or matrix zero with corresponding dimensions, depending on the context.

For other notations, we might use the same symbol to denote different things in different chapters or sections. If this case happens, we will explicitly explain what the symbol stands for.

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2

Fundamentals of RFID Systems

2.1 Operating Principles

In this section, the basic operating principle of RFID will be discussed. Sending back the incident radio frequency (RF) power, which is modulated by the on-board information bits in a tag, is the communication principle used in passive RFID systems. The operation of an RFID involves four steps [26]: First, the reader emits electromagnetic power in the form of radio waves to the tag. Second, the antenna at the tag receives the electromagnetic power and thus charges the on-board capacitor. Third, once the energy built up in the capacitor reaches a threshold, it switches on RFID-tag circuit and then a modulated signal at the tag will be transmitted back to the reader. Finally, the returned signal is demodulated and the information bits are detected at the reader's receiver. The whole process is illustrated in Figure 2.1.

The conventional method for powering RFID tags wirelessly is to use a continuous-wave (which often has a constant envelope) power transmission from the reader, as specified by EPCglobal, Class 1, Generation 2 standard [7]. This provides a steady source of power for the tag to harvest, although very inefficiently.

There are several ways for the interaction between tag and reader for the tag to capture required energy: inductive coupling, backscattering coupling and capacitive coupling.

Inductive coupling is illustrated in Figure 2.2. In Figure 2.2, the capacitor C_r together with the coil of the reader's antenna forms a parallel resonant circuit, whose resonant frequency corresponds with the transmission frequency of the reader. The capacitor C_1 together with the coil of the tag's antenna forms another parallel resonant circuit, whose resonant frequency is tuned to the transmission frequency of the reader. Very high currents are generated at the antenna coil of the reader, which induce a voltage across the antenna coil of the tag. This voltage is rectified by the diode D_1, serving as the power supply for the data-carrying microchip of the tag.

The power captured by the coil of tag's antenna can be assessed by using transformer theory.

Both amplitude and phase of the returned signal are affected by the impendence of the tag, which can be again adjusted by a load connected to the microchip in the tag. Thus the tag's ID data information can be sent back to the reader. This kind of data modulation is called load modulation.

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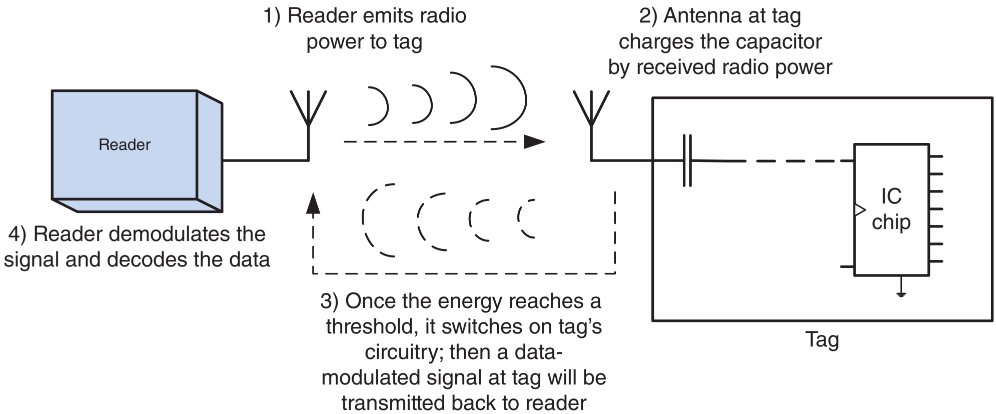

Figure 2.1 An illustration of RFID principle.

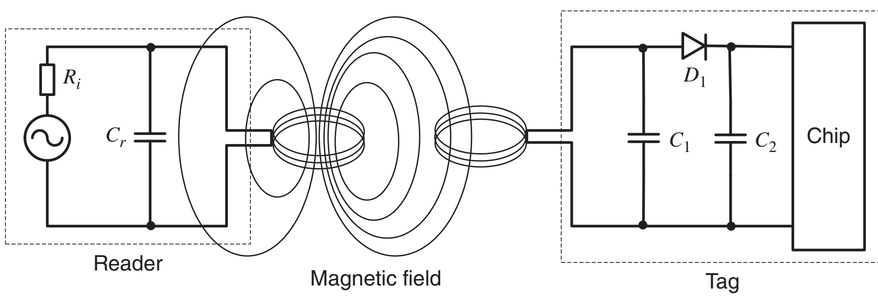

Figure 2.2 An illustration of electromagnetic field coupling between reader and tag.

Inductive coupling is a near-field effect. Accordingly the distance between the coils of readers and tags must be kept within the range of the effect: normally this is about 0.15 wavelength of the frequency in use. Therefore, inductive coupling is often used on the lower RFID frequencies, that is, below 135 kHz or at 13.56 MHz.

When the frequency of the radio signal emitted by the reader is so high that the wavelength of the signal is much smaller than the gap between reader and tag, the radio signal will propagate away from the reader and the inductive coupling between the coils of reader and tag will become very weak. In this case, the power required to power up the tag's circuitry is intercepted by the tag's antenna and a part of the incident radio waves to the tag will be reflected back towards the RFID reader. This process is referred to as backscattering coupling, which is also called radiative coupling. The backscattering coupling is illustrated in Figure 2.3.

The power received by the tag's antenna via backscattering coupling can be assessed by free-space path loss law.

The way in which the signal is reflected back depends on the properties of the tag. Factors such as the cross sectional area and antenna properties and so on within the tag all can affect the strength of the reflected power. Therefore, changing factors such as adding or subtracting a load resistor across the antenna of the tag can change both amplitude and phase of the

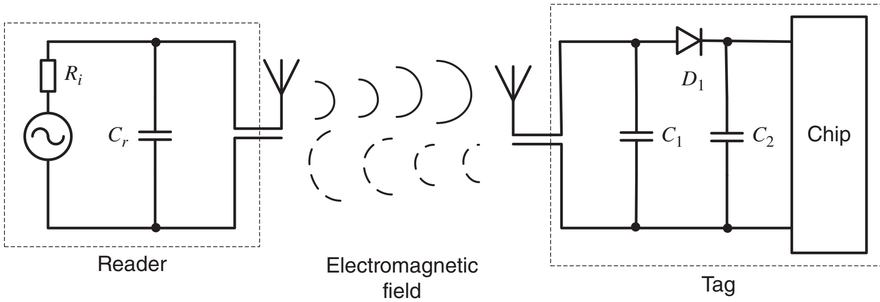

Figure 2.3 An illustration of backscattering coupling between reader and tag.

Table 2.1 Typical RFID operating frequencies and characteristics

	low frequency	high frequency	ultra high frequency	microwave
frequency	125∼134 kHz	13.56 MHz	860–960 MHz	2.45/5.8 GHz
EM coupling	inductive	inductive	radiative	radiative
read range	≈ 1 m	≈ 1 m	3 m (typical) 10 m (achievable)	4.5 m (typical)
data rate	≈ 1 kbps	tens of kpbs	50–150 kbps	not specified

re-radiated signal. Using the tag's ID data to control the addition or subtraction of the load resistor can thus send the data information back to the reader. This kind of data modulation is called backscattering modulation.

Capacitive coupling is used for very short ranges (0.1 cm–1 cm) where a form of close coupling is needed. It uses electrodes–the plates of the capacitor, to provide the required coupling between tag and reader. Capacitive coupling operates best when items like smart cards are inserted into a reader: in this way the card is in very close proximity to the reader. Therefore, capacitive coupling is often used for smart cards. The data information in the tag is sent back to the reader by modulating the load in the tag.

In this book, our attention will be focused on the RFID with inductive coupling and backscattering coupling.

Typical operating frequencies of RFID and corresponding characteristics are summarized in Table 2.1.

2.2 Passive, Semi-Passive/Semi-Active and Active RFID

According to the power source from which the energy for RFID tags is obtained, RFID tags can be classified into passive tags (or passive RFID), semi-passive (or semi-active) tags (or semi-passive RFID) and active tags (or active RFID), as illustrated in Figure 2.4.

A passive tag has neither a battery nor a radio transmitter. The power for operating the tag chip is obtained by rectifying RF energy intercepted by the tag antenna. A semi-passive tag is equipped with a battery to provide power for the tag chip, but still uses the power captured

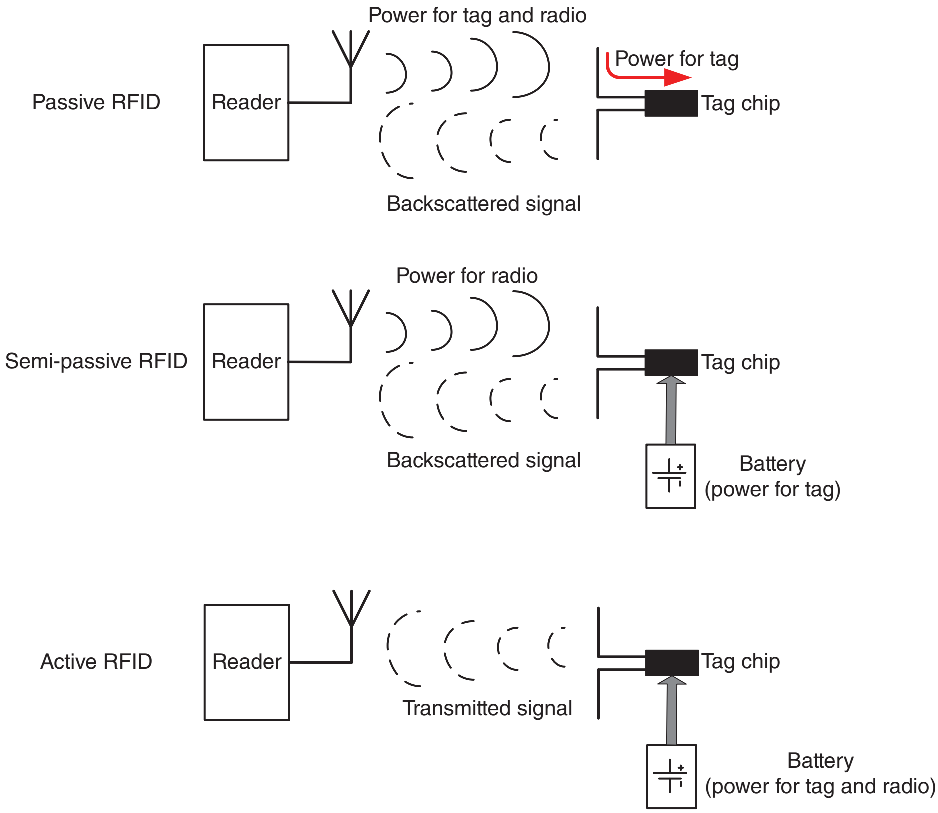

Figure 2.4 Classification of RFID tags according to power sources.

from the reader's emitted radio waves to communicate with the reader. Note that the battery of a semi-passive tag never provides the power for data transmission between tag and reader, but serves exclusively to supply the microchip and for the retention of the stored data. The power of the electromagnetic field received from the reader is the only power used for the data transmission between tag and reader [9].

An active tag is an architecturally conventional radio system. It has its own transmitter and receiver and uses a battery to power up its transmitter, receiver and chip [5]. From a pure technical perspective, active tags are not genuine 'RFID' tags, but short-range radio devices [9]. Almost all the advanced signal processing techniques can be applied to active tags without special consideration. Therefore, the contents of this book are confined on passive and semi-passive RFID.

Since passive tags have no internal power supply, they are much cheaper than active tags and have relatively long life span. The majority of RFID tags in the market are passive. Semi-passive tags are very similar to passive tags except for the addition of a small battery, which allows the tag chip to be immediately powered up once being woken up and removes the need for the antenna to be designed to collect power from the impinging signal. As a result, semi-passive tags can provide much longer read range than passive tags do.

As passive UHF RFID technology has matured, many new application scenarios have been proposed where a tag is expected to transmit ever-increasing amount of data. These scenarios include tags with expanded on-chip memory of 128 KB or more, tags including complex cryptographic security protocols, or tags that transfer stored sensor data in a semi-passive mode [24]. An extreme example of this trend is the Intel WiSP, a passive UHF RFID platform including a fully accessible, programmable 16-bit microcontroller with a variety of sensor peripherals [23]. The WiSP platform is currently being used for a variety of research applications. There are a variety of ways to increase the data rates of the communications between tag and reader.

2.3 Analogue Circuits for RFID

Figure 2.5 shows an example circuit for a load-modulation RFID tag with subcarrier communications [9]. This circuit consists of four functional parts: the tag antenna, power rectifier, timing clock and load modulator.

The power rectifier is mainly constructed by four diodes D_1–D_4, which form a typical bridge rectifier. The input voltage is provided by the induced high-frequency sinusoidal waves from the antenna coil. The output voltage is further smoothed by capacitor C_2. The zener diode D_5 (ZD 5V6) provides protection for possible surcharge of the bridge rectifier due to various reasons, for example, when the tag is very near to the reader. Due to the usage of D_5 and C_2, the voltage across the zener diode can be kept at exactly 5.6 V when the tag is well charged. The timing clock is mainly built up by the ripple counter IC 4024. The output Q_n is the nth stage of the counter, meaning that the frequency of the timing clock signal Q_n is the frequency of the input signal CLK divided by 2^n. The external timing signal CLK is produced by the induced sinusoidal signal from the antenna coil, where resistor R_2 provides protection for the ripple counter. Supposing that the operating frequency of the RFID is 13.56 MHz, the output Q_6 will provide an internal clocking signal of frequency $13.56\,\text{MHz}/2^6 = 212\,\text{kHz}$.

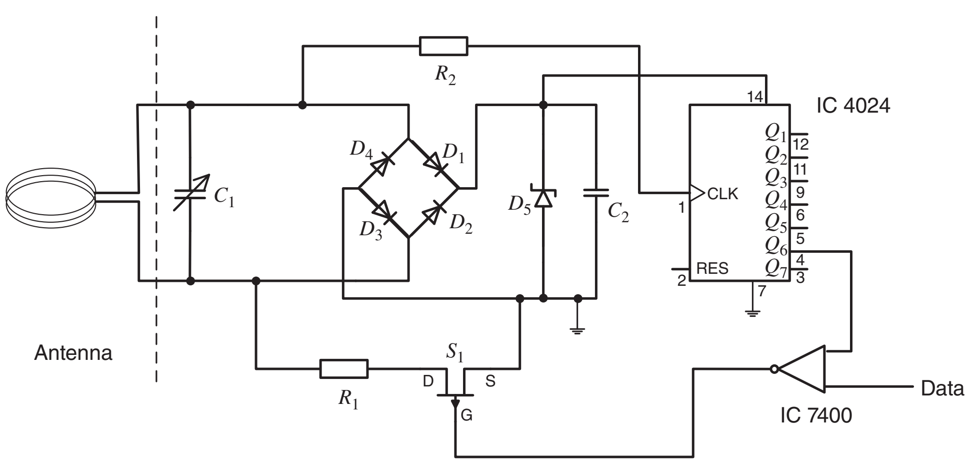

Figure 2.5 An example circuit for the load modulation RFID tag with subcarrier communications. (Reproduced with permission from Figure 3.18, K. Finkenzeller. RFID Handbook, 3rd ed. Wiley, Chichester, pp. 45, 2010.)