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CONTENTS

PREFACE

Introduction to Radio Frequency Identification (RFID): RFID is a wireless modulation and demodulation technique for automatic identification of objects, tracking goods, smart logistics, and access control. RFID is a contactless, usually short-distance transmission and reception technique for unique ID data transfer from a tagged object to an interrogator (reader). The generic configuration of an RFID system comprises (i) an ID data-carrying tag, (ii) a reader, (iii) a middleware, and (iv) an enterprise application. The reader interrogates the tag with the RF signal, and the tag in return responds with an ID signal. Middleware controls the reader and processes the signal and finally feeds into enterprise application software in the IT layer for further processing. The RFID technology has the potential of replacing barcodes due to its large information-carrying capacity, flexibility in operation, and versatility of application [1]. Due to its unique identification, tracing, and tracking capabilities, RFID also gives value-added services incorporating various sensors for real-time monitoring of assets and public installations in many fields. However, the penetration of RFID technology is hindered due to its high price tag, and many ambitious projects have stalled due to the cost of the chips in the tags. Chipless RFID tags mitigate the cost issues and have the potential to penetrate mass markets for low-cost item tagging [2]. Due to its cost advantages and unique features, chipless RFID will dominate 60% of the total RFID market with a market value of $4 billion by 2019 [3]. Since the removal of the microchip causes a chipless tag to have no intelligence-processing capability, the signal processing is done only in the reader. Consequently, a fully new set of requirements and challenges need to be incorporated and addressed, respectively, in a chipless RFID tag reader. This book addresses the new reader architecture and signal processing techniques for reading various chipless RFID tags.

Recent Development of Chipless RFID Tags: IDTechEx (2009) [3] predicts that 60% of the total tag market will be occupied by the chipless tag if the tag can be made at a cost of less than a cent. However, removal of an application-specific integrated circuit (ASIC) from the tag is not a trivial task as it performs many RF signal and information-processing tasks. Intensive investigation and investment are required for the design of low cost but robust passive microwave circuits and antennas using low-conductivity ink on low-cost and lossy substrates. Some types of chipless RFID tags are made of microwave resonant structures using conductive ink. Obtaining high-fidelity (high-quality factor) responses from microwave passive circuits made of low-conductivity ink on low-cost and lossy materials is very difficult [4]. Great design flexibility is required to meet the benchmark of reliable and high-fidelity performance from these low-grade laminates and poor conductivity ink. This exercise has opened up a new discipline in microwave printing electronics in low-grade laminates [5].

The low-cost chipless tag will place new demands on the reader as new fields of applications open up. IDTechEx [3] predicts that, while optical barcodes are printed in only a few billions a year, close to one trillion (>700 billion) chipless RFIDs will be printed each year. The chipless RFID has unique features and much wider ranges of applications compared to optical barcodes. However, very little progress has been achieved in the development of the chipless RFID tag reader and its control software, because conventional methods of reading RFID tags are not implementable in chipless RFID tags. As for an example, handshaking protocol cannot be implemented in chipless RFID tags. Dedicated chipless RFID tag readers and middleware [6] need to be developed to read these tags reliably.

The development of chipless RFID has reached its second generation with more data capacity, reliability, and compliance to some existing standards. For example, RF-SAW tags have new standards, can be made smaller with higher data capacity, and currently are being sold in millions [7]. Approximately 30 companies have been developing TFTC tags. TFTC tags target the HF (13.65 MHz) frequency band (60% of existing RFID market) and have read–write capability [7]. However, neither RF-SAW nor TFTC is printable and could not reach sub-cent-level prices. In generation-1 of conductive ink-based fully printable chipless RFID tag development, few chipless RFID tags, which are in the inception stage, have been reported in the open literature. They include a capacitive gap-coupled dipole array [8], a reactively loaded transmission line [9], a ladder network [10], and finally a piano and a Hilbert curve fractal resonators [11]. These tags are in prototype stage, and no further development to commercial grade has been reported to date. A comprehensive review of chipless RFID can be found in the author's most recent books [12].

Following 20 years of RF and microwave research experiences, the author has pioneered multi-bit chipless RFID research [13, 14]. For the last 10 years at Monash University, the author's research activities include numerous chipless tag and reader developments as follows.

At Monash University, the author's research group has developed a number of printable, multi-bit chipless tags featuring high data capacity. These tags can be categorized into two types: *retransmission based* and *backscattered based*. The *retransmission-based* tag, originally presented by Preradovic et al. [13], uses two orthogonally polarized wideband monopole antennas and a series of spiral resonators. The RFID reader sends a UWB signal to the tag, and the receiving antenna of the tag receives it, and then it passes through the microstrip transmission line. The gap-coupled spiral resonator-based stopband filters create attenuations and phase jumps in designated frequency bands, and this magnitude and phase-encoded signal is retransmitted back to the reader by the tag's transmitting antenna. The attenuation in the received signal due to the resonator encodes the data bits. In two Australian Research Council (ARC) Grants (DP0665523: *Chipless RFID for Barcode Replacement*, 2006–2008, and LP0989652: *Printable Multi-Bit Radio Frequency Identification for Banknotes*, 2009–2011), the author developed up to 128 data bits of chipless RFID with four slot-loaded monopole antennas and wideband feed networks [15]. This chipless tag is fully printable on polymer substrate.

Backscatter-Based Chipless Tag: Balbin et al. [13] have presented a multiantenna backscattered chipless tag. Here, only the resonator structure is present on the tag, and as no transmitter–receiver tag antenna exists, it is more compact than retransmission-type tags. The interrogation signal from a reader is backscattered by the tag. By analyzing this backscattered signal's attenuation at particular frequencies, the tag ID is decoded.

Monash University Chipless RFID Systems: Under various research grant schemes, the CI has developed various chipless RFID tag reader architectures and associated signal processing schemes. To date, four different varieties of chipless RFID tag readers have been developed for the 2.45, 4–8, and 22–26.5 GHz frequency bands. Feasibility studies of advanced level detection [13] and error correction algorithm have been developed.

As stated [2, 12–14], the author's group has developed four different varieties of chipless RFID tag readers in various frequency bands at 2.45, 4–8, and 22–26.5 GHz frequency bands. The readers comprised an RF transceiver section, a digital control section, and a middleware (control and processing). The reader transmitter comprises a swept frequency voltage-controlled oscillator (VCO) [6, 16]. The VCO is controlled by a tuning voltage that is generated by a digital-to-analog converter (DAC). Each frequency over the ultra-wideband (UWB) from 4 to 8 GHz is generated with a single tuning voltage from the DAC. In addition, the VCO has a finite settling time to generate a CW signal against its tuning voltage. Combining all these operational requirements and linearity of the devices, the UWB signal generation is a slow process (taking a few seconds to read a tag). To alleviate this problem and improve the reading speed, some corrective measures can be taken. They are (i) high-speed ADC and (ii) low settling time VCO. These two devices will be extremely expensive if available in the market. The reader cost will be very high to cater for the requirement specifications of the chipless RFID reader. In this regard, signal processing for advanced detection techniques alleviates the reading process in greater details. Also, the sensitivity of the reader architecture using dual antenna in bistatic radar configuration and I/Q modulation techniques can be greatly enhanced. Highly sensitive receiver design is imperative in detecting very weak backscattering signal from the chipless tag. With the presence of interferers and movement and the variable trajectory of the moving tags, this situation is worsened. In this regard, a highly sensitive UWB reader receiver needs to be designed. Designing such a receiver is not a trivial task where the power transmission is limited by UWB regulations. I\Q modulation in the receiver will improve the sensitivity to a greater magnitude.

Additional to this high-sensitivity receiver design, high-end digital board with a powerful algorithm will alleviate the reading process. The digital board serves as the centerpiece of the reader where data would be processed, and numerous control signals to the RF section of the reader would be generated. The digital board has a Joint Test Action Group (JTAG) port where a host PC can be connected to monitor, control, and reprogram the reader if necessary. In addition, it is also the host to the power supply circuit, which is used to generate the necessary supply voltages for most components of the reader. The digital board consists of (i) an FPGA board with ADC, (ii) a power supply circuit, and (iii) a DAC. High sampling rate A/D and D/A converters and an FPGA controller will augment the powerful capturing and processing of backscattering signals. The digital electronics and interface with a PC will accommodate custom-made powerful algorithm such as singular value decomposition for improved detection [17] and time–frequency analysis [18] for localization [19] and anticollision [20] of chipless RFID tags. All this control algorithm and signal processing software will be innovations in the field. The book has addressed these advanced level analog and digital designs of the chipless RFID reader.

In conventional chipped RFID system, established protocols are readily available for tag detection and collision avoidance. Reading hundreds of proximity tags with the flick of an eye is commonplace. However, reading multiple chipless RFID tags in close proximity is not demonstrated as yet. RFID middleware is an IT layer to process the captured data from a tag by a reader. Middleware applies filtering, formatting, or logic to tag data captured by a reader so that the data can be processed by a software application. For chipped RFID, there are established protocols for these tasks. However, in chipless RFID, tasks such as handshaking are not possible. Therefore, a completely new set of IT layers needs to be developed. Raw data obtained from a chipless tag need to be processed and denoised, and new techniques need to be developed. They are as follows: (i) signal space representation of chipless RFID signatures [21], (ii) detection of frequency signature-based chipless RFID using UWB impulse radio interrogation [22], (iii) a singularity expansion method for data extraction from chipless RFID [23], and finally (iv) noise reduction and filtering techniques [23, 24]. These methods will improve the efficacy and throughput of various types of reading processes. For example, in (i), tag signatures are visualized as signal points in a signal space (Euclidian space). (i) performs better than a threshold-based approach to detection. In (ii), the received signal from a chipless tag is processed in time domain, and information-carrying antenna mode RCS is processed to identify tags. In (iii), transient response from the tag is processed in poles and residues, and tag ID is detected. In (iv), wavelet transforms and prolate spheroidal wave functions are used for noise filtering. All these detection and filtering techniques are investigated in the context of the chipless RFID system, and the best approach to tag detection is integrated in the IT application layer.

The book aims to provide the reader with comprehensive information with the recent development of chipless RFID signal processing, software development algorithm, and protocols. To serve the goal of the book, the book features ten chapters in two sections. They offer in-depth descriptions of terminologies and concepts relevant to chipless RFID detection algorithm and anticollision protocols related to the chipless RFID reader system. The chapters of the book are organized into two distinct topics: (i) *Section 1:* Detection and Denoising and (ii) *Section 2:* Multiple Access and Localization. In chapter 1 chipless RFID fundamentals with a comprehensive overview are given. The physical layer development of reader architecture for conventional RFID systems is an established discipline. However, a physical layer implementation of the chipless RFID reader is a fully new domain of research. This author group has already published a book in this area [25]. This book focuses on the back-end postprocessing and detection algorithms for chipless RFID reader. Various detection algorithms for chipless RFID tags such as signal space representation, time-domain analysis, singularity expansion method for data extraction, and finally denoising and filtering techniques for frequency signature-based chipless RFID tags are presented in Chapters 2–5. Collision and error correction protocols, multi-tag identification through time–frequency analysis, FMCW-radar-based collision detection and multi-access for chipless RFID tags, and localization and tracking of tag are presented in Chapters 6–9. Finally, a state-of-the-art chipless RFID tag reader that incorporates all the physical and IT layer developments stated previously are presented in Chapter 10. The chapter has demonstrated how the reader can mitigate interferences and collisions keeping the data integrity in reading multiple tags in challenging environments such as retails, libraries, and warehouses.

In the book, utmost care has been paid to keep the sequential flow of information related to the chipless RFID reader architecture and signal processing. Hope that the book will serve as a good reference of chipless RFID systems and will pave the ways for further motivation and research in the field.

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CHAPTER 1

INTRODUCTION

1.1 CHIPLESS RFID

Radio frequency identification (RFID) is a wireless data communication technology widely used in various aspects in identification and tracking. In this era of communication, information, and technology, RFID is undergoing tremendous research and developments. It has the potential of replacing barcodes due to its information capacity, flexibility, reliability, and versatilities in application [1]. The unique identification, tracking, and tracing capabilities of RFID systems have the potential to be used in various fields like real-time asset monitoring, tracking of item and animals, and in sensor environments. However, the mass application of RFID is hindered due to its high price tag, and many ambitious projects had been killed due to the cost of chipped tags. The low-cost alternative of chipped RFID system is the printable chipless RFID that has the potential to penetrate mass markets for low-cost item tagging [2]. The chipless tag doesn't have any chips, and hence, the most burdens for signal and data processing go to the reader side. This introduces a set of new challenges and requirements for the chipless RFID reader that need to be addressed. This book comprises the new

Chipless Radio Frequency Identification Reader Signal Processing, First Edition.
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advanced signal processing and tag detection methods that are being used in chipless RFID for identification and tracking of tags.

RFID is an evolving wireless technology for automatic identifications, access controls, asset tracking, security and surveillance, database management, inventory control, and logistics. A generic RFID system has two main components: a tag and a reader [3]. As shown in Figure 1.1, the reader sends an interrogating radio frequency (RF) signal to the tag. The interrogation signal comprises clock signal, data, and energy. In return, the tag responds with a unique identification code (data) to the reader. The reader processes the returned signal from the tag into a meaningful identification code. Some tags coupled with sensors can also provide data on surrounding environment such as temperature, pressure, moisture contents, acceleration, and location. The tags are classified into active, semi-active and passive tags based on their onboard power supplies. An active tag contains an onboard battery to energize the processing chip and to amplify signals. A semi-active tag also contains a battery, but the battery is used only to energize the chip, hence yields better longevity compared to an active tag. A passive tag does not have a battery. It scavenges power for its processing chip from the interrogating signal emitted by a reader; hence, it lasts forever. However, the processing power and reading distance are limited by the transmitted power (energy) of the reader. The middleware does the back-end processing, command, and control and interfacing with enterprise application as shown in Figure 1.1.

As mentioned previously, the main hindrance in mass deployment of RFID tags for low-cost item tagging is the cost of the tag. The cost of the tag mainly comes from the application-specific integrated circuit

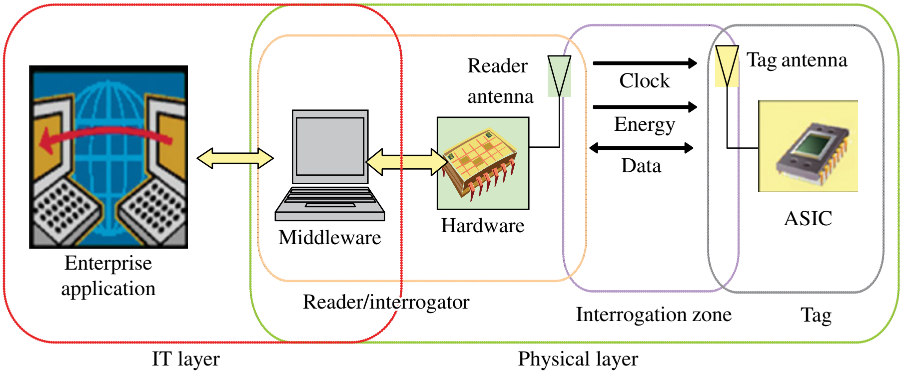

Figure 1.1 Architecture of conventional radio frequency identification system.

(ASIC) or the microchip of the tag. The removal of chip from the tag will lower the cost of tag to a great extent. This can be an excellent alternative for traditional barcodes, which suffer from several issues such as the following: (a) each barcode is individually read, (b) needs human intervention, (c) has less data handling capability, (d) soiled barcodes cannot be read, and (e) barcodes need line-of-sight operation. Despite these limitations, the low-cost benefit of the optical barcode makes it very attractive as it is printed almost without any extra cost. Therefore, there is a pressing need to remove the ASIC from the RFID tag to make it competitive in mass deployment. After removing the ASIC from the RFID tag, the tag can be printed on paper or polymer, and the cost will be less than a cent for each tag [4]. The IDTechEx research report [2] advocates that 60% of the total tag market will be occupied by the chipless tag if the tag can be made less than a cent. As most of the tasks for RFID tag are performed in the ASIC, it's not a trivial task to remove it from the tag. It needs tremendous investigation and investment in designing low-cost but robust passive microwave circuits and antennas using conductive ink on low-cost substrates. Additionally to these, obtaining high-fidelity response from low-cost lossy materials is very difficult [4]. In the interrogation and decoding aspects of the RFID system is the development of the RFID reader, which is capable to read the chipless RFID tag. Conventional methods of reading RFID tags are not implementable in reading chipless RFID tags. Therefore, dedicated chipless RFID tag readers need to be implemented [5]. This is the first book in this discipline that presents detailed aspects, challenges, and solutions for advanced signal processing for chipless RFID readers for detection, tracking, and anticollision.

The market of chipless RFID is emerging slowly, and the demand is increasing day by day. As forecasted by IDTechEx, the market volume of chipless RFID was less than $5 million in 2009. However, this market will grow to approximately $4 billion in 2019 [6, 7]. In contrast to 4–5 billion optical barcodes that are printed yearly, approximately 700 billion chipless tags will be sold in 2019. Therefore, a significant interest is growing in researchers for the development and implementation of low-cost chipless RFID systems. This book is presenting the advanced signal processing methods that are being used in chipless RFID system for detection, identification, and tracking, and collision avoidance.

The development of chipless RFID systems has already come a long way. Compared to early days, it has already in its second-generation development phase with more data capacity, reliability, and compliances of some existing standards. RF-SAW tags got new standards, can be made smaller with higher data capacity, and currently are being sold in millions. Approximately 30 companies have been developing TFTC. TFTC targets HF (13.65 MHz) band (60% of existing RFID market) and has the read–write capability [7].

In generation I, only a few chipless RFID tags, which were in the inception stage, were reported in the open literature. They include a capacitive gap coupled dipole array [8], a reactively loaded transmission line [9], a ladder network [10], and finally a piano and a Hilbert curve fractal resonators [11]. These tags were in prototype stage, and no further development in commercial grade was reported so far.

It is obvious that chipless RFID is a potential option for replacing barcodes and hence realizing the fact big industry players such as IBM, Xerox, Toshiba, Microsoft, HP, and new players such as Kavio and Inksure have been investing tremendously in the development of low-cost chipped and chipless RFID. Figure 1.2 shows the motivational factors in developing chipless RFID tags and reader systems. The data shown in the figure is approximated from two sources [6, 7]. Currently, the conventional chipped tags cost more than 10¢ if purchased in large

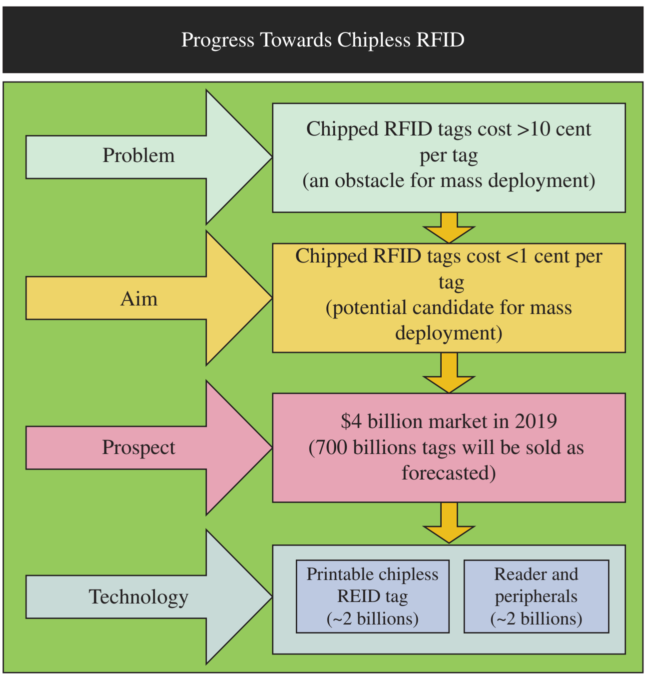

Figure 1.2 Prospect of chipless RFID technology.

quantities. This high tag price hinders mass deployment of RFID in low-cost item-level tagging. The goal is to develop sub-cent chipless tags that will augment the low-cost item-level tagging. The technological advancements in both the chipless tags and their readers and peripherals will create approximately $4 bn market in 2019 [6, 7].

According to the prediction of www.MarketsandMarkets.com (accessed on June 9, 2012) [6], the revenue generated in global chipless RFID market is expected to reach $3925 million in 2016 from $1087 million in 2011, at an estimated combined annual growth rate of 29.3% from 2011 to 2016. The targeted market sectors for the chipless RFID include retail, supply chain management, access cards, airline luggage tagging, aged care and general healthcare, public transit, and library database management system. The author's group has been developing chipless RFID tag technologies targeting many of these sectors since 2004.

To the best of the author's knowledge, there is only one book so far by the same author group regarding the chipless RFID reader development [12]. The published book mainly focuses on the hardware development and implementation for chipless RFID tag reader. However, the background signal processing and identification have not been discussed in detail. This book focuses on the signal postprocessing for tag identification, tracking, noise mitigation, and multi-tag identification aspects. The author group and their chipless RFID research team has been working on the chipless RFID tag readers since 2004 [13]. Significant strides have been achieved to tag not only the polymer banknotes but also many low-cost items such as books, postage stamps, secured documents, bus tickets, and hanging cloth tags. The technology relies on encoding spectral signatures and decoding the amplitude and phase of the spectral signature [14]. The other methods are phase encoding of backscattered spectral signals [15] and time-domain delay lines [16]. So far, as many as more than twenty varieties of chipless RFID tags and five generations of readers are designed by this team. The proof of concept technology is being transferred to the banknote polymer and paper for low-cost item tagging. These tags have potential to coexist or replace trillions of optical barcodes printed each year. To this end, it is imperative to invest on low-cost conductive ink, high-resolution printing process, and characterization of laminates on which the tag will be printed. The design of a spectral signature-based tag needs to push in higher frequency bands to accommodate and increase the number of bits in the chipless tag to compete with the optical barcode. In this space, the reader design needs to accommodate large reading distance and high-speed reading, multiple tag reading in close proximity, error correction coding, and anticollision protocols. Also, wide acceptance of RFID technology by consumers and businesses requires robust privacy and security protection [16, 17]. The book aims to address all these issues mentioned earlier to make the chipless RFID system a viable commercial product for mass deployment.

Figure 1.3 shows the salient features of a chipless RFID tag, and Figure 1.4 shows the burdens of a chipless RFID tag reader to meet the market demands. It is a highly challenging and interesting task to design a dedicated chipless RFID tag reader with all the requirements fulfilled as well as cost-effective. Figure 1.4 shows the chipless RFID system, which needs to address a whole spectrum of technical and regulatory requirements such as the number of data bits to be read and processed, operating frequencies, radiated (transmitted) power levels, and hence reading distance, mode of readings (time, frequency, or hybrid domain), compatibility with existing technological framework, simultaneous multiple tag reading, and resulting anticollision and security issues. All of these considerations will impact the development and commercialization of the new technology. IDTechEx [7] reports on the chipless RFID tag development by commercial entities and highlights the synergies to address all these issues to make the chipless RFID a commercially viable and competitive technology. The objective of the book is to address many significant issues and provide technical solutions of chipless RFID readers.

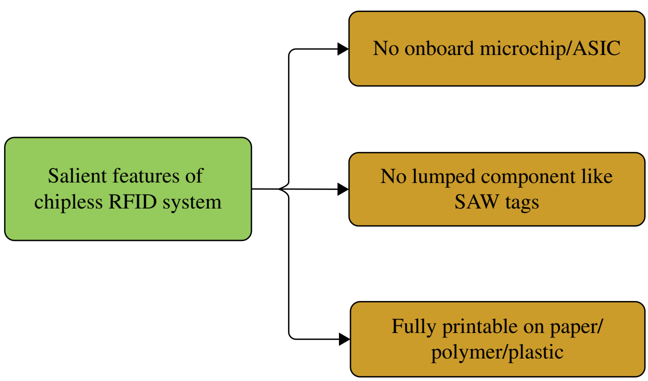

Figure 1.3 Salient features of chipless RFID tag (© 2010 Editor © Karmakar, N. C. Published 2010 by John Wiley & Sons, Ltd.).

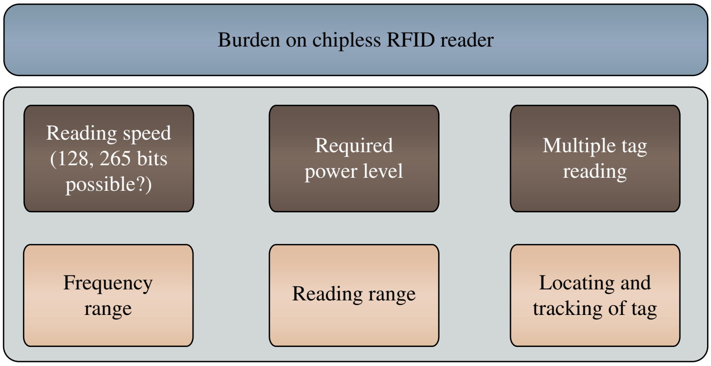

Figure 1.4 Design considerations for chipless RFID tag reader.

1.2 CHIPLESS RFID TAG READER

As advocated by IDTechEx [7], the chipless RFID tag readers and data processing software will cost similar to their chipped counterparts. The market segment of hardware and related middleware is more than the cost of tags used. Therefore, there are huge commercial potentials to invest in readers and related software development. However, there are no such resources on chipless RFID reader systems in the open literature as yet. This is the first initiative by the author to introduce the potential field in a combined and comprehensive body of literature. The book covers the following topics in the field in five sections:

1. Introduction to chipless RFID
2. Chipless RFID tag detection techniques
3. Noise mitigation for improving detection accuracy
4. Multi-tag identification and collision avoidance
5. Tag localization and tracking

Figure 1.5 shows the organization of the chapters in this book. The topics covered in each chapter are highlighted below:

Section 1: Detection and Denoising

Some fundamental system-level issues of the chipless RFID tag reader systems and their detection methods are presented in Chapters 2–5. In an efficient system, raw data obtained from the RF transceiver of the

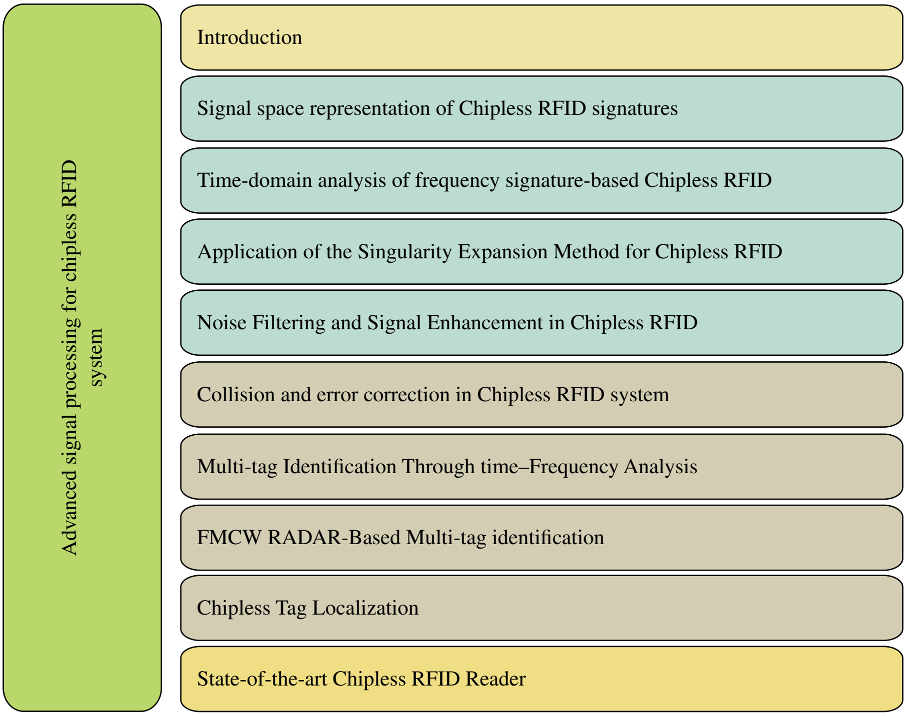

Figure 1.5 Organization of sections and chapters of chipless RFID systems.

chipless reader needs to be processed and denoised. In this aspect, a few new techniques are reported in this section. They are (i) signal space representation of chipless RFID signatures, (ii) detection of frequency signature-based chipless RFID using UWB impulse radio interrogation, (iii) singularity expansion method (SEM) for data extraction from chipless RFID, and finally (iv) noise reduction and filtering techniques used for the chipless RFID. These methods improve the efficacy and throughput of various types of reading processes. The following are the detailed descriptions of the chapters.

Chapter 2: Signal Space Representation of Chipless RFID Signatures

In this chapter, the decoding of information contained in a chipless RFID tag signature is realized using signal space representation technique. This method is commonly used in conventional digital communication systems. Therefore, this is a new approach to chipless RFID detection. A different perspective on the detection of chipless RFID is presented where a mathematical model based on signal space representation is used. Here, the chipless RFID tag's signatures are visualized as signal points in a signal space (Euclidian space), which enables the detection of data bits contained in these signatures through conventional methods used in digital communications. It is shown that the proposed method has better performance compared to a threshold-based approach to detection.

Chapter 3: Time-Domain Analysis of Frequency Signature-Based Chipless RFID

This chapter presents the use of UWB impulse radio interrogation to remotely estimate the frequency signature of chipless RFID tags that are operating using the backscatter principle. Two types of frequency signature-based chipless RFID tags are investigated: (i) a multiresonator-loaded chipless RFID tag [14] and (ii) a multipatch-based chipless RFID tag [15]. Here, the received signal from a frequency signature-based chipless RFID tag is captured in the time domain. The spectral contents of the tag's returned echo signal are analyzed to identify the key components that make up the information-carrying signal. It is shown that the information-carrying portion of the signal is contained in the *antenna mode* of the backscattered signal, and the *structural mode* of the backscatter holds no information about the resonant features of the tag [18, 19]. The performance of the method is investigated under different tag positions. The theory of operation is validated using simulation, semianalytical methods, and experimental results.

Chapter 4: Singularity Expansion Method for Data Extraction for Chipless RFID

This chapter details the use of the SEM for extracting information from the chipless RFID tag. The theory of the SEM is reviewed, and its application to chipless RFID is explained. The SEM technique is used to characterize the response of an object that is subjected to a burst of high-energy electromagnetic (EM) radiation. Here, the transient response of an object that is excited by an impulse of EM energy is characterized using a set of poles and residues. Several works reported in literature that are based on the application of SEM for chipless RFID research are discussed.