HANDBOOK OF SMART ANTENNAS FOR RFID SYSTEMS

Edited by

NEMAI CHANDRA KARMAKAR

WILEY

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To my eldest brother, Mr. Hirendra Nath Karmakar, who constructively influenced my childhood and supported me tirelessly in all stages of my life

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FOREWORD

Radio-frequency identification (RFID) is one of the fastest growing wireless technologies in recent decades. The market volume of the RFID-related hardware and software exceeded $5 billion in 2009 and is expected to have an exponential growth of $25 billion within a decade. Contrary to other wireless mobile terrestrial and satellite communications that have only a few dedicated sectors of applications, RFID enjoys an infinite number of applications of tracking items, resources movement, supply chain management and logistics, and even monitoring the settlement of an implanted organ in a human body. The derivatives of developing RFID for goods and services accelerated after the largest retail chain, Wal-Mart of USA, made it mandatory to tag each item they purchase from their vendors. The objective is to track the goods and services from their origin to the end of sale when boxes are crushed after the goods are sold. The process needs a huge amount of data gathering and processing. However, the benefit is enormous because the data may provide not only the health of the goods and their inventory control and logistics, but also the customers' buying patterns that can leverage the sales of items in a timely manner. Other organizations such as the US Department of Defense, K-Mart, and Myer in Australia followed Wal-Mart's practice. The outbreak of mad cow disease motivated Australia to implement a mandatory national livestock information management system. This is another step forward for mandatory RFID applications on a massive scale.

Every technology that grows very fast will put forward technological and management challenges. RFID is no exception. With the increased volume of RFID development and its emerging applications, there is a need for solving the issues of efficient reading and retrieval of data from the read tags. Another goal is to remove the chip from the tag in order to lower the cost of the tag and compete with the optical barcodes that have been dominating the market for about the last four decades. If the tag can be made chipless, it has the potential to replace trillions of barcodes printed each year. IDTechEx, a respected RFID market research and forecast company based in the United Kingdom, has predicted that 60% of the total tag market will be dominated by chipless tags. However, without a chip the tag becomes dumb and its data processing capacity will be limited. To mitigate this problem, the reader needs to be smart enough to read and process the data from the dumb tag. For issues such as improving throughput and system capacity, as well as mitigating collisions of proximity tags, smart antennas will play significant roles in RFID technology. Prudent research on the smart antennas for RFID reflects that researchers have been trying to implement smart antennas in the readers in all possible ways to improve the performance of the reader. The advent of smart antennas with their capabilities to provide spatial, temporal, and polarization diversities and improved signal to interference and signal to noise ratio (SINR) will significantly advance RFID technology. Implementation of smart antennas in RFID is still in the research phase. Only recently, Omron Corporation based in Japan has announced the development of smart antennas in Omron's readers. However, the system has not yet become a mainstream commercial solution. Therefore, the *Handbook of Smart Antennas for RFID Systems* is a timely publication. The book covers a broad spectrum of topics: the historical perspective and comprehensive review of modern development of RFID; RFID reader architecture where the smart antennas will be implemented; the physical layer development of smart antennas for RFID systems; directional of arrival and localization of RFID tags using smart antennas; multi-antenna RFID tags for system capacity improvement, MIMO antennas for RFID; and, finally, anti-collision protocols using smart antennas. This book, which includes comprehensive coverage on smart antennas applied to emerging RFID technology, will be a fantastic resource for the research community.

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PREFACE

Radio-frequency identification (RFID) is a contactless, usually short distance, wireless data transmission and reception technique for identification of items, asset tracking, surveillance, access control, electronic ticketing, car immobilizers, toll collection, and many other emerging applications. With the recent advent and accelerated development of RFID technologies, and strong patronization by giant retail chains and their suppliers such as Wal-Mart, Kmart, and the US Department of Defense, the application areas have also been increasing from simple identification and security to the retail markets, military, original part manufacturing, medicine, animal tagging, and space applications. The reliable prediction of IDTechEX was for an RFID market value of $5.56 billion in 2009. This prediction relates to the total sales of RFID tags, readers, and related software. The applications of RFID are also increasing with the developments of new technologies. Again referring to the IDTechEX prediction, more than 60% development will encompass low-cost, fully printable chipless RFID tags. The current bottleneck for implementation of RFID system in a new business and its return on investment is the cost of tags.

Our industry partner, FE Technologies Pty Ltd., based in Geelong, Victoria, Australia, has been marketing their Smart Library® RFID system in Australia and overseas. In February 2009, FE Technologies demonstrated their automated library database management system to a group of librarians from Monash University. Smart Library®, which comprises an automatic checkout kiosk, a smart trolley, and a magic wand for inventory checking and misplaced items, is a fantastic solution for the library. Monash University's library possesses more than 3 million books to cater to about 10,000 staff and 50,000 students in Australia and overseas campuses in Malaysia and South Africa. With a book tag costing 50 cents a piece, Monash University immediately needs to invest about $2 million to implement their RFID system.

While the existing optical barcodes for books cost less than 10 cents per unit and the existing library database management system based on the optical barcode works very well within the existing infrastructure and operational culture, a question always remains about the return on investment of more than $2 million to implement the RFID system for the library database system for Monash University's libraries. This is a big question mark and an uphill battle to persuade management to finance RFID for the library. This is only one example. The huge potential of RFID in many other applications is hindered by the high price of the chipped tags. The viable solution is the low-cost printable chipless RFID tag that will cost less than 10 cents and can compete with the optical barcode. The chipless RFID tags developed by the editor's research group at Monash University are simple and passive printable microwave electronic circuits, which can be printed with inkjet printer or other printing methods with conductive inks. Some conductive inks are invisible. How fantastic will that be if an RFID tag can be made invisible, but work very well with a compatible RFID reader? This technology will open up a full new spectrum of applications starting with Australian polymer banknotes, library books, apparel, shoes, and tagging of low-cost and perishable items such as apples, bananas, and so on. Now imagine the market volume if low-cost tags can be delivered and reliably read. To make the tag chipless and simple in operation, the bulk of the operation will be bestowed on the reader electronics. Certainly, the reader should be built more powerfully than the conventional chipped tag readers to process the returned echoes of the tags and encode the unique identification and location of the tag. The smart antennas in the reader will play a major role in improving the reading of the tags. Parallel to the RFID development and deployment, we also have been observing the explosive growth of wireless mobile communications and wireless ad hoc networks for portable electronic communication devices such as notebook PCs, plum tops, PDAs, and even mobile phones. In every aspect we can implement RFID system. With the increase in the subscribers' demand and the invent of value added services alongside the conventional voice communications, the questions of capacity improvement, the quality of services, and the throughput always agitate technologists. The smart antenna came into play once the technologists realized that the multiplexing schemes such as time division multiplexing (TDMA), code division multiplexing (CDMA), frequency division multiplexing (FDMA), and other advanced modulation schemes were not adequate to meet the requirements. Technologists looked into the electromagnetic signals and antennas to enhance the capacity within the existing available bandwidth, throughput, and quality of services. *Necessity is the mother of invention*! And the new invention that has significant footprints in the existing mobile communications is the *smart antenna*!! So beautiful!! The problem could not be solved alone with the advanced signal processing algorithms and modulation schemes; however, the problem has been significantly reduced by dealing with electromagnetic propagation with the smart antennas. As happened in the mobile communication industries about a couple of decades ago, which has now reached maturity and physical implementation, *smart antennas* paved the way to *dreams-come-true technologies* for mobile subscribers. A recent book edited by my former PhD student Dr. Chen Sun entitled *Handbook on Advances in Smart Antenna Technologies for Wireless Networks* by IGI in 2008 has presented the most recent development of smart antennas for wireless communications. An invited chapter in the book on RFID Smart Antennas has motivated the editor to publish the current book.

RFID is an emerging technology that has been going through various development phases in terms of technological developments and businesses (applications), the potential as well as the challenges are huge. As for the example of the implementation of RFID in Monash University's Library above, the bottleneck is the cost of the tag and its mass deployment. The answer to the problem lies in the development of new materials and printing technologies that can appropriately address the problem and produce a sustainable solution in terms of economy and technological advancements. When the tags become dumb, the reader should be smart. The smartness will come from the smart signal capturing capabilities from the dumb tags and the post-processing of the returned echoes, which are the signals from the uniquely identifiable tags. Again the answer lies in the implementation of the smart antennas in the reader and, if feasible, in the tag. Durgin and Griffin (2007)* proved that multiple antennas in the tag can significantly improve the throughput of the tag. Searching the open literature on the topic of smart antennas specifically dedicated to RFID applications was a frustrating experience. Only one article was found in a scholarly conference in the IEEExplore database. The rest came in the form of patents. The information obtained from a patent could not be as good as writing a book chapter. The information provided in the patents was not presented in technical detail but was, instead, written in plain English. The editor has undertaken the daunting task of editing a book wholly dedicated to *Smart Antennas for RFID*. The initial responses from the contributors were not at all promising. In the first phase of the invitation, only three contributions from Spain, Singapore, and the United States were received. Then in the later phase of personal contacts and repeated invitations, a few more contributions were obtained from Taiwan, Australia, and Japan. The low responses from potential authors and researchers indicate the very specialized area of the topic.

The smart antennas for RFID have exploited all possible features of smart antennas, as was done for the wireless telecommunications and networks. The work presented in this book focuses on the following main categories: Fundamentals of RFID and smart antennas, RFID reader architecture, smart antenna physical layer development, RFID position location using electronically steerable parasitic array radiator (ESPAR), RFID multiple-input multiple-output (MIMO) antenna systems, multi-antenna RFID tags, anti-collision and throughput improvement, and, finally, ultra-wideband (UWB) RFID direction of arrival (DOA) estimation. Besides the contributions from outside, the members of the editor's research group at Monash University have contributed significantly to the physical layer development of RFID reader architectures for chipped and chipless RFID tag systems, RFID smart antennas, and the anti-collision algorithm. The research group was supported by the Australian Research Council Discovery Project Grant DP665523: *Chipless RFID for Barcode Replacement* in the Department of Electrical and Computer Systems

*G. D. Durgin and J. D. Griffin: Reduced fading for RFID tags with multiple antennas, IEEE Antenna and Propagation Society International Symposium Digest, July 2007, Honololu, USA

Engineering, Monash University from 2006 to 2009. The dedication of the postgraduate students Dr. Sushim Mukul Roy, Dr. Stevan Preradovic, and Mr. Isaac Balbin under the supervision of the editor has made the chipless RFID tag system a viable commercial product for the Australian polymer banknote (ARC Linkage Project LP0989652: Printable Multi-bit Radio Frequency Identification for Banknotes) and library database management systems (ARC Linkage Project LP0991435: Backscatter based RFID system capable of reading multiple chipless tags for regional and suburban libraries) and possibly the diagnostic RFID tags for partial discharge from faulty power apparatus (ARC LP0989355: Smart Information Management of Partial Discharge in Switchyards using Smart Antennas). The editor has been supervising five RFID-related Australian Research Council Discovery and Linkage Projects that are worth more than AUD 2 million.

The dramatic growth of the RFID industry has created a huge market opportunity. Patronage by Wal-Mart alone has prompted more than two thousand suppliers to implement RFID systems for their products and services. The motto is to track the goods, items, and services from their manufacturing point until the boxes are crushed once the goods are sold. How fantastic the idea is! The RFID system providers are searching all possible technologies that can be implemented in the existing RFID system (GEN2 becomes a worldwide standard) that can be made inexpensively, can be implemented to provide high accuracy in multiple tags reading with minimum errors and extremely low false alarm rate, location finding of tags for inventory control and asset tracking. Employing smart antennas in the reader and, if possible, in tags presents an elegant way to improve the performance of the RFID system.

By deploying smart antennas in the reader architecture and network, there may be outstanding improvement in throughput, high-speed reading, and position detection of tagged items. These facilities can be obtained with an efficient beamforming scheme and diversity techniques. Positioning of tagged items has many applications in industry, thanks to the direction finding ability of the smart antennas.

Smart antennas can also be used in handheld RFID readers, making the reading more efficient and long range. The beamforming and interference suppression abilities of smart antennas enable the reader to increase throughput. In a networked RFID environment where each reader represents a node and where the smart antenna is in a node with packet routing protocols, the direction finding and suppression of interference abilities from the neighboring nodes may provide the optimum reading capability of multiple tags hence efficacy of the reader.

A MIMO wireless communication channel can be built by installing antenna arrays that provide uncorrelated signal outputs at both readers and tags. The MIMO system provides a large number of channels with antenna elements in both transmit and receive chains. The MIMO system enhances the channel capacity, and hence the throughput, of the RFID reader. Even multiple antennas are proposed in the RFID tags by pushing the operating frequency at the 5.8-GHz frequency band to incorporate multiple antennas in a credit card size tag (Durgin and Griffin, Chapter 18). The benefit is the high-speed tag reading and significant throughput improvement. MIMO also enhances the anti-collision capability and capturing effect of the tag when the reader reads multiple tags in close proximity.

To take advantage of the smart antennas' abilities to improve the effectiveness of the RFID system, researchers in both academia and industry recently have envisaged all possible ways of designing smart antennas, modulation and diversity techniques. One very good example is Lia et al.'s patent (Lia et al. 2005)* for redundant networked multimedia RFID systems incorporating both wireless local area network and Ethernet connections. The smart antenna for the RFID reader has a wide variety of capabilities such as frequency hopping, timeslotting, antenna positioning, beam scanning, subset antenna switching, and polarization diversity to exploit the maximum signal readability from multiple tags.

This book aims to provide the reader with comprehensive information about recent developments of smart antennas for RFID systems both in the physical layer development and the software algorithms and protocols. To serve this goal, the book features 24 chapters authored by leading experts in both academia and industry. They offer in-depth descriptions of terminologies and concepts relevant to RFID systems and smart antennas related to RFID. The chapters of the handbook are organized into seven distinct topics. The first two chapters present a comprehensive overview of RFID fundamentals. A smart antenna overview and recent developments of smart antennas specifically applied to RFID system are presented next. These chapters form the foundation for the subsequent chapters in the book. Usually researchers ignore the physical layer development of smart antennas, with the perception that smart antennas require the algorithms to calculate the weight vectors and maximize the signal-to-noise ratio. However, a smart physical layer implementation of a smart antenna can make the antenna more efficient and can save significant cost and implementation of the intelligence. One good example is the electronically steerable parasitic array radiator (ESPAR) antenna, which needs only one RF port and one A/D converter. If the process can be followed in the RF and microwave layers, the baseband processing can be simplified, the speed of the processing can be enhanced, and the processing cost can be minimized. The types of practical smart antennas are presented: a planar fixed-beam high-gain antenna with delay line beamforming, a smart radial power divider-based switched beam smart antenna for handheld RFID readers, a phased-array antenna with 3D scanning capabilities, an optically controlled phased-array antenna, and finally an adaptive-array antenna. All developments were done as the smart RFID reader antennas. In the next section, RFID DoA estimation and position location using two types of smart antennas—ESPAR and conventional smart antennas—are presented. Position location of tags is vital in asset tracking, security, and surveillance. Therefore, these chapters will offer efficient and elegant solutions to the tracking problems of tagged items. Next, multiple antennas for RFID tags are presented. A chipless multi-antenna tag with large bit size in phase-encoded mode is reported first. The fading channel statistics and multiple antenna RFID tag are presented next. These tags are for the throughput and system capacity improvement. RFID MIMO antennas are reported for optimum power allocation under independent Rayleigh fading, low cost, and compact RF-MIMO transceivers for RFID readers and blind

*Y. Lia et al. Radio Frequency Identification (RFID) system, United States Patent Application 20060261938.

channel estimation in MIMO using multi-carrier reception. The low-cost solution for RF-MIMO and the optimum power-handling MIMO system are useful for handheld readers. In the final section, three chapters report anti-collision algorithms: slotted ALOHA, frame-slotted ALOHA using MIMO antennas, and capture effect analysis using Agilent's Advance Design System (ADS) simulation. The capture effect takes care of the power budget issues where the tag with a higher power level is read first and then the tag with a lower power level is read. This is contrary to conventional anti-collision algorithms where data are discarded when collision between tags are detected in the reader.

In this book, utmost care has been paid to keep the sequential flow of information related to the RFID system-based smart antennas. I hope that the book will serve as a good reference for smart antennas for RFID and will pave the way for further motivation and research in the field.

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Monash University
August 2010

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PART I

INTRODUCTION TO RFID

CHAPTER 1

THE EVOLUTION OF RFID

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1.1 INTRODUCTION

Radio-frequency identification (RFID) is a relatively new technology. Some believe that its concept might have originated in military plane identification during World War II and that it really started to be intensively developed for tracking and access applications during the 1980s. These wireless systems allow for noncontact and non-line-of-sight reading of data from electronic labels by the means of electromagnetic signals, and consequently they are attractive for numerous tracking and tagging scenarios. For example, they are effective in hostile environments such as manufacture halls, where bar code labels could not survive. Furthermore, RFID tags can be read in challenging circumstances when there is no physical contact or direct line of sight. RFID has established itself in a wide range of markets, including livestock identification and automated vehicle identification systems, because of its ability to track moving objects. RFID technology is becoming a primary player in automated data collection, identification, and analysis systems worldwide.

RFID, its application, its standardization, and its innovation are constantly changing. It is a new and complex technology that is not well known and well understood by the general public, or even by many practitioners. Many areas of RFID operation need development to achieve a longer reading range, larger memory capacity, faster signal processing, and more secure data transmission.

1.2 ELECTROMAGNETIC TIMELINE

In this section we will provide an anecdotal history of the most important electromagnetic personalities in chronological order. A short biography of each scientist is also provided along with their main contribution to this field

Handbook of Smart Antennas for RFID Systems, Edited by Nemai Chandra Karmakar

Charles-Augustin de Coulomb (1736–1806) was a military civil engineer, retired from the French army because of ill health after years in the West Indies. During his retirement years he became interested in electricity and discovered that the torsion characteristics of long fibers made them ideal for the sensitive measurement of magnetic and electric forces. He was familiar with Newton's inverse-square law, and in the period 1785–1791 he succeeded in showing that electrostatic forces obey the same rule.

$$\mathbf{F}_{e12} = \frac{Q_1 Q_2}{4\pi \varepsilon r^2}\mathbf{u}_{r12} \tag{1.1}$$

Luigi Galvani (1737–1798) was an Italian physician who, in the 1770s, began to investigate the nature and effects of what he conceived to be electricity in animal tissue and of muscular stimulation by electrical means. He discovered that contact of two different metals with the muscle of a frog resulted in an electric current.

Alessandro Giuseppe Antonio Volta (1745–1827) was a professor at the University of Pisa. He was a close friend of Galvani. After he heard about Galvani's discovery, Volta began experimenting in 1794 with metals alone and found that animal tissue was not needed to produce a current. His invention and demonstration of the electric battery in 1800 provided the first continuous electric power source.

Hans Christian Oersted (1777–1851) was born in a village without a school. He was educated by the villagers and went on to become a professor at the University of Copenhagen. In 1820 he was performing a classroom demonstration of the heating effect of electric currents when he observed the deflection of a nearby compass. He had discovered a connection between electricity and magnetism.

Andre-Marie Ampere (1775–1836) learned about Oersted's discovery in 1820 that a magnetic needle can be deflected by a nearby current conducting wire. He then prepared within a week the first of several papers on the theory of this phenomenon, formulating the law of electromagnetism, known as Ampere's Law, which describes mathematically the magnetic force between two current-conducting elements.

$$\oint_C \mathbf{B} \cdot d\mathbf{l} = \mu_0 I \tag{1.2}$$

Jean-Baptiste Biot (1774–1862), along with Felix Savart, formulated the Biot–Savart law of magnetic fields:

$$d\mathbf{B} = \frac{\mu_0}{4\pi} \cdot \frac{Idr \times \mathbf{u}_r}{r^2} \tag{1.3}$$

Karl Friedrich Gauss (1777–1855) ranks as one of the greatest mathematicians of all time. Beginning in 1830, Gauss worked closely with Weber. Gauss lived to an advanced age; and having systematically studied the financial markets and invested accordingly, he died a very wealthy man. Gauss' law of electrostatics states that the