

Solutions for Hard-to-Tag Objects in UHF RFID Systems

by

Zhonghao Hu

B.E. (Electrical & Electronic),
Northwestern Polytechnical University, China, 2006.

Thesis submitted for the degree of

Doctor of Philosophy

in

School of Electrical and Electronic Engineering
The University of Adelaide, Australia

March 2011



© 2011
Zhonghao Hu
All Rights Reserved



To my parents

Contents

Contents	v
Abstract	xiii
Statement of Originality	xv
Acknowledgments	xvii
Conventions	xix
Publications	xxi
Abbreviations	xxiii
List of Figures	xxvii
List of Tables	xxxv
Chapter 1. Introduction and Motivation	1
1.1 Research Area	2
1.2 Motivation	3
1.3 Original Contributions	6
1.4 Thesis Structure	9
Chapter 2. RFID Background	13
2.1 Introduction	14
2.2 The History of RFID	14
2.3 RFID Classification	16
2.3.1 Mode of Excitation	16

2.3.2 Operating Frequency 17

2.4 Regulations and Standards 17

2.4.1 Regulations 18

2.4.2 Standards 20

2.5 Conclusion 23

Chapter 3. Operating Range Evaluation of RFID Systems 25

3.1 Introduction 26

3.2 Fundamental Parameters of Antennas and the Friis Equation 26

3.2.1 Power Transmission in a Tag 26

3.2.2 Effective Area 29

3.2.3 Effective Length 30

3.2.4 Gain 31

3.2.5 EIRP and ERP 32

3.2.6 Polarisation 33

3.2.7 The Friis Transmission Equation 34

3.3 Tag Antenna Design 35

3.4 Threshold Power of a Transponder 36

3.4.1 Modulator 37

3.4.2 Rectifier Efficiency 38

3.4.3 Memory Chosen 39

3.5 The Reader Sensitivity 41

3.6 The Literature Review on the Existing Work in Evaluating Operating Range 42

3.7 Interpretation and limitations of the Friis Transmission Equation in an RFID Perspective 44

3.7.1 Forward Link 45

3.7.2 Backward Link 46

3.7.3	Limitations in Implementing the Friis Transmission Equation . . .	47
3.8	The Use of S-parameters in Analysing the Operating Range of RFID Systems	49
3.8.1	Formula Derivation	49
3.8.2	Formula Validation	53
3.9	Conclusion	60
 Chapter 4. Analysis and Design of Meander Line Dipole Antennas		61
4.1	Introduction	62
4.2	Introduction and Validation of the Formula for Calculating Resonant Frequency of an MDA in Free Space	63
4.2.1	Formula Derivation	63
4.2.2	Validation of Equation (4.11)	66
4.3	Modifications on Equation (4.11) for RFID Tag Antenna Design	68
4.3.1	Limitations of Equation (4.11) in RFID Tag Antenna Design . . .	68
4.3.2	Method for Calculating Relative Effective Permittivity of an MDA on a Dielectric Substrate	69
4.3.3	Further Validation of the Method for Calculating the ϵ_{reff} of an MDA on a Dielectric Substrate	76
4.4	Experimental Validation of Equation (4.12)	78
4.5	Radiation Pattern and Efficiency	79
4.5.1	Physical Dimension of MDA	80
4.5.2	Dielectric Substrate	83
4.6	Conclusion	84
 Chapter 5. A Security Tag Design		85
5.1	Introduction	86
5.2	T-Seal Concept	86
5.3	Chip and Antenna Selection	89

5.3.1	Chip Selection	90
5.3.2	Antenna Selection	90
5.4	The Security Tag Antenna Design	91
5.4.1	Semi Finished Tag Design	92
5.4.2	Completely Finished Tag Design	95
5.5	Conclusion	102
Chapter 6. Solutions for the Antenna on Metal Problem		103
6.1	Introduction and Outline	104
6.2	The Antenna on Metal Problem	104
6.2.1	Metallic Boundary Conditions	104
6.2.2	Antenna Parameters in Proximity to Metal	107
6.2.3	The Performance of Commercial Tags Above a Metal Plate	108
6.3	Previous Solutions to the Problem	112
6.3.1	One Quarter Wavelength Isolator Solution	112
6.3.2	Antenna Selection Solutions	113
6.3.3	Artificial Magnetic Conductor Solutions	114
6.4	Conclusion	118
Chapter 7. The Slitted Decoupler Design for Metallic Item Detection		121
7.1	Introduction and Outline	122
7.2	Structure of the Slitted Decoupler	124
7.3	Design Principles	125
7.4	Simulation	126
7.4.1	Construction of the Simulated Devices	126
7.4.2	Simulation Results	126
7.5	Patch Antenna Resonant Property Analysis	130
7.5.1	Theoretical Analysis	131

7.5.2	Simulation results	136
7.6	Slitted Decoupler Parameter Settings	144
7.6.1	Simulation Model	144
7.6.2	Length and Width of Each Top Patch Selection	146
7.6.3	Dielectric Material Layer Thickness Selection	147
7.6.4	Slit Width Selection	148
7.6.5	Dielectric Material Selection	149
7.6.6	The Ground Plane Size Selection	150
7.6.7	Design Principles for the Slitted Decoupler	152
7.7	A Dipole on the Slitted Decoupler	153
7.7.1	Induced Voltage in the Middle Port of the Dipole on the Decoupler	154
7.7.2	Input Impedance of the Half Wavelength Dipole on the Decoupler	158
7.7.3	Power Collected by the Half Wavelength Dipole on the Decoupler	159
7.7.4	Antenna Design Principles for the Slitted Decoupler	161
7.8	Measurement	162
7.8.1	Measurement Facilities	163
7.8.2	Measurement Results and Comparison	165
7.9	Conclusion	168
 Chapter 8. Detection of Massive Numbers of DVDs		171
8.1	Introduction and Motivation	172
8.1.1	Motivation	172
8.1.2	An Operational Constraint	173
8.1.3	Some General Perspectives	173
8.1.4	Literature Treatments	174
8.1.5	Chapter Outline	175
8.2	Parameters of a Packaged DVD Product	177

8.3 Theoretical Analysis and Simulation Verification of the Effect on a Uni-
form Plane Wave from a Thin Metal Film 179

8.3.1 Surface Resistance of a Thin Metal Film 179

8.3.2 Simulation on a DVD Disc 183

8.4 Investigation of Tag Labelling Method 185

8.4.1 Tag Lying on the Case Cover 186

8.4.2 Tag Lying on the Case Faces: Opening A and Spine 188

8.4.3 Tag Folded on the Case Faces: Opening A and Spine 189

8.5 DVD Detection in a Stack 191

8.5.1 Testing Strategy and DVD Stack Description 192

8.5.2 Single Tagged DVD Film in a DVD Stack 195

8.5.3 Multiple Tag Detection in a DVD Stack 198

8.6 Further Validation 202

8.6.1 Q Parameter in EPC C1G2 Protocol for Anti-Collision 202

8.6.2 Method of Packaging and Stacking DVDs in Industry 203

8.6.3 Experiments 205

8.7 The Optimisation of the Distance Between the Reader Antenna and the
DVD stack 215

8.8 Conclusion 217

8.8.1 Stacking Policies 217

8.8.2 Results for Side and Base Stacking 218

8.8.3 Further Work 219

Chapter 9. Conclusions and Future Work 221

9.1 Review of and Conclusions from the Work in This Thesis 222

9.2 Recommendations on Future Work 224

9.3 Summary of Original Contributions to Knowledge 228

9.4 Conclusion 230

Appendix A. Tests of the Tags in Chapter 5	231
A.1 Test Scheme	232
A.2 Test Result on the Semi-finished Security Tag	233
A.3 Test Result on the Final Design of the Security Tag	233
Appendix B. Open Circuit Voltage of A Half Wavelength Dipole	235
Appendix C. Original Testing Data Corresponding to the Work in Section 8.4	239
Appendix D. Evaluation of Reflections in the Aperture Surrounded by Absorbing Foam Used in Chapter 8	241
D.1 Introduction	242
D.2 Reflection Coefficient of Waves Incident on a Lossless Dielectric Interface	242
D.3 The Structure of the Absorbing Foam and Its Reflection Coefficient . . .	246
D.4 Reflection in the Aperture Surrounded by the Absorbing Foam	248
D.5 Conclusions	250
Bibliography	253

Abstract

Radio frequency identification (RFID) is an auto-identification technology realised by radio waves. The ultimate goal of RFID is the item-level tagging of all kinds of products in supply chains. This goal challenges industry and academia in many aspects.

Passive UHF RFID systems, when compared with other RFID systems, are believed to possess advantages in achieving that goal. However, UHF RFID systems possess two serious disadvantages: (i) the relatively large antenna size, and (ii) the sensitiveness to the metallic items on which a tag is mounted. Those two deficiencies make a large number of small size objects and metallic objects hard to tag. In addition, different applications also bring special requirements or limitations in adopting UHF RFID systems, such as in the case of a container seal, the requirement for tags to have a physical security function, and in other cases such as pallet shipping, the requirement for detecting massive numbers of items densely stacked together. Finally, of course, cost is one of the key limitations if one intends to apply his or her design down to item-level tagging commercially. Hence each of the inherent deficiencies of the system itself and the limitations caused by the application, or a combination of all or some of the deficiencies and limitations make a large number of items hard to tag and impedes the item-level tagging target.

The research in this thesis aims, by antenna design and electromagnetic wave analysis, to provide feasible and affordable solutions for some of those hard-to-tag objects in UHF RFID systems, and the thesis can be divided into five parts.

In detail, the first part of the thesis gives the motivations, contributions and structure of this thesis. In addition it also provides a brief introduction to RFID systems and about how they are operated, developed, classified, regulated and standardised.

The second part of this thesis presents basic terminologies and design criteria in tag antenna design, transponder IC design and reader design. Factors which limit the operating range of UHF RFID systems are discussed. Following this discussion, a novel

method making use of a scattering matrix for evaluating the operating range of a UHF RFID system deployed in an arbitrary environment is proposed.

In the third part, concerning the meander line dipole antenna (MDA), one of the approaches to minimising tag antenna size is analysed in terms of its resonant frequency, size reduction contributors, radiation pattern and efficiency. An analytic formula for calculating the resonant frequency of an MDA on a dielectric substrate as an RFID tag antenna is established. Based on the analysis, a novel tag antenna with a physical security function (an electronic seal) for protecting shipping containers was designed and experimentally verified.

The fourth part of this thesis puts emphasis on metallic item detection. The reason of why common dipole based tag antennas cannot work well in close proximity to metal is given. Previous solutions and their own demerits in solving this problem are summarised. Then, a low profile, simple structure, compact size solution is introduced via the artificial magnetic conductor concept. Furthermore, a general DVD disc contains a very thin metal layer inside for the purpose of reflecting laser. That layer may not bring many troubles in identifying a single DVD by a UHF RFID system, but if thousands of DVDs were stacked, the role the metal component plays in degrading the detection of each DVD in the stack should be investigated. An approach in detecting a large number of DVDs (up to 2000) densely stacked is thus presented.

Conclusions of the work in this thesis are drawn as the last part of the thesis. Besides conclusions the last part also includes some recommendations for future work and the description of the original contributions of this thesis.

The potential benefits of item-level tagging in supply chains are enormous. The existence of a large number of hard-to-tag objects is one of the main challenges in achieving item-level tagging. The studies in this thesis extend the scope of the detectable objects and this extension makes item-level tagging more realisable.

Statement of Originality

This work contains no material that has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of the thesis, when deposited in the University Library, being available for loan, photocopying and dissemination through the library digital thesis collection.

The author of this thesis acknowledges that copyright of published work contained within this thesis (as listed in the publications page) resides with the copyright holder(s) of that work.

Signed

Date

Acknowledgments

First and foremost, I must recognise my principal supervisor Prof. Peter H. Cole for his constant and patient guidance during the period of my Ph.D study. His meticulous approach to learning and tolerance towards others will influence me for the rest of my life. Talking with him not only in professional areas but also in music and culture has always been enjoyable and beneficial. In addition, many thanks to him for generously providing my living allowance.

I would also like to wholeheartedly thank my co-supervisors Dr Christophe Fumeaux and Dr Christopher Coleman for providing valuable suggestions to my research.

Sincere thanks to my colleagues and also to successful graduates in the Auto-ID Lab, Adelaide for their unselfish help in extending my knowledge. They are Behnam Jamali, David Hall, Damith Ranasinghe, Ng Mun Leng and Kin Seong Leong. Thanks also to Mr Alfio R. Grasso for arranging projects with industrial partners.

I am indebted for the work done by the staff in the School of Electrical and Electronic Engineering, particularly, Mr Pavel Simcik and Mr Brandon Pullen who fabricated most of my designs, and Associate Professor Michael Liebelt, Associate Professor Cheng Chew Lim and Mr Stephen Guest who managed my scholarship and travelling issues. Of course thanks to the four kind ladies in the school office.

Many thanks to my friends, specifically Thomas McLean, Matthew Trinkle, Yang Ruiting, Guo Bin, Wang Yuexian in Adelaide and also Liu Tan, Wu Xiao, Ye Yang in China for their constant support and encouragement during my Ph.D studies.

I am grateful to my parents who dedicate their love to me. Since I first entered primary school, all through my educational journey of twenty years, their love has always accompanied me. Last but not least, thanks for the unconditional love and encouragement from my girlfriend Xin Xia. Without her, I could not imagine how I could have accomplished this work.

Zhonghao Hu (September 2010)

Conventions

Typesetting

This thesis is typeset using the $\text{\LaTeX}2\text{e}$ software.

The fonts used in this thesis are Times New Roman and Sans Serif.

Referencing

Referencing and citation style in this thesis are based on the Institute of Electrical and Electronics Engineers (IEEE) Transaction style [1].

For electronic references, the last accessed date is shown at the end of a reference.

Units

The units used in this thesis are based on the International System of Units (SI units) [2].

Spelling

The Australian English spelling is adopted in this thesis.

Publications

Book Chapter

- [1] P. H. Cole, L. Turner, Z. Hu, and D. Ranasinghe, "The Future of RFID," in *Unique Radio Innovation for the 21st Century*, D. Ranasinghe, M. Sheng, and S. Zeadally, Eds. Springer, 2010.

Book Chapter Accepted

- [1] P. H. Cole and Z. Hu, "Operating Range Evaluation of UHF RFID Systems," in *Advances in RFID Tags*. Vienna, Austria: InTech, 2010.
- [2] Z. Hu, P. H. Cole, and C. Fumeaux, "Analysis and Design of Meander Line Dipole Antennas," in *Chipless Radio Frequency Identification: Systems for Ubiquitous Tagging*, N. Karmakar, Ed. Hershey, USA: IGI Global, 2011.

Journal Accepted

- [1] Z. Hu, P. H. Cole, and A. Grasso, "Compact solution for metallic item detection in RFID systems by means of artificial magnetic conductor," *International Journal of Radio Frequency Identification Technology and Applications (IJRFITA)*, 2010.
- [2] Z. Hu and P. H. Cole, "Detection of Massive Numbers of DVDs by a UHF RFID system," *Progress In Electromagnetics Research B (PIER-B)*, 2010.

Conference

- [1] Z. Hu, P. H. Cole, and L. Zhang, "A method for calculating the resonant frequency of meander-line dipole antenna," in *4th IEEE Conference on Industrial Electronics and Applications, ICIEA 2009*, Xi'an, China, May 2009, pp. 1783–1786.
- [2] Z. Hu and P. H. Cole, "Detection of DVDs in a stack by an RFID system," in *Asia-Pacific Symposium on Electromagnetic Compatibility, APEMC 2010*, Beijing, China, April 2010.
- [3] Z. Hu and P. H. Cole, "The Slitted Decouple Design for Metallic Item Detection in UHF RFID Systems," in *Asia-Pacific Symposium on Electromagnetic Compatibility, APEMC 2010*, Beijing, China, April 2010.

Publications

- [4] Z. Hu and P. H. Cole, "Bottle Packaged Wine Product Detection By UHF RFID Systems," in *International Conference on Electromagnetics in Advanced Applications, ICEAA 2010*, Sydney, Australia, September 2010.

Non-refereed

- [1] P. H. Cole and Z. Hu, "Solving the Water and Metal Problem," *RFID Journal*, April 2009. [Online]. Available: <http://www.rfidjournal.com/article/view/4755> [29 July 2010].
- [2] P. H. Cole and Z. Hu, "Every DVD Tells a Story," *RFID Journal*, July 2010. [Online]. Available: <http://www.rfidjournal.com/article/view/7717> [29 July 2010].

Abbreviations

AC	Alternating Current
ACMA	Australia Communications and Media Authority
AMC	Artificial Magnetic Conductor
ASK	Amplitude Shift Keying
BOPP	Biaxially Oriented Polypropylene
BTA	Bow Tie Antenna
CMOS	Complementary Metal Oxide Semiconductor
CPS	Coplanar Strip
CST	Computer Simulation Technology (a commercial simulation software)
DC	Direct Current
DVD	Digital Video Disc
DVD R	Recordable Digital Video Disc
DVD-ROM	Digital Video Disc-Read Only Memory
EAS	Electronic Article Surveillance
EAN	European Article Numbering
EBG	Electromagnetic Band Gap
EEPROM	Electrically Erasable Programmable Read Only Memory
EIRP	Equivalent Isotropic Radiated Power
EPC	Electronic Product Code

Abbreviations

ERP	Effective Radiated Power
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FDA	Folded Dipole Antenna
FEM	Finite Element Method
FeRAM	Ferroelectric Random Access Memory
FHSS	Frequency Hopping Spread Spectrum
FSS	Frequency Selective Surfaces
GA	Genetic Algorithms
GS1	Global Standards 1
HF	High Frequency
HFSS	High Frequency Structural Simulator (a commercial simulation software)
IC	Integrated Circuit
IEC	International Electrotechnical Commission
IFA	Inverted F Antenna
IPICO	Intellectual Property and Innovation Company
ISM	Industrial, Scientific and Medical (frequency range)
ISO	International Organization for Standardization
LBT	Listen Before Talk
LF	Low Frequency
MDA	Meander Line Dipole Antenna
MOM	Method Of Moments

PBG	Photonic Band Gap
PIE	Pulse Interval Encoding
PP	Polypropylene
PSK	Phase Shift Keying
PZT	Lead Zirconate Titanate
RAM	Random Access Memory
RCS	Radar Cross Section
RF	Radio Frequency
RFID	Radio Frequency Identification
SAW	Surface Acoustic Waves
SBT	Strontium Bismuth Tantalate
SHF	Super High Frequency
SMA	Sub-Miniature version A
UCC	Uniform Code Council
UHF	Ultra High Frequency
UID	Ubiquitous Identification

List of Figures

1.1	Components of a basic RFID system	2
1.2	The tree diagram of the thesis	12
<hr/>		
2.1	Power limitation in EN 302 208	19
<hr/>		
3.1	Thevenin equivalent of a receiving antenna	27
3.2	Thevenin equivalent of a transponder	27
3.3	Coordinate used in the definition of effective length	30
3.4	Block chart of a transponder	37
3.5	Two port junction representing coupled antennas in an RFID system	50
3.6	A self-made tag used in experiment	55
3.7	The chip impedance illustration	55
3.8	A shielding tunnel	56
3.9	Comparison between the reading range calculated by (3.61) after deriving the S parameters from the simulation and the tested reading range	59
<hr/>		
4.1	A sample of meander line dipole antenna with approximate current distribution	63
4.2	Meander line dipole antenna loaded with two meanders	64
4.3	Three models of MDA with various numbers of meander lines	66
4.4	The resonant frequency of MDA as a function of its physical parameters	67
4.5	Two coplanar strips on a dielectric substrate	70
4.6	The transverse electric field distribution in the cross section of an CPS on board	70

List of Figures

4.7	An MDA loaded with four identical meander lines	72
4.8	Cross section view of electric field magnitude distribution of the MDA shown in Figure 4.7	73
4.9	The relative effective permittivity of the MDA in Figure 4.7	74
4.10	The variation of the MDA's electric field magnitude distribution at the resonant frequency along with the variation of the ϵ_r	76
4.11	An MDA loaded with three different meander lines	77
4.12	The relative effective permittivity of the MDA in Figure 4.11	78
4.13	The half MDA on a ground plane being tested	79
4.14	Smith chart derived by the network analyser 8714C showing input impedance of the half MDA on a ground plane	80
4.15	A tag based on the MDA in Figure 4.11	80
4.16	Radiation efficiency comparison between two types of MDA	83

5.1	T-seal structure	88
5.2	A regular sample of MDA with two meander lines	91
5.3	The semi finished tag shape	93
5.4	Simulated gain pattern of the semi finished tag antenna by HFSS	94
5.5	A fabricated sample of semi finished tag	95
5.6	Semi finished tag with a loop in the down-narrow part of the board	96
5.7	Simulated gain pattern of the semi finished tag antenna with a complete loop	96
5.8	Simulated gain pattern of the semi finished tag antenna with a incomplete loop	97
5.9	The final design of the security tag	100
5.10	Simulated gain pattern of <i>Tag</i> ₁	100
5.11	Simulated gain pattern of <i>Tag</i> ₂	101

6.1	Boundary conditions at a perfect conductor surface	105
6.2	Electric field when a charge is put above the perfect conductor	106
6.3	A straight wire carrying current and its image underneath the ground plane	107
6.4	A shielding tunnel	110
6.5	Reading ranges of labelled commercial tags when they are placed above the aluminium plate at various distances	111
6.6	Side view of an antenna placed at one quarter wavelength distance above a metal plate	112
6.7	Sievenpiper high impedance electromagnetic surface	115
6.8	Origin of the capacitance and inductance in each cell	116
6.9	Three conductive layer high impedance electromagnetic surface	116
6.10	Hilbert curve in various orders	117
6.11	Hilbert curve AMC based on order 4 Hilbert curves	119

7.1	The structure of the slitted decoupler	124
7.2	Slitted decoupler placement illustration	124
7.3	The simulated slitted decoupler	127
7.4	Magnitude of the r.m.s. phasors representing the simulated electric fields of the slitted decoupler	128
7.5	The magnitude of y -directed electric field variation along the y and x axes at various heights.	129
7.6	The structure of a simple rectangular patch antenna without excitation .	130
7.7	Electric field distribution of a rectangular patch antenna	131
7.8	Patch width and length values making the antenna resonant at 923MHz	133
7.9	Charge and current distribution in a rectangular patch antenna	134

List of Figures

7.10	A rectangular patch antenna fed by a coaxial cable	137
7.11	A typical input impedance of patch antenna as a function of frequency .	138
7.12	The equivalent circuit of a patch antenna which is fed by a coax cable . .	139
7.13	The comparison between the simulation results and the theoretical results in terms of patch size at resonance	140
7.14	The comparison between the simulation results and the theoretical results in terms of the resonant input impedance	141
7.15	The r.m.s phasor of the electric field distribution underneath top patch obtained by HFSS	142
7.16	The y -directed electric fields as a function of the patch width at various patch length	143
7.17	The structure of the slitted decoupler illuminated by a uniform plane wave	144
7.18	The y -directed electric fields in the slit as a function of the patch width at various patch length	146
7.19	The y -directed electric fields in the slit as a function of the dielectric layer thickness at the particular patch size $90.5\text{mm} \times 32.5\text{mm}$	147
7.20	The y -directed electric fields in the slit at various slit width	148
7.21	The y -directed electric fields in the slit as a function of the patch width at various patch lengths when the loss tangent is increased to 0.02	149
7.22	Slitted decoupler with a ground plane larger than the top layer	150
7.23	The y -directed electric fields in the slit as a function of margin at 923MHz	151
7.24	A dipole on the slitted decoupler	154
7.25	The induced voltage comparison among the dipole on the slitted decoupler, the dipole on the metal and the dipole in free space	155
7.26	The induced voltage of a short dipole on the slitted decoupler	157
7.27	The induced voltages of the half wavelength dipole on the slitted decoupler as a function of the slit width	158
7.28	The input impedance of the dipole in various distances above the slitted decoupler	159

7.29	The four fabricated slitted decouplers	165
7.30	The placement of the tag on both the decoupler and the plate.	167
<hr/>		
8.1	The structure of a regular DVD case and the SPI code on it	178
8.2	The structure of a regular DVD disc	178
8.3	Transmission line model of a uniform plane wave perpendicularly inci- dent on an infinite aluminium metal film	180
8.4	Simulation model of the square aluminium film	181
8.5	Total electric field distribution shown in the xz plane of the simulation on the square aluminium film	182
8.6	Simulation model of the aluminium film in the disc	184
8.7	Total electric field distribution shown in the xz plane of the simulation on the aluminium film in the disc	184
8.8	A shielding tunnel	185
8.9	Tag lying on the case cover	186
8.10	Tag lying on the case faces: opening A and spine	188
8.11	Tag folded on a DVD case	189
8.12	Tag staggered on a DVD case	190
8.13	Three selected testing schemes	192
8.14	Testing strategy illustration	193
8.15	Three forms of testing a DVD stack in terms of the three testing schemes shown in Figure 8.13	194
8.16	Aperture structure illustration	195
8.17	Two types of DVD stack in the aperture	196
8.18	The level and floor division of the stack shown in Figure 8.17(a)	199
8.19	Flow chart of the method examining the testing schemes “1”, “2” and “3” respectively.	200

List of Figures

8.20	DVD carton and its dimension	203
8.21	A sample of a real pallet.	204
8.22	The DVD stack structure for testing scheme “3”	206
8.23	The real DVD stack for testing scheme “3”	207
8.24	The reader antenna’s positions in relation to the stack in terms of the testing scheme “3”	207
8.25	The DVD stack structure for testing scheme “2”	210
8.26	The real DVD stack for testing scheme “2”	211
8.27	The reader antenna’s positions in relation to the stack in terms of the testing scheme “2”	212
8.28	The DVD stack structure for testing scheme 2. The reader scans the back side of the stack.	213
8.29	Illustrating reflection symmetry of tag positions about a vertical mid-plane	215
8.30	The variation of the reader antenna input impedance in the form of Smith Chart along with the variation of the distance between the reader antenna and the DVD stack d_e measured by the network analyzer	216
<hr/>		
A.1	A shielding tunnel	232
A.2	Two tested tags	233
<hr/>		
B.1	A half wavelength dipole in the rectangular coordinate system	237
B.2	$ V_{inr.m.s} $ as a function of the ratio z/λ at 923MHz	238
<hr/>		
<hr/>		
D.1	Plane wave incident on a dielectric interface	243
D.2	The reflection coefficient at a dielectric interface as a function of incident angle, for $\epsilon_r = 1.5$	245

D.3	Cross section of the absorbing foam	247
D.4	Aperture structure illustration	249
D.5	The deployment of the reader antenna in front of the aperture	251

List of Tables

2.1	Comparison among RFID systems	17
2.2	Regulation status of UHF RFID among countries	20
3.1	Comparison among RAM, EEPROM and FeRAM	41
3.2	Reading ranges of the self-made tag in proximity to the aluminium plate by experiments	57
3.3	Reading ranges of the self-made tag in proximity to the aluminium plate calculated by (3.61) after deriving S parameters from the simulation . . .	59
6.1	Reading ranges of commercial tags in free space	110
7.1	Geometrical parameters of the fabricated slitted decoupler	165
7.2	Reading ranges of the tag on the decouplers varied in size	166
7.3	Reading ranges of the tag on both the decoupler and the aluminium plate	167
7.4	Reading ranges of the tag above the decouplers in a certain distance ($D_z=6.5\text{mm}$)	168
8.1	Reading range test results of the tag shown in Figure 8.9	187
8.2	Reading range test results of the tag shown in Figure 8.10	188
8.3	Reading range test results of the tag shown in Figure 8.11	189
8.4	Outside reading range of the tag at the end of the DVD stack	197
8.5	Pallet top surface dimensions standardised by ISO	205
8.6	Misreading tag distribution in the stack shown in Figure 8.24(a). For these results the reader antenna occupied four positions.	208
8.7	Misreading tag distribution in the stack shown in Figure 8.24(b). For these results the reader antenna occupied twelve positions.	210
8.8	Misreading tag distribution in the stack shown in Figure 8.27(a). For these results the reader antenna occupied four positions.	212

List of Tables

8.9	Misreading tag distribution in the stack shown in Figure 8.27(b). For these results the reader antenna occupied ten positions.	212
8.10	Misreading tag distribution when those tags are read from the back of the stack. For these results the reader antenna occupied ten positions. . .	214
C.1	Original testing data corresponding to Table 8.1, unit: mm	240
C.2	Original testing data corresponding to Table 8.2, unit: mm	240
C.3	Original testing data corresponding to Table 8.3, unit: mm	240