

 WILEY

RFID HANDBOOK

**Fundamentals and Applications in Contactless
Smart Cards and Identification**

Second Edition



KLAUS FINKENZELLER

Contents

PREFACE	xiii
LIST OF ABBREVIATIONS	xv
1 Introduction	1
1.1 Automatic Identification Systems	2
1.1.1 Barcode systems	2
1.1.2 Optical character recognition	3
1.1.3 Biometric procedures	4
1.1.3.1 Voice identification	4
1.1.3.2 Fingerprinting procedures (dactyloscopy)	4
1.1.4 Smart cards	5
1.1.4.1 Memory cards	5
1.1.4.2 Microprocessor cards	6
1.1.5 RFID systems	6
1.2 A Comparison of Different ID Systems	7
1.3 Components of an RFID System	7
2 Differentiation Features of RFID Systems	11
2.1 Fundamental Differentiation Features	11
2.2 Transponder Construction Formats	13
2.2.1 Disks and coins	13
2.2.2 Glass housing	14
2.2.3 Plastic housing	14
2.2.4 Tool and gas bottle identification	15
2.2.5 Keys and key fobs	17
2.2.6 Clocks	18
2.2.7 ID-1 format, contactless smart cards	18
2.2.8 Smart label	19
2.2.9 Coil-on-chip	20
2.2.10 Other formats	21
2.3 Frequency, Range and Coupling	22
2.4 Information Processing in the Transponder	23
2.4.1 Low-end systems	23
2.4.2 Mid-range systems	24
2.4.3 High-end systems	25
2.5 Selection Criteria for RFID Systems	25
2.5.1 Operating frequency	26
2.5.2 Range	26

2.5.3	Security requirements	27
2.5.4	Memory capacity	28
3	Fundamental Operating Principles	29
3.1	1-Bit Transponder	29
3.1.1	Radio frequency	30
3.1.2	Microwaves	33
3.1.3	Frequency divider	35
3.1.4	Electromagnetic types	36
3.1.5	Acoustomagnetic	37
3.2	Full and Half Duplex Procedure	40
3.2.1	Inductive coupling	41
3.2.1.1	Power supply to passive transponders	41
3.2.1.2	Data transfer transponder → reader	42
3.2.2	Electromagnetic backscatter coupling	47
3.2.2.1	Power supply to the transponder	47
3.2.2.2	Data transmission → reader	49
3.2.3	Close coupling	49
3.2.3.1	Power supply to the transponder	49
3.2.3.2	Data transfer transponder → reader	50
3.2.4	Electrical coupling	51
3.2.4.1	Power supply of passive transponders	51
3.2.4.2	Data transfer transponder → reader	53
3.2.5	Data transfer reader → transponder	53
3.3	Sequential Procedures	54
3.3.1	Inductive coupling	54
3.3.1.1	Power supply to the transponder	54
3.3.1.2	A comparison between FDX/HDX and SEQ systems	54
3.3.1.3	Data transmission transponder → reader	56
3.3.2	Surface acoustic wave transponder	57
4	Physical Principles of RFID Systems	61
4.1	Magnetic Field	61
4.1.1	Magnetic field strength H	61
4.1.1.1	Path of field strength $H(x)$ in conductor loops	62
4.1.1.2	Optimal antenna diameter	65
4.1.2	Magnetic flux and magnetic flux density	66
4.1.3	Inductance L	67
4.1.3.1	Inductance of a conductor loop	68
4.1.4	Mutual inductance M	68
4.1.5	Coupling coefficient k	70
4.1.6	Faraday's law	71
4.1.7	Resonance	73
4.1.8	Practical operation of the transponder	78
4.1.8.1	Power supply to the transponder	78
4.1.8.2	Voltage regulation	78

4.1.9	Interrogation field strength $H_{\min}$	80
4.1.9.1	Energy range of transponder systems	82
4.1.9.2	Interrogation zone of readers	84
4.1.10	Total transponder — reader system	86
4.1.10.1	Transformed transponder impedance Z'_T	88
4.1.10.2	Influencing variables of Z'_T	90
4.1.10.3	Load modulation	97
4.1.11	Measurement of system parameters	103
4.1.11.1	Measuring the coupling coefficient k	103
4.1.11.2	Measuring the transponder resonant frequency	105
4.1.12	Magnetic materials	106
4.1.12.1	Properties of magnetic materials and ferrite	107
4.1.12.2	Ferrite antennas in LF transponders	108
4.1.12.3	Ferrite shielding in a metallic environment	109
4.1.12.4	Fitting transponders in metal	110
4.2	Electromagnetic Waves	111
4.2.1	The generation of electromagnetic waves	111
4.2.1.1	Transition from near field to far field in conductor loops	112
4.2.2	Radiation density S	114
4.2.3	Characteristic wave impedance and field strength E	115
4.2.4	Polarisation of electromagnetic waves	116
4.2.4.1	Reflection of electromagnetic waves	117
4.2.5	Antennas	119
4.2.5.1	Gain and directional effect	119
4.2.5.2	EIRP and ERP	120
4.2.5.3	Input impedance	121
4.2.5.4	Effective aperture and scatter aperture	121
4.2.5.5	Effective length	124
4.2.5.6	Dipole antennas	125
4.2.5.7	Yagi-Uda antenna	127
4.2.5.8	Patch or microstrip antenna	128
4.2.5.9	Slot antennas	130
4.2.6	Practical operation of microwave transponders	131
4.2.6.1	Equivalent circuits of the transponder	131
4.2.6.2	Power supply of passive transponders	133
4.2.6.3	Power supply of active transponders	140
4.2.6.4	Reflection and cancellation	141
4.2.6.5	Sensitivity of the transponder	142
4.2.6.6	Modulated backscatter	143
4.2.6.7	Read range	145
4.3	Surface Waves	148
4.3.1	The creation of a surface wave	148
4.3.2	Reflection of a surface wave	150
4.3.3	Functional diagram of SAW transponders (Figure 4.95)	151
4.3.4	The sensor effect	153
4.3.4.1	Reflective delay lines	154
4.3.4.2	Resonant sensors	155

4.3.4.3	Impedance sensors	157
4.3.5	Switched sensors	159
5	Frequency Ranges and Radio Licensing Regulations	161
5.1	Frequency Ranges Used	161
5.1.1	Frequency range 9–135 kHz	161
5.1.2	Frequency range 6.78 MHz	163
5.1.3	Frequency range 13.56 MHz	163
5.1.4	Frequency range 27.125 MHz	163
5.1.5	Frequency range 40.680 MHz	165
5.1.6	Frequency range 433.920 MHz	165
5.1.7	Frequency range 869.0 MHz	166
5.1.8	Frequency range 915.0 MHz	166
5.1.9	Frequency range 2.45 GHz	166
5.1.10	Frequency range 5.8 GHz	166
5.1.11	Frequency range 24.125 GHz	166
5.1.12	Selection of a suitable frequency for inductively coupled RFID systems	167
5.2	European Licensing Regulations	169
5.2.1	CEPT/ERC REC 70-03	169
5.2.1.1	Annex 1: Non-specific short range devices	170
5.2.1.2	Annex 4: Railway applications	171
5.2.1.3	Annex 5: Road transport and traffic telematics	172
5.2.1.4	Annex 9: Inductive applications	172
5.2.1.5	Annex 11: RFID applications	172
5.2.1.6	Frequency range 868 MHz	173
5.2.2	EN 300 330: 9 kHz–25 MHz	173
5.2.2.1	Carrier power — limit values for H field transmitters	173
5.2.2.2	Spurious emissions	175
5.2.3	EN 300 220-1, EN 300 220-2	175
5.2.4	EN 300 440	176
5.3	National Licensing Regulations in Europe	177
5.3.1	Germany	177
5.4	National Licensing Regulations	179
5.4.1	USA	179
5.4.2	Future development: USA–Japan–Europe	180
6	Coding and Modulation	183
6.1	Coding in the Baseband	184
6.2	Digital Modulation Procedures	186
6.2.1	Amplitude shift keying (ASK)	186
6.2.2	2 FSK	189
6.2.3	2 PSK	190
6.2.4	Modulation procedures with subcarrier	191
7	Data Integrity	195
7.1	The Checksum Procedure	195

7.1.1	Parity checking	195
7.1.2	LRC procedure	196
7.1.3	CRC procedure	197
7.2	Multi-Access Procedures — Anticollision	200
7.2.1	Space division multiple access (SDMA)	202
7.2.2	Frequency domain multiple access (FDMA)	204
7.2.3	Time domain multiple access (TDMA)	205
7.2.4	Examples of anticollision procedures	206
7.2.4.1	ALOHA procedure	206
7.2.4.2	Slotted ALOHA procedure	208
7.2.4.3	Binary search algorithm	212
8	Data Security	221
8.1	Mutual Symmetrical Authentication	221
8.2	Authentication Using Derived Keys	223
8.3	Encrypted Data Transfer	224
8.3.1	Stream cipher	225
9	Standardisation	229
9.1	Animal Identification	229
9.1.1	ISO 11784 — Code structure	229
9.1.2	ISO 11785 — Technical concept	230
9.1.2.1	Requirements	230
9.1.2.2	Full/half duplex system	232
9.1.2.3	Sequential system	232
9.1.3	ISO 14223 — Advanced transponders	233
9.1.3.1	Part 1 — Air interface	233
9.1.3.2	Part 2 — Code and command structure	234
9.2	Contactless Smart Cards	236
9.2.1	ISO 10536 — Close coupling smart cards	237
9.2.1.1	Part 1 — Physical characteristics	238
9.2.1.2	Part 2 — Dimensions and locations of coupling areas	238
9.2.1.3	Part 3 — Electronic signals and reset procedures	238
9.2.1.4	Part 4 — Answer to reset and transmission protocols	239
9.2.2	ISO 14443 — Proximity coupling smart cards	240
9.2.2.1	Part 1 — Physical characteristics	240
9.2.2.2	Part 2 — Radio frequency interference	240
9.2.2.3	Part 3 — Initialisation and anticollision	245
9.2.2.4	Part 4 — Transmission protocols	251
9.2.3	ISO 15693 — Vicinity coupling smart cards	256
9.2.3.1	Part 1 — Physical characteristics	256
9.2.3.2	Part 2 — Air interface and initialisation	256
9.2.4	ISO 10373 — Test methods for smart cards	260
9.2.4.1	Part 4: Test procedures for close coupling smart cards	261
9.2.4.2	Part 6: Test procedures for proximity coupling smart cards	261
9.2.4.3	Part 7: Test procedure for vicinity coupling smart cards	264

9.3	ISO 69873 — Data Carriers for Tools and Clamping Devices	265
9.4	ISO 10374 — Container Identification	265
9.5	VDI 4470 — Anti-theft Systems for Goods	265
9.5.1	Part 1 — Detection gates — inspection guidelines for customers	265
9.5.1.1	Ascertaining the false alarm rate	266
9.5.1.2	Ascertaining the detection rate	267
9.5.1.3	Forms in VDI 4470	267
9.5.2	Part 2 — Deactivation devices, inspection guidelines for customers	268
9.6	Item Management	268
9.6.1	ISO 18000 series	268
9.6.2	GTAG initiative	269
9.6.2.1	GTAG transport layer (physical layer)	270
9.6.2.2	GTAG communication and application layer	271

10 The Architecture of Electronic Data Carriers 273

10.1	Transponder with Memory Function	273
10.1.1	HF interface	273
10.1.1.1	Example circuit — load modulation with subcarrier	274
10.1.1.2	Example circuit — HF interface for ISO 14443 transponder	276
10.1.2	Address and security logic	278
10.1.2.1	State machine	279
10.1.3	Memory architecture	280
10.1.3.1	Read-only transponder	280
10.1.3.2	Writable transponder	281
10.1.3.3	Transponder with cryptological function	281
10.1.3.4	Segmented memory	284
10.1.3.5	MIFARE® application directory	286
10.1.3.6	Dual port EEPROM	289
10.2	Microprocessors	292
10.2.1	Dual interface card	293
10.2.1.1	MIFARE® plus	295
10.2.1.2	Modern concepts for the dual interface card	296
10.3	Memory Technology	298
10.3.1	RAM	299
10.3.2	EEPROM	299
10.3.3	FRAM	300
10.3.4	Performance comparison FRAM — EEPROM	302
10.4	Measuring Physical Variables	302
10.4.1	Transponder with sensor functions	302
10.4.2	Measurements using microwave transponders	303
10.4.3	Sensor effect in surface wave transponders	305

11 Readers 309

11.1	Data Flow in an Application	309
11.2	Components of a Reader	309

11.2.1	HF interface	311
11.2.1.1	Inductively coupled system, FDX/HDX	312
11.2.1.2	Microwave systems — half duplex	313
11.2.1.3	Sequential systems — SEQ	314
11.2.1.4	Microwave system for SAW transponders	315
11.2.2	Control unit	316
11.3	Low Cost Configuration — Reader IC U2270B	317
11.4	Connection of Antennas for Inductive Systems	319
11.4.1	Connection using current matching	320
11.4.2	Supply via coaxial cable	322
11.4.3	The influence of the Q factor	325
11.5	Reader Designs	326
11.5.1	OEM readers	326
11.5.2	Readers for industrial use	327
11.5.3	Portable readers	328

12 The Manufacture of Transponders and Contactless Smart Cards 329

12.1	Glass and Plastic Transponders	329
12.1.1	Module manufacture	329
12.1.2	Semi-finished transponder	330
12.1.3	Completion	332
12.2	Contactless Smart Cards	332
12.2.1	Coil manufacture	333
12.2.2	Connection technique	336
12.2.3	Lamination	338

13 Example Applications 341

13.1	Contactless Smart Cards	341
13.2	Public Transport	342
13.2.1	The starting point	343
13.2.2	Requirements	344
13.2.2.1	Transaction time	344
13.2.2.2	Resistance to degradation, lifetime, convenience	344
13.2.3	Benefits of RFID systems	345
13.2.4	Fare systems using electronic payment	346
13.2.5	Market potential	346
13.2.6	Example projects	347
13.2.6.1	Korea — seoul	347
13.2.6.2	Germany — Lüneburg, Oldenburg	349
13.2.6.3	EU Projects — ICARE and CALYPSO	350
13.3	Ticketing	354
13.3.1	Lufthansa miles & more card	354
13.3.2	Ski tickets	356

13.4	Access Control	357
13.4.1	Online systems	357
13.4.2	Offline systems	358
13.4.3	Transponders	360
13.5	Transport Systems	361
13.5.1	Eurobalise S21	361
13.5.2	International container transport	363
13.6	Animal Identification	364
13.6.1	Stock keeping	364
13.6.2	Carrier pigeon races	367
13.7	Electronic Immobilisation	371
13.7.1	The functionality of an immobilisation system	372
13.7.2	Brief success story	375
13.7.3	Predictions	376
13.8	Container Identification	376
13.8.1	Gas bottles and chemical containers	376
13.8.2	Waste disposal	378
13.9	Sporting Events	379
13.10	Industrial Automation	381
13.10.1	Tool identification	381
13.10.2	Industrial production	385
13.10.2.1	Benefits from the use of RFID systems	387
13.10.2.2	The selection of a suitable RFID system	388
13.10.2.3	Example projects	389
13.11	Medical Applications	392
14	Appendix	394
14.1	Contact Addresses, Associations and Technical Periodicals	394
14.1.1	Industrial associations	394
14.1.2	Technical journals	398
14.1.3	RFID on the internet	399
14.2	Relevant Standards and Regulations	400
14.2.1	Sources for standards and regulations	405
14.3	References	406
14.4	Printed Circuit Board Layouts	412
14.4.1	Test card in accordance with ISO 14443	412
14.4.2	Field generator coil	413