ISO/IEC/IEEE 8802-15-4:2018-03 (E)

Information technology - Telecomm unications and information exchange between systems - Local and metropolitan area networks - Specific requirements - Part 15-4: Wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (WPANs)

Contents

1. Overview ... 35

1.1 Scope ... 35
1.2 Purpose ... 35

2. Normative references ... 36

3. Definitions, acronyms, and abbreviations ... 37

3.1 Definitions ... 37
3.2 Acronyms and abbreviations ... 38

4. Format conventions ... 42

4.1 General ... 42
4.2 Fields ... 42
4.3 Numbers ... 43
4.4 Strings ... 43
4.5 Reserved fields and values ... 43

5. General description ... 44

5.1 Introduction ... 44
5.2 Special application spaces ... 44
5.2.1 Smart utility network (SUN) ... 44
5.2.2 Rail communications and control (RCC) ... 44
5.2.3 Television white space (TVWS) ... 45
5.2.4 Radio frequency identification (RFID) ... 45
5.2.5 Low-energy, critical infrastructure monitoring (LECIM) ... 45
5.2.6 Medical body area network (MBAN) services ... 45
5.3 Components of the IEEE 802.15.4 WPAN ... 45
5.4 Multi-PHY management (MPM) of the SUN WPAN ... 45
5.5 Network topologies ... 46
5.5.1 Star network formation ... 46
5.5.2 Peer-to-peer network formation ... 47
5.6 Architecture ... 48
5.6.1 PHY ... 49
5.6.2 MAC sublayer ... 49
5.7 Functional overview ... 50
5.7.1 Superframe structure ... 50
5.7.1.1 Beacon superframe ... 50
5.7.1.2 DSME multi-superframe structure ... 51
5.7.1.3 Slotframes ... 51
5.7.1.4 TMCTP superframe ... 51
5.7.2 Data transfer model ... 52
5.7.2.1 Types of data transfer models ... 52
5.7.2.2 Data transfer to a coordinator ... 52
5.7.2.3 Data transfer from a coordinator ... 52
5.7.2.4 Peer-to-peer data transfers ... 53
5.7.3 Frame structure ... 53
5.7.4 Access methods ... 53

5.7.4.1 Frame acknowledgment ... 53
5.7.4.2 Frak ... 54
5.7.4.3 Data verification ... 54
5.7.5 Power consumption considerations ... 54
5.7.5.1 Low-energy mechanisms ... 54
5.7.6 Security ... 55
5.8 Concept of primitives ... 56
5.9 Deprecation of features ... 56

6. MAC functional description ... 57

6.1 Device types and conventions ... 57
6.2 Channel access ... 57
6.2.1 Superframe structure ... 57
6.2.1.1 Contention access period (CAP) ... 59
6.2.1.2 Contention-free period (CFP) ... 59
6.2.1.3 BOP ... 59
6.2.2 Incoming and outgoing superframe timing ... 59
6.2.3 Enhanced Beacon frame timing for MPM procedure ... 60
6.2.4 IFS ... 61
6.2.5 Random access methods ... 61
6.2.5.1 CSMA-CA algorithm ... 61
6.2.5.2 TSCH CCA algorithm ... 64
6.2.5.3 TSCH CSMA-CA retransmission algorithm ... 64
6.2.5.4 CSMA-CA with PCA ... 66
6.2.5.5 LECIM ALOHA PCA ... 69
6.2.6 TSCH slotframe structure ... 69
6.2.6.1 General ... 69
6.2.6.2 Absolute slot number (ASN) ... 70
6.2.6.3 Links ... 70
6.2.6.4 Multiple slotframes ... 70
6.2.7 LE functional description ... 71
6.2.7.1 LE contention access period (LE CAP) ... 71
6.2.7.2 LE superframe structure ... 71
6.2.7.3 LE-incoming and outgoing superframe timing ... 71
6.2.7.4 LE scan ... 71
6.2.8 Superframe use for TMCTP operation ... 72
6.2.9 Rail communications and control network (RCCN) superframe structure ... 72
6.2.10 Channel hopping ... 73
6.3 Starting and maintaining PANs ... 75
6.3.1 Scanning through channels ... 75
6.3.1.1 ED channel scan ... 75
6.3.1.2 Active and passive channel scan ... 75
6.3.1.3 Orphan channel scan ... 78
6.3.1.4 RIT passive channel scan ... 80
6.3.2 PAN ID conflict resolution ... 81
6.3.2.1 Detection ... 81
6.3.2.2 Resolution ... 82
6.3.3 Starting and realigning a PAN ... 82
6.3.3.1 Starting a PAN ... 82
6.3.3.2 Realigning a PAN ... 82
6.3.3.3 Realignment in a PAN ... 84
6.3.3.4 Updating superframe configuration and channel PIB attributes ... 84
6.3.4 Beacon generation ... 84

6.3.5 Device discovery ... 86
6.3.6 TSCH PAN formation ... 86
6.4 Association and disassociation ... 87
6.4.1 Association ... 87
6.4.2 Disassociation ... 90
6.4.3 Fast association ... 92
6.5 Synchronization ... 93
6.5.1 General ... 93
6.5.2 Synchronization with beacons ... 93
6.5.3 Synchronization without beacons ... 95
6.5.4 Synchronization in TSCH PAN ... 95
6.5.4.1 Timeslot communication ... 96
6.5.4.2 Node synchronization ... 97
6.5.5 Orphaned device realignment ... 98
6.6 Transaction handling ... 98
6.7 Transmission, reception, and acknowledgment ... 99
6.7.1 Transmission ... 99
6.7.2 Reception and rejection ... 101
6.7.3 Extracting pending data from a coordinator ... 102
6.7.4 Use of acknowledgments and retransmissions ... 104
6.7.4.1 No acknowledgment ... 104
6.7.4.2 Acknowledgment ... 105
6.7.4.3 Retransmissions ... 106
6.7.5 Transmission timing restrictions ... 106
6.7.6 Guard time ... 107
6.7.7 Promiscuous mode ... 109
6.7.8 Transmission scenarios ... 109
6.7.9 Device announcement ... 110
6.8 GTS allocation and management ... 111
6.8.1 GTS general requirements ... 111
6.8.2 CAP maintenance ... 112
6.8.3 GTS allocation ... 112
6.8.4 GTS usage ... 113
6.8.5 GTS deallocation ... 114
6.8.6 GTS reallocation ... 115
6.8.7 GTS expiration ... 117
6.9 Ranging ... 117
6.9.1 Ranging requirements ... 117
6.9.2 Set-up activities before a ranging exchange ... 117
6.9.3 Finish-up activities after a ranging exchange ... 117
6.9.4 Managing DPS ... 118
6.9.5 The ranging exchange ... 119
6.10 PHY parameter change notification procedure ... 120
6.10.1 Signaling using Beacon frames ... 120
6.10.2 Signaling using multipurpose frames ... 120
6.11 Deterministic and synchronous multi-channel extension (DSME) ... 121
6.11.1 DSME command requirements ... 121
6.11.2 DSME multi-superframe structure ... 121
6.11.3 Channel diversity ... 123
6.11.3.1 Channel adaptation ... 123
6.11.3.2 Channel hopping ... 124
6.11.4 CAP reduction ... 126
6.11.5 DSME GTS allocation and management ... 126
6.11.5.1 DSME GTS allocation ... 127

6.11.5.2 DSME GTS deallocation ... 130
6.11.5.3 DSME GTS expiration ... 131
6.11.5.4 DSME GTS retrieve ... 131
6.11.5.5 DSME GTS change ... 132
6.11.6 Beacon scheduling ... 132
6.11.7 Time synchronization ... 133
6.11.8 Deferred beacon ... 134
6.11.9 Passive channel scan ... 134
6.12 LE transmission, reception and acknowledgment ... 134
6.12.1 LE transmission, reception, and acknowledgment with positive handshakes ... 134
6.12.2 Coordinated sampled listening (CSL) ... 135
6.12.2.1 CSL idle listening ... 136
6.12.2.2 CSL transmission ... 136
6.12.2.3 Unicast transmission ... 137
6.12.2.4 Broadcast transmission ... 137
6.12.2.5 CSL reception ... 138
6.12.2.6 CSL over multiple channels ... 138
6.12.2.7 Turning off CSL mode to reduce latency ... 138
6.12.3 RIT ... 138
6.12.3.1 General ... 138
6.12.3.2 Periodic RIT data request transmission and reception ... 139
6.12.3.3 RIT transmission ... 141
6.12.4 Implicit RIT (I-RIT) ... 143
6.13 Starting and maintaining TMCTPs ... 143
6.14 MPM procedure for inter-PHY coexistence ... 146
6.15 TVWS access procedures ... 149
6.16 Channel timing management (CTM) ... 149

7. MAC frame formats ... 151

7.1 Device extended address ... 151
7.2 General MAC frame format ... 151
7.2.1 Frame Control field ... 151
7.2.1.1 Frame Type field ... 152
7.2.1.2 Security Enabled field ... 152
7.2.1.3 Frame Pending field ... 152
7.2.1.4 AR field ... 153
7.2.1.5 PAN ID Compression field ... 153
7.2.1.6 Sequence Number Suppression ... 154
7.2.1.7 IE Present field ... 154
7.2.1.8 Destination Addressing Mode field ... 154
7.2.1.9 Frame Version field ... 154
7.2.1.10 Source Addressing Mode field ... 155
7.2.2 Sequence Number field ... 155
7.2.3 Destination PAN ID field ... 155
7.2.4 Destination Address field ... 155
7.2.5 Source PAN ID field ... 156
7.2.6 Source Address field ... 156
7.2.7 Auxiliary Security Header field ... 156
7.2.8 IE field ... 156
7.2.9 Frame Payload field ... 156
7.2.10 FCS field ... 156
7.3 Format of individual frame types ... 158
7.3.1 Beacon frame format ... 158

7.3.1.1 Beacon frame MHR field ... 159
7.3.1.2 IEs field ... 160
7.3.1.3 Superframe Specification field ... 160
7.3.1.4 GTS Info field ... 161
7.3.1.5 Pending Address field ... 162
7.3.1.6 Beacon Payload field ... 162
7.3.2 Data frame format ... 163
7.3.2.1 Data frame MHR field ... 163
7.3.2.2 Data Payload field ... 163
7.3.3 Ack frame format ... 163
7.3.4 MAC command frame format ... 165
7.3.4.1 MHR field ... 165
7.3.4.2 Command ID field ... 165
7.3.4.3 Payload field ... 165
7.3.5 Multipurpose frame format ... 165
7.3.5.1 Frame Type field ... 166
7.3.5.2 Long Frame Control field ... 166
7.3.5.3 Destination Addressing Mode field ... 166
7.3.5.4 Source Addressing Mode field ... 166
7.3.5.5 PAN ID Present field ... 166
7.3.5.6 Security Enabled field ... 167
7.3.5.7 Sequence Number Suppression field ... 167
7.3.5.8 Frame Pending field ... 167
7.3.5.9 Frame Version field ... 167
7.3.5.10 Ack Request field ... 167
7.3.5.11 IEs Present field ... 167
7.3.5.12 Sequence Number field ... 167
7.3.5.13 Destination PAN ID field ... 167
7.3.5.14 Destination Address field ... 167
7.3.5.15 Source Address field ... 167
7.3.5.16 Auxiliary Security Header field ... 167
7.3.5.17 IEs field ... 168
7.3.5.18 Payload field ... 168
7.3.6 Extended frame format ... 168
7.4 IEs ... 168
7.4.1 IE list termination ... 168
7.4.2 Header IEs ... 169
7.4.2.1 Header IE format ... 169
7.4.2.2 Vendor Specific Header IE ... 171
7.4.2.3 CSL IE ... 171
7.4.2.4 RIT IE ... 171
7.4.2.5 DSME PAN descriptor IE ... 172
7.4.2.6 Rendezvous Time IE ... 174
7.4.2.7 Time Correction IE ... 174
7.4.2.8 Extended DSME PAN descriptor IE ... 175
7.4.2.9 Fragment Sequence Context Description (FSCD) IE ... 176
7.4.2.10 Simplified Superframe Specification IE ... 177
7.4.2.11 Simplified GTS Specification IE ... 178
7.4.2.12 LECIM Capabilities IE ... 178
7.4.2.13 RCC Capabilities IE ... 180
7.4.2.14 RCCN Descriptor IE ... 182
7.4.2.15 Global Time IE ... 183
7.4.2.16 DA IE ... 183
7.4.2.17 Header Termination 1 IE ... 184

7.4.2.18 Header Termination 2 IE ... 184
7.4.3 Payload IEs ... 184
7.4.3.1 Encapsulated Service Data Unit (ESDU) IE ... 184
7.4.3.2 MLME IE ... 185
7.4.3.3 Payload Termination IE ... 185
7.4.4 Nested IE ... 185
7.4.4.1 Format of Nested IE ... 185
7.4.4.2 TSCH Synchronization IE ... 188
7.4.4.3 TSCH Slotframe and Link IE ... 188
7.4.4.4 TSCH Timeslot IE ... 190
7.4.4.5 Hopping timing IE ... 191
7.4.4.6 Enhanced Beacon Filter IE ... 191
7.4.4.7 MAC Metrics IE ... 192
7.4.4.8 All MAC Metrics IE ... 192
7.4.4.9 Coexistence Specification IE ... 193
7.4.4.10 SUN Device Capabilities IE ... 193
7.4.4.11 SUN FSK Generic PHY IE ... 199
7.4.4.12 Mode Switch Parameter IE ... 200
7.4.4.13 PHY Parameter Change IE ... 200
7.4.4.14 O-QPSK PHY Mode IE ... 201
7.4.4.15 PCA Allocation IE ... 201
7.4.4.16 LECIM DSSS Operating Mode IE ... 202
7.4.4.17 LECIM FSK Operating Mode IE ... 204
7.4.4.18 TVWS PHY Operating Mode Description IE ... 205
7.4.4.19 TVWS Device Capabilities IE ... 208
7.4.4.20 TVWS Device Category IE ... 213
7.4.4.21 TVWS Device Identification IE ... 213
7.4.4.22 TVWS Device Location IE ... 214
7.4.4.23 TVWS Channel Information Query IE ... 215
7.4.4.24 TVWS Channel Information Source IE ... 217
7.4.4.25 CTM IE ... 218
7.4.4.26 Timestamp IE ... 219
7.4.4.27 Timestamp Difference IE ... 219
7.4.4.28 TMCTP Specification IE ... 219
7.4.4.29 RCC PHY Operating Mode IE ... 220
7.4.4.30 Vendor Specific Nested IE ... 221
7.4.4.31 Channel hopping IE ... 221
7.5 MAC commands ... 222
7.5.1 Command ID field ... 222
7.5.2 Association Request command ... 223
7.5.3 Association Response command ... 224
7.5.4 Disassociation Notification command ... 225
7.5.5 Data Request command ... 226
7.5.6 PAN ID Conflict Notification command ... 227
7.5.7 Orphan Notification command ... 227
7.5.8 Beacon Request command ... 228
7.5.9 Enhanced Beacon Request command ... 228
7.5.10 Coordinator realignment command ... 228
7.5.11 GTS request command ... 230
7.5.12 DSME Association Request command ... 230
7.5.13 DSME Association Response command ... 232
7.5.14 DSME GTS Request command ... 233
7.5.15 DSME GTS Response command ... 235
7.5.16 DSME GTS Notify command ... 237

7.5.17 DSME Information Request command ... 238
7.5.18 DSME Information Response command ... 238
7.5.19 DSME Beacon Allocation Notification command ... 239
7.5.20 DSME Beacon Collision Notification command ... 240
7.5.21 DSME Link Report command ... 240
7.5.22 RIT Data Request command ... 241
7.5.23 DBS Request command ... 242
7.5.24 DBS Response command ... 243
7.5.25 RIT Data Response command ... 244
7.5.26 Vendor Specific command ... 244

8. MAC services ... 245

8.1 Overview ... 245
8.2 MAC management service ... 245
8.2.1 Primitives supported by the MLME-SAP interface ... 245
8.2.2 Common requirements for MLME primitives ... 247
8.2.3 Association primitives ... 248
8.2.3.1 MLME-ASSOCIATE.request ... 248
8.2.3.2 MLME-ASSOCIATE.indication ... 249
8.2.3.3 MLME-ASSOCIATE.response ... 251
8.2.3.4 MLME-ASSOCIATE.confirm ... 252
8.2.4 Disassociation primitives ... 254
8.2.4.1 MLME-DISASSOCIATE.request ... 254
8.2.4.2 MLME-DISASSOCIATE.indication ... 256
8.2.4.3 MLME-DISASSOCIATE.confirm ... 256
8.2.5 Communications notification primitives ... 257
8.2.5.1 MLME-BEACON-NOTIFY.indication ... 257
8.2.5.2 MLME-COMM-STATUS.indication ... 260
8.2.5.3 MLME-IE-NOTIFY.indication ... 262
8.2.6 Primitives for reading and writing PIB attributes ... 264
8.2.6.1 MLME-GET.request ... 264
8.2.6.2 MLME-GET.confirm ... 264
8.2.6.3 MLME-SET.request ... 265
8.2.6.4 MLME-SET.confirm ... 265
8.2.7 GTS management primitives ... 266
8.2.7.1 MLME-GTS.request ... 266
8.2.7.2 MLME-GTS.confirm ... 267
8.2.7.3 MLME-GTS.indication ... 268
8.2.8 Primitives for orphan notification ... 269
8.2.8.1 MLME-ORPHAN.indication ... 269
8.2.8.2 MLME-ORPHAN.response ... 270
8.2.9 Primitives for resetting the MAC sublayer ... 271
8.2.9.1 MLME-RESET.request ... 271
8.2.9.2 MLME-RESET.confirm ... 271
8.2.10 Primitives for specifying the receiver enable time ... 272
8.2.10.1 MLME-RX-ENABLE.request ... 272
8.2.10.2 MLME-RX-ENABLE.confirm ... 273
8.2.11 Primitives for channel scanning ... 274
8.2.11.1 MLME-SCAN.request ... 274
8.2.11.2 MLME-SCAN.confirm ... 277
8.2.12 Primitives for updating the superframe configuration ... 279
8.2.12.1 MLME-START.request ... 279
8.2.12.2 MLME-START.confirm ... 282

8.2.13 Primitives for synchronizing with a coordinator 283
8.2.13.1 MLME-SYNC.request 283
8.2.13.2 MLME-SYNC-LOSS.indication 284
8.2.14 Primitives for requesting data from a coordinator 286
8.2.14.1 MLME-POLL.request 286
8.2.14.2 MLME-POLL.confirm 287
8.2.15 Primitives for specifying dynamic preamble 287
8.2.15.1 MLME-DPS.request 288
8.2.15.2 MLME-DPS.confirm 288
8.2.15.3 MLME-DPS.indication 289
8.2.16 Primitives for channel sounding 289
8.2.16.1 MLME-SOUNDING.request 289
8.2.16.2 MLME-SOUNDING.confirm 289
8.2.17 Primitives for ranging calibration 290
8.2.17.1 MLME-CALIBRATE.request 291
8.2.17.2 MLME-CALIBRATE.confirm 291
8.2.18 Primitives for Beacon Generation 292
8.2.18.1 MLME-BEACON.request 292
8.2.18.2 MLME-BEACON.confirm 294
8.2.18.3 MLME-BEACON-REQUEST.indication 295
8.2.19 Primitives for TSCH 296
8.2.19.1 MLME-SET-SLOTFRAME.request 296
8.2.19.2 MLME-SET-SLOTFRAME.confirm 297
8.2.19.3 MLME-SET-LINK.request 297
8.2.19.4 MLME-SET-LINK.confirm 299
8.2.19.5 MLME-TSCH-MODE.request 300
8.2.19.6 MLME-TSCH-MODE.confirm 301
8.2.19.7 MLME-KEEP-ALIVE.request 301
8.2.19.8 MLME-KEEP-ALIVE.confirm 302
8.2.20 Primitives for DSME GTS management 302
8.2.20.1 MLME-DSME-GTS.request 302
8.2.20.2 MLME-DSME-GTS.indication 305
8.2.20.3 MLME-DSME-GTS.response 306
8.2.20.4 MLME-DSME-GTS.confirm 308
8.2.21 Primitives for reporting the link status 309
8.2.21.1 MLME-DSME-LINK-REPORT.request 309
8.2.21.2 MLME-DSME-LINK-REPORT.indication 310
8.2.21.3 MLME-DSME-LINK-REPORT.confirm 311
8.2.22 Operating parameter change primitives 311
8.2.22.1 MLME-PHY-OP-SWITCH.request 311
8.2.22.2 MLME-PHY-OP-SWITCH.indication 313
8.2.22.3 MLME-PHY-OP-SWITCH.confirm 315
8.2.23 TMCTP DBS allocation primitives 316
8.2.23.1 MLME-DBS.request 316
8.2.23.2 MLME-DBS.indication 317
8.2.23.3 MLME-DBS.response 318
8.2.23.4 MLME-DBS.confirm 319
8.2.24 Primitives for device announcement 320
8.2.24.1 MLME-DA.request primitive 320
8.2.24.2 MLME-DA.indication primitive 321
8.2.24.3 MLME-DA.confirm primitive 321
8.2.25 RIT data commands 322
8.2.25.1 MLME-RIT-REQ.indication 322
8.2.25.2 MLME-RIT-RES.request 324

8.2.25.3 MLME-RIT-RES.indication ... 325
8.2.25.4 MLME-RIT-RES.confirm ... 327
8.3 MAC data service ... 328
8.3.1 MCPS-DATA.request ... 328
8.3.2 MCPS-DATA.confirm ... 332
8.3.3 MCPS-DATA.indication ... 335
8.3.4 MCPS-PURGE.request ... 338
8.3.5 MCPS-PURGE.confirm ... 338
8.4 MAC constants and PIB attributes ... 339
8.4.1 MAC constants ... 339
8.4.2 MAC PIB attributes ... 340
8.4.2.1 General MAC PIB attributes for functional organization ... 345
8.4.2.2 TSCH-specific MAC PIB attributes ... 348
8.4.2.2.1 TSCH MAC PIB attributes for macSlotframeTable ... 348
8.4.2.2.2 TSCH MAC PIB attributes for macLinkTable ... 349
8.4.2.2.3 TSCH MAC PIB attributes for macTimeslotTemplate ... 350
8.4.2.3 MAC PIB attributes for hopping sequence ... 351
8.4.2.4 DSME specific MAC PIB attributes ... 352
8.4.2.5 LE specific MAC PIB attributes ... 355
8.4.2.6 MAC performance metrics specific MAC PIB attributes ... 357
8.4.2.7 Enhanced Beacon Request command specific MAC PIB attributes ... 358
8.4.2.8 Enhanced Beacon frame specific MAC PIB attributes ... 359

9. Security ... 360

9.1 Overview ... 360
9.2 Functional description ... 360
9.2.1 Outgoing frame security procedure ... 360
9.2.2 KeyDescriptor lookup procedure ... 362
9.2.3 Incoming frame security procedure, Security Enabled field is set to one ... 362
9.2.4 Incoming frame security procedure, Security Enabled field is set to zero ... 364
9.2.5 DeviceDescriptor lookup procedure ... 365
9.2.6 SecurityLevelDescriptor lookup procedure ... 366
9.2.7 Incoming IE security level checking procedure ... 366
9.2.8 Incoming IE key usage policy checking procedure ... 367
9.2.9 Incoming security level checking procedure ... 367
9.2.10 Incoming key usage policy checking procedure ... 367
9.3 Security operations ... 368
9.3.1 Integer and octet representation ... 368
9.3.2 CCM* nonce ... 368
9.3.2.1 CCM* nonce for non-TSCH mode ... 368
9.3.2.2 CCM* nonce for TSCH mode ... 368
9.3.2.3 CCM* nonce for Fragment frames ... 369
9.3.3 CCM* prerequisites ... 369
9.3.4 CCM* transformation data representation ... 370
9.3.4.1 Key and nonce data inputs ... 370
9.3.4.2 a data and m data ... 370
9.3.4.3 c data output ... 370
9.3.5 CCM* inverse transformation data representation ... 371
9.3.5.1 Key and nonce data inputs ... 371
9.3.5.2 c data and a data ... 371
9.3.5.3 m data output ... 372
9.4 Auxiliary security header ... 372
9.4.1 Security Control field ... 372

9.4.1.1 Security Level field ... 372
9.4.1.2 Key Identifier Mode field ... 373
9.4.1.3 Frame Counter Suppression field ... 374
9.4.1.4 ASN in Nonce ... 374
9.4.2 Frame Counter field ... 374
9.4.3 Key Identifier field ... 375
9.4.3.1 Key Source field ... 375
9.4.3.2 Key Index field ... 375
9.5 Security-related MAC PIB attributes ... 375

10. General PHY requirements ... 381

10.1 General requirements and definitions ... 381
10.1.1 Operating frequency range ... 382
10.1.2 Channel assignments ... 387
10.1.2.1 Channel numbering for 780 MHz band ... 387
10.1.2.2 Channel numbering for 868 MHz, 915 MHz, and 2450 MHz bands ... 387
10.1.2.3 Channel numbering for CSS PHY ... 388
10.1.2.4 Channel numbering for HRP UWB PHY ... 388
10.1.2.5 Channel numbering for MSK PHY 433 MHz band ... 389
10.1.2.6 Channel numbering for MSK PHY 2450 MHz band ... 390
10.1.2.7 Channel numbering for LRP UWB PHY ... 392
10.1.2.8 Channel numbering for SUN and TVWS PHYs ... 392
10.1.2.9 Channel numbering for 2380 MHz band ... 395
10.1.2.10 Channel numbering for LECIM PHYs ... 395
10.1.2.10.1 Channel numbering for LECIM DSSS PHY ... 396
10.1.2.10.2 Channel numbering for LECIM FSK PHY ... 396
10.1.2.11 Channel numbering for RCC PHYs ... 397
10.1.3 Minimum LIFS and SIFS periods ... 398
10.1.4 RF power measurement ... 399
10.1.5 Transmit power ... 399
10.1.6 Out-of-band spurious emission ... 399
10.1.7 Receiver sensitivity definitions ... 399
10.1.8 Common signaling mode (CSM) for SUN PHY ... 400
10.2 General radio specifications ... 400
10.2.1 TX-to-RX turnaround time ... 400
10.2.2 RX-to-TX turnaround time ... 400
10.2.3 Error-vector magnitude (EVM) definition ... 400
10.2.4 Receiver maximum input level of desired signal ... 401
10.2.5 Receiver ED ... 401
10.2.6 Link quality indicator (LQI) ... 402
10.2.7 Clear channel assessment (CCA) ... 402

11. PHY services ... 404

11.1 Overview ... 404
11.2 PHY constants ... 404
11.3 PHY PIB attributes ... 404

12. O-QPSK PHY ... 411

12.1 PPDU format ... 411
12.1.1 SHR field format ... 411
12.1.1.1 Preamble field ... 411

12.1.1.2 SFD field ... 411
12.1.2 PHR field format ... 411
12.1.2.1 Frame Length field ... 411
12.1.2.2 PHY Payload field ... 411
12.2 Modulation and spreading ... 412
12.2.1 Data rate ... 412
12.2.2 Reference modulator diagram ... 412
12.2.3 Bit-to-symbol mapping ... 412
12.2.4 Symbol-to-chip mapping ... 412
12.2.5 O-QPSK modulation ... 414
12.2.6 Pulse shape ... 414
12.2.7 Chip transmission order ... 415
12.3 O-QPSK PHY RF requirements ... 415
12.3.1 Operating frequency range ... 415
12.3.2 Transmit power spectral density (PSD) mask ... 416
12.3.3 Symbol rate ... 416
12.3.4 Receiver sensitivity ... 416
12.3.5 Receiver interference rejection ... 416
12.3.6 TX-to-RX turnaround time ... 417
12.3.7 RX-to-TX turnaround time ... 417
12.3.8 EVM ... 417
12.3.9 Transmit center frequency tolerance ... 417
12.3.10 Transmit power ... 417
12.3.11 Receiver maximum input level of desired signal ... 417
12.3.12 Receiver ED ... 417
12.3.13 LQI ... 417

13. Binary phase-shift keying (BPSK) PHY ... 418

13.1 PPDU format ... 418
13.2 Modulation and spreading ... 418
13.2.1 BPSK PHY data rates ... 418
13.2.2 Reference modulator ... 418
13.2.3 Differential encoding ... 418
13.2.4 Bit-to-chip mapping ... 419
13.2.5 BPSK modulation ... 419
13.2.5.1 Pulse shape ... 419
13.2.5.2 Chip transmission order ... 419
13.3 BPSK PHY RF requirements ... 419
13.3.1 Operating frequency range ... 419
13.3.2 915 MHz band transmit PSD mask ... 419
13.3.3 Symbol rate ... 420
13.3.4 Receiver sensitivity ... 420
13.3.5 Receiver interference rejection ... 420
13.3.6 TX-to-RX turnaround time ... 420
13.3.7 RX-to-TX turnaround time ... 420
13.3.8 EVM ... 421
13.3.9 Transmit center frequency tolerance ... 421
13.3.10 Transmit power ... 421
13.3.11 Receiver maximum input level of desired signal ... 421
13.3.12 Receiver ED ... 421
13.3.13 LQI ... 421

14. Amplitude shift keying (ASK) PHY ... 422

14.1 Status of ASK PHY 422
14.2 PPDU format 422
14.2.1 Preamble field for ASK PHY 422
14.2.2 SFD for ASK PHY 422
14.3 Modulation and spreading 422
14.3.1 ASK PHY data rates 422
14.3.2 Reference modulator 423
14.3.3 Bit-to-symbol mapping 423
14.3.4 Symbol-to-chip mapping 423
14.3.5 ASK modulation 424
14.3.6 Pulse shape 426
14.3.7 Chip transmission order 426
14.4 ASK PHY RF requirements 426
14.4.1 Operating frequency range 426
14.4.2 915 MHz band transmit PSD mask 426
14.4.3 Symbol rate 426
14.4.4 Receiver sensitivity 427
14.4.5 Receiver interference rejection 427
14.4.6 TX-to-RX turnaround time 427
14.4.7 RX-to-TX turnaround time 427
14.4.8 EVM 427
14.4.9 Transmit center frequency tolerance 427
14.4.10 Transmit power 427
14.4.11 Receiver maximum input level of desired signal 428
14.4.12 Receiver ED 428
14.4.13 LQI 428
14.4.14 Example of PSSS encoding 428

15. Chirp spread spectrum (CSS) PHY 430

15.1 CSS PPDU format 430
15.1.1 Preamble field 430
15.1.2 SFD field 430
15.1.3 PHR field 431
15.1.4 PHY Payload field 431
15.2 Modulation and spreading 431
15.2.1 Data rates 431
15.2.2 Reference modulator 431
15.2.3 De-multiplexer (DEMUX) 431
15.2.4 Serial-to-parallel mapping 431
15.2.5 Data-symbol-to-bi-orthogonal-codeword mapping 432
15.2.6 Parallel-to-serial converter and QPSK symbol mapping 436
15.2.7 DQPSK coding 436
15.2.8 DQPSK-to-DQCSK modulation 437
15.2.9 CSK generator 437
15.2.10 Bit interleaver 437
15.3 Waveform and subchirp sequences 438
15.3.1 Graphical presentation of chirp symbols (subchirp sequences) 438
15.3.2 Active usage of time gaps 438
15.3.3 Mathematical representation of the continuous time CSS base-band signal 439
15.3.4 Raised cosine window for chirp pulse shaping 441
15.3.5 Subchirp transmission order 441
15.3.6 Example of CSK signal generation 442
15.4 CSS RF requirements 443

15.4.1 Transmit power spectral density (PSD) mask and signal tolerance ... 443
15.4.2 Symbol rate ... 444
15.4.3 Receiver sensitivity ... 444
15.4.4 Receiver interference rejection ... 444
15.4.5 TX-to-RX turnaround time ... 444
15.4.6 RX-to-TX turnaround time ... 444
15.4.7 Transmit center frequency tolerance ... 444
15.4.8 Transmit power ... 445
15.4.9 Receiver maximum input level of desired signal ... 445
15.4.10 Receiver ED ... 445
15.4.11 LQI ... 445

16. HRP UWB PHY ... 446

16.1 General ... 446
16.2 HRP UWB PPDU format ... 446
16.2.1 PPDU encoding process ... 447
16.2.2 Symbol structure ... 449
16.2.3 PSDU timing parameters ... 450
16.2.4 Preamble timing parameters ... 452
16.2.5 SHR field ... 454
16.2.5.1 SYNC field ... 454
16.2.5.2 SFD field ... 457
16.2.6 PHR field ... 457
16.2.7 PHY Payload field ... 458
16.3 Modulation ... 459
16.3.1 Modulation mathematical framework ... 459
16.3.2 Spreading ... 459
16.3.3 FEC ... 461
16.3.3.1 Reed-Solomon encoding ... 461
16.3.3.2 Systematic convolutional encoding ... 462
16.4 RF requirements ... 463
16.4.1 Operating frequency bands ... 463
16.4.2 Channel assignments ... 464
16.4.3 Regulatory compliance ... 464
16.4.4 Operating temperature range ... 464
16.4.5 Baseband impulse response ... 464
16.4.6 Transmit PSD mask ... 466
16.4.7 Chip rate clock and chip carrier alignment ... 467
16.4.8 TX-to-RX turnaround time ... 467
16.4.9 RX-to-TX turnaround time ... 467
16.4.10 Transmit center frequency tolerance ... 467
16.4.11 Receiver maximum input level of desired signal ... 467
16.4.12 Receiver ED ... 467
16.4.13 LQI ... 467
16.4.14 CCA ... 467
16.5 HRP UWB PHY optional pulse shapes ... 467
16.5.1 HRP UWB PHY optional chirp on UWB (CoU) pulses ... 468
16.5.2 HRP UWB PHY optional continuous spectrum (CS) pulses ... 469
16.5.3 HRP UWB PHY linear combination of pulses (LCP) ... 470
16.6 Extended preamble for optional CCA mode 6 ... 471
16.7 Ranging ... 472
16.7.1 Ranging counter ... 472
16.7.2 Crystal characterization ... 472

16.7.2.1 Ranging tracking offset ... 472
16.7.2.2 Ranging tracking interval ... 472
16.7.3 Ranging FoM ... 473

17. GFSK PHY ... 475

17.1 PPDU formats ... 475
17.2 Modulation ... 475
17.2.1 GFSK PHY data rates ... 475
17.2.2 Reference modulator diagram ... 475
17.2.3 Data whitening ... 475
17.2.4 GFSK modulation ... 476
17.3 GFSK PHY RF requirements ... 476
17.3.1 Operating frequency range ... 476
17.3.2 Transmit PSD mask ... 476
17.3.3 Symbol rate ... 477
17.3.4 Receiver sensitivity ... 477
17.3.5 Receiver interference rejection ... 477
17.3.6 TX-to-RX turnaround time ... 477
17.3.7 RX-to-TX turnaround time ... 477
17.3.8 Transmit center frequency tolerance ... 477
17.3.9 Transmit power ... 477
17.3.10 Receiver maximum input level of desired signal ... 477
17.3.11 Receiver ED ... 478
17.3.12 LQI ... 478

18. MSK PHY ... 479

18.1 PPDU formats ... 479
18.2 Data rate ... 479
18.3 SFD for the MSK PHY ... 479
18.4 MSK modulation ... 480
18.4.1 Reference modulator diagram ... 480
18.4.2 Data whitening ... 480
18.4.3 Bit-to-symbol mapping ... 480
18.4.4 Signal modulation ... 480
18.5 MSK PHY requirements ... 481
18.5.1 Operating frequency range ... 481
18.5.2 Transmit PSD mask ... 481
18.5.3 Symbol rate ... 481
18.5.4 Transmit center frequency tolerance ... 482
18.5.5 Transmit power ... 482
18.5.6 Receiver maximum input level of desired signal ... 482
18.5.7 Modulation frequency deviation tolerance ... 482
18.5.8 Zero crossing tolerance ... 482

19. LRP UWB PHY specification ... 483

19.1 Overview ... 483
19.2 LRP UWB PHY symbol structure ... 483
19.2.1 Base mode LRP UWB PHY symbol structure ... 483
19.2.1.1 Base mode LRP UWB PHY PSDU synchronization signal ... 484
19.2.2 Extended mode LRP UWB PHY symbol structure ... 484
19.2.2.1 Extended mode LRP UWB PHY PSDU synchronization signal ... 485

19.2.3 Long-range mode LRP UWB PHY symbol structure 486
19.2.3.1 Long-range mode LRP UWB PHY PSDU synchronization signal 486
19.3 LRP UWB SHR 487
19.3.1 LRP UWB SHR preamble 487
19.3.1.1 LRP UWB base mode SHR preamble 487
19.3.1.2 RP UWB extended mode SHR preamble 487
19.3.1.3 LRP UWB long-range mode SHR preamble 487
19.3.2 LRP UWB SHR SFD 487
19.4 LRP UWB PHR 487
19.4.1 Encoding Type field 488
19.4.2 Header Extension field 488
19.4.3 SECDED field 489
19.4.4 Frame Length field 489
19.4.5 LEIP Length field 489
19.4.6 LEIP Position field 489
19.5 LRP UWB PSDU 490
19.6 LRP UWB location enhancing information postamble 490
19.7 LRP UWB transmitter specification 490
19.7.1 Pulse shape 490
19.7.2 Pulse timing 491
19.7.3 Transmit PSD mask 491
19.8 LRP UWB receiver specification 492

20. SUN FSK PHY 493

20.1 Introduction 493
20.2 PPDU format for SUN FSK 493
20.2.1 SHR field format 494
20.2.1.1 Preamble field 494
20.2.1.2 SFD 494
20.2.2 PHR field format 495
20.2.3 Mode Switch PHR 495
20.2.4 PHY Payload field 497
20.3 Modulation and coding for SUN FSK 497
20.3.1 Reference modulator 499
20.3.2 Bit-to-symbol mapping 500
20.3.3 Modulation quality 501
20.3.3.1 Frequency deviation tolerance 501
20.3.3.2 Zero crossing tolerance 502
20.3.4 FEC 502
20.3.5 Code-symbol interleaving 505
20.4 Data whitening for SUN FSK 506
20.5 Mode switch mechanism for SUN FSK 506
20.6 SUN FSK PHY RF requirements 509
20.6.1 Operating frequency range 509
20.6.2 Regulatory compliance 509
20.6.3 Radio frequency tolerance 509
20.6.4 Channel switch time 510
20.6.5 Transmitter symbol rate 510
20.6.6 Transmit spectral mask 510
20.6.7 Receiver sensitivity 510
20.6.8 Receiver interference rejection 511
20.6.9 TX-to-RX turnaround time 511
20.6.10 RX-to-TX turnaround time 511

20.6.11 Transmit power 511
20.6.12 Receiver maximum input level of desired signal 511
20.6.13 Receiver ED 511
20.6.14 LQI 511

21. SUN OFDM PHY 512

21.1 Introduction 512
21.2 PPDU format for SUN OFDM 512
21.2.1 Short Training field (STF) 512
21.2.1.1 Frequency domain STF 512
21.2.1.2 Time domain STF generation 515
21.2.1.3 Time domain STF repetition 515
21.2.1.4 STF normalization 516
21.2.2 Long Training field (LTF) 516
21.2.2.1 Frequency domain LTF 516
21.2.2.2 Time domain LTF generation 519
21.2.2.3 LTF normalization 519
21.2.3 PHR 519
21.2.4 PSDU field 520
21.3 Data rates for SUN OFDM 520
21.4 Modulation and coding for SUN OFDM 521
21.4.1 Reference modulator diagram 521
21.4.2 Bit-to-symbol mapping 521
21.4.3 PIB attribute values for phySymbolsPerOctet 523
21.4.4 FEC 523
21.4.5 Interleaver 524
21.4.6 Frequency spreading 526
21.4.6.1 Frequency spreading by 2x 526
21.4.6.2 Frequency spreading by 4x 526
21.4.6.3 No spreading 527
21.4.7 Pilot tones/null tones 527
21.4.8 Cyclic prefix (CP) 530
21.4.9 PPDU Tail field 530
21.4.10 Pad field 530
21.4.11 Scrambler and scrambler seeds 531
21.5 SUN OFDM PHY RF requirements 532
21.5.1 Operating frequency range 532
21.5.2 Transmit power spectral density (PSD) mask 532
21.5.3 Receiver sensitivity 532
21.5.4 Adjacent channel rejection 532
21.5.5 Alternate channel rejection 533
21.5.6 TX-to-RX turnaround time 533
21.5.7 RX-to-TX turnaround time 533
21.5.8 EVM definition 533
21.5.9 Transmit center frequency and symbol tolerance 535
21.5.10 Transmit power 535
21.5.11 Receiver maximum input level of desired signal 535
21.5.12 Receiver ED 535
21.5.13 LQI 535

22. SUN O-QPSK PHY 536

22.1 Introduction 536

22.2 PPDU format for SUN O-QPSK 536
22.2.1 SHR field format 536
22.2.1.1 Preamble field format 536
22.2.1.2 SFD field format 537
22.2.2 PHR field format 537
22.2.3 PHY Payload field 538
22.3 Modulation and coding for SUN O-QPSK 538
22.3.1 Reference modulator 538
22.3.2 SHR coding and spreading 539
22.3.3 PHR coding and spreading 540
22.3.4 PSDU coding and spreading for DSSS 540
22.3.5 PSDU coding and spreading for MDSSS 542
22.3.6 FEC 543
22.3.7 Code-bit interleaving 545
22.3.8 Bit differential encoding (BDE) 546
22.3.9 DSSS bit-to-chip mapping 547
22.3.10 MDSSS bit-to-chip mapping 551
22.3.11 Chip whitening 555
22.3.12 Pilot insertion 556
22.3.13 Modulation parameters for O-QPSK 557
22.4 Support of legacy devices of the 780 MHz, 915 MHz, and 2450 MHz O-QPSK PHYs 558
22.5 SUN O-QPSK PHY RF requirements 558
22.5.1 Operating frequency range 558
22.5.2 Transmit power spectral density (PSD) mask 558
22.5.3 Receiver sensitivity 559
22.5.4 Adjacent channel rejection 559
22.5.5 TX-to-RX turnaround time 560
22.5.6 RX-to-TX turnaround time 560
22.5.7 EVM definition 560
22.5.8 Transmit center frequency and symbol tolerance 560
22.5.9 Transmit power 561
22.5.10 Receiver maximum input level of desired signal 561
22.5.11 Receiver ED 561
22.5.12 LQI 561
22.5.13 CCA 561

23. LECIM DSSS PHYs 562

23.1 PPDU format for DSSS 562
23.2 Modulation and spreading 562
23.2.1 Data rate 562
23.2.2 Reference modulator diagram 563
23.2.3 Convolutional FEC encoding 563
23.2.4 Interleaver 564
23.2.4.1 256-bit fragment size 564
23.2.4.2 384-bit fragment size 564
23.2.4.3 512-bit fragment size 565
23.2.5 Differential encoding 565
23.2.6 Bit-to-symbol and symbol-to-chip encoding 566
23.2.6.1 Gold code generator 566
23.2.6.2 Orthogonal variable spreading factor (OVSF) code generator 567
23.2.7 BPSK/O-QPSK modulation 570
23.2.7.1 BPSK modulation 570
23.2.7.2 O-QPSK modulation 570

23.3 PSDU fragmentation 570
23.3.1 Configuration 571
23.3.2 Fragmentation 571
23.3.3 Fragment packet 572
23.3.4 Calculating FICS field using MIC 572
23.3.5 Fragment acknowledgment and retransmission 573
23.3.6 Frak 573
23.3.6.1 Frak policy 573
23.3.6.2 Frak format 574
23.3.7 Reassembly 575
23.4 DSSS PHY RF requirements 575
23.4.1 Radio frequency tolerance 575
23.4.2 Channel switch time 575
23.4.3 Transmit spectral mask 575
23.4.4 Receiver sensitivity 575
23.4.5 Receiver interference rejection 576
23.4.6 TX-to-RX turnaround time 577
23.4.7 RX-to-TX turnaround time 577
23.4.8 Transmit power 577

24. LECIM FSK PHY specification 578

24.1 General 578
24.2 PPDU format for LECIM FSK PHY 578
24.2.1 SHR field format 578
24.2.1.1 Preamble field format 578
24.2.1.2 SFD field format 578
24.2.2 PHR field format 578
24.2.3 PHY Payload field 579
24.3 Modulation and coding for LECIM FSK PHY 579
24.3.1 Reference modulator 579
24.3.2 Bit-to-symbol mapping 580
24.3.3 Modulation quality 581
24.3.3.1 Frequency deviation tolerance 581
24.3.3.2 Zero crossing tolerance 581
24.3.4 FEC 581
24.3.5 Code-bit interleaving 582
24.3.6 Spreading 583
24.4 Data whitening for LECIM FSK PHY 584
24.5 LECIM FSK PHY RF requirements 585
24.5.1 Operating frequency range 585
24.5.2 Radio frequency tolerance 585
24.5.3 Channel switch time 585
24.5.4 Transmit spectral mask 585
24.5.5 Receiver sensitivity 585
24.5.6 TX-to-RX turnaround time 586
24.5.7 RX-to-TX turnaround time 586
24.5.8 Transmit power 586

25. TVWS-FSK PHY 587

25.1 PPDU format for TVWS-FSK 587
25.1.1 SHR field format 587
25.1.1.1 Preamble field format 587

25.1.1.2 SFD field format 587
25.1.2 PHR field format 587
25.1.3 PHY Payload field 588
25.2 Modulation and coding for TVWS-FSK 588
25.2.1 Reference modulator 589
25.2.2 FEC and interleaving 589
25.2.3 Data whitening 589
25.2.4 Spreading 589
25.2.5 Bit-to-symbol mapping 590
25.2.6 Modulation quality 590
25.2.7 Values for phySymbolsPerOctet 590
25.3 TVWS-FSK RF requirements 591
25.3.1 Operating frequency range 591
25.3.2 Clock frequency and timing accuracy 591
25.3.3 Channel switch time 591
25.3.4 Receiver sensitivity 591
25.3.5 TX-to-RX turnaround time 591
25.3.6 RX-to-TX turnaround time 591
25.3.7 Receiver maximum input level of desired signal 591
25.3.8 Receiver ED 591
25.3.9 LQI 591

26. TVWS-OFDM PHY 592

26.1 General 592
26.2 PPDU format for TVWS-OFDM 592
26.2.1 STF 592
26.2.1.1 Frequency domain STF 592
26.2.1.2 Time domain STF generation 593
26.2.1.3 Time domain STF repetition 594
26.2.1.4 STF power boosting 594
26.2.2 LTF 594
26.2.2.1 Frequency domain LTF 594
26.2.2.2 Time domain LTF generation 595
26.2.3 PHR field format 596
26.2.4 PSDU field 596
26.3 System parameters for TVWS-OFDM 597
26.4 Modulation and coding for TVWS-OFDM 597
26.4.1 Reference modulator 597
26.4.2 Bit-to-symbol mapping 598
26.4.3 FEC 599
26.4.4 Interleaver 599
26.4.5 Pilot tones/null tones 601
26.4.6 CP 602
26.4.7 PPDU Tail field 602
26.4.8 Pad field 602
26.4.9 Scrambler and scrambler seeds 602
26.5 TVWS-OFDM RF requirements 603
26.5.1 Operating frequency range 603
26.5.2 Pulse shaping 603
26.5.3 Transmit power spectral density (PSD) mask 603
26.5.4 Receiver sensitivity 603
26.5.5 TX-to-RX turnaround time 603
26.5.6 RX-to-TX turnaround time 603

26.5.7 EVM definition 603
26.5.8 Transmit center frequency and symbol tolerance 605

27. TVWS-NB-OFDM PHY 606

27.1 PPDU format for TVWS-NB-OFDM 606
27.1.1 Short Training field (STF) 606
27.1.1.1 Frequency domain STF 606
27.1.1.2 Time domain STF generation 609
27.1.1.3 Time domain STF repetition 609
27.1.1.4 STF normalization 610
27.1.2 Long training field (LTF) 610
27.1.2.1 Frequency domain LTF generation 610
27.1.2.2 Time domain LTF generation 613
27.1.2.3 Time domain LTF repetition 614
27.1.2.4 LTF normalization 614
27.1.3 PHR 615
27.1.4 PHY Payload field 615
27.2 System parameters for TVWS-NB-OFDM 615
27.3 Modulation and coding parameters for TVWS-NB-OFDM 616
27.3.1 Reference modulator 616
27.3.2 Scrambler and scrambler seed 617
27.3.3 Outer encoding 617
27.3.4 Inner encoding 618
27.3.5 Pad bit insertion 620
27.3.6 Spreader 620
27.3.7 Bit interleaving 621
27.3.8 Subcarrier mapping 621
27.3.9 Frequency interleaving 623
27.3.10 Pilot tones 624
27.3.11 Cyclic prefix 624
27.3.12 Pulse shaping 624
27.3.13 PIB attribute values for phySymbolsPerOctet 625
27.4 Channel aggregation for TVWS-NB-OFDM 625
27.5 TVWS-NB-OFDM RF requirements 625
27.5.1 Operating frequency range 625
27.5.2 Receiver sensitivity 625
27.5.3 TX-to-RX turnaround time 626
27.5.4 RX-to-TX turnaround time 626
27.5.5 EVM definition 626
27.5.6 Transmit center frequency and symbol tolerance 627

28. RCC LMR PHY 628

28.1 RCC PHY overview 628
28.2 PPDU format 628
28.2.1 SHR 628
28.2.2 PHR 629
28.2.3 PHY payload 629
28.2.4 Tail bits 629
28.3 FEC 629
28.4 Interleaver 630
28.5 Data whitening 630
28.6 Modulation 631

28.6.1 GMSK ... 631
28.6.2 4-FSK ... 631
28.6.3 QPSK ... 632
28.6.4 p/4 DQPSK ... 633
28.6.5 DSSS DPSK ... 633
28.7 Reference modulator ... 635
28.8 LMR PHY RF requirements ... 635
28.8.1 Transmitter symbol rate tolerance ... 635
28.8.2 Channel switching time ... 635
28.8.3 Error vector magnitude ... 635
28.8.4 Receiver sensitivity ... 635
28.8.5 Receiver interference rejection ... 635
28.8.6 Receiver maximum input level of desired signal ... 636
28.8.7 TX-to-RX turnaround time ... 636
28.8.8 RX-to-TX turnaround time ... 636
28.8.9 Receiver ED ... 636
28.8.10 LQI ... 636

29. RCC DSSS BPSK PHY ... 637

29.1 Overview ... 637
29.2 RCC DSSS BPSK PHY specification ... 637

Annex A (informative) Bibliography ... 638

Annex B (normative) CCM* mode of operation ... 640

Annex C (informative) Test vectors for cryptographic building blocks ... 646

Annex D (informative) Protocol implementation conformance statement (PICS) proforma ... 659

Annex E (informative) MPSK PHY ... 678

Annex F (normative) Time-slot relaying based link extension (TRLE) ... 683