Contents

Foreword vii
Acknowledgments xiii
Introduction xv
Acronyms xxvii

1 5G versus 4G: What's New? 1
1.1 Overview 1
1.2 LTE: A Success Story 2
1.3 Physical Layer Changes in 5G 4
1.4 Protocol Changes in 5G 14
1.5 Main Physical Layer Features of LTE over Releases 16

2 Deployment Scenarios 19
2.1 LTE-NR Spectrum Sharing 19
2.2 Switched NR UL Carrier Aggregation Enhancements 26
2.3 Nonaligned Carrier Aggregation Operation 28
2.4 Frequency Ranges and Frequency Bands 32

3 Architecture Options for 5G 43
3.1 Introduction 43
3.2 The 5G RAN Architecture 46
3.3 The 5G Core 49
3.4 EPC versus 5GC (What Is 5GC For?) 51
3.5 Main Functional Entities of the 5G Core 51
3.6 High-Level Features of 5G Core 53
3.7 Network Slicing 60
3.8 QoS 62
3.9 Interworking with Non-3GPP Access Technologies 64
3.10 Policy Control 65
3.11 5G Security 67
3.12 Access Control and Barring 70
3.13 Support for Operator and Regulatory Services 72
3.14 Interworking with EPC 76
3.15 EPC to 5GC Migration 78

4 Evolution of 5G Architecture 87
4.1 Introduction 87
4.2 Non-Public Networks 87
4.3 Cellular V2X 91
4.4 Cellular IoT 93
4.5 "Big Data" Collection (Enhanced Network Automation) 95

4.6 Enhancements to Interworking with Non-3GPP Accesses 97
4.7 URLLC 97
4.8 Slice Authentication 99
4.9 Other Release 16 Features 99

5 Numerology and Slot Structure 101
5.1 Numerology and Slot Structure in 4G LTE 101
5.2 Lessons Learned from 4G LTE and 5G Considerations. 104
5.3 SCSs for 5G NR 106
5.4 Frequency Ranges, Bandwidths, and Bands for 5G NR 110
5.5 gNB Channel Bandwidth versus UE Channel Bandwidth. 112
5.6 Symbol, Slot, Subframe, and Frame for 5G NR 113
5.7 Slot Structure for 5G NR and Forward Compatibility Considerations. 117

6 Initial Access and Mobility 125
6.1 Overview 125
6.2 Initial Access 125
6.3 Random Access 135
6.4 Paging 142
6.5 Mobility 143

7 Downlink Control Operation 151
7.1 Downlink Control in 4G LTE. 151
7.2 Control Region Management in 5G NR. 159
7.3 PDCCH Structure in 5G NR 161
7.4 Search Space for NR PDCCH 168
7.5 DCI Formats for NR PDCCH 173
7.6 Physical Layer Block Diagram for NR PDCCH 177
7.7 Power Saving Considerations 180

8 Downlink Data Operation. 185
8.1 Channel Coding for Data. 185
8.2 Channel Code Rate Matching 190
8.3 DL Soft Buffer Management 194
8.4 DL MCS and TBS Determination 196
8.5 DL Resource Allocation in the Time Domain 203
8.6 DL Resource Allocation in the Frequency Domain 207
8.7 DL Rate Matching 210
8.8 DL HARQ Operation 220
8.9 DL Data Rate Capability 221
8.10 Processing Time for DL Data. 227
8.11 Demodulation Reference Signals for Data 230
8.12 PDSCH DM-RS 234
8.13 DL Phase Tracking Reference Signal 250
8.14 Channel State Information Reference Signal 255
8.15 Tracking Reference Signal 264

8.16 DL MIMO Scheme 266
8.17 CSI Feedback 268
8.18 Beam Management for the PDSCH 280
8.19 Signal Quasi Co-Location 283

9 Uplink Control Operation 293
9.1 Uplink Control in 4G LTE 293
9.2 UCI Types and Payload Sizes in 5G NR 298
9.3 PUCCH Formats in 5G NR 305
9.4 PUCCH Resource Determination in 5G NR 315
9.5 UCI on PUSCH in 5G NR 317
9.6 Channel Coding for UCI 322

10 Uplink Data Operation 325
10.1 UL MCS and TBS Determination 325
10.2 UL Resource Allocation in the Time Domain 328
10.3 UL Resource Allocation in the Frequency Domain 332
10.4 UL Rate Matching 336
10.5 UL HARQ Operation 337
10.6 UL Soft Buffer Management 339
10.7 UL Data Rate Capability 339
10.8 Processing Time for UL Data 340
10.9 PUSCH DM-RS 342
10.10 UL Phase Tracking Reference Signal 350
10.11 Sounding Reference Signal 356
10.12 UL MIMO Scheme 359
10.13 Beam Management for the PUSCH 362
10.14 UL Power Control 365
10.15 UL Timing 376

11 Coexistence of 4G and 5G 379
11.1 Adjacent Channel Coexistence 379
11.2 Same Channel Coexistence 382
11.3 EN-DC Power Control 386
11.4 Switched EN-DC UL 387

12 5G in Unlicensed and Shared Spectrum 391
12.1 Unlicensed Operation in LTE 391
12.2 Overview 393
12.3 Channel Access 397
12.4 Discovery Burst 404
12.5 Physical Layer Extensions for Uplink 406
12.6 Increased Scheduling Flexibility 410

13 Vertical Expansion: URLLC 415
13.1 A Brief History of 3GPP Standardization Related to URLLC 416
13.2 Use Cases and Deployment Scenarios for 5G NR URLLC 421
13.3 Resource Management for URLLC 423

13.4 Optimizing Link Efficiency for URLLC 428
13.5 Downlink Resource Sharing for Distinct Service Types 435
13.6 Uplink Resource Sharing for Distinct Service Types 440
13.7 Handling Distinct Services at the UE 442
13.8 Other Related Aspects 443

14 Vertical Expansion: MTC 449
14.1 A Brief History of MTC in 3GPP 449
14.2 Key Technical Enablers for eMTC 453
14.3 Key Technical Enablers for NB-IoT 471
14.4 Integration of eMTC and NB-IoT into 5G NR 481
14.5 Future Trends 482

15 5G Vertical Expansion: V2X 485
15.1 Overview 485
15.2 Background: LTE V2X 488
15.3 NR V2X 494

16 Vertical Expansion: Broadcast and Multicast 509

17 Miscellaneous Topics for 5G 515
17.1 Overview 515
17.2 Interference Management 515
17.3 UE Power Savings 518
17.4 NR Positioning 522
17.5 Two-Step RACH 529
17.6 Multi-RAT DC/CA Enhancements 535
17.7 Mobility Enhancements 536
17.8 Integrated Access and Backhaul 538

18 A Look at Typical 5G Commercial Deployments 547

19 5G: What's Next? 557
19.1 Overview 557
19.2 Radio Projects in Release 17 557
19.3 Systems Projects in Release 17 563
19.4 NR Expansion into Higher Frequencies 566
19.5 Sidelink Beyond V2X 568
19.6 Relaying Operation 569
19.7 Edge Applications 569
19.8 On the Path to 6G 570

Index 575