Contents

Authors' Biographies xv

Preface xvii

Acknowledgments xix

Abbreviations and Acronyms xxi

1 LTE Network Architecture and Protocols 1
Ayman Elnashar and Mohamed A. El-saidny

1.1 Evolution of 3GPP Standards 2
1.1.1 3GPP Release 99 3
1.1.2 3GPP Release 4 3
1.1.3 3GPP Release 5 3
1.1.4 3GPP Release 6 4
1.1.5 3GPP Release 7 4
1.1.6 3GPP Release 8 5
1.1.7 3GPP Release 9 and Beyond 5
1.2 Radio Interface Techniques in 3GPP Systems 6
1.2.1 Frequency Division Multiple Access (FDMA) 6
1.2.2 Time Division Multiple Access (TDMA) 6
1.2.3 Code Division Multiple Access (CDMA) 7
1.2.4 Orthogonal Frequency Division Multiple Access (OFDMA) 7
1.3 Radio Access Mode Operations 7
1.3.1 Frequency Division Duplex (FDD) 8
1.3.2 Time Division Duplex (TDD) 8
1.4 Spectrum Allocation in UMTS and LTE 8
1.5 LTE Network Architecture 10
1.5.1 Evolved Packet System (EPS) 10
1.5.2 Evolved Packet Core (EPC) 11
1.5.3 Evolved Universal Terrestrial Radio Access Network (E-UTRAN) 13
1.5.4 LTE User Equipment 13
1.6 EPS Interfaces 14
1.6.1 S1-MME Interface 14
1.6.2 LTE-Uu Interface 15
1.6.3 S1-U Interface 17
1.6.4 S3 Interface (SGSN-MME) 18

	1.6.5	*S4 (SGSN to SGW)*	18
	1.6.6	*S5/S8 Interface*	19
	1.6.7	*S6a (Diameter)*	21
	1.6.8	*S6b Interface (Diameter)*	21
	1.6.9	*S6d (Diameter)*	22
	1.6.10	*S9 Interface (H-PCRF-VPCRF)*	23
	1.6.11	*S10 Interface (MME-MME)*	23
	1.6.12	*S11 Interface (MME–SGW)*	23
	1.6.13	*S12 Interface*	23
	1.6.14	*S13 Interface*	24
	1.6.15	*SGs Interface*	24
	1.6.16	*SGi Interface*	25
	1.6.17	*Gx Interface*	26
	1.6.18	*Gy and Gz Interfaces*	27
	1.6.19	*DNS Interface*	27
	1.6.20	*Gn/Gp Interface*	27
	1.6.21	*SBc Interface*	28
	1.6.22	*Sv Interface*	28
1.7	EPS Protocols and Planes		29
	1.7.1	*Access and Non-Access Stratum*	29
	1.7.2	*Control Plane*	29
	1.7.3	*User Plane*	30
1.8	EPS Procedures Overview		31
	1.8.1	*EPS Registration and Attach Procedures*	31
	1.8.2	*EPS Quality of Service (QoS)*	34
	1.8.3	*EPS Security Basics*	36
	1.8.4	*EPS Idle and Active States*	38
	1.8.5	*EPS Network Topology for Mobility Procedures*	39
	1.8.6	*EPS Identifiers*	44
	References		44
2	**LTE Air Interface and Procedures**		**47**
	Mohamed A. El-saidny		
2.1	LTE Protocol Stack		47
2.2	SDU and PDU		48
2.3	LTE Radio Resource Control (RRC)		50
2.4	LTE Packet Data Convergence Protocol Layer (PDCP)		52
	2.4.1	*PDCP Architecture*	53
	2.4.2	*PDCP Data and Control SDUs*	53
	2.4.3	*PDCP Header Compression*	54
	2.4.4	*PDCP Ciphering*	54
	2.4.5	*PDCP In-Order Delivery*	54
	2.4.6	*PDCP in LTE versus HSPA*	55
2.5	LTE Radio Link Control (RLC)		55
	2.5.1	*RLC Architecture*	56
	2.5.2	*RLC Modes*	57

	2.5.3	*Control and Data PDUs*	60
	2.5.4	*RLC in LTE versus HSPA*	60
2.6	LTE Medium Access Control (MAC)		61
2.7	LTE Physical Layer (PHY)		61
	2.7.1	*HSPA(+) Channel Overview*	61
	2.7.2	*General LTE Physical Channels*	71
	2.7.3	*LTE Downlink Physical Channels*	71
	2.7.4	*LTE Uplink Physical Channels*	72
2.8	Channel Mapping of Protocol Layers		73
	2.8.1	*E-UTRAN Channel Mapping*	73
	2.8.2	*UTRAN Channel Mapping*	76
2.9	LTE Air Interface		76
	2.9.1	*LTE Frame Structure*	76
	2.9.2	*LTE Frequency and Time Domains Structure*	76
	2.9.3	*OFDM Downlink Transmission Example*	80
	2.9.4	*Downlink Scheduling*	81
	2.9.5	*Uplink Scheduling*	88
	2.9.6	*LTE Hybrid Automatic Repeat Request (HARQ)*	89
2.10	Data Flow Illustration Across the Protocol Layers		90
	2.10.1	*HSDPA Data Flow*	90
	2.10.2	*LTE Data Flow*	91
2.11	LTE Air Interface Procedures		92
	2.11.1	*Overview*	92
	2.11.2	*Frequency Scan and Cell Identification*	92
	2.11.3	*Reception of Master and System Information Blocks (MIB and SIB)*	93
	2.11.4	*Random Access Procedures (RACH)*	94
	2.11.5	*Attach and Registration*	95
	2.11.6	*Downlink and Uplink Data Transfer*	96
	2.11.7	*Connected Mode Mobility*	96
	2.11.8	*Idle Mode Mobility and Paging*	99
	References		100
3	**Analysis and Optimization of LTE System Performance**		**103**
	Mohamed A. El-saidny		
3.1	Deployment Optimization Processes		104
	3.1.1	*Profiling Device and User Behavior in the Network*	105
	3.1.2	*Network Deployment Optimization Processes*	107
	3.1.3	*Measuring the Performance Targets*	108
	3.1.4	*LTE Troubleshooting Guidelines*	119
3.2	LTE Performance Analysis Based on Field Measurements		123
	3.2.1	*Performance Evaluation of Downlink Throughput*	127
	3.2.2	*Performance Evaluation of Uplink Throughput*	131
3.3	LTE Case Studies and Troubleshooting		134
	3.3.1	*Network Scheduler Implementations*	135
	3.3.2	*LTE Downlink Throughput Case Study and Troubleshooting*	136
	3.3.3	*LTE Uplink Throughput Case Studies and Troubleshooting*	139

	3.3.4 LTE Handover Case Studies	146
3.4	LTE Inter-RAT Cell Reselection	153
	3.4.1 Introduction to Cell Reselection	155
	3.4.2 LTE to WCDMA Inter-RAT Cell Reselection	155
	3.4.3 WCDMA to LTE Inter-RAT Cell Reselection	160
3.5	Inter-RAT Cell Reselection Optimization Considerations	165
	3.5.1 SIB-19 Planning Strategy for UTRAN to E-UTRAN Cell Reselection	165
	3.5.2 SIB-6 Planning Strategy for E-UTRAN to UTRAN Cell Reselection	167
	3.5.3 Inter-RAT Case Studies from Field Test	168
	3.5.4 Parameter Setting Trade-off	174
3.6	LTE to LTE Inter-frequency Cell Reselection	177
	3.6.1 LTE Inter-Frequency Cell Reselection Rules	177
	3.6.2 LTE Inter-Frequency Optimization Considerations	177
3.7	LTE Inter-RAT and Inter-frequency Handover	180
	3.7.1 Inter-RAT and Inter-Frequency Handover Rules	187
	3.7.2 Inter-RAT and Inter-Frequency Handover Optimization Considerations	188
	References	189
4	**Performance Analysis and Optimization of LTE Key Features: C-DRX, CSFB, and MIMO**	**191**
	Mohamed A. El-saidny and Ayman Elnashar	
4.1	LTE Connected Mode Discontinuous Reception (C-DRX)	192
	4.1.1 Concepts of DRX for Battery Saving	193
	4.1.2 Optimizing C-DRX Performance	195
4.2	Circuit Switch Fallback (CSFB) for LTE Voice Calls	204
	4.2.1 CSFB to UTRAN Call Flow and Signaling	206
	4.2.2 CSFB to UTRAN Features and Roadmap	216
	4.2.3 Optimizing CSFB to UTRAN	231
4.3	Multiple-Input, Multiple-Output (MIMO) Techniques	252
	4.3.1 Introduction to MIMO Concepts	252
	4.3.2 3GPP MIMO Evolution	256
	4.3.3 MIMO in LTE	258
	4.3.4 Closed-Loop MIMO (TM4) versus Open-Loop MIMO (TM3)	261
	4.3.5 MIMO Optimization Case Study	267
	References	270
5	**Deployment Strategy of LTE Network**	**273**
	Ayman Elnashar	
5.1	Summary and Objective	273
5.2	LTE Network Topology	273
5.3	Core Network Domain	276
	5.3.1 Policy Charging and Charging (PCC) Entities	280
	5.3.2 Mobility Management Entity (MME)	283
	5.3.3 Serving Gateway (SGW)	286
	5.3.4 PDN Gateway (PGW)	287

	5.3.5	*Interworking with PDN (DHCP)*	289
	5.3.6	*Usage of RADIUS on the Gi/SGi Interface*	291
	5.3.7	*IPv6 EPC Transition Strategy*	293
5.4	IPSec Gateway (IPSec GW)		294
	5.4.1	*IPSec GW Deployment Strategy and Redundancy Options*	299
5.5	EPC Deployment and Evolution Strategy		300
5.6	Access Network Domain		303
	5.6.1	*E-UTRAN Overall Description*	303
	5.6.2	*Home eNB*	305
	5.6.3	*Relaying*	307
	5.6.4	*End-to-End Routing of the eNB*	308
	5.6.5	*Macro Sites Deployment Strategy*	312
	5.6.6	*IBS Deployment Strategy*	317
	5.6.7	*Passive Inter Modulation (PIM)*	319
5.7	Spectrum Options and Guard Band		327
	5.7.1	*Guard Band Requirement*	327
	5.7.2	*Spectrum Options for LTE*	327
5.8	LTE Business Case and Financial Analysis		333
	5.8.1	*Key Financial KPIs [31]*	334
5.9	Case Study: Inter-Operator Deployment Scenario		341
	References		347
6	**Coverage and Capacity Planning of 4G Networks**		**349**
	Ayman Elnashar		
6.1	Summary and Objectives		349
6.2	LTE Network Planning and Rollout Phases		349
6.3	LTE System Foundation		351
	6.3.1	*LTE FDD Frame Structure*	351
	6.3.2	*Slot Structure and Physical Resources*	353
	6.3.3	*Reference Signal Structure*	356
6.4	PCI and TA Planning		360
	6.4.1	*PCI Planning Introduction*	360
	6.4.2	*PCI Planning Guidelines*	361
	6.4.3	*Tracking Areas (TA) Planning*	362
6.5	PRACH Planning		370
	6.5.1	*Zadoff-Chu Sequence*	371
	6.5.2	*PRACH Planning Procedures*	372
	6.5.3	*Practical PRACH Planning Scenarios*	373
6.6	Coverage Planning		375
	6.6.1	*RSSI, RSRP, RSRQ, and SINR*	375
	6.6.2	*The Channel Quality Indicator*	378
	6.6.3	*Modulation and Coding Scheme and Link Adaptation*	381
	6.6.4	*LTE Link Budget and Coverage Analysis*	385
	6.6.5	*Comparative Analysis with HSPA+*	401
	6.6.6	*Link Budget for LTE Channels*	405
	6.6.7	*RF Propagation Models and Model Tuning*	409

6.7 LTE Throughput and Capacity Analysis 418
6.7.1 Served Physical Layer Throughput Calculation 418
6.7.2 Average Spectrum Efficiency Estimation 418
6.7.3 Average Sector Capacity 419
6.7.4 Capacity Dimensioning Process 419
6.7.5 Capacity Dimensioning Exercises 423
6.7.6 Calculation of VoIP Capacity in LTE 426
6.7.7 LTE Channels Planning 431
6.8 Case Study: LTE FDD versus LTE TDD 437
References 443

7 Voice Evolution in 4G Networks 445
Mahmoud R. Sherif
7.1 Voice over IP Basics 445
7.1.1 VoIP Protocol Stack 445
7.1.2 VoIP Signaling (Call Setup) 449
7.1.3 VoIP Bearer Traffic (Encoded Speech) 449
7.2 Voice Options for LTE 451
7.2.1 SRVCC and CSFB 451
7.2.2 Circuit Switched Fallback (CSFB) 452
7.3 IMS Single Radio Voice Call Continuity (SRVCC) 455
7.3.1 IMS Overview 456
7.3.2 VoLTE Call Flow and Interaction with IMS 460
7.3.3 Voice Call Continuity Overview 469
7.3.4 SRVCC from VoLTE to 3G/2G 471
7.3.5 Enhanced SRVCC (eSRVCC) 480
7.4 Key VoLTE Features 482
7.4.1 End-to-End QoS Support 482
7.4.2 Semi-Persistent Scheduler 486
7.4.3 TTI Bundling 488
7.4.4 Connected Mode DRX 491
7.4.5 Robust Header Compression (ROHC) 492
7.4.6 VoLTE Vocoders and De-Jitter Buffer 497
7.5 Deployment Considerations for VoLTE 503
References 505

8 4G Advanced Features and Roadmap Evolutions from LTE to LTE-A 507
Ayman Elnashar and Mohamed A. El-saidny
8.1 Performance Comparison between LTE's UE Category 3 and 4 509
8.1.1 Trial Overview 512
8.1.2 Downlink Performance Comparison in Near and Far Cell Conditions 513
8.1.3 Downlink Performance Comparison in Mobility Conditions 515
8.2 Carrier Aggregation 516
8.2.1 Basic Definitions of LTE Carrier Aggregation 518
8.2.2 Band Types of LTE Carrier Aggregation 519
8.2.3 Impact of LTE Carrier Aggregation on Protocol Layers 520

8.3	Enhanced MIMO		520
	8.3.1	*Enhanced Downlink MIMO*	522
	8.3.2	*Uplink MIMO*	523
8.4	Heterogeneous Network (HetNet) and Small Cells		523
	8.4.1	*Wireless Backhauling Applicable to HetNet Deployment*	524
	8.4.2	*Key Features for HetNet Deployment*	528
8.5	Inter-Cell Interference Coordination (ICIC)		529
8.6	Coordinated Multi-Point Transmission and Reception		531
	8.6.1	*DL CoMP Categories*	531
	8.6.2	*UL CoMP Categories*	533
	8.6.3	*Performance Evaluation of CoMP*	533
8.7	Self-Organizing, Self-Optimizing Networks (SON)		535
	8.7.1	*Automatic Neighbor Relation (ANR)*	536
	8.7.2	*Mobility Robust Optimization (MRO)*	537
	8.7.3	*Mobility Load Balancing (MLB)*	539
	8.7.4	*SON Enhancements in LTE-A*	540
8.8	LTE-A Relays and Home eNodeBs (HeNB)		540
8.9	UE Positioning and Location-Based Services in LTE		541
	8.9.1	*LBS Overview*	541
	8.9.2	*LTE Positioning Architecture*	543
	References		544

Index **547**