

Contents

	<i>List of Contributors</i>	page xvi
	<i>Preface</i>	xxi
1	Overview of New Technologies for 5G Systems	1
	Vincent W. S. Wong, Robert Schober, Derrick Wing Kwan Ng, and Li-Chun Wang	
	1.1 Introduction	1
	1.2 Cloud Radio Access Networks	3
	1.3 Cloud Computing and Fog Computing	4
	1.4 Non-orthogonal Multiple Access	4
	1.5 Flexible Physical Layer Design	6
	1.6 Massive MIMO	7
	1.7 Full-Duplex Communications	9
	1.8 Millimeter Wave	12
	1.9 Mobile Data Offloading, LTE-Unlicensed, and Smart Data Pricing	13
	1.10 IoT, M2M, and D2D	14
	1.11 Radio Resource Management, Interference Mitigation, and Caching	16
	1.12 Energy Harvesting Communications	17
	1.13 Visible Light Communication	19
	Acknowledgments	20
	References	20
	Part I Communication Network Architectures for 5G Systems	25
2	Cloud Radio Access Networks for 5G Systems	27
	Chih-Lin I, Jinri Huang, Xueyan Huang, Rongwei Ren, and Yami Chen	
	2.1 Rethinking the Fundamentals for 5G Systems	27
	2.2 User-Centric Networks	29
	2.3 C-RAN Basics	29
	2.3.1 C-RAN Challenges Toward 5G	30
	2.4 Next Generation Fronthaul Interface (NGFI): The FH Solution for 5G C-RAN	31
	2.4.1 Proof-of-Concept Development of NGFI	33

2.5	Proof-of-Concept Verification of Virtualized C-RAN	35
2.5.1	Data Packets	37
2.5.2	Test Procedure	38
2.5.3	Test Results	39
2.6	Rethinking the Protocol Stack for C-RAN	40
2.6.1	Motivation	40
2.6.2	Multilevel Centralized and Distributed Protocol Stack	40
2.7	Conclusion	45
	Acknowledgments	46
	References	46
3	Fronthaul-Aware Design for Cloud Radio Access Networks	48
	Liang Liu, Wei Yu, and Osvaldo Simeone	
3.1	Introduction	48
3.2	Fronthaul-Aware Cooperative Transmission and Reception	49
3.2.1	Uplink	51
3.2.2	Downlink	57
3.3	Fronthaul-Aware Data Link and Physical Layers	61
3.3.1	Uplink	63
3.3.2	Downlink	69
3.4	Conclusion	73
	Acknowledgments	74
	References	74
4	Mobile Edge Computing	76
	Ben Liang	
4.1	Introduction	76
4.2	Mobile Edge Computing	77
4.3	Reference Architecture	79
4.4	Benefits and Application Scenarios	80
4.4.1	User-Oriented Use Cases	80
4.4.2	Operator-Oriented Use Cases	81
4.5	Research Challenges	82
4.5.1	Computation Offloading	82
4.5.2	Communication Access to Computational Resources	83
4.5.3	Multi-resource Scheduling	84
4.5.4	Mobility Management	85
4.5.5	Resource Allocation and Pricing	85
4.5.6	Network Functions Virtualization	86
4.5.7	Security and Privacy	86
4.5.8	Integration with Emerging Technologies	87
4.6	Conclusion	88
	References	88

5	Decentralized Radio Resource Management for Dense Heterogeneous Wireless Networks	92
	Abolfazl Mehdodniya and Fumiyuki Adachi	
5.1	Introduction	92
5.2	System Model	93
5.2.1	SINR Expression	95
5.2.2	Load and Cost Function Expressions	95
5.3	Joint BSCSA/UECSA ON/OFF Switching Scheme	96
5.3.1	Strategy Selection and Beacon Transmission	96
5.3.2	UE Association	96
5.3.3	Proposed Channel Segregation Algorithms	98
5.3.4	Mixed-Strategy Update	100
5.4	Computer Simulation	101
5.5	Conclusion	104
	Acknowledgments	104
	References	105
	Part II Physical Layer Communication Techniques	107
6	Non-Orthogonal Multiple Access (NOMA) for 5G Systems	109
	Wei Liang, Zhiguo Ding, and H. Vincent Poor	
6.1	Introduction	110
6.2	NOMA in Single-Input Single-Output (SISO) Systems	112
6.2.1	The Basics of NOMA	112
6.2.2	Impact of User Pairing on NOMA	113
6.2.3	Cognitive Radio Inspired NOMA	116
6.3	NOMA in MIMO Systems	120
6.3.1	System Model for MIMO-NOMA Schemes	121
6.3.2	Design of Precoding and Detection Matrices with Limited CSIT	123
6.3.3	Design of Precoding and Detection Matrices with Perfect CSIT	126
6.4	Summary and Future Directions	128
	References	130
7	Flexible Physical Layer Design	133
	Maximilian Matthé, Martin Danneberg, Dan Zhang, and Gerhard Fettweis	
7.1	Introduction	133
7.2	Generalized Frequency Division Multiplexing	135
7.3	Software-Defined Waveform	137
7.3.1	Time Domain Processing	138
7.3.2	Implementation Architecture	138
7.4	GFDM Receiver Design	141
7.4.1	Synchronization Unit	142
7.4.2	Channel Estimation Unit	144
7.4.3	MIMO-GFDM Detection Unit	145

7.5	Summary and Outlook	147
	Acknowledgments	148
	References	148
8	Distributed Massive MIMO in Cellular Networks	151
	Michail Matthaiou and Shi Jin	
8.1	Introduction	151
8.2	Massive MIMO: Basic Principles	152
8.2.1	Uplink/Downlink Channel Models	153
8.2.2	Favorable Propagation	154
8.3	Performance of Linear Receivers in a Massive MIMO Uplink	154
8.4	Performance of Linear Precoders in a Massive MIMO Downlink	157
8.5	Channel Estimation in Massive MIMO Systems	158
8.5.1	Uplink Transmission	159
8.5.2	Downlink Transmission	160
8.6	Applications of Massive MIMO Technology	161
8.6.1	Full-Duplex Relaying with Massive Antenna Arrays	161
8.6.2	Joint Wireless Information Transfer and Energy Transfer for Distributed Massive MIMO	163
8.7	Open Future Research Directions	167
8.8	Conclusion	168
	References	169
9	Full-Duplex Protocol Design for 5G Networks	172
	Taneli Riihonen and Risto Wichman	
9.1	Introduction	172
9.2	Basics of Full-Duplex Systems	173
9.2.1	In-Band Full-Duplex Operation Mode	173
9.2.2	Self-Interference and Co-channel Interference	174
9.2.3	Full-Duplex Transceivers in Communication Links	175
9.2.4	Other Applications of Full-Duplex Transceivers	178
9.3	Design of Full-Duplex Protocols	179
9.3.1	Challenges and Opportunities in Full-Duplex Operation	179
9.3.2	Full-Duplex Communication Scenarios in 5G Networks	180
9.4	Analysis of Full-Duplex Protocols	182
9.4.1	Operation Modes in Wideband Fading Channels	182
9.4.2	Full-Duplex Versus Half-Duplex in Wideband Transmission	184
9.5	Conclusion	184
9.5.1	Prospective Scientific Research Directions	184
9.5.2	Full-Duplex in Commercial 5G Networks	185
	References	186
10	Millimeter Wave Communications for 5G Networks	188
	Jiho Song, Miguel R. Castellanos, and David J. Love	

10.1	Motivations and Opportunities	188
10.2	Millimeter Wave Radio Propagation	189
10.2.1	Radio Attenuation	189
10.2.2	Free-Space Path Loss	191
10.2.3	Severe Shadowing	193
10.2.4	Millimeter Wave Channel Model	193
10.2.5	Link Budget Analysis	194
10.3	Beamforming Architectures	195
10.3.1	Analog Beamforming Solutions	196
10.3.2	Hybrid Beamforming Solutions	200
10.3.3	Low-Resolution Receiver Architecture	201
10.4	Channel Acquisition Techniques	201
10.4.1	Subspace Sampling for Beam Alignment	202
10.4.2	Compressed Channel Estimation Techniques	205
10.5	Deployment Challenges and Applications	207
10.5.1	EM Exposure at Millimeter Wave Frequencies	207
10.5.2	Heterogeneous and Small-Cell Networks	208
	Acknowledgments	209
	References	209
11	Interference Mitigation Techniques for Wireless Networks	214
	Koralia N. Pappi and George K. Karagiannidis	
11.1	Introduction	214
11.2	The Interference Management Challenge in the 5G Vision	214
11.2.1	The 5G Primary Goals and Their Impact on Interference	214
11.2.2	Enabling Technologies for Improving Network Efficiency and Mitigating Interference	216
11.3	Improving the Cell-Edge User Experience: Coordinated Multipoint	218
11.3.1	Deployment Scenarios and Network Architecture	218
11.3.2	CoMP Techniques for the Uplink	220
11.3.3	CoMP Techniques for the Downlink	221
11.4	Interference Alignment: Exploiting Signal Space Dimensions	223
11.4.1	The Concept of Linear Interference Alignment	224
11.4.2	The Example of the X-Channel	225
11.4.3	The K -User Interference Channel and Cellular Networks: Asymptotic Interference Alignment	226
11.4.4	Cooperative Interference Networks	227
11.4.5	Insight from IA into the Capacity Limits of Wireless Networks	227
11.5	Compute-and-Forward Protocol: Cooperation at the Receiver Side for the Uplink	228
11.5.1	Encoding and Decoding of the CoF Protocol	228
11.5.2	Achievable-Rate Region and Integer Equation Selection	230
11.5.3	Advantages and Challenges of the CoF Protocol	232
11.6	Conclusion	233
	References	233

12	Physical Layer Caching with Limited Backhaul in 5G Systems	236
	Vincent Lau, An Liu, and Wei Han	
12.1	Introduction	236
12.2	What Is PHY Caching?	238
12.2.1	Typical Physical Layer Topologies	238
12.2.2	Basic Components of PHY Caching	240
12.2.3	Benefits of PHY Caching	241
12.2.4	Design Challenges and Solutions in PHY Caching	243
12.3	DoF Upper Bound for Cached Wireless Networks	245
12.3.1	Architecture of Cached Wireless Networks	246
12.3.2	Generic Cache Model	246
12.3.3	Cache-Assisted PHY Transmission Model	249
12.3.4	Upper Bound of Sum DoF for Cached Wireless Networks	251
12.4	MDS-Coded PHY Caching and the Achievable DoF	255
12.4.1	MDS-Coded PHY Caching with Asynchronous Access	256
12.4.2	Cache-Assisted MIMO Cooperation in the PHY	256
12.4.3	MIMO Cooperation Probability of MDS-Coded PHY Caching with Asynchronous Access	258
12.4.4	Achievable DoF for Cached Wireless Networks	260
12.5	Cache Content Placement Algorithm for DoF Maximization	261
12.6	Closed-Form DoF Analysis and Discussion	264
12.6.1	Content Popularity Model and Definition of DoF Gain	264
12.6.2	Asymptotic DoF Gain with Respect to the Number of Files	265
12.6.3	Asymptotic DoF Gain with Respect to the Number of Users	267
12.7	Conclusion and Future Work	267
	References	268
13	Cost-Aware Cellular Networks Powered by Smart Grids and Energy Harvesting	271
	Jie Xu, Lingjie Duan, and Rui Zhang	
13.1	Introduction	271
13.2	Energy Supply and Demand of Cellular Systems	274
13.3	Energy Cooperation	276
13.3.1	Aggregator-Assisted Energy Trading	276
13.3.2	Aggregator-Assisted Energy Sharing	277
13.4	Communication Cooperation	278
13.4.1	Cost-Aware Traffic Offloading	278
13.4.2	Cost-Aware Spectrum Sharing	279
13.4.3	Cost-Aware Coordinated Multipoint	280
13.5	Joint Energy and Communication Cooperation	280
13.5.1	Joint Energy and Spectrum Sharing	281
13.5.2	Joint Energy Cooperation and CoMP	281
13.5.3	A Case Study	282
13.6	Extensions and Future Directions	284
13.7	Conclusion	286
	References	286

14	Visible Light Communication in 5G	289
	Harald Haas and Cheng Chen	
14.1	Introduction	289
14.2	Differences between Light-Fidelity and Visible Light Communication	290
14.3	LiFi LED Technologies	292
14.4	LiFi Attocell Networks	293
14.4.1	Optical OFDM Transmission	294
14.4.2	Channel Model	296
14.4.3	Light Source Output Power	302
14.4.4	Signal Clipping	303
14.4.5	Noise at Receiver	303
14.4.6	Multiple Access and Spatial-Reuse Schemes	304
14.5	Design of Key Parameters for LiFi Attocell Networks	304
14.5.1	Co-channel Interference Minimization	305
14.5.2	Maximization of Strength of Desired Signal	306
14.5.3	Parameter Configurations	307
14.6	Signal-to-Interference-Plus-Noise Ratio in LiFi Attocell Networks	308
14.6.1	System Model Assumptions	309
14.6.2	Hexagonal Cell Deployment	309
14.6.3	PPP Cell Deployment	312
14.6.4	SINR Statistics Results and Discussion	316
14.7	Cell Data Rate and Outage Probability	318
14.8	Performance of Finite Networks and Multipath Effects	322
14.9	Practical Cell Deployment Scenarios	324
14.9.1	Square Network	324
14.9.2	Hard-Core Point Process Network	324
14.9.3	Performance Comparison	325
14.10	LiFi Attocell Networks Versus Other Small-Cell Networks	325
14.11	Summary	328
	References	329
Part III	Network Protocols, Algorithms, and Design	333
15	Massive MIMO Scheduling Protocols	335
	Giuseppe Caire	
15.1	Introduction	335
15.2	Network Model and Problem Formulation	337
15.2.1	Timescales	337
15.2.2	Request Queues and Network Utility Maximization	338
15.3	Dynamic Scheduling Policy	342
15.3.1	The Drift-Plus-Penalty Expression	342
15.3.2	Pull Congestion Control at the UEs	344

15.3.3	Greedy Maximization of the Individual Utilities at the UEs	344
15.3.4	PHY Rate Scheduling at the BSs	344
15.4	Policy Performance	345
15.5	Wireless System Model with Massive MU-MIMO Helpers	347
15.5.1	PHY Rates of Massive MIMO BSs	347
15.5.2	Transmission Scheduling with Massive MIMO BSs	350
15.6	Numerical Experiments	351
15.7	Conclusion	355
	References	356
16	Mobile Data Offloading for Heterogeneous Wireless Networks	358
	Man Hon Cheung, Haoran Yu, and Jianwei Huang	
16.1	Introduction	358
16.2	Current Standardization Efforts	359
16.2.1	Access Network Discovery and Selection Function (ANDSF)	359
16.2.2	Hotspot 2.0	360
16.2.3	Next Generation Hotspot (NGH)	361
16.2.4	Radio Resource Management	361
16.2.5	Design Considerations in Data Offloading Algorithms	361
16.3	DAWN: Delay-Aware Wi-Fi Offloading and Network Selection	363
16.3.1	System Model	363
16.3.2	Problem Formulation	364
16.3.3	General DAWN Algorithm	366
16.3.4	Threshold Policy	367
16.3.5	Performance Evaluation	369
16.4	Data Offloading Considering Energy–Delay Trade-off	370
16.4.1	Background on Energy-Aware Data Offloading	371
16.4.2	System Model	372
16.4.3	Problem Formulation	374
16.4.4	Energy-Aware Network Selection and Resource Allocation (ENSRA) Algorithm	375
16.4.5	Performance Analysis of ENSRA	376
16.4.6	Performance Evaluation	376
16.5	Open Problems	377
16.6	Conclusion	378
	Acknowledgment	378
	References	378
17	Cellular 5G Access for Massive Internet of Things	380
	Germán Corrales Madueño, Nuno Pratas, Čedomir Stefanović, and Petar Popovski	
17.1	Introduction to the Internet of Things (IoT)	380
17.2	IoT Traffic Patterns in Network Access	381
17.3	The Features of Cellular Access That Are Suitable for the IoT	386
17.4	Overview of Cellular Access Protocols	387

17.4.1	One-Stage Access	388
17.4.2	Two-Stage Access	389
17.4.3	Periodic Reporting	390
17.4.4	Case Study: LTE Connection Establishment	390
17.5	Improving the Performance of One-Stage Access for 5G Systems	392
17.6	Reliable Two-Stage Access for 5G Systems	393
17.7	Reliable Periodic Reporting Access for 5G Systems	395
17.8	Emerging Technologies for the IoT	396
17.8.1	LTE-M: LTE for Machines	397
17.8.2	Narrowband IoT (NB-IoT): A 3GPP Approach to Low-Cost IoT	397
17.8.3	Extended Coverage GSM (EC-GSM): Evolution of GSM for the IoT	398
17.9	Conclusion	398
	References	399
18	Medium Access Control, Resource Management, and Congestion Control for M2M Systems	402
	Shao-Yu Lien and Hsiang Hsu	
18.1	Introduction	402
18.2	Architectures for M2M Communications	403
18.2.1	WLAN Architecture for M2M Communications	403
18.2.2	Cellular Radio Access Network for M2M Communications	404
18.2.3	Heterogeneous Cloud Radio Access Network for M2M Communications	405
18.2.4	FogNet Architecture for M2M Communications	407
18.3	MAC Design for M2M Communications	408
18.3.1	Grouping-Based M2M MAC in H-CRAN	409
18.3.2	Access Class Barring Based M2M MAC in FogNet/WLAN	410
18.3.3	Random-Backoff-Based M2M MAC	411
18.3.4	Harmonized M2M MAC for Low-Power/Low-Complexity Machines	412
18.4	Congestion Control and Low-Complexity/Low-Throughput Massive M2M Communications	416
18.4.1	Congestion Control in ACB-Based M2M MAC	416
18.4.2	Massive MTC and Low-Complexity/Low-Throughput IoT Communications	417
18.5	Conclusion	419
	References	420
19	Energy-Harvesting Based D2D Communication in Heterogeneous Networks	423
	Howard H. Yang, Jemin Lee, and Tony Q. S. Quek	
19.1	Introduction	423
19.2	Energy Harvesting Heterogeneous Network	425
19.2.1	Energy Harvesting Region	426

	19.2.2 Energy Harvesting Process and UE Relay Distribution	427
	19.2.3 Transmission Mode Selection and Outage Probability	429
	19.3 Numerical Analysis and Discussion	432
	19.4 Conclusion	435
	References	435
20	LTE-Unlicensed: Overview and Distributed Coexistence Design	438
	Yunan Gu, Lin X. Cai, Lingyang Song, and Zhu Han	
	20.1 Motivations	438
	20.1.1 Better Network Performance	441
	20.1.2 Enhanced User Experience	441
	20.1.3 Unified LTE Network Architecture	441
	20.1.4 Fair Coexistence with Wi-Fi	441
	20.2 Coexistence Issues in LTE-Unlicensed	441
	20.3 Distributed Resource Allocation Applications of LTE-Unlicensed	444
	20.3.1 Matching Theory Framework	444
	20.3.2 Static Resource Allocation: Student–Project Allocation Matching	446
	20.3.3 Dynamic Resource Allocation: Random Path to Matching Stability	451
	20.4 Conclusion	457
	References	458
21	Scheduling for Millimeter Wave Networks	460
	Lin X. Cai, Lin Cai, Xuemin Shen, and Jon W. Mark	
	21.1 Introduction	460
	21.2 Background	461
	21.2.1 Multiplexing Technologies for mmWave Networks	461
	21.2.2 Directional Antennas	461
	21.2.3 Network Architecture	462
	21.3 Exclusive Regions	462
	21.3.1 Case 1: Omni-antenna to Omni-antenna	464
	21.3.2 Case 2: Directional Antenna to Omni-antenna	465
	21.3.3 Case 3: Omni-antenna to Directional Antenna	465
	21.3.4 Case 4: Directional Antenna to Directional Antenna	465
	21.4 REX: Randomized Exclusive Region Based Scheduler	466
	21.5 Estimating the Average Number of Concurrent Transmissions Using REX	467
	21.5.1 Case 1: Omni-antenna to Omni-antenna	468
	21.5.2 Case 2: Directional Antenna to Omni-antenna	468
	21.5.3 Case 3: Omni-antenna to Directional Antenna	469
	21.5.4 Case 4: Directional Antenna to Directional Antenna	469
	21.5.5 Edge Effect	469
	21.6 Performance Evaluation	470
	21.6.1 Spatial Multiplexing Gain	470
	21.6.2 Fairness	472

21.7	Further Discussion	473
21.7.1	Fast Fading	473
21.7.2	Shadowing Effect	473
21.7.3	Three-Dimensional Networks	473
21.7.4	Distributed Medium Access	474
21.7.5	Hybrid Medium Access	474
21.7.6	Optimal Scheduling	475
21.8	Conclusion	475
	References	475
22	Smart Data Pricing in 5G Systems	478
	Carlee Joe-Wong, Liang Zheng, Sangtae Ha, Soumya Sen, Chee Wei Tan, and Mung Chiang	
22.1	Introduction	478
22.2	Smart Data Pricing	482
22.2.1	How Should ISPs Charge for Data?	482
22.2.2	Whom Should ISPs Charge for Data?	483
22.2.3	What Should ISPs Charge For?	484
22.3	Trading Mobile Data	485
22.3.1	Related Work on Data Auctions	485
22.3.2	Modeling User and ISP Behavior	486
22.3.3	User and ISP Benefits	487
22.4	Sponsoring Mobile Data	489
22.4.1	Modeling Content Provider Behavior	489
22.4.2	Implications of Sponsored Data	490
22.5	Offloading Mobile Data	491
22.5.1	User Adoption and Example Scenarios	491
22.5.2	Optimal ISP Behavior	494
22.6	Future Directions	494
22.6.1	Capacity Expansion and New Supplementary Networks	495
22.6.2	Two-Year Contracts Versus Usage-Based Pricing	495
22.6.3	Incentivizing Fog Computing	496
22.7	Conclusion	496
	References	497
	<i>Index</i>	501