

# Contents

	<i>List of contributors</i>	<i>page</i> xiv
	<i>Foreword</i>	xvii
	<i>Acknowledgments</i>	xix
	<i>Acronyms</i>	xxii
<b>1</b>	<b>Introduction</b>	<b>1</b>
	1.1 Historical background	1
	1.1.1 Industrial and technological revolution: from steam engines to the Internet	1
	1.1.2 Mobile communications generations: from 1G to 4G	2
	1.1.3 From mobile broadband (MBB) to extreme MBB	6
	1.1.4 IoT: relation to 5G	7
	1.2 From ICT to the whole economy	7
	1.3 Rationale of 5G: high data volume, twenty-five billion connected devices and wide requirements	9
	1.3.1 Security	11
	1.4 Global initiatives	12
	1.4.1 METIS and the 5G-PPP	12
	1.4.2 China: 5G promotion group	14
	1.4.3 Korea: 5G Forum	14
	1.4.4 Japan: ARIB 2020 and Beyond Ad Hoc	14
	1.4.5 Other 5G initiatives	14
	1.4.6 IoT activities	15
	1.5 Standardization activities	15
	1.5.1 ITU-R	15
	1.5.2 3GPP	16
	1.5.3 IEEE	16
	1.6 Scope of the book	16
	References	18
<b>2</b>	<b>5G use cases and system concept</b>	<b>21</b>
	2.1 Use cases and requirements	21
	2.1.1 Use cases	21
	2.1.2 Requirements and key performance indicators	30

2.2	5G system concept	32
2.2.1	Concept overview	32
2.2.2	Extreme mobile broadband	34
2.2.3	Massive machine-type communication	36
2.2.4	Ultra-reliable machine-type communication	38
2.2.5	Dynamic radio access network	39
2.2.6	Lean system control plane	43
2.2.7	Localized contents and traffic flows	45
2.2.8	Spectrum toolbox	46
2.3	Conclusions	48
	References	48
<b>3</b>	<b>The 5G architecture</b>	<b>50</b>
3.1	Introduction	50
3.1.1	NFV and SDN	50
3.1.2	Basics about RAN architecture	53
3.2	High-level requirements for the 5G architecture	56
3.3	Functional architecture and 5G flexibility	57
3.3.1	Functional split criteria	58
3.3.2	Functional split alternatives	59
3.3.3	Functional optimization for specific applications	61
3.3.4	Integration of LTE and new air interface to fulfill 5G requirements	63
3.3.5	Enhanced Multi-RAT coordination features	66
3.4	Physical architecture and 5G deployment	67
3.4.1	Deployment enablers	67
3.4.2	Flexible function placement in 5G deployments	71
3.5	Conclusions	74
	References	75
<b>4</b>	<b>Machine-type communications</b>	<b>77</b>
4.1	Introduction	77
4.1.1	Use cases and categorization of MTC	77
4.1.2	MTC requirements	80
4.2	Fundamental techniques for MTC	83
4.2.1	Data and control for short packets	83
4.2.2	Non-orthogonal access protocols	85
4.3	Massive MTC	86
4.3.1	Design principles	86
4.3.2	Technology components	86
4.3.3	Summary of mMTC features	94
4.4	Ultra-reliable low-latency MTC	94
4.4.1	Design principles	94
4.4.2	Technology components	96

4.4.3	Summary of uMTC features	101
4.5	Conclusions	102
	References	103
<b>5</b>	<b>Device-to-device (D2D) communications</b>	107
5.1	D2D: from 4G to 5G	107
5.1.1	D2D standardization: 4G LTE D2D	109
5.1.2	D2D in 5G: research challenges	112
5.2	Radio resource management for mobile broadband D2D	113
5.2.1	RRM techniques for mobile broadband D2D	114
5.2.2	RRM and system design for D2D	114
5.2.3	5G D2D RRM concept: an example	115
5.3	Multi-hop D2D communications for proximity and emergency services	120
5.3.1	National security and public safety requirements in 3GPP and METIS	121
5.3.2	Device discovery without and with network assistance	122
5.3.3	Network-assisted multi-hop D2D communications	122
5.3.4	Radio resource management for multi-hop D2D	124
5.3.5	Performance of D2D communications in the proximity communications scenario	125
5.4	Multi-operator D2D communication	127
5.4.1	Multi-operator D2D discovery	127
5.4.2	Mode selection for multi-operator D2D	128
5.4.3	Spectrum allocation for multi-operator D2D	129
5.5	Conclusions	133
	References	134
<b>6</b>	<b>Millimeter wave communications</b>	137
6.1	Spectrum and regulations	137
6.2	Channel propagation	139
6.3	Hardware technologies for mmW systems	139
6.3.1	Device technology	139
6.3.2	Antennas	142
6.3.3	Beamforming architecture	143
6.4	Deployment scenarios	144
6.5	Architecture and mobility	146
6.5.1	Dual connectivity	147
6.5.2	Mobility	147
6.6	Beamforming	149
6.6.1	Beamforming techniques	149
6.6.2	Beam finding	150
6.7	Physical layer techniques	152
6.7.1	Duplex scheme	152

6.7.2	Transmission schemes	152
6.8	Conclusions	155
	References	156
<b>7</b>	<b>The 5G radio-access technologies</b>	158
7.1	Access design principles for multi-user communications	159
7.1.1	Orthogonal multiple-access systems	160
7.1.2	Spread spectrum multiple-access systems	164
7.1.3	Capacity limits of multiple-access methods	165
7.2	Multi-carrier with filtering: a new waveform	169
7.2.1	Filter-bank based multi-carrier	169
7.2.2	Universal filtered OFDM	175
7.3	Non-orthogonal schemes for efficient multiple access	178
7.3.1	Non-orthogonal multiple access (NOMA)	179
7.3.2	Sparse code multiple access (SCMA)	181
7.3.3	Interleave division multiple access (IDMA)	183
7.4	Radio access for dense deployments	184
7.4.1	OFDM numerology for small-cell deployments	186
7.4.2	Small-cell sub-frame structure	188
7.5	Radio access for V2X communication	192
7.5.1	Medium access control for nodes on the move	192
7.6	Radio access for massive machine-type communication	194
7.6.1	The massive access problem	195
7.6.2	Extending access reservation	198
7.6.3	Direct random access	199
7.7	Conclusions	202
	References	202
<b>8</b>	<b>Massive multiple-input multiple-output (MIMO) systems</b>	208
8.1	Introduction	208
8.1.1	MIMO in LTE	210
8.2	Theoretical background	211
8.2.1	Single user MIMO	212
8.2.2	Multi-user MIMO	215
8.2.3	Capacity of massive MIMO: a summary	217
8.3	Pilot design for massive MIMO	217
8.3.1	The pilot-data trade-off and impact of CSI	218
8.3.2	Techniques to mitigate pilot contamination	220
8.4	Resource allocation and transceiver algorithms for massive MIMO	225
8.4.1	Decentralized coordinated transceiver design for massive MIMO	225
8.4.2	Interference clustering and user grouping	228
8.5	Fundamentals of baseband and RF implementations in massive MIMO	233

8.5.1	Basic forms of massive MIMO implementation	233
8.5.2	Hybrid fixed BF with CSI-based precoding (FBCP)	235
8.5.3	Hybrid beamforming for interference clustering and user grouping	238
8.6	Channel models	241
8.7	Conclusions	242
	References	243
<b>9</b>	<b>Coordinated multi-point transmission in 5G</b>	248
9.1	Introduction	248
9.2	JT CoMP enablers	250
9.2.1	Channel prediction	252
9.2.2	Clustering and interference floor shaping	253
9.2.3	User scheduling and precoding	257
9.2.4	Interference mitigation framework	257
9.2.5	JT CoMP in 5G	258
9.3	JT CoMP in conjunction with ultra-dense networks	259
9.4	Distributed cooperative transmission	260
9.4.1	Decentralized precoding/filtering design with local CSI	261
9.4.2	Interference alignment	265
9.5	JT CoMP with advanced receivers	268
9.5.1	Dynamic clustering for JT CoMP with multiple antenna UEs	268
9.5.2	Network-assisted interference cancellation	271
9.6	Conclusions	272
	References	273
<b>10</b>	<b>Relaying and wireless network coding</b>	277
10.1	The role of relaying and network coding in 5G wireless networks	277
10.1.1	The revival of relaying	278
10.1.2	From 4G to 5G	279
10.1.3	New relaying techniques for 5G	279
10.1.4	Key applications in 5G	281
10.2	Multi-flow wireless backhauling	284
10.2.1	Coordinated direct and relay (CDR) transmission	285
10.2.2	Four-way relaying (FWR)	287
10.2.3	Wireless-emulated wire (WEW) for backhaul	288
10.3	Highly flexible multi-flow relaying	290
10.3.1	Basic idea of multi-flow relaying	290
10.3.2	Achieving high throughput for 5G	293
10.3.3	Performance evaluation	294
10.4	Buffer-aided relaying	295
10.4.1	Why buffers?	296
10.4.2	Relay selection	297
10.4.3	Handling inter-relay interference	299

	10.4.4 Extensions	299
	10.5 Conclusions	299
	References	300
<b>11</b>	<b>Interference management, mobility management, and dynamic reconfiguration</b>	<b>303</b>
	11.1 Network deployment types	304
	11.1.1 Ultra-dense network or densification	305
	11.1.2 Moving networks	305
	11.1.3 Heterogeneous networks	306
	11.2 Interference management in 5G	306
	11.2.1 Interference management in UDN	307
	11.2.2 Interference management for moving relay nodes	310
	11.2.3 Interference cancelation	314
	11.3 Mobility management in 5G	314
	11.3.1 User equipment-controlled versus network-controlled handover	315
	11.3.2 Mobility management in heterogeneous 5G networks	317
	11.3.3 Context awareness for mobility management	320
	11.4 Dynamic network reconfiguration in 5G	323
	11.4.1 Energy savings through control/user plane decoupling	323
	11.4.2 Flexible network deployment based on moving networks	327
	11.5 Conclusions	330
	References	331
<b>12</b>	<b>Spectrum</b>	<b>336</b>
	12.1 Introduction	336
	12.1.1 Spectrum for 4G	337
	12.1.2 Spectrum challenges in 5G	339
	12.2 5G spectrum landscape and requirements	341
	12.2.1 Bandwidth requirements	343
	12.3 Spectrum access modes and sharing scenarios	345
	12.4 5G spectrum technologies	346
	12.4.1 Spectrum toolbox	346
	12.4.2 Main technology components	347
	12.5 Value of spectrum for 5G: a techno-economic perspective	349
	12.6 Conclusions	352
	References	353
<b>13</b>	<b>The 5G wireless propagation channel models</b>	<b>357</b>
	13.1 Introduction	357
	13.2 Modeling requirements and scenarios	358
	13.2.1 Channel model requirements	359
	13.2.2 Propagation scenarios	361

13.3	The METIS channel models	362
13.3.1	Map-based model	363
13.3.2	Stochastic model	371
13.4	Conclusions	379
	References	379
<b>14</b>	<b>Simulation methodology</b>	<b>381</b>
14.1	Evaluation methodology	381
14.1.1	Performance indicators	381
14.1.2	Channel simplifications	383
14.2	Calibration	387
14.2.1	Link-level calibration	388
14.2.2	System-level calibration	391
14.3	New challenges in the 5G modeling	392
14.3.1	Real scenarios	393
14.3.2	New waveforms	394
14.3.3	Massive MIMO	395
14.3.4	Higher frequency bands	396
14.3.5	Device-to-device link	396
14.3.6	Moving networks	397
14.4	Conclusions	397
	References	398
	<i>Index</i>	401