
Contents

Preface	xv
About the editors	xxvii
1 Role of satellite communications in 5G ecosystem: perspectives and challenges	1
<i>Oluwakayode Onireti and Muhammad Ali Imran</i>	
1.1 Introduction	1
1.2 The 5G vision	2
1.3 Satellites and previous cellular generations	4
1.4 Areas where satellite can play a part in 5G	6
1.4.1 Coverage	6
1.4.2 Massive machine-type communications	7
1.4.3 Resilience provisioning	8
1.4.4 Content caching and multi-cast	8
1.4.5 Satellite-terrestrial integration in 5G	9
1.4.6 Ultra-reliable communications	12
1.5 Recent advances in 5G satellite communications	13
1.5.1 Ongoing project works on satellite-terrestrial integration	13
1.5.2 Terrestrial and satellite spectrum in 5G	14
1.5.3 Mega-LEO constellation	14
1.5.4 On-board processing	15
1.5.5 GaN technology	16
1.5.6 Software-defined networking	17
1.5.7 Multi-casting	18
1.5.8 Integrated signalling	18
1.6 Challenges and future research recommendations	19
1.6.1 Integrated satellite-terrestrial architecture	19
1.6.2 Integrated signalling in satellite communications	19
1.6.3 On-board processing	20
1.7 Conclusion	20
References	21

2	Satellite use cases and scenarios for 5G eMBB	25
	<i>Konstantinos Liolis, Alexander Geurtz, Ray Sperber, Detlef Schulz, Simon Watts, Georgia Poziopoulou, Barry Evans, Ning Wang, Oriol Vidal, Boris Tiomela Jou, Michael Fitch, Salva Sendra Diaz, Pouria Sayyad Khodashenas, and Nicolas Chuberre</i>	
2.1	Introduction	25
2.2	Selected satellite use cases	28
2.2.1	Selection methodology	28
2.2.2	Selected satellite use cases for eMBB	29
2.2.3	Relevance to satellite ‘sweet spots’ in 5G	30
2.2.4	Relevance to SaT5G research pillars	32
2.2.5	Relevance to 5G PPP KPIs	34
2.2.6	Relevance to 3GPP SA1 SMARTER use case families	37
2.2.7	Relevance to 5G market verticals	40
2.2.8	Market size assessment	43
2.3	Scenarios for selected satellite use cases	44
2.3.1	Scenarios for selected satellite use case 1: edge delivery and offload for multimedia content and MEC VNF software	45
2.3.2	Scenarios for selected satellite use case 2: 5G fixed backhaul	48
2.3.3	Scenarios for selected satellite use case 3: 5G to premises	51
2.3.4	Scenarios for selected satellite use case 4: 5G moving platform backhaul	53
2.4	Conclusions	55
	Acknowledgements	56
	References	56
3	SDN-enabled SatCom networks for satellite-terrestrial integration	61
	<i>Fabián Mendoza, Ramon Ferrús, and Oriol Sallent</i>	
3.1	Introduction	61
3.2	SDN-based functional architectures for satellite networks	63
3.2.1	Foundations on SDN architectures	63
3.2.2	Satellite network architecture	66
3.2.3	SDN-enabled satellite network architecture	68
3.2.4	Candidate SDN data models and interfaces	70
3.3	Integration approach for E2E SDN-based TE in satellite-terrestrial backhaul networks	74
3.3.1	Network architecture framework	74
3.3.2	Illustrative TE workflows	78
3.4	Illustrative SDN-based TE application	81
3.4.1	Traffic and link characterization for TE	82
3.4.2	TE decision-making logic	84
3.4.3	Performance assessment	89
3.5	Concluding remarks and future recommendations	97
	References	99

4	NFV-based scenarios for satellite–terrestrial integration	103
	<i>H. Koumaras, G. Gardikis, Ch. Sakkas, G. Xilouris, V. Koumaras, and M.A. Kourtis</i>	
4.1	Brief introduction to cloud computing	104
4.2	NFV orchestration overview	107
4.3	Integration scenarios	108
4.3.1	Scenario 1: virtual CDN as a Service	109
4.3.2	Scenario 2: satellite virtual network operator (SVNO)	112
4.3.3	Scenario 3: dynamic backhauling with edge processing	115
4.3.4	Scenario 4: customer functions virtualization	118
4.4	Conclusions	121
	References	121
5	Propagation and system dimensions in extremely high frequency broadband aeronautical SatCom systems	125
	<i>Nicolas Jeannin, Barry Evans, and Argyrios Kyrgiazos</i>	
5.1	Traffic demand and characterization	126
5.2	Regulatory environment	129
5.3	Propagation channel	131
5.3.1	Distribution of tropospheric margins	131
5.4	System sizing	141
5.4.2	Satellite model	143
5.5	Conclusion	147
	Acknowledgement	147
	References	148
6	Next-generation non-geostationary satellite communication systems: link characterization and system perspective	151
	<i>Charilaos Kourogiorgas, Apostolos Z. Papafragkakis, Athanasios D. Panagopoulos, and Spiros Ventouras</i>	
6.1	Next-generation NGSO satellite systems	152
6.2	Propagation characteristics and models	155
6.2.1	Local environment effects	155
6.2.2	Propagation characteristics through atmosphere	158
6.3	NGSO satellite communication systems capacity enhancement through transmission techniques	167
6.3.1	Variable and adaptive coding and modulation	167
6.3.2	Diversity techniques	168
6.3.3	Interference issues and NGSO–GSO cooperation	171
6.4	Conclusions	173
	References	174

7 Diversity combining and handover techniques: enabling 5G using MEO satellites	181
<i>Nicolò Mazzali, Bhavani Shankar M. R., Ashok Rao, Marc Verheecke, Peter De Cleyn, and Ivan De Baere</i>	
7.1 Introduction	181
7.2 Medium Earth orbit satellites: architectures, services and applications, challenges	182
7.2.1 The O3b satellite network	183
7.3 Channel characterization for MEO satellites	186
7.3.1 Uplink radio propagation effects	186
7.3.2 Downlink radio propagation effects	186
7.3.3 Payload effects	187
7.3.4 User terminal effects	187
7.4 Handover: satellite switching for MEO	187
7.4.1 Literature	189
7.4.2 Handover architecture	191
7.4.3 Dynamic interactions	192
7.4.4 Proof of concept and results	193
7.5 Diversity combining for MEO satellite applications	196
7.5.1 Combining mechanisms: state-of-art-review	197
7.5.2 Combining position	198
7.5.3 Performance of combining techniques	199
7.5.4 Switching threshold computation using downlink SNR	201
7.5.5 Switching threshold computation using total SNR	203
7.5.6 Combining gain	204
7.6 Roadmap	205
7.7 Conclusions	206
References	207
8 Powerful nonlinear countermeasures for multicarrier satellites: progression to 5G	209
<i>Bassel F. Beidas</i>	
8.1 Introduction	209
8.2 System description	211
8.2.1 Signal model	211
8.2.2 Satellite channel model	213
8.3 Multicarrier analysis of IMD	214
8.3.1 Multicarrier Volterra representation	214
8.3.2 Multicarrier Volterra filter formulation	219
8.3.3 Reduced-complexity Volterra construction	220
8.4 Powerful nonlinear countermeasures	221
8.4.1 Turbo Volterra equalization	222
8.4.2 Volterra-based data predistortion	224

8.4.3	Volterra-based successive signal predistortion	226
8.4.4	Successive data predistortion	231
8.5	OFDM-like signaling	234
8.5.1	OFDM-like transmitter	235
8.5.2	OFDM-like receiver	238
8.5.3	Successive transmitter- and receiver-based compensation	239
8.6	Conclusion	243
	References	244
9	Satellite multi-beam precoding software-defined radio demonstrator	249
	<i>Stefano Andrenacci, Juan Carlos Merlano Duncan, Jevgenij Krivochiza, and Symeon Chatzinotas</i>	
9.1	Introduction on precoding	250
9.1.1	Recent projects on precoding	250
9.1.2	Related literature on precoding for SATCOMs	251
9.2	Analysis of the practical constraints for precoding and possible solutions	252
9.2.1	System model	252
9.2.2	Differential phase distortion for precoded waveforms	253
9.2.3	Timing misalignment on precoded waveforms	256
9.2.4	Numerical results on the quality of CSI with timing pre-compensated waveforms	258
9.2.5	Numerical results on precoding degradations with timing misaligned waveforms	263
9.3	Description of the precoding implementation	265
9.3.1	Precoding technique	265
9.3.2	Non-negative least squares algorithm	266
9.3.3	Impact of proposed SLP on constellation	266
9.4	In-lab validation of the precoding techniques	267
9.4.1	Experimental validation of a 2×2 sub-system	267
9.4.2	Symbol-level optimized precoding evaluation	269
9.4.3	Un-coded bit error performance of NNLS-SLP	270
9.5	Conclusions and future works	273
	References	273
10	Beam-hopping systems for next-generation satellite communication systems	277
	<i>Christian Rohde, Rainer Wansch, Sonya Amos, Hector Fenech, Nader Alagha, Stefano Cioni, Gerhard Mocker, and Achim Trutschel-Stefan</i>	
10.1	Introduction	277
10.2	Beam-hopping system concepts	278

10.3	Application of DVB-S2X waveform for beam-hopping	281
10.3.1	DVB-S2X conventional framing	283
10.3.2	DVB-S2X Annex E super-framing	285
10.3.3	Waveform conclusion	289
10.4	Technology and implementation	289
10.4.1	Upcoming Eutelsat Quantum satellite for beam-hopping	289
10.4.2	Wideband transmission for beam-hopping	294
10.4.3	Network synchronization aspects	295
10.4.4	Signal synchronization at terminals	296
10.5	Summary and conclusions	303
	References	303
11	Optical on–off keying data links for low Earth orbit downlink applications	307
	<i>Dirk Giggenbach, Florian Moll, Christopher Schmidt, Christian Fuchs, and Amita Shrestha</i>	
11.1	The scenario and history of optical LEO data downlinks	308
11.1.1	Optical LEO downlink experiments overview	308
11.1.2	Performance and geometrical restrictions	309
11.1.3	Data rates and rate change for a variable link budget	313
11.2	Link design	315
11.2.1	Propagation channel model	316
11.2.2	Transmission equation	318
11.2.3	Link budget	320
11.2.4	Pointing, acquisition and tracking	322
11.2.5	Direct detection modulation formats and rate variation	322
11.2.6	OOK RFE performance and impact on link budget	326
11.2.7	Error control techniques for Gaussian channels	328
11.2.8	Interleaving in the atmospheric fading channel	328
11.3	Hardware	330
11.3.1	Space hardware	330
11.3.2	Ground hardware	333
11.4	Summary and outlook	335
	References	336
12	Ultra-high-speed data relay systems	341
	<i>Ricardo Barrios, Balazs Matuz, and Ramon Mata-Calvo</i>	
12.1	Introduction	342
12.2	Relevant missions and demos	342
12.3	System architectures	344
12.4	Optical channel model	347
12.4.1	Atmospheric channel	347
12.4.2	Pointing errors and microvibrations	350
12.4.3	Light coupling efficiency	352

12.5	Noise model	353
12.6	Link budget	354
12.7	Forward error correction	358
12.7.1	Full decoding on board of the relay	360
12.7.2	Decoding on ground only	360
12.7.3	Partial decoding scheme	362
12.7.4	Layered coding scheme	363
12.7.5	Interleaving options	365
12.7.6	Comparison of coding schemes	366
12.8	Summary	367
	References	369
13	On-board processing for satellite-terrestrial integration	375
	<i>Rainer Wansch, Alexander Hofmann, Christopher Stender, and Rob�rt Glein</i>	
13.1	Brief history of on-board processing	375
13.1.1	Airbus Inmarsat processor	375
13.1.2	Thales Alenia Space Spaceflex processor	376
13.1.3	Thales Alenia Space Redsat	378
13.2	Classification and applications of OBPs	379
13.2.1	Satellite payload architectures	379
13.2.2	Digital payload technology matrix	381
13.2.3	Advantages of reconfigurable OBPs	383
13.3	The Fraunhofer OBP as an example	387
13.3.1	Payload architecture	387
13.3.2	Main building blocks	387
13.3.3	Digital signal processing	389
13.3.4	Virtual TM/TC	390
13.4	Exemplary 5G use case for OBP using LEO satellites	393
13.5	Summary	394
	References	395
14	On-board interference detection and localization for satellite communication	397
	<i>Christos Politis, Ashkan Kalantari, Sina Maleki, and Symeon Chatzinotas</i>	
14.1	Introduction	398
14.2	On-board digitization	399
14.3	Satellite interference	401
14.3.1	Intrasystem interference	401
14.3.2	External interference	402
14.4	Interference detection techniques	404
14.4.1	Conventional energy detector	404
14.4.2	Energy detector with imperfect signal cancellation in the pilot domain	405

14.4.3	Energy detector with imperfect signal cancellation in the data domain	407
14.5	Current localization techniques	410
14.6	Interference localization using frequency of arrival via a single satellite	412
14.7	Localization algorithm and solution	415
14.8	Numerical results	417
14.8.1	Performance analysis of interference detection techniques	417
14.8.2	Performance analysis of interference localization techniques	418
14.9	Conclusion	420
	References	420
15	Random access in satellite communications: a background on legacy and advanced schemes	425
	<i>Karine Zidane, Jérôme Lacan, Mathieu Gineste, Marie-Laure Boucheret and Jean-Baptiste Dupé</i>	
15.1	Introduction	426
15.2	Legacy RA techniques for satellite communications	427
15.2.1	ALOHA	427
15.2.2	Slotted versions ALOHA	428
15.2.3	Conclusion on legacy RA techniques for the return link	429
15.3	Advanced RA techniques for satellite communications	430
15.3.1	Main metrics for the evaluation of advanced RA schemes via simulations	430
15.3.2	Advanced synchronous RA techniques	431
15.4	General comparison metrics for different advanced RA techniques	451
15.4.1	Power limitations at the terminal side	451
15.4.2	Communications at very low data rates	451
15.4.3	High throughput performance at MAC-layer level	451
15.4.4	Signalling overhead	451
15.4.5	Comparative table	452
15.5	General summary and final remarks	452
	References	453
16	Interference avoidance and mitigation techniques for hybrid satellite-terrestrial networks	459
	<i>Konstantinos Ntougias, Dimitrios K. Ntaikos, George K. Papageorgiou, and Constantinos B. Papadias</i>	
16.1	Introduction	459
16.1.1	5G radio access technologies	459
16.1.2	MIMO communication technologies	460

16.1.3	Flexible hybrid satellite-terrestrial backhaul	461
16.1.4	Chapter objectives and structure	463
16.2	Load-controlled parasitic antenna arrays	464
16.3	Robust arbitrary channel-dependent precoding method	465
16.4	Low-complexity communication protocol for single-cell MU-MIMO/CoMP setups	467
16.5	Signal and interference modeling	467
16.5.1	SU-MIMO setup	467
16.5.2	Single-cell MU-MIMO/JT CoMP setup	469
16.6	Joint precoding schemes	470
16.6.1	Linear precoding schemes	470
16.6.2	Symbol-level precoding	471
16.7	Optimal transmission technique under an interfered receiver constraint	473
16.7.1	Problem formulation	473
16.7.2	Derivation of the solution	475
16.8	Proposed LC-MAMP design	478
16.9	Numerical simulations	479
16.9.1	SU-MIMO setup	479
16.9.2	CoMP setup	482
16.9.3	Symbol-level ZFBF	485
16.10	Summary	485
	References	488
17	Dynamic spectrum sharing in hybrid satellite–terrestrial systems	491
	<i>Marko Höyhtyä and Sandrine Boumard</i>	
17.1	Introduction	491
17.2	Classification of hybrid satellite–terrestrial spectrum sharing scenarios	493
17.2.1	Uncoordinated systems: coexistence of terrestrial and satellite	493
17.2.2	Coordinated systems: coexistence of terrestrial and satellite	496
17.3	Satellite band sharing techniques	497
17.3.1	Spectrum sensing	497
17.3.2	Spectrum databases	498
17.3.3	Beamforming and smart antennas	500
17.3.4	Beam hopping	502
17.3.5	Frequency and power allocations	503
17.3.6	Core network functionality	503
17.4	Interference analysis	504
17.5	Practical application scenarios	507
17.5.1	Autonomous ships	507
17.5.2	Citizens broadband radio service	509

17.6	Future recommendations	511
17.6.1	Spectrum sensing	511
17.6.2	Spectrum databases	511
17.6.3	Beamforming	511
17.6.4	Beam hopping	511
17.6.5	Frequency and power allocations	512
17.6.6	Core network functionality and network slicing	512
17.6.7	Implementation challenges	512
17.7	Conclusions	512
	References	513
18	Two-way satellite relaying	519
	<i>Arti M.K.</i>	
18.1	Background	520
18.2	Two-way satellite relaying	521
18.3	Training-based two-way satellite relaying system	524
18.3.1	Average BER	528
18.3.2	Ergodic capacity	529
18.3.3	Numerical results and discussion	530
18.4	Differential modulation-based TWSR	533
18.4.1	Constellation rotation angle calculation	535
18.5	Multiple antennas-based TWSR system	536
18.5.1	Beamforming and combining using local channel information	537
18.5.2	Received SNR optimal beamforming and combining	538
18.6	Analytical performance of TWSR scheme based on local channel information	538
18.6.1	Expression of the SER	539
18.6.2	Diversity order	539
18.6.3	Numerical results and discussion	540
18.7	Analytical performance of TWSR scheme based on optimal beamforming and combining	542
18.7.1	Expression of SER	543
18.7.2	Diversity order	543
18.8	Numerical results and discussion	544
18.9	Conclusions	546
	References	546
	List of Acronyms	549
	Index	555