
Contents

Preface.....xvi

Chapter 1 Overview 1

 6G Artificial Intelligence-Native Architecture Framework 3

 6G AI-Native vs. 6G AI-Standard-Based Network 8

 Semiconductor Technology 8

 Radio Technologies 9

 Seamless Mobility 11

 Spectrum Sharing 12

 Millimeter Waves..... 13

 Sub-Millimeter or Terahertz Band..... 13

 Joint Communications and Sensing..... 14

 JCAS for Massive MIMO..... 16

 References 17

Chapter 2 MIMO..... 18

 Network MIMO, Cooperative MIMO, Distributed MIMO, or virtual MIMO..... 22

 Advantages 22

 Disadvantages 22

 AI/ML/DL Application in MIMO 23

 Merits of MIMO in Communication Systems..... 23

 Merits of MIMO in Sensing Systems..... 24

 Summary 24

 References 25

 Massive MIMO 25

Chapter 3 High-Level Capacity Estimation for Massive MIMO with Single Antenna-Based Multi-User..... 27

 High-Level Capacity Estimation for Massive MIMO with Multiple Antennas-Based Multi-User 30

 Uplink Achievable Channel Capacity..... 32

 Uplink Achievable Channel Capacity..... 34

 Asymptotic Analysis..... 35

 Power Scaling Laws 35

 Simulation Results..... 35

 Massive MIMO with Multiple Antennas-Based Multi-User 37

 MU-MIMO vs. SU-MIMO..... 37

 MU-MIMO Basics..... 38

 Summary 40

 References 41

Chapter 4	Ultra-Massive MIMO: Ultra-Massive MIMO Platforms	42
	Plasmonic Transmit–Receive Arrays.....	43
	Reference.....	44
Chapter 5	Vehicle-to-Everything Ultra-Massive MIMO Communications	45
	System Performance Comparison	47
	Application of Artificial Intelligence and Machine Learning into Ultra-Massive MIMO Wireless Systems	50
	Summary	52
	References	52
Chapter 6	Reconfigurable Intelligent Surface	53
	Distributed RIS Communications	53
	Cooperative Beamforming in RIS Communications.....	54
	JCAS for RIS and Massive MIMO	54
	RIS and Massive MIMO-Enabled Applications.....	54
	Summary	55
	Reference.....	55
Chapter 7	Cell-Free Communications	56
	Ultra-Dense Cell-Free Massive MIMO Systems	57
	System Model.....	58
	Uplink Training	58
	Power Consumption Model.....	60
	Power Control.....	61
	Spectral Efficiency.....	61
	Advantages of Cell-Free CD-Massive MIMO	62
	Disadvantages of Cell-Free CD-Massive MIMO	63
	Summary	63
	Reference.....	64
Chapter 8	Non-Terrestrial Communications	65
	Aerial Communications.....	65
	Satellite Communications	65
	Summary	66
	Reference.....	66
Chapter 9	Massive MIMO Radar	67
	Massive MIMO Radar System	67
	MIMO Signal Model.....	69
	Phased-Array Signal Model	70
	Clutter Model.....	71

Moving Target Detector	71
Centralized MIMO Moving Target Detector	72
Distributed MIMO Moving Target Detector.....	73
Phased-Array Moving Target Detector.....	74
Adaptive MIMO Moving Target Detector	74
Simulation Results and Inferences	75
Receiver Operating Characteristics	76
Comparing Centralized and Distributed MIMO Radars	77
Distributed Transmitter Elements.....	78
CFAR Properties of the Test Statistics	79
References	79
Chapter 10 Massive MIMO Radar for Target Detection.....	80
Background	80
Technical Considerations.....	81
Summary	90
References	92
Chapter 11 Massive MIMO Radar Scaling.....	93
Overview	93
System Model.....	94
Unambiguous Bounds and Resolution of Parameters	95
Aperture Extension with Spatial Subsampling.....	97
Algorithm	97
Numerical Results	100
Summary	100
Reference.....	101
Chapter 12 Ultra-Massive MIMO Radar Sensors and Multiuser Communications.....	102
Overview	102
System Model.....	105
Communications Model	105
Radar Model	110
Model-Based Hybrid Beamforming	111
Simulation Results.....	112
Summary	115
Reference.....	116
Chapter 13 Device-to-Device Communications with Mesh Networking	117
System Architecture	117
Resilience and Robustness	119

Relevant: User Location Context	120
Security and Privacy	120
Summary	120
Reference.....	120

Chapter 14	Vehicle-to-Vehicle and Vehicle-to-Everything	121
	Communications.....	121
	Overview	121
	Vehicle-to-Vehicle Communication	122
	Vehicle-to-Everything Communications	123
	Overview.....	123
	Vehicle-to-Everything (V2X) Communications	124
	Brain Controlled V2X.....	124
	UAV/Satellite-Assisted V2X	125
	Integrated Control V2X.....	125
	Block-Based V2X.....	125
	Intelligent Reflecting Surface V2X.....	126
	Tactile Communications V2X	126
	Hybrid RF-VLC V2X.....	127
	Terahertz-Assisted V2X.....	128
	Quantum Computing-Aided V2X.....	129
	AI-enabled V2X.....	130
	Vehicle-to-Vehicle (V2V) Communication	132
	References	134
Chapter 15	V2V Communications Network.....	135
	Self-Driving V2V Communications.....	135
	Which Information to be Transmitted	136
	Leveraging Multiple Vehicles.....	137
	LiDAR Convolution Block.....	138
	Compression.....	138
	Cross-vehicle Aggregation.....	139
	Output Network.....	140
	Learning.....	140
	V2V Simulation – Dataset for V2V Communication.....	141
	Experimental Evaluation	142
	Baselines.....	142
	Experimental Details	142
	Comparison to Existing Approaches	143
	Compression.....	143
	SDV Density.....	143
	Number of LiDAR Points and Velocity	144
	Imperfect Localization.....	144
	Asynchronous Propagation.....	144

Mixed Fleet.....	145
Qualitative Results.....	145
Summary	145
Reference.....	145
Chapter 16 Peer-to-Peer V2V Communication.....	146
Overview	146
P2P Network.....	147
Distributed Conscious	147
P2P V2V Network Communications Network.....	147
Self-Organization of Vehicle Networking	148
Simulation of V2V Communication at a Crossroad	152
Experimental Results.....	153
Selection of Relay for Multihop Termination Conditions.....	155
Implementation Cost	156
Summary	157
Reference.....	157
Chapter 17 V2V Massive MIMO Channels.....	158
BER Results	159
Capacity Results.....	159
Summary	160
Reference.....	160
Chapter 18 V2X Communications Network.....	161
V2X Ultra-Massive MIMO Communications.....	161
System Performance Comparison	163
Summary	166
Reference.....	167
Chapter 19 V2X Millimeter Wave MIMO Radar Communications	168
AoA/AoDs Estimation Performance	169
Path Gains Estimation Performance.....	169
Channel Estimation Performance	170
Summary	170
Reference.....	171
Chapter 20 Robotics and Autonomous System Communications	172
Overview	172
Robot Network Design.....	174
Multi-Robot Communication Schemes.....	175

Peer-to-Peer Communications Scheme	176
Communication-Aware Algorithms.....	177
Communication-Aware Planning	177
Plan-Aware Communications	178
Joint Planning	178
AI/ML/DL for Robots and Autonomous Systems.....	179
AI/ML/DL-Based Communication Mechanisms	179
AI/ML/DL-Based Communication Behaviors	179
Challenges and Open Problems.....	181
Trustworthy Robots and Autonomous Systems.....	182
Summary	182
References	182
 Chapter 21 Virtual, Augmented, Mixed Reality, and Extended Reality	183
Overview	183
Brief Description of XR, AR, MR, and VR	183
Extended Reality	186
XR and AI/ML/DL	188
Augmented Reality.....	189
Mixed Reality	191
Virtual Reality	192
Technical Differences.....	193
Existing XR Devices	194
Use Cases	194
Augmented Reality	195
Mixed Reality	195
Virtual Reality	196
Technical Requirements	196
Challenges and Future Research Directions.....	198
Summary	202
References	202
 Chapter 22 Unmanned Aerial Vehicles Communication Systems	203
Overview	203
Quadrotor Drone.....	204
Reference Frames	204
Aerial Quadrotor Robot Kinematics and Dynamics.....	221
Deep Reinforcement Learning-Based Attitude and Altitude Control.....	233
Quadrotor Attitude Control Preliminaries	243
Summary	256
References	256

Chapter 23 Unmanned Robot Network with Swarm Capabilities257

 Overview257

 Swarm Robotics Behavior.....257

 Taxonomy259

 Detailed Description of Additional Swarm Behavior Categories.....260

 Collective Localization.....260

 Synchronization.....264

 Self-Reproduction.....267

 Artificial Intelligence-Based Swarm Robotics268

 Automatic Design Methods.....268

 Particles Swarm Optimization269

 Reinforcement Learning.....270

 Deep Reinforcement Learning in Swarm Robotics Systems.....272

 Summary273

 References274

Chapter 24 Digital Twins275

 Overview275

 Digital Twins Applications275

 Digital Twin Categories.....276

 Digital Twin Characteristics276

 AI Integration of Digital Twins278

 Digital Twin for 6G Network284

 Fundamental Building Block.....287

 Summary291

 References292

 Holographic Communications.....292

 Overview.....292

 Holographic MIMO.....293

 Basic Principle of Holography295

 Conventional Holography.....297

 EM Holography298

 Holographic LWA-Based EM Holography.....298

 Photonic TCA-Based EM Holography.....300

 Locally Maximum Phase Lines of Hologram300

 Macroscopic Surface Impedance-Based Approach301

 Geometric Polarizable Particle-Based Approach303

 Tuning Mechanisms of HMIMO Surfaces305

 HMIMO Surface Fabrication Methodologies.....305

 HMIMO Surfaces Aperture Shapes.....305

 HMIMO Surfaces Functionalities305

 HMIMO Surfaces Prototypes306

HMIMO Surface-Aided Communication Prototypes.....	306
HMIMO Communications Networking.....	306
Summary	312
References	313
Ultra-Dense Network	313
Overview.....	313
Challenges of UDNs.....	313
Rethink Universal Frequency Reuse	314
Integrated Resource Allocation, Interference Management, and Traffic Steering	315
Standards Consideration	315
Summary	316
Reference.....	316
 Chapter 25 Quantum Communications.....	317
Overview	317
Quantum Physics/Mechanics	319
No Cloning and No Deleting.....	319
Superposition	320
Entanglement.....	320
Teleportation	321
Quantum Measurement and Disturbance	321
Quantum Communications Architecture Model and Protocols.....	322
Quantum Teleportation Protocol	323
Superdense Coding.....	325
Entanglement Distribution.....	325
Quantum Key Distribution	327
Quantum Secure Direct Communications	327
Quantum Secret Sharing.....	328
Quantum Computing	328
Quantum Sensing.....	329
Quantum Information Science for 6G Networks	330
Quantum Radio Access Network.....	330
Quantum Edge Network	332
Quantum Satellite Networks.....	332
Quantum Data Center.....	332
Quantum Blockchain	333
Quantum Artificial Intelligence	333
Quantum Internet Management and Control.....	334
Quantum Network Devices.....	334
Repeater, Switch, and Router for Quantum Entanglement.....	335
Quantum Error Correction.....	336
QKD Implementation	337
Quantum Cloud Computing	338

Systems with Entangle Distribution	339
Hybrid Classical-Quantum Network Evolution	339
Summary	340
References	341
Chapter 26 6G Cybersecurity.....	342
Overview	342
Digital Services	342
Core Service Integration.....	343
Layer Integration	343
Challenges and Possible Solutions.....	343
Latency and Reliability	344
Connectivity	344
Spectral Efficiency	345
Energy Efficiency	345
Network Intelligence	345
New Approaches to Securing User Data	346
Cybersecurity Complexity with AI/ML/DL	347
Blockchain.....	347
Future Research Areas	347
Autonomous Vehicles.....	348
Problem Statement	348
Proposed Model.....	350
Results	352
Discussion and Analysis.....	354
Challenges and Limitations	355
Conclusion and Future Work.....	356
Summary	357
References	357
Index	358