

Contents

Foreword	xii
Ian F. AKYILDIZ	
Preface	xiii
Tara ALI-YAHIA and Wrya MONNET	
List of Acronyms	xv
Chapter 1. Introduction to Tactile Internet	1
Tara ALI-YAHIA	
1.1. Human perception and Tactile Internet	2
1.2. The roadmap towards Tactile Internet	3
1.3. What is Tactile Internet?	5
1.4. Cyber-Physical Systems and TI	7
1.4.1. Physical world	7
1.4.2. Internet of Things	7
1.4.3. Communication	7
1.4.4. Storage and computation	8
1.4.5. Feedback	8
1.4.6. Smart computing	10
1.5. References	11

Chapter 2. Reference Architecture of the Tactile Internet	13
Tara ALI-YAHIA	
2.1. Tactile Internet system architecture	13
2.2. IEEE 1918.1 use cases	15
2.2.1. Teleoperation	16
2.2.2. Automotive	17
2.2.3. Immersive virtual reality (IVR)	17
2.2.4. Internet of drones	18
2.2.5. Interpersonal communication	18
2.2.6. Live haptic-enabled broadcast	19
2.2.7. Cooperative automated driving	19
2.3. Conclusion	20
2.4. References	20
 Chapter 3. Tactile Internet Key Enablers	 21
Tara ALI-YAHIA	
3.1. Introduction	21
3.1.1. The fifth-generation system architecture	21
3.1.2. Network slicing	23
3.1.3. Network function virtualization	25
3.1.4. Software-defined networking	26
3.1.5. Edge computing	27
3.1.6. Artificial intelligence	29
3.2. Conclusion	31
3.3. References	31
 Chapter 4. 6G for Tactile Internet	 35
Pinar KIRCI and Tara ALI-YAHIA	
4.1. Introduction	35
4.2. The architecture of 6G	37
4.2.1. Network performance of 6G	38
4.2.2. Space network	39
4.2.3. Air network	40
4.2.4. Ground network	40
4.2.5. Underwater network	41
4.3. 6G channel measurements and characteristics	41
4.3.1. Optical wireless channel	41
4.3.2. Unmanned aerial vehicle (UAV) channel	42
4.3.3. Underwater acoustic channel	43
4.3.4. Satellite channel	43
4.3.5. RF and terahertz networks in 6G	45

4.3.6. Visible light communication technology	48
4.3.7. Orbital angular momentum technology	48
4.4. 6G cellular Internet of Things	49
4.5. Energy self-sustainability (ESS) in 6G	50
4.6. IoT-integrated ultrasmart city life	52
4.7. AI-enabled 6G networks	55
4.8. AI- and ML-based security management in super IoT	59
4.9. Security for 6G	60
4.10. The WEAF Mnecosystem (water, earth, air, fire micro/nanoecosystem) with 6G and Tactile Internet	61
4.11. References	63
 Chapter 5. IoT, IoE and Tactile Internet	65
Wrya MONNET	
5.1. From M2M to IoT	66
5.2. Classification of remote monitoring and control systems	66
5.3. IoT-enabling technologies	67
5.3.1. IoT hardware	67
5.3.2. IoT software	67
5.3.3. IoT connectivity	67
5.4. Architectural design and interfaces	68
5.5. IoT communication protocols	71
5.5.1. Message Queuing Telemetry Transport (MQTT)	72
5.5.2. Constrained Application Protocol (CoAP)	74
5.5.3. Data Distribution Service for real-time systems (DDS)	76
5.5.4. Open Mobile Alliance Device Management (OMA-DM)	79
5.6. Internet of Everything (IoE)	80
5.6.1. Enabling technologies for the IoE	81
5.7. Protocol comparisons and the readiness for TI	82
5.8. TI-IoT models and challenges	83
5.9. Edge computing in the IoT	85
5.9.1. Edge computing paradigms	86
5.10. Real-time IoT and analytics versus real time in TI	88
5.11. From IoT towards TI	88
5.12. Conclusion	90
5.13. References	91
 Chapter 6. Telerobotics	95
Wrya MONNET	
6.1. Introduction	95
6.2. Teleoperation evolution to telepresence	96

6.3. Telepresence applications	97
6.4. Teleoperation system components	99
6.4.1. Master domains	102
6.4.2. Network domain (communication channel)	102
6.4.3. Slave domain	102
6.5. Architecture of bilateral teleoperation control system	103
6.5.1. Classification of the control systems architectures	106
6.5.2. Discrete architecture with transmission delay	107
6.6. Performance and transparency of telepresence systems	110
6.6.1. Passivity and stability	110
6.6.2. Time delay issues	112
6.7. Other methods for time-delay mitigation	116
6.8. Teleoperation over the Internet	117
6.9. Multiple access to a teleoperation system	119
6.10. A use case	121
6.11. Conclusion	122
6.12. References	122
 Chapter 7. Haptic Data: Compression and Transmission Protocols	127
Wrya MONNET	
7.1. Introduction	127
7.2. Haptic perception	128
7.2.1. Human haptic perception	128
7.2.2. Telerobotic tactile and haptic perception	128
7.2.3. Tactile sensing for material recognition	129
7.2.4. Tactile sensing for object shape recognition	130
7.2.5. Tactile sensing for pose estimation	131
7.3. Haptic interfaces	133
7.3.1. Haptic interface for telepresence	133
7.3.2. Haptic and tactile sensors and actuators	135
7.4. Haptic compression	139
7.5. Haptic transport protocols	142
7.5.1. Application layer protocols	143
7.5.2. Transport layer protocols	146
7.6. Multi-transport protocols	149
7.7. Haptic transport protocol performance metrics	149
7.8. Conclusion	150
7.9. References	150

Chapter 8. Mapping Wireless Networked Robotics into Tactile Internet	155
Nicola Roberto ZEMA and Tara ALI-YAHIA	
8.1. Wireless networked robots	155
8.2. WNR traffic requisites	158
8.2.1. Types of traffic in WNRs	158
8.3. Traffic shaping and TI haptic codecs	160
8.3.1. Introduction	161
8.3.2. Mapping WNR control traffic to TI	161
8.4. WNRs in the Tactile Internet architecture	164
8.4.1. WNRs in the TI architecture and interfaces	165
8.5. Conclusion	169
8.6. References	170
Chapter 9. HoIP over 5G for Tactile Internet Teleoperation Application	173
Tara ALI-YAHIA, Wrya MONNET and Bakhtiar M. AMIN	
9.1. Related works	174
9.2. 5G architecture design for Tactile Internet	179
9.2.1. Tactile edge A	180
9.2.2. Network domain	182
9.2.3. Protocol stack of 5G integration with IEEE 1918.1	182
9.3. Haptics over IP	183
9.4. Teleoperation case study	185
9.4.1. Master to slave (uplink) data rate in edge A	187
9.4.2. Slave to master (downlink) data rate in edge B	187
9.4.3. Encapsulating the haptic data in HoIP	188
9.4.4. 5G network data and control handling	188
9.4.5. Case study operational states	190
9.4.6. Case study protocol stack	191
9.5. Simulation results	192
9.5.1. Simulation topology	193
9.5.2. NS3 network architecture	194
9.5.3. Simulation scenario	196
9.5.4. Simulation results	198
9.6. Conclusion	203
9.7. References	203

Chapter 10. Issues and Challenges Facing Low Latency in the Tactile Internet	209
Tara ALI-YAHIA	
10.1. Introduction	209
10.1.1. Technical requirements for the TI	211
10.2. Low latency in the Tactile Internet	212
10.2.1. Resource allocation	212
10.2.2. Mobile edge computing	213
10.2.3. Network coding	214
10.2.4. Haptic communication protocols	214
10.3. Intelligence and the Tactile Internet	216
10.4. Edge intelligent	216
10.5. Open issues	219
10.6. Conclusion	220
10.7. References	221
List of Authors	227
Index	229