Contents

Preface xv
Ashu TANEJA, Abhishek KUMAR, Suresh Vishnudas LIMKAR, Mariya OUAISSA and Mariyam OUAISSA

Chapter 1. AI-Driven Digital Twins for 6G-Enabled Urban Traffic Optimization 1
Saurabh YADAV, Imene Elhachfi ESSOUSSI, Ankish NAIR, Shubneet and Anushka Raj YADAV

1.1. Introduction 2
1.2. Foundations of digital twins for 6G smart cities 5
1.3. 6G network digital twins 7
1.4. AI-driven urban mobility twins in 6G 9
1.5. Energy grids and sustainability in urban twins 11
1.6. Data, encoding and model risk in 6G urban twins 14
1.7. Cyber-physical and systemic risks in 6G twins 17
1.8. Advanced hybrid and algorithmic developments 19
1.9. Case studies and pilots 21
1.10. Conclusion 23
1.11. References 25

Chapter 2. Exploring Quantum Simulation Techniques for Predictive Real-Time Traffic Control in Smart Cities 29
Muhammad YOUNUS, Halimah Abdul MANAF, Bhimo Widyo ANDOKO, Andi ADAWIAH, Bambang IRAWAN, Dyah MUTIARIN, Eliza MEIYANI, Imron SOHSAN, Dian Suluh Kusuma DEWI and Andi Luhur PRIANTO

2.1. Introduction 30
2.2. Literature review 31
2.2.1. Smart cities, traffic control and the rise of predictive systems 31

2.2.2. Quantum simulation techniques: emerging applications and potentials . . 32
2.2.3. Toward quantum-based predictive traffic control in smart cities 33
2.3. Research method. 34
2.4. Results and discussion. 35
2.4.1. Accuracy and performance of quantum algorithms 36
2.4.2. Real-time simulation and scalability 36
2.4.3. Energy efficiency and resource utilization 36
2.4.4. Findings 37
2.4.5. Discussion 37
2.4.6. Implications 38
2.4.7. Recommendations 38
2.5. Conclusion 39
2.6. References 40

Chapter 3. 6G-Enabled Cooperative ADAS and Autonomous Driving: Role of AI and Digital Twin 45
Poonam SINGH, Manju BAGGA, Pooja RANI and Neelima

3.1. Introduction 45
3.2. Study purpose 47
3.3. Literature review. 47
3.4. Critical analysis 51
3.5. Structured assessment of AI and digital twins in cooperative ADAS and autonomous driving 53
3.6. Literature limitations 56
3.7. Gaps and future research directions 58
3.8. Overall synthesis and conclusion. 60
3.9. References 61

Chapter 4. A Multi-Agent and Digital Twin Framework for Simulating Daily Urban Mobility in Smart Cities 65
Khalid QBOUCHE and Khadija RHOULAMI

4.1. Introduction 65
4.2. Related works 67
4.3. A conceptual framework for digital twin-based multi-agent systems. 69
4.3.1. Heterogeneous real-world agents 69
4.3.2. Data-driven digital twin layer 70
4.3.3. Model development core 70
4.3.4. Data-driven agent-based modeling layer 70
4.3.5. Implementation and execution platform 71
4.4. Results and discussion. 71
4.4.1. Morning transition phase. 74

4.4.2. Stationary working phase 74
4.4.3. Evening transition phase 74
4.4.4. System-level interpretation. 74
4.5. Conclusion 75
4.6. References 75

Chapter 5. Algorithmic Accountability in Autonomous Vehicles: Legal Frameworks for 6G-Enabled Smart Cities 79
Kalpna SHARMA and Shashank SOLANKI

5.1. Introduction 79
5.1.1. Background 79
5.1.2. Research gap 80
5.1.3. Objectives 80
5.1.4. Methodology 81
5.2. Technological environment 6G-enhanced autonomous mobility 81
5.2.1. The history of ADAS to fully autonomous vehicles 81
5.2.2. 6G connectivity and its legal implications 82
5.2.3. Digital twin in smart cities 82
5.3. The normative framework of algorithmic accountability. 84
5.3.1. Conceptual foundations 84
5.3.2. The black-box problem. 85
5.3.3. Emerging global principles. 85
5.4. Limitations of classical liability doctrines 86
5.4.1. Negligence and foreseeability 86
5.4.2. Product liability problems 87
5.5. Comparative international regulatory framework. 87
5.5.1. Overview 87
5.5.2. European Union. 88
5.5.3. United States 88
5.5.4. India 88
5.5.5. Comparative assessment 89
5.6. Real-case-based examples 90
5.6.1. Uber autonomous vehicle fatality 90
5.6.2. Tesla autopilot litigation 90
5.7. In-depth case study legality: Uber ATG crash 90
5.7.1. Factual matrix 90
5.7.2. Prosecutor and regulatory response 91
5.7.3. Doctrinal analysis. 91
5.7.4. Implications to 6G smart cities 91
5.8. Insurances and victim compensation models 92
5.8.1. Overview 92
5.8.2. Fault-based regimes. 93
5.8.3. No-fault compensation systems 93

5.8.4. Mandatory insurance pools . . . 93
5.8.5. Ecosystems in 6G usage-based insurance . . . 94
5.9. Smart city governance and regulatory sandboxes . . . 94
5.9.1. Governance imperative . . . 94
5.9.2. Experimental instruments – regulatory sandboxes . . . 95
5.9.3. Municipal and infrastructure liability . . . 95
5.9.4. Connected ecosystem distributed risk . . . 96
5.9.5. Data governance and algorithmic accountability . . . 96
5.10. Universal legal framework (core contribution) proposal . . . 97
5.10.1. Guiding principles . . . 97
5.10.2. Graded liability model . . . 97
5.10.3. Obligatory algorithm accountability responsibilities . . . 98
5.10.4. Shared responsibility matrix . . . 98
5.11. India-based policy recommendations . . . 99
5.11.1. Reform of motor vehicles act in autonomous vehicle integration . . . 99
5.11.2. Dedicated AI liability statute . . . 99
5.11.3. Compulsory self-driving vehicle data recorder regime . . . 99
5.11.4. Development of a national autonomous vehicle regulatory sandbox . . . 100
5.11.5. Establishment of statutory autonomous mobility compensation fund . . . 100
5.11.6. Strategic support of UNECE and OECD normative frameworks . . . 100
5.12. Conclusion . . . 101
5.13. References . . . 101

Chapter 6. AI-Driven Zero Trust Architecture for Resilient Fog–Cloud Systems: Foundations, Frameworks and Future Directions . . . 105
Prachi CHATURVEDI, Shahnawaz AHMAD and Arvind MEWADA

6.1. Introduction . . . 105
6.1.1. Background and motivation . . . 105
6.1.2. Urban intelligence evolution: cloud to fog . . . 106
6.1.3. AI and digital twins in 6G smart cities . . . 107
6.1.4. Chapter contributions . . . 107
6.1.5. Chapter organization . . . 108
6.2. Foundations of fog computing for urban intelligence . . . 108
6.2.1. Fog computing: concepts and architecture . . . 108
6.2.2. Fog versus edge versus cloud in 6G environments . . . 109
6.2.3. Smart city requirements and fog integration . . . 110
6.3. AI-driven intelligence at the fog layer . . . 112
6.3.1. Distributed AI models and resource-aware deployment . . . 112
6.3.2. Federated learning in fog networks . . . 113
6.3.3. Real-time analytics and decision-making . . . 113

6.4. Digital twin architectures for 6G smart cities 114
6.4.1. Digital twin concepts and life cycle 114
6.4.2. Physical–virtual synchronization 115
6.4.3. AI-enabled digital twin intelligence 115
6.5. Fog-enabled digital twin frameworks for 6G 116
6.5.1. Reference architecture 116
6.5.2. AI orchestration and 6G network integration 117
6.5.3. Security and privacy mechanisms 118
6.6. Use cases and applications 119
6.6.1. Intelligent transportation systems 119
6.6.2. Smart energy and healthcare 119
6.7. Research challenges and future directions 121
6.7.1. Scalability and autonomous operation 121
6.7.2. Energy efficiency and sustainability 121
6.7.3. Future research roadmap 123
6.8. Conclusion 124
6.8.1. Summary and implications 124
6.8.2. Future outlook 124
6.9. References 125

Chapter 7. Secure 6G Framework for Urban IoT Ecosystems using AI: Smart Transportation, Energy and Grid Intelligence 129
Delsi Robinsha S., Tanmay SHARMA, Vaidhehi M. and Pradeep SUDHAKARAN

7.1. Introduction 130
7.2. Background and motivation 130
7.2.1. Evolution from 5G to 6G 130
7.2.2. Security challenges in an urban IoT ecosystem 131
7.3. Core technologies enabling secure 6G cities 131
7.3.1. AI for security 132
7.3.2. DT technology 133
7.3.3. Blockchain for trust and integrity 134
7.3.4. Privacy-preserving analytics 135
7.4. Proposed secure 6G framework architecture 135
7.4.1. Device and perception layer 136
7.4.2. 6G communication and network layer 136
7.4.3. Edge intelligence and computing layer 137
7.4.4. DT and simulation layer 137
7.4.5. Security, trust and privacy layer 138
7.4.6. Cross-layer orchestration and operational workflow 138
7.5. Smart transportation security: AI-driven protection for intelligent mobility system 139
7.5.1. Overview of smart transportation in 6G-enabled cities 139

7.5.2. Threat landscape and security challenges . . . 140
7.5.3. AI-based intrusion detection and anomaly monitoring . . . 140
7.5.4. DT-enabled simulation and predictive defense . . . 141
7.5.5. Blockchain-based trust and secure communication . . . 141
7.5.6. Privacy-preserving data analytics in mobility systems . . . 142
7.5.7. Integrated operational workflow and response mechanism . . . 142
7.5.8. Performance benefits and practical implications . . . 142
7.6. Energy and grid intelligence security: protecting smart power infrastructure in 6G-enabled cities . . . 143
7.6.1. Overview of smart energy and grid intelligence . . . 143
7.6.2. Threat landscape and vulnerabilities in smart grids . . . 144
7.6.3. AI-driven anomaly detection and predictive analytics . . . 144
7.6.4. DT-based grid modeling and risk simulation . . . 144
7.6.5. Blockchain for secure energy transaction and trust management . . . 145
7.6.6. Privacy-preserving data management in energy systems . . . 145
7.7. Ethical, governance and sustainability considerations . . . 146
7.7.1. Ethical and responsible AI . . . 146
7.7.2. Privacy and data protection . . . 146
7.7.3. Governance and regulatory frameworks . . . 146
7.7.4. Trust, transparency and public engagement . . . 147
7.7.5. Sustainability and green 6G deployment . . . 147
7.8. Challenges and future research directions . . . 147
7.8.1. Technical and infrastructure challenges . . . 147
7.8.2. Security and privacy limitations . . . 148
7.8.3. Integration and operational complexity . . . 148
7.8.4. Economic and deployment barriers . . . 148
7.8.5. Future research directions . . . 148
7.9. Conclusion . . . 149
7.10. References . . . 149

Chapter 8. A Cognitive Digital Twin Framework for Causal and Multi-Agent Urban Healthcare in 6G Cities . . . 153
Jareena Begam J., Karthika A., Vaisali BALASUBRAMANIAM, Pradeep S., Karthikeyan A. and Kaaviyakanth K.

8.1. Introduction . . . 154
8.2. Related work . . . 156
8.2.1. Healthcare DT systems . . . 156
8.2.2. AI in smart cities . . . 157
8.2.3. 6G-enabled healthcare . . . 158
8.2.4. Multi-agent health systems . . . 158
8.2.5. Foundation models in medicine . . . 159
8.3. UCH-DT . . . 160
8.4. System architecture . . . 163

8.5. Healthcare foundation model design 166
8.6. Multi-agent intelligence 168
8.7. Causal and prescriptive intelligence 171
8.8. Ethical, privacy and governance layer 173
8.9. Case study: smart city healthcare twin 175
8.10. Open challenges and future directions 177
8.11. Conclusion 179
8.12. References 181

Chapter 9. Adaptive Digital Twins and AI-Native 6G Networks with Neuromorphic Phase-Change Memory: Facilitating Future Urban Intelligence 185
G. Sreevidya VARMA, Prachi GUPTA and Mamatha M.

9.1. Introduction 185
9.2. 6G networks and AI-native intelligence 187
9.2.1. Advancing toward 6G 187
9.2.2. AI-native radio access networks 188
9.3. Digital twins in urban systems 188
9.4. Neuromorphic functionality in phase change memory 190
9.4.1. Spike-timing-dependent plasticity (STDP) 191
9.4.2. Long-term potentiation and depression 192
9.4.3. Stochastic learning 192
9.5. In-memory computing architectures 193
9.5.1. Crossbar arrays 193
9.6. PCM-enabled adaptive digital twins 195
9.6.1. Edge learning 195
9.6.2. Physical–digital parallelism 195
9.7. PCM in AI-native 6G networks 196
9.8. Energy efficiency and sustainability 197
9.9. Reliability challenges and mitigation strategies in PCM systems 198
9.10. Research roadmap 199
9.11. References 200

Chapter 10. The GEO-IoT-6G Data Ecosystem: A Systematic Literature Review of Geospatial Data Exploitation for Smart Cities and Intelligent Territorial Governance 205
Ayoub OUCHLIF, Hicham HAJJI and Kenza AITELKADI

10.1. Introduction 206
10.2. Methodology 208
10.2.1. Selection criteria 209
10.2.2. Data extraction and analysis 210

10.3. Results. 211
10.3.1. Classification of territorial data 211
10.3.2. Levels of geospatial integration 212
10.3.3. Consideration of data quality and cleaning 213
10.3.4. Multi-source data (heterogeneous) structuring and interoperability 213
10.3.5. Relationship between emerging technologies and data exploitation 213
10.3.6. Implications of intelligent territorial governance 214
10.4. Discussion. 215
10.5. Conclusion 218
10.6. Prospects 219
10.7. Chapter contributions 219
10.8. References 219

Chapter 11. AI and Digital Twin Synergy for Immersive Experiences in Future Smart Cities 223
Vijayanand SELVARAJ, Jawahar GOVINDARAJ and Ramkumar JAGANATHAN

11.1. Introduction 223
11.2. Conceptual foundations of urban intelligence 224
11.3. Digital twin technology in smart cities 225
11.4. AI as the cognitive engine of digital twins 225
11.5. AI and digital twin synergy architecture for 6G cities 226
11.6. Immersive experiences in future smart cities 227
11.7. Application domains of AI-driven digital twins 227
11.7.1. Urban planning and design 227
11.7.2. Intelligent mobility and transportation. 228
11.7.3. Environmental monitoring and sustainability 229
11.7.4. Public safety and disaster management 229
11.8. Human-centered urban experiences. 229
11.9. Governance and ethical considerations 229
11.10. Challenges and limitations 231
11.11. Future research directions 231
11.12. Conclusion. 231
11.13. References 231

Chapter 12. Toward AI-Driven, Federated and Self-Adaptive Urban Ecosystems for Cognitive Cities 235
Archana G. SAID and Mohammed Eltahir ABDELHAG

12.1. Introduction 236
12.1.1. Background context 236

12.1.2. Evolution from smart cities to cognitive cities 236
12.1.3. Gaps in existing urban computing paradigms 237
12.1.4. Why do cognitive cities matter? 238
12.1.5. Motivating role of AI, edge computing, digital twins and federated systems 239
12.1.6. Chapter structure and contribution 239
12.2. Technological foundations of cognitive cities 240
12.2.1. Perception and sensory infrastructure 240
12.2.2. Integration of cyber-physical systems (CPS) 241
12.2.3. Technology: communication and networking fabric 242
12.2.4. Urban intelligence infrastructure and distributed computing 242
12.2.5. Semantic knowledge modeling and urban knowledge integration 243
12.2.6. Actuation mechanisms and cognitive decision systems 244
12.2.7. Architectural analysis and loops of cognition in cognitive cities 245
12.2.8. Summary 249
12.3. Key challenges and practical constraints in cognitive cities 249
12.3.1. Organizational and structural issues 249
12.3.2. Operation and technological constraints 250
12.3.3. Information governance, privacy and trust 250
12.3.4. Overcoming practical constraints 251
12.3.5. Summary 251
12.3.6. Analyzing real-world deployment perspectives 251
12.3.7. Governance, integration and meso-scale deployments 253
12.3.8. The maturity trajectories of deployment 253
12.3.9. Summary 254
12.4. Future research directions 254
12.5. Conclusion 255
12.6. References 256

Chapter 13. Future Vision for Cognitive Cities: Challenges, Practical Constraints and Real-World Deployment Perspectives 259
Prachi GUPTA and Abhishek KUMAR

13.1. Introduction to cognitive cities 260
13.1.1. Evolution of urban systems: from smart to cognitive cities 260
13.1.2. Motivation for cognitive urban intelligence 262
13.1.3. Scope and deployment-focused perspective 262
13.2. Cognitive cities: concepts and architectural foundations 263
13.2.1. Core functional characteristics of cognitive cities 263
13.2.2. Reference architecture for cognitive cities 265
13.3. Enabling technologies for cognitive urban intelligence 266
13.3.1. AI-driven analytics for urban decision-making 267
13.3.2. Edge and distributed intelligence in urban infrastructure 267

13.3.3. Signal and image processing for large-scale urban sensing 269
13.3.4. Digital twins for cognitive city modeling and simulation 270
13.4. Application domains of cognitive cities 271
13.4.1. Intelligent transportation and mobility 271
13.4.2. Energy systems and smart grids 271
13.4.3. Public safety and surveillance 272
13.4.4. Environmental monitoring and sustainability 272
13.4.5. Healthcare and emergency response 273
13.5. Technical challenges in cognitive city systems 274
13.5.1. Data heterogeneity and quality issues 275
13.5.2. Scalability of AI models at city scale 275
13.5.3. Real-time processing and reliability constraints 276
13.5.4. Integration with legacy infrastructure 276
13.6. Practical constraints and socio-technical concerns 277
13.6.1. Readiness to infrastructure and cost limits 277
13.6.2. Data governance, data privacy and data ethics 277
13.6.3. Institutional, policy and socioeconomic factors 278
13.6.4. Citizen acceptance and trust 279
13.7. Deployment-oriented case discussions 279
13.7.1. Pilot deployments in urban mobility and surveillance 279
13.7.2. Lessons learned from partial implementations 280
13.7.3. Challenges in scaling cognitive city solutions 280
13.8. Framework for real-world deployment of cognitive cities 281
13.8.1. Phased deployment strategy 281
13.8.2. Governance, feedback and continuous learning 282
13.8.3. Stakeholder and public–private partnerships 282
13.9. Future research directions and policy priorities 282
13.9.1. Emerging research directions 283
13.9.2. Policy and standardization needs 284
13.10. Conclusion 284
13.11. References 284

List of Authors 289

Index 295