

# **Metaverse**

## **Communication and Computing Networks**

**Applications, Technologies, and Approaches**

Edited by

Dinh Thai Hoang | Diep N. Nguyen  
Cong T. Nguyen | Ekram Hossain | Dusit Niyato

  
**IEEE PRESS**

**WILEY**



## **Metaverse Communication and Computing Networks**

**IEEE Press**  
445 Hoes Lane  
Piscataway, NJ 08854

**IEEE Press Editorial Board**  
Sarah Spurgeon, *Editor in Chief*

Jón Atli Benediktsson  
Anjan Bose  
James Duncan  
Amin Moeness  
Desineni Subbaram Naidu

Behzad Razavi  
Jim Lyke  
Hai Li  
Brian Johnson

Jeffrey Reed  
Diomidis Spinellis  
Adam Drobot  
Tom Robertazzi  
Ahmet Murat Tekalp

# **Metaverse Communication and Computing Networks**

Applications, Technologies, and Approaches

*Edited by*

*Dinh Thai Hoang*

University of Technology Sydney, Australia

*Diep N. Nguyen*

University of Technology Sydney, Australia

*Cong T. Nguyen*

Duy Tan University, Vietnam

*Ekram Hossain*

University of Manitoba, Canada

*Dusit Niyato*

Nanyang Technological University, Singapore



**IEEE PRESS**  
**WILEY**

Copyright © 2024 by The Institute of Electrical and Electronics Engineers, Inc.  
All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.  
Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at [www.copyright.com](http://www.copyright.com). Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permission>.

Trademarks: Wiley and the Wiley logo are trademarks or registered trademarks of John Wiley & Sons, Inc. and/or its affiliates in the United States and other countries and may not be used without written permission. All other trademarks are the property of their respective owners. John Wiley & Sons, Inc. is not associated with any product or vendor mentioned in this book.

*Limit of Liability/Disclaimer of Warranty*

While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Further, readers should be aware that websites listed in this work may have changed or disappeared between when this work was written and when it is read. Neither the publisher nor authors shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at [www.wiley.com](http://www.wiley.com).

***Library of Congress Cataloging-in-Publication Data applied for:***

Hardback ISBN: 9781394159987

Cover Design: Wiley

Cover Image: © Olga Siletskaya/Getty Images

Set in 9.5/12.5pt STIXTwoText by Straive, Chennai, India

*To my family*  
— *Dinh Thai Hoang*

*To my family*  
— *Diep N. Nguyen*

*To my family*  
— *Cong T. Nguyen*

*To my parents*  
— *Ekram Hossain*

*To my family*  
— *Dusit Niyato*

## Contents

<b>Editors' Biography</b>	<i>xvi</i>
<b>List of Contributors</b>	<i>xix</i>
<b>Preface</b>	<i>xxiv</i>
<b>Acknowledgments</b>	<i>xxv</i>
<b>Introduction</b>	<i>xxvi</i>

<b>1</b>	<b>Metaverse: An Introduction</b>	<b>1</b>
	<i>Lik-Hang Lee, Dimitris Chatzopoulos, Pengyuan Zhou, and Tristan Braud</i>	
1.1	Introduction	1
1.2	The Metaverse: Fantasy, Text, 3D Worlds	3
1.3	The Rise of Edge Computing	4
1.3.1	Offloading	4
1.3.2	Scale to Outdoor	5
1.4	Universality, Interoperability, and Openness	6
1.4.1	Using the World Wide Web as an Illustration	6
1.4.2	Realizing the Potential of Interoperability in the Metaverse	7
1.4.3	The Argument in Favor of Immersive Technologies	8
1.5	Steps Toward Mobile User Interaction Within the Metaverse	9
1.6	Bringing Users' Profiles and Assets on the Metaverse	10
1.6.1	The Role of Distributed Ledgers, Smart Contracts, and Decentralized Storage	11
1.7	Conclusions and Future Research Directions	12
	Bibliography	13
<b>2</b>	<b>Potential Applications and Benefits of Metaverse</b>	<b>17</b>
	<i>Mshari Aljumaie, Hieu Chi Nguyen, Nam H. Chu, Cong T. Nguyen, Diep N. Nguyen, Dinh Thai Hoang, and Eryk Dutkiewicz</i>	
2.1	Metaverse Applications for Entertainment	17
2.1.1	Introduction to Entertainment	17



2.1.2	Existing Entertainment Activities	18
2.1.3	Entertainment Activities in Metaverse	20
2.1.4	Challenges of Entertainment in the Metaverse	22
2.2	Virtual Office in Metaverse	22
2.2.1	Introduction to Virtual Office	22
2.2.2	Current Virtual Office Platforms Toward Metaverse	23
2.2.3	Benefits and Potential Use Cases of Metaverse Workplace	25
2.2.4	Challenges of Virtual Office in Metaverse	26
2.3	Education	27
2.3.1	The Development of Online Learning	27
2.3.2	Current Online Learning Platforms and Challenges	28
2.3.3	Education in Metaverse	29
2.3.4	Challenges of Education in Metaverse	30
2.4	Metaverse for Healthcare Services	31
2.5	Metaverse for Autonomous Vehicles	32
2.6	Metaverse for Virtual Travelling	33
2.7	Conclusions and Future Research Directions	34
	Bibliography	34
<b>3</b>	<b>Metaverse Prototype: A Case Study</b>	<b>39</b>
	<i>Haihan Duan and Wei Cai</i>	
3.1	Overview	39
3.1.1	Related Work	39
3.1.2	Motivation and Implementation	40
3.2	Newbie at CUHKSZ	42
3.2.1	Gameplay in <i>Newbie at CUHKSZ</i>	43
3.2.1.1	University Campus Exploration	43
3.2.1.2	School and Major Selection	44
3.2.1.3	The Sense of Social Good	45
3.2.2	Limitations and Iteration	46
3.3	CUHKSZ Metaverse	47
3.3.1	Three-Layer System Design	47
3.3.2	Campus Metaverse Prototype	49
3.3.2.1	Infrastructure Layer	49
3.3.2.2	Interaction Layer	50
3.3.2.3	Ecosystem Layer	55
3.4	Conclusions and Future Research Directions	59
	Acknowledgement	60
	Bibliography	61

<b>4</b>	<b>Wireless Technologies for the Metaverse</b>	<b>63</b>
	<i>Hongliang Zhang, Shiwen Mao, and Zhu Han</i>	
4.1	Introduction	63
4.2	XR over NR: Standardization in 3GPP	64
4.2.1	Selected XR Applications	65
4.2.2	Traffic Models	65
4.2.3	Major XR-Specific 3GPP KPIs	66
4.2.3.1	Capacity	66
4.2.3.2	Power Consumption	66
4.3	Case Study: Location-Dependent AR Services in the Wireless Edge-Enabled Metaverse	67
4.3.1	System Model	67
4.3.1.1	Uplink Phase	69
4.3.1.2	Downlink Phase	70
4.3.2	Problem Formulation	72
4.3.2.1	Impact of Estimation Error	73
4.3.2.2	QoE Model	74
4.3.2.3	Problem Statement	74
4.3.3	Algorithm Design	75
4.3.3.1	Waveform Design Algorithm for the Uplink Subproblem	75
4.3.3.2	Joint Resolution and Transmit Power Optimization Algorithm for the Downlink Subproblem	76
4.3.4	Simulation Results	77
4.3.4.1	Settings	77
4.3.4.2	Evaluation Results	79
4.4	Conclusions and Future Research Directions	81
	Acknowledgment	82
	Bibliography	82
<b>5</b>	<b>AI and Computer Vision Technologies for Metaverse</b>	<b>85</b>
	<i>Thien-Huynh The, Quoc-Viet Pham, Xuan-Quy Pham, Tan Do-Duy, and Thippa Reddy Gadekallu</i>	
5.1	Introduction	85
5.1.1	Main Contributions	86
5.1.2	Chapter Organization	87
5.2	AI for the Metaverse	87
5.2.1	Preliminary of AI	87
5.2.1.1	Conventional Techniques	87

5.2.1.2	Advanced Techniques	89
5.2.2	Roles of AI in the Metaverse	90
5.2.2.1	Data Processing	91
5.2.2.2	Data Management	92
5.2.2.3	Resource Management	93
5.2.2.4	Modeling	95
5.2.2.5	Neural Interface	96
5.2.3	AI for Metaverse Applications	97
5.2.3.1	Healthcare	97
5.2.3.2	Manufacturing	98
5.2.3.3	Smart Cities	99
5.2.3.4	Gaming	100
5.2.3.5	Others	101
5.3	Computer Vision for the Metaverse	101
5.3.1	Fundamental Computer Vision Tasks	103
5.3.1.1	Image Classification	103
5.3.1.2	Object Detection	104
5.3.1.3	Image Segmentation	105
5.3.1.4	Human Pose Estimation	107
5.3.1.5	Others	109
5.3.2	Computer Vision for Metaverse Applications	110
5.3.2.1	Autonomous Driving	110
5.3.2.2	Healthcare	111
5.3.2.3	Manufacturing	113
5.3.2.4	Others	114
5.4	Conclusions and Future Research Directions	115
	Bibliography	117
<b>6</b>	<b>Virtual/Augmented/Mixed Reality Technologies for Enabling Metaverse</b>	<b>125</b>
	<i>Howe Yuan Zhu and Chin-Teng Lin</i>	
6.1	Introduction	125
6.1.1	Into the Metaverse: Human Consciousness in a Virtual World	125
6.1.2	VR/AR/MR Challenges	127
6.2	Virtual Reality	129
6.2.1	Technology Overview	129
6.2.2	User Immersion	130
6.2.3	Metaverse Continuity	132
6.2.4	User Interaction	133
6.2.5	Summary	135
6.3	Augmented Reality	135

6.3.1	Technology Overview	135
6.3.2	User Immersion	136
6.3.3	Metaverse Continuity	137
6.3.4	User Interaction	138
6.3.5	Summary	139
6.4	Mixed Reality	139
6.4.1	Technology Overview	139
6.4.2	User Immersion	140
6.4.3	Metaverse Continuity	141
6.4.4	User Interaction	141
6.4.5	Summary	143
6.5	Conclusions and Future Research Directions	143
	Acknowledgments	144
	Bibliography	145

## **7 Blockchain for the Metaverse: State-of-the-Art and Applications** 157

*Pawan Kumar Hegde, Rajeswari Chengoden, Nancy Victor, Thien Huynh The, Sweta Bhattacharya, Praveen Kumar Reddy Maddikunta, Thippa Reddy Gadekallu, and Quoc-Viet Pham*

7.1	Introduction	157
7.2	Background	161
7.2.1	Blockchain	161
7.2.2	Blockchain-Based Solutions for the Metaverse	164
7.3	Use Cases of Blockchain for the Metaverse	167
7.3.1	Privacy	168
7.3.2	Security	169
7.3.3	Traceability	170
7.3.4	Decentralization	170
7.3.5	Ownership	171
7.3.6	Governance	172
7.3.7	Trust and Accountability	173
7.4	Projects	174
7.4.1	Axie Infinity	174
7.4.2	Decentraland MANA	174
7.4.3	The Sandbox (SAND)	175
7.4.4	Enjin (ENJ)	176
7.5	Conclusions and Future Research Directions	176
	Bibliography	177

<b>8</b>	<b>Edge Computing Technologies for Metaverse</b>	<b>183</b>
	<i>Minrui Xu and Dusit Niyato</i>	
8.1	An Overview of Edge-enabled Metaverse	184
8.1.1	Communication and Networking	185
8.1.1.1	Rate-Reliability-Latency 3D Multimedia Networks	186
8.1.1.2	Human-in-the-loop Communication	187
8.1.1.3	Real-time Physical-Virtual Synchronization	187
8.1.2	Computation at the Edge	188
8.1.2.1	Efficient AR/VR Cloud-Edge-End Rendering	189
8.1.2.2	Scalable AI Model Training	190
8.1.2.3	Computational Privacy and Security	190
8.2	Opportunities and Challenges in the Edge-enabled Metaverse	191
8.2.1	Opportunities and Challenges in Edge Communication	191
8.2.2	Opportunities and Challenges in Edge Computing	192
8.3	Edge-Enabled Metaverse: Release the Ubiquitous Computing and Intelligence at the Edge	194
8.3.1	VR Remote Rendering via Edge Computing Technologies	194
8.3.1.1	Background	194
8.3.1.2	Motivation	194
8.3.1.3	Contribution	195
8.3.2	Edge-Enabled Physical-Virtual Synchronization	196
8.3.2.1	Background	196
8.3.2.2	Motivation	197
8.3.2.3	Contribution	198
8.4	Conclusions and Future Research Directions	199
	Bibliography	200
<b>9</b>	<b>Security Issues in Metaverse</b>	<b>205</b>
	<i>Yuntao Wang, Zhou Su, Ning Zhang, Dongxiao Liu, Rui Xing, Tom H. Luan, and Xuemin Shen</i>	
9.1	Overview of Security and Privacy Threats in Metaverse	205
9.2	Threats and Countermeasures to Authentication and Access Control in Metaverse	207
9.2.1	Threats to Authentication in Metaverse	207
9.2.2	Threats to Access Control in Metaverse	208
9.2.3	Security Countermeasures to Metaverse Authentication and Access Control	209
9.2.3.1	Key Management for Wearable Devices	210
9.2.3.2	Identity Authentication for Wearable Devices	210
9.2.3.3	Cross-Domain Identity Authentication	211

- 9.2.3.4 Fine-Grained Access Control and Usage Audit for Wearables and UGCs 211
- 9.3 Threats and Countermeasures to Data Management in Metaverse 212
  - 9.3.1 Threats to Data Management in Metaverse 212
  - 9.3.2 Security Countermeasures to Metaverse Data Management 213
    - 9.3.2.1 Data Reliability of AIGC, Digital Twin, and Physical Input 214
    - 9.3.2.2 Data Quality of UGC and Physical Input 215
    - 9.3.2.3 Secure Data Sharing in XR Environment 215
    - 9.3.2.4 Provenance of UGC 216
  - 9.4 Privacy Threats and Countermeasures in Metaverse 216
    - 9.4.1 Privacy Threats in Metaverse 216
    - 9.4.2 Privacy Countermeasures in Metaverse 219
      - 9.4.2.1 Privacy in Metaverse Games 219
      - 9.4.2.2 Privacy-Preserving UGC Sharing and Processing 219
      - 9.4.2.3 Confidentiality Protection of UGC and Physical Input 220
      - 9.4.2.4 Digital Footprints Protection 220
      - 9.4.2.5 Personalized Privacy-Preserving Metaverse 220
      - 9.4.2.6 Privacy-Enhancing Advances in Industry 221
  - 9.5 Network-Related Threats and Countermeasures in Metaverse 222
    - 9.5.1 Threats to Metaverse Network 222
    - 9.5.2 Situational Awareness in Metaverse 222
      - 9.5.2.1 Local Situational Awareness 223
      - 9.5.2.2 Global Situational Awareness 224
  - 9.6 Economy-Related Threats and Countermeasures in Metaverse 225
    - 9.6.1 Threats to Metaverse Economy 225
    - 9.6.2 Open and Decentralized Creator Economy 226
      - 9.6.2.1 Trusted UGC/Asset/Resource Trading 226
      - 9.6.2.2 Economic Fairness for Manipulation Prevention 227
      - 9.6.2.3 Ownership Traceability of Digital Assets 227
  - 9.7 Threats to Physical World and Human Society and Countermeasures in Metaverse 228
    - 9.7.1 Threats to Physical World and Human Society 228
    - 9.7.2 Physical Safety 229
      - 9.7.2.1 Cyber Insurance-Based Solutions 229
      - 9.7.2.2 CPSS-Based Solutions 229
    - 9.7.3 Society Management 229
      - 9.7.3.1 Misinformation Spreading Mitigation 229
      - 9.7.3.2 Human Safety and Cyber Syndromes 230
  - 9.8 Governance-Related Threats and Countermeasures in Metaverse 230
    - 9.8.1 Threats to Metaverse Governance 230
    - 9.8.2 Digital Governance in Metaverse 231

9.8.2.1	AI Governance	231
9.8.2.2	Decentralized Governance	232
9.9	Conclusions and Future Research Directions	232
	Bibliography	233
<b>10</b>	<b>IoT-Assisted Metaverse Services</b>	<b>241</b>
	<i>Yue Han, Cyril Leung, and Dong In Kim</i>	
10.1	Why Need IoT for Metaverse Services	241
10.1.1	Metaverse and Virtual Services	241
10.1.1.1	Augmenting an Individual's Experience	242
10.1.1.2	Augmenting Industry Services or Operations	242
10.1.2	Digital Twins	243
10.1.2.1	Definition of DTs	244
10.1.2.2	Difference Between Metaverse and DTs	244
10.1.2.3	Position of IoT in Metaverse DT Construction	245
10.2	How to Use IoT for Metaverse DTs	246
10.2.1	Mobile Crowdsensing	246
10.2.2	Scenarios	247
10.2.3	Challenges of Using IoT-Enabled MCS for Metaverse DTs	247
10.2.3.1	Incentives	248
10.2.3.2	Data Quality	248
10.2.3.3	Resource Management	248
10.2.3.4	DT Value for the Virtual Business	248
10.2.3.5	VSPs' Tolerance to Nonupdated DTs	248
10.2.3.6	Decision Sequence Among VSPs in the Metaverse Ecosystem	249
10.3	A Dynamical Hierarchical Game-Theoretical Approach for IoT-Assisted Metaverse Synchronization	249
10.3.1	Lower-Level Evolutionary Game	252
10.3.2	Upper-Level Differential Game for VSPs	253
10.3.2.1	Simultaneous Decision-Making Setting	253
10.3.2.2	Open-Loop Nash Solutions	255
10.3.2.3	Hierarchical Decision-Making Setting	257
10.3.3	Simulation Results	259
10.4	Conclusions and Future Research Directions	260
	Bibliography	262
<b>11</b>	<b>Quantum Technologies for the Metaverse: Opportunities and Challenges</b>	<b>267</b>
	<i>Mahdi Chehimi and Walid Saad</i>	
11.1	Introduction	267
11.2	Preliminaries	270

11.3	Quantum Computing for a Faster Metaverse	274
11.3.1	Quantum Computing Speedups	274
11.3.2	Quantum Computing for Low Latency	275
11.3.3	Quantum Computing for Synchronized DTs	275
11.3.4	Quantum Computing for Responsive XR	275
11.3.5	Challenges for Quantum Computing in the Metaverse	276
11.4	Quantum Machine Learning for Contextual Metaverse	277
11.4.1	The Power of QML Models	277
11.4.2	QML for Semantics' Extraction	278
11.4.3	QML for Quantum Conversational AI	279
11.4.4	Quantum Federated Learning in the Metaverse	279
11.4.5	Challenges Facing QML in the Metaverse	280
11.5	Quantum Communications for Secure Metaverse	281
11.5.1	Quantum-Enhanced Security	281
11.5.2	Quantum-Secured XR and DTs	282
11.5.3	Quantum-Enhanced Throughput	283
11.5.4	Quantum Cloud Service	283
11.5.5	Challenges Facing Quantum Communications in the Metaverse	284
11.6	Conclusions and Future Research Directions	285
	Bibliography	286

## **12 The Metaverse with Life and Everything: An Overview of Privacy, Ethics, and Governance**

*Lik-Hang Lee, Carlos Bermejo, and Pan Hui*

12.1	Introduction	293
12.2	Privacy and Security	295
12.2.1	Confidentiality with Regard to the Senses	295
12.2.2	Protection of One's Actions and Conversations in Private	296
12.2.3	The Protection of Participants and Bystanders	297
12.2.4	Open Challenges	298
12.3	Governance	299
12.3.1	Statutes and Regulations	299
12.3.2	Distributed Ledger Technology (DLT) and Decentralized Autonomous Organizations (DAO)	300
12.3.3	Ethical Governance Based on Modules	300
12.3.4	The Role of Online Platforms in Contributing to the Common Good	301
12.3.5	Open Challenges	301
12.4	Creation, Social Good, and Ethical Design	302
12.4.1	The Beginning of Everything in the Metaverse	302
12.4.2	The Online Community Space	304



12.4.3	Ethical Structure with Modular Designs	305
12.5	Conclusions and Future Research Directions	308
	Bibliography	308
	<b>Index</b>	<b>311</b>

## Editors' Biography

**Dinh Thai Hoang** received his PhD degree from the School of Computer Science and Engineering, Nanyang Technological University, Singapore, in 2016. He is currently a faculty member at the University of Technology Sydney (UTS), Australia. Over the past 10 years, he has significantly contributed to advanced wireless communications and networking systems. This is evidenced by his excellent record with one patent filed by Apple Inc., two authored books, one edited book, four book chapters, more than 80 IEEE Q1 journals, and 60 flagship IEEE conference papers in the areas of communications and networking. Most of his journal papers have been published in top IEEE journals, including IEEE JSAC, IEEE TWC, IEEE COMST, and IEEE TCOM. Furthermore, his research papers have had a high impact, as evidenced by nearly 14,000 citations with an h-index of 44 (according to Google Scholar) over the past 10 years. Since joining UTS in 2018, he has received more than AUD 3 million in external funding and several precious awards, including the Australian Research Council Discovery Early Career Researcher Award for his project “Intelligent Backscatter Communications for Green and Secure IoT Networks” and IEEE TCSC Award for Excellence in Scalable Computing for Contributions on “Intelligent Mobile Edge Computing Systems” (Early Career Researcher). Alternatively, he is the lead author of two authored books, “*Ambient Backscatter Communication Networks*,” published by Cambridge Publisher in 2020 and “*Deep Reinforcement Learning for Wireless Communications and Networking*,” published by IEEE-Wiley Publisher in 2022. He is currently an Editor of IEEE TMC, IEEE TWC, IEEE TCCN, IEEE TVT, and IEEE COMST.

**Diep N. Nguyen** is a faculty member of the Faculty of Engineering and Information Technology, University of Technology Sydney (UTS). He received ME and PhD in Electrical and Computer Engineering from the University of California San Diego (UCSD) and the University of Arizona (UA), respectively. Before joining UTS, he was a DECRA Research Fellow at Macquarie University,

a member of technical staff at Broadcom (California), ARCON Corporation (Boston), consulting the Federal Administration of Aviation on turning detection of UAVs and aircraft, US Air Force Research Lab on anti-jamming. He has received several awards from LG Electronics, the University of California San Diego, the University of Arizona, US National Science Foundation, and Australian Research Council, including nominations for the outstanding RA (2013) awards, the best paper award at the WiOpt conference (2014), Discovery Early Career Researcher Award (DECRA, 2015), and outstanding Early Career Researcher award (SEDE, University of Technology Sydney, 2018). His recent research interests are in the areas of computer networking, wireless communications, and machine learning application, with an emphasis on systems' performance and security/privacy. Dr. Nguyen is a senior member of IEEE and an editor/associate editor of the *IEEE Transactions on Mobile Computing*, *IEEE Access*, *Sensors* journal, and *IEEE Open Journal of the Communications Society* (OJ-COMS).

**Cong T. Nguyen** received his BE degree in Electrical Engineering and Information Technology from Frankfurt University of Applied Sciences in 2014, his MSc in Global Production Engineering and Management from the Technical University Berlin in 2016, and his PhD in Information Technology from University of Technology Sydney in 2023. He is currently with Duy Tan University, Vietnam. His research interests include blockchain technology, operation research, game theory, and optimization.

**Ekram Hossain** is a professor and an associate head (Graduate Studies) at the Department of Electrical and Computer Engineering, University of Manitoba, Canada. He is a member (Class of 2016) of the College of the Royal Society of Canada. His current research interests include design, analysis, and optimization of 6G cellular wireless networks. He was listed as a Clarivate Analytics Highly Cited Researcher in Computer Science for six years in a row from 2017 to 2022. He received the 2017 IEEE ComSoc Technical Committee on Green Communications and Computing Distinguished Technical Achievement Recognition Award "for outstanding technical leadership and achievement in green wireless communications and networking." He has won several research awards, including the 2017 IEEE Communications Society Best Survey Paper Award and the 2011 IEEE Communications Society Fred Ellersick Prize Paper Award. He served as the editor-in-chief for the IEEE Communications Surveys and Tutorials from 2012 to 2016 and the editor-in-chief for IEEE Press. He was a distinguished lecturer of the IEEE Communications Society and the IEEE Vehicular Technology Society. He was an elected member of the board of governors of the IEEE Communications Society for the term from 2018 to 2020. He was elevated to an IEEE fellow "for contributions to spectrum management and resource allocation in cognitive and

cellular radio networks.” He is a fellow of the Canadian Academy of Engineering and a fellow of the Engineering Institute of Canada.

**Dusit Niyato** is a professor at the School of Computer Science and Engineering, Nanyang Technological University, Singapore. He received BE from King Mongkut’s Institute of Technology Ladkrabang (KMITL), Thailand, in 1999 and a PhD in Electrical and Computer Engineering from the University of Manitoba, Canada, in 2008. Dusit’s research interests are in the areas of distributed collaborative machine learning, the Internet of Things (IoT), edge intelligent metaverse, mobile and distributed computing, and wireless networks. Dusit won the Best Young Researcher Award of IEEE Communications Society (ComSoc) Asia Pacific and the 2011 IEEE Communications Society Fred W. Ellersick Prize Paper Award and the IEEE Computer Society Middle Career Researcher Award for Excellence in Scalable Computing in 2021 and Distinguished Technical Achievement Recognition Award of IEEE ComSoc Technical Committee on Green Communications and Computing 2022. Dusit also won a number of best paper awards, including IEEE Wireless Communications and Networking Conference (WCNC), IEEE International Conference on Communications (ICC), IEEE ComSoc Communication Systems Integration and Modelling Technical Committee, and IEEE ComSoc Signal Processing and Computing for Communications Technical Committee 2021. Currently, Dusit is serving as editor-in-chief of IEEE Communications Surveys and Tutorials, an area editor of IEEE Transactions on Vehicular Technology, editor of IEEE Transactions on Wireless Communications, associate editor of IEEE Internet of Things Journal, IEEE Transactions on Mobile Computing, IEEE Wireless Communications, IEEE Network, and ACM Computing Surveys. He was a guest editor of the IEEE Journal on Selected Areas on Communications. He was a distinguished lecturer of the IEEE Communications Society for 2016–2017. He was named the 2017–2021 highly cited researcher in computer science. He is a fellow of IEEE and a fellow of IET.

## List of Contributors

### ***Mshari Aljumaie***

School of Electrical and Data  
Engineering  
University of Technology Sydney  
Ultimo, NSW  
Australia

and

Department of Information  
Technology  
Taif University  
Taif  
Saudi Arabia

### ***Carlos Bermejo***

Department of Computer Science and  
Engineering, School of Engineering  
The Hong Kong University of Science  
and Technology  
Hong Kong SAR  
China

### ***Sweta Bhattacharya***

School of Information Technology and  
Engineering  
Vellore Institute of Technology  
Tamil Nadu  
India

### ***Tristan Braud***

Division of Integrative Systems and  
Design  
Hong Kong University of Science and  
Technology  
Hong Kong SAR  
China

### ***Wei Cai***

School of Science and Engineering  
The Chinese University of Hong Kong  
Shenzhen, Shenzhen  
China

### ***Dimitris Chatzopoulos***

School of Computer Science  
University College Dublin  
Dublin  
Ireland

### ***Mahdi Chehimi***

Wireless@VT  
Bradley Department of Electrical and  
Computer Engineering, Virginia Tech  
Arlington, VA  
USA

**Rajeswari Chengoden**

School of Information Technology and  
Engineering  
Vellore Institute of Technology  
Tamil Nadu  
India

**Hieu Chi Nguyen**

School of Electrical and Data  
Engineering  
University of Technology Sydney  
Ultimo, NSW  
Australia

**Nam H. Chu**

School of Electrical and Data  
Engineering  
University of Technology Sydney  
Ultimo, NSW  
Australia

**Tan Do-Duy**

Department of Computer and  
Communication Engineering  
Ho Chi Minh City University of  
Technology and Education  
Ho Chi Minh City  
Vietnam

**Haihan Duan**

School of Science and Engineering  
The Chinese University of Hong Kong  
Shenzhen, Shenzhen  
China

**Eryk Dutkiewicz**

School of Electrical and Data  
Engineering  
University of Technology Sydney  
Ultimo, NSW  
Australia

**Thippa Reddy Gadekallu**

School of Information Technology and  
Engineering  
Vellore Institute of Technology  
Tamil Nadu  
India

and

Department of Electrical and  
Computer Engineering  
Lebanese American University  
Byblos  
Lebanon

**Zhu Han**

Department of Electrical and  
Computer Engineering  
University of Houston  
Houston, TX  
USA

**Yue Han**

Alibaba-NTU Singapore Joint  
Research Institute  
Nanyang Technological University  
Singapore

**Pawan Kumar Hegde**

School of Information Technology and  
Engineering  
Vellore Institute of Technology  
Tamil Nadu  
India

**Dinh Thai Hoang**

School of Electrical and Data  
Engineering  
University of Technology Sydney  
Ultimo, NSW  
Australia

***Pan Hui***

Department of Computer Science and  
Engineering, School of Engineering  
The Hong Kong University of Science  
and Technology  
Hong Kong SAR  
China

***Dong In Kim***

Department of Electrical and  
Computer Engineering  
Sungkyunkwan University  
Suwon, Gyeonggi-do  
Korea

***Cyril Leung***

Department of Electrical and  
Computer Engineering  
University of British Columbia  
Vancouver, BC  
Canada

***Lik-Hang Lee***

Department of Industrial and Systems  
Engineering (ISE)  
The Hong Kong Polytechnic University  
Hong Kong SAR  
China

***Chin-Teng Lin***

Computational Intelligence and  
Brain-Computer Interface,  
Australian Artificial Intelligence  
Institute  
University of Technology Sydney  
Ultimo, NSW  
Australia

***Dongxiao Liu***

Department of Electrical and  
Computer Engineering  
University of Waterloo  
Waterloo, ON  
Canada

***Tom H. Luan***

School of Cyber Science and  
Engineering  
Xi'an Jiaotong University  
Xi'an, Shaanxi  
China

***Praveen Kumar Reddy Maddikunta***

School of Information Technology and  
Engineering  
Vellore Institute of Technology  
Tamil Nadu  
India

***Shiwen Mao***

Department of Electrical and  
Computer Engineering  
Auburn University  
Auburn, AL  
USA

***Dusit Niyato***

School of Computer Science and  
Engineering  
Nanyang Technological University  
Singapore

***Cong T. Nguyen***

School of Electrical and Data  
Engineering  
University of Technology Sydney  
Ultimo, NSW  
Australia

**Diep N. Nguyen**

School of Electrical and Data  
Engineering  
University of Technology Sydney  
Ultimo, NSW  
Australia

**Quoc-Viet Pham**

School of Computer Science and  
Statistics  
Trinity College Dublin  
Dublin  
Ireland

**Xuan-Qui Pham**

ICT Convergence Research Center  
Kumoh National Institute of  
Technology  
Gumi  
Korea

**Walid Saad**

Wireless@VT  
Bradley Department of Electrical and  
Computer Engineering, Virginia Tech  
Arlington, VA  
USA

**Xuemin Shen**

Department of Electrical and  
Computer Engineering  
University of Waterloo  
Waterloo, ON  
Canada

**Zhou Su**

School of Cyber Science and  
Engineering  
Xi'an Jiaotong University  
Xi'an, Shaanxi  
China

**Thien-Huyh The**

Department of Computer and  
Communication Engineering  
Ho Chi Minh City University of  
Technology and Education  
Ho Chi Minh City  
Vietnam

**Nancy Victor**

School of Information Technology and  
Engineering  
Vellore Institute of Technology  
Tamil Nadu  
India

**Yuntao Wang**

School of Cyber Science and  
Engineering  
Xi'an Jiaotong University  
Xi'an, Shaanxi  
China

**Rui Xing**

School of Cyber Science and  
Engineering  
Xi'an Jiaotong University  
Xi'an, Shaanxi  
China

**Minrui Xu**

School of Computer Science and  
Engineering  
Nanyang Technological University  
Singapore

**Hongliang Zhang**

School of Electronics  
Peking University  
Beijing  
China



***Ning Zhang***

Department of Electrical and  
Computer Engineering  
University of Windsor  
Windsor, ON  
Canada

***Pengyuan Zhou***

School of Cyber Science and  
Technology  
University of Science and Technology  
of China  
Hefei  
China

***Howe Yuan Zhu***

Computational Intelligence and  
Brain-Computer Interface  
Australian Artificial Intelligence  
Institute  
University of Technology Sydney  
Ultimo, NSW  
Australia

## Preface

Recently, Metaverse has gained paramount interest and huge investment from the tech industry. Microsoft acquired Activision Blizzard for \$70 billion in 2022 to set its first footsteps in the Metaverse game development race. Along with its huge investment in AR, one of the core technologies of Metaverse, Google has invested \$39.5 million in a private equity fund for all Metaverse projects. Nvidia has created Omniverse, a developing tool for Metaverse applications. Besides huge investments from big tech companies, the economic activities of virtual worlds are also significant, with transactions that exceed the magnitude of millions of dollars. As a result, there is no doubt that the Metaverse will become one of the most prominent directions of development in both industry and academia. However, the development of the Metaverse, especially in academia, is still in a nascent stage. Currently, researchers are striving to judge the shape and boundary of the future Metaverse. They are only able to envision some of its possible characteristics, such as open space, decentralization, human–computer interaction experience, digital assets, and digital economy. Moreover, Metaverse applications are expected to face various challenges such as massive resource demands, ultralow latency requirements, interoperability among applications, and security and privacy concerns. Given the above, this book aims to provide a comprehensive overview of Metaverse and discuss its enabling technologies and how these technologies can be utilized to develop Metaverse applications.

Sydney, Australia

*Dinh Thai Hoang*

*Diep N. Nguyen*

*Cong T. Nguyen*

*Ekram Hossain*

*Dusit Niyato*

## Acknowledgments

The contribution made by Dr. Dinh Thai Hoang was supported in part by the Australian Research Council's Discovery Projects funding scheme (project DE210100651).

The contribution done by Prof. Dusit Niyato was supported in part by the National Research Foundation (NRF), Singapore, and Infocomm Media Development Authority under the Future Communications Research Development Programme (FCP); DSO National Laboratories under the AI Singapore Programme (AISG Award No: AISG2-RP-2020-019); and under DesCartes and the Campus for Research Excellence and Technological Enterprise (CREATE) programme.

## Introduction

*Edited by:* Dinh Thai Hoang, Diep N. Nguyen, Cong T. Nguyen, Ekram Hossain, and Dusit Niyato

The term “Metaverse” refers to next-generation Internet applications that aim to create virtual 3D environments where humans can interact with each other and the applications’ functionalities via digital avatars. Although the original concept dates back to 1992, Metaverse has recently attracted paramount attention due to the huge potential to rival, or even replace, conventional Internet applications in the near future.

However, the development of the Metaverse, especially in academia, is still in a nascent stage. Currently, researchers are striving to judge the shape and boundary of the future Metaverse. They can only envision some of its possible characteristics, such as open space, decentralization, human–computer interaction experience, digital assets, and digital economy. Moreover, Metaverse applications are expected to face various challenges, such as massive resource demands, ultralow latency requirements, application interoperability, and security and privacy concerns.

Given the above, this book aims first to introduce the emerging paradigm of Metaverse, which is expected to pave the way for the evolution of the future Internet. The book also provides a comprehensive review of the state-of-the-art research and development covering different aspects of Metaverse for a wide range of readers, from general readers to experts. Advanced knowledge including innovative models, techniques, and approaches to overcome the limitations and challenges in developing Metaverse are then discussed. Finally, emerging applications of Metaverse are presented, along with the related challenges and open issues.

# 1

## Metaverse: An Introduction

Lik-Hang Lee<sup>1</sup>, Dimitris Chatzopoulos<sup>2</sup>, Pengyuan Zhou<sup>3</sup>, and  
Tristan Braud<sup>4#</sup>

<sup>1</sup>Department of Industrial and Systems Engineering (ISE), The Hong Kong Polytechnic University, Hong Kong SAR, China

<sup>2</sup>School of Computer Science, University College Dublin, Dublin, Ireland

<sup>3</sup>School of Cyber Science and Technology, University of Science and Technology of China, Hefei, China

<sup>4</sup>Division of Integrative Systems and Design, Hong Kong University of Science and Technology, Hong Kong SAR, China

After reading this chapter you should be able to:

- 
- Understand the current trends and challenges that building such a virtual environment will face.
  - Focus on three major pillars to guide the development of the Metaverse: privacy, governance, and ethical design and to guide the sustainable yet acceptable development of the Metaverse.
  - Illustrate a preliminary modular-based framework for an ethical design of the Metaverse.
- 

### 1.1 Introduction

The term “Metaverse” was first introduced to the public in 1992 by Neal Stephenson in his work of science fiction, “Snow Crash.” The main characters of the book are shown to coexist with their avatars in a world that is an integration of the virtual and the real, and it is populated by persistent virtual entities that are superimposed on our actual surroundings. People are able to execute a wide variety of immersive activities in this integrated reality.

# All authors equally contributed to this chapter.

*Metaverse Communication and Computing Networks: Applications, Technologies, and Approaches*, First Edition. Edited by Dinh Thai Hoang, Diep N. Nguyen, Cong T. Nguyen, Ekram Hossain, and Dusit Niyato.

© 2024 The Institute of Electrical and Electronics Engineers, Inc. Published 2024 by John Wiley & Sons, Inc.

Several noticeable instances of this trend include people getting together with their friends in a different location, working jointly with their coworkers, and participating in shared virtual experiences (e.g. dating and virtual fitting). In other words, diverse digital or virtual contents originating from cyberspace will eventually go beyond the boundary of 2D displays in the Internet that we are now using and gradually make their way into three-dimensional (3D) settings.

As was said before, coincidentally, the projected environment is congruent with Mark Weiser's vision of ubiquitous computing in 1991: computer services would be integrated into a multitude of facets of our lives, and users will have access to virtual information whenever and wherever they choose. With such a compelling vision, the landscape of ubiquitous computing has been advanced throughout the course of the previous three decades by the proliferation of computing devices. These computing devices include laptop computers, smartphones, the Internet of Things (IoTs), and intelligent wearables.

According to Milgram and Kishino's Reality-Virtuality Continuum [16], the current cyberspace has undergone significant development in recent years, and recent attempts have been made to provide human users with services and digital experiences by means of virtual environments such as augmented reality (AR) and virtual reality (VR). Although no one can say for certain what the Metaverse will bring about once it is fully realized, recent pre-metaverse apps have most likely identified AR and VR on smartphones as the major testbed for immersive user experiences. Pokémon Go, for example, has become the most popular AR program on ubiquitous smartphones, astoundingly with 1 billion downloads, while Google Cardboard is bringing VR content to mainstream audiences (for example, YouTube VR) [4].

As such, the term "Metaverse" refers to a blended space at the intersection between physical and digital in which multiple users can concurrently interact with a persistent and unified computer-generated environment, and other users. This space has the potential to become the next important milestone in the development of cyberspace as it exists today.

It is worth noting that modern devices that enable entrance to Metaverse get access to multiple types of users' data. Also services based on artificial intelligence (AI) use derivatives of data generated by users in their function, making data the new commodity that spawns a lucrative, fast-growing industry.

This introductory chapter focuses primarily on discussing the evolution of the Metaverse as well as the difficulties that have been encountered. First, we will provide a concise overview of the evolution of cyberspace as well as the importance of technological enablers. As a result, our bottom-up methodology places an emphasis on the following three crucial technological enablers for the Metaverse: networks, systems, and users. In addition, we emphasize a number of essential challenges, both from a technical and an ecosystemic point of view, that are necessary for the construction and maintenance of the Metaverse.