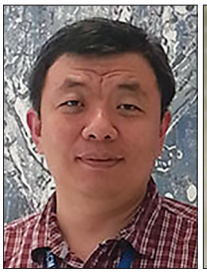
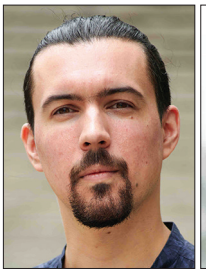
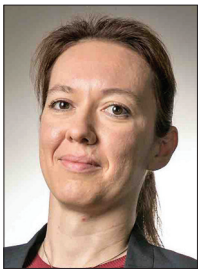
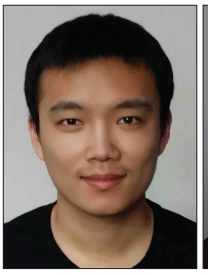
Networking Challenges and Opportunities for Multi-user XR and the Metaverse


Bo Han


Tristan Braud


Mario Di Francesco


Maria Gorlatova


Luyang Liu


Gábor Sörös


Pengyuan Zhou

Immersive technologies, such as virtual, augmented, and mixed reality (VR, AR, and MR), which are often referred to as a universal term - extended reality (XR), have enabled numerous appealing applications in education, training, entertainment, healthcare, etc. While recent research on immersive computing and communication has focused mainly on improving the quality of experience for single-user scenarios, the emerging applications enabled by XR, especially the burgeoning Metaverse, naturally involve multiple geographically distributed users.

Although there is still no commonly agreed definition, a narrow illustration of the Metaverse is a utopian convergence of various virtual environments, by connecting them via the Internet to facilitate social interaction among users. Thus, social VR platforms, such as Meta's Horizon Worlds and Microsoft's AltspaceVR, have been deemed as the early prototypes of the Metaverse. Besides social VR, the industry has been heavily investing in multi-user XR/Metaverse for creating novel hardware, software, and content. For example, the Metaverse Standards Forum was formed in 2022 with members including tech giants such as Google, Meta, Microsoft, and Nvidia. Other existing standards organizations such as the World Wide Web Consortium (W3C) and the European Telecommunications Standards Institute (ETSI) have created working groups for XR.

However, there is still limited research on understanding the technical challenges and opportunities for boosting the performance of multi-user XR and the Metaverse by leveraging recent advances in deep learning, edge computing, 5G, etc. For example, there is no software framework with commonly used building blocks for designing and implementing multi-user XR systems, and there is a lack of widely acceptable tools, datasets, and testbeds for building and evaluating multi-user XR applications.

Moreover, given its interdisciplinary nature, XR has been extensively investigated in computer graphics, computer vision, and human-computer interaction communities. Nonetheless, multi-user XR and the Metaverse put more strain on the underlying networks to deliver high-quality immersive content in real time and guarantee a satisfactory user experience, which is still underexplored in the networking community.

This Special Issue (SI) is motivated by the above-mentioned issues, and its goal is to bring together researchers, engineers, practitioners, mobile device manufacturers, use case owners, content creators, and policymakers from academia, industry, and government to discuss the latest research and identify future opportunities for multi-user XR and the Metaverse. To inspire more fundamental research for this promising field, we seek high-quality original research, novel developments that promote innovations, or review articles to advance multi-user XR and the Metaverse. The submission should be comprehensible to all readers of the magazine regardless of their specialty.

We received 16 high-quality submissions, of which five articles were eventually accepted after a rigorous review process. These articles cover several different aspects of multi-user XR and the Metaverse. In the first article, "Design Frameworks for Hyper-Connected Social XRI Immersive Metaverse Environments," the authors from OCAD University present the concept and design of a social XR-IoT (XRI) framework in the Metaverse, which enables social interaction between the physical and virtual worlds. They consider the Metaverse as a hyper-connected meta-environment for multiple users and propose a design architecture for multi-user social interactions.

The article, "Standardization of Extended Reality (XR) over 5G and 5G-Advanced 3GPP New Radio," discusses integrating support for XR into the 3GPP new radio standard. After presenting a classification of XR use cases in three meta-categories, the authors discuss the 3GPP traffic models and KPIs for the selected XR services. The article follows with a simulation of XR services over the latest 3GPP NR standard (release 17), which finally leads the authors to propose recommendations towards future 5G standards and beyond.

In the next article, "Towards 6G-based Metaverse: Supporting Highly-Dynamic Deterministic Multi-User Extended Reality Services," the authors from Oulu University, Futurewei Technologies, and Sejong University focus on the challenges of satisfying quality of experience/quality of service (QoE/QoS) of multiple users simultaneously. They present a comprehensive system

and component design for immersive and seamless multi-user XR experiences, integrated with an AI-powered deterministic multi-user extended reality orchestrator for the deterministic service provisioning of multi-user XR applications.

The fourth article, "Look-Ahead Task Offloading for Multi-User Mobile Augmented Reality in Edge-Cloud Computing," investigates the migration overhead and scalability of task offloading for augmented reality in a multi-user setting of an edge-cloud collaborative computing system. It first analyzes the task interdependency of multi-user AR services and models it with directed acyclic graphs. It then presents a task-offloading scheme that benefits from a modified Monte Carlo tree search for estimating the long-term effect of immediate action. Finally, it evaluates the effectiveness of the proposed scheme and compares it with four benchmarks.

In the last article, "FikoRE: 5G and Beyond RAN Emulator for Application Level Experimentation and Prototyping," the authors from Nokia XR Lab and Universidad Carlos III de Madrid present an open-source real-time emulator for radio access networks, named FikoRE, with the goal of boosting the development of novel use cases for XR and the Metaverse. FikoRE allows multidisciplinary users to handle actual real-time IP traffic over 1 Gbps from multiple sources, which is typically needed for evaluating the performance of multi-user XR applications.

In conclusion, the articles presented in this special issue demonstrate the networking challenges and opportunities for multi-user XR and the Metaverse. We extend our gratitude to the authors for sharing their pioneering research and to the reviewers for their diligent contributions in delivering punctual and enriching assessments that have notably elevated the articles' quality. Moreover, our appreciation extends to Dr. Chonggang Wang, the Editor-in-Chief, and the dedicated IEEE Network team for affording us this platform and offering invaluable assistance throughout the production of this special issue. Ultimately, we genuinely trust that readers will derive fascination and utility from the articles featured in this special issue.

Biographies

Bo Han (bohan@gmu.edu) received his Ph.D. degree in Computer Science from the University of Maryland. He is an Associate Professor of the Department of Computer Science at George Mason University. Before that, he was a Principal Inventive Scientist at AT&T Labs-Research. His research interests are in the areas of networked systems, mobile computing, and wireless networking. His research recently focuses on immersive video streaming, augmented, virtual, and mixed reality, and their applications in various domains, such as education, training, healthcare, data visualization and analytics, and digital twins. He received the best paper award from ACM CoNEXT 2016 and the DASH-IF Excellence Award from ACM MMSys 2019. He serves on the editorial board of *IEEE Network* and is the co-founder of the ACM SIGCOMM Workshop on 5G Measurements, Modeling, and Use Cases (5G-MeMU) and ACM MobiCom Workshop on Mobile Immersive Computing,

Tristan Braud is an Assistant Professor at the Hong Kong University of Science and Technology. He studied communication systems engineering at Grenoble INP Phelma/Ensimag, France, and received a dual Masters degree from the Politecnico di Torino, Italy, and Grenoble INP, France. He followed with a Ph.D. in Computer Science at the Universite Grenoble Alpes, France before joining the Hong Kong University of Science and Technology. His primary research foci are augmented and virtual reality, with interests in pervasive and cloud computing as well as human-centered system designs.

Mario Di Francesco received his Ph.D. degree in information engineering from the University of Pisa, Italy, in 2009. He is a Full Professor at the Department of Computer Science, Aalto University, Finland. His current research interests include the IoT, pervasive computing, mobile networking, and performance evaluation. He was a recipient of the Best Paper Award at the UbiComp Conference, in 2014, and at the International Conference on the IoT, in 2015. He is an Area Editor of the *Proceedings of the ACM on Interactive, Mobile, Wearable, and Ubiquitous Technologies* as well as of the Pervasive and Mobile Computing Journal. He was the Co-Chair of the Third IEEE Workshop on the IoT: Smart Objects and Services, in 2014.

Maria Gorlatova is a Nortel Networks Assistant Professor of Electrical and Computer Engineering and Computer Science at Duke University. Her research is in emerging pervasive technologies, with a particular focus on next-generation augmented reality and the Internet of Things. She received her Ph.D. in Electrical Engineering from Columbia University, and her M.Sc. and B.Sc. (Summa Cum Laude) degrees in Electrical Engineering from the University of Ottawa, Canada. She spent two years at Princeton University Electrical Engineering Department as an Associate Research Scholar and an Associate Director of the Princeton University EDGE Lab. She received multiple awards, including the NSF CAREER Award, Facebook Research Award, CISCO Research Award, ACM SenSys Best Student Demonstration Award, IEEE/ACM IPSN Best Research Artifact Award, Google Anita Borg Fellowship, the IEEE Communications Society (ComSoc) Young Author Best Paper Award, and the IEEE ComSoc Award for Advances in Communications.

Luyang Liu is a Researcher at Google working at the intersection of machine intelligence, mobile systems, and digital well-being. He obtained his Ph.D. degree at Rutgers University. His research has been published in top-tier conferences and journals, including Science, Nature, NeurIPS, CVPR, MobiCom, etc.

Gábor Sörös is a senior research scientist at Nokia Bell Labs in Budapest, Hungary. His research interests span from mobile and wearable computer vision, location-based augmented reality, computational audio, and augmenting humans with wearable technology for interaction in smart environments. He studied electrical engineering in Budapest (HU) and in Karlsruhe (DE) with a focus on communication systems, visual computing in Vienna (AT) with a focus on mobile augmented reality, and he obtained his Ph.D. degree in computer science at the Institute for Pervasive Computing of ETH Zurich (CH). He has gained extensive research and engineering experience as an early member of three highly successful Swiss AR startups Scandit, Kapanu, and Arbrea Labs, he formerly worked in the Vuforia team of Qualcomm Research, and he is currently also active in the Open AR Cloud Association and in the Metaverse Standards Forum.

Pengyuan Zhou is currently a Research Associate Professor at the University of Science and Technology of China (USTC). He was an EU Marie-Curie ESR and received his Ph.D. from the University of Helsinki, Finland, in 2020. His research interests include ubiquitous computing and metaverse.