# 6G: THE PARADIGM FOR FUTURE WIRELESS COMMUNICATIONS


Shahid Mumtaz


Chunxiao Jiang


Antti Tölli


Anwer Al-Dulaimi


M. Majid Butt


Hafiz M. Asif


Muhammad Ikram Ashraf

While 5G research is maturing toward a global standard, the focus has now shifted toward the development of beyond 5G solutions. Wireless data traffic is estimated to reach 4394 EB by 2030 (Source: International Telecommunication Union), and the number of connected devices might surge beyond 50 billion. 5G will be unable to provide adequate support for various applications that depend on this huge data generated from massively interconnected devices. Many future data-intensive applications and services like pervasive edge intelligence, holographic rendering, high-precision manufacturing, ultra-massive machine-type communications, and virtual/augmented reality (VR/AR)-based gaming are expected to demand higher bit rates (terabits per second) and lower latency (less than 1 ms). Here, 6G is expected to extend 5G capabilities to higher levels where millions of connected devices and applications could operate seamlessly with trust, low latency, and high bandwidth. Research in 6G has already begun and is expected to gain momentum very soon. Industries and academia have allocated enormous funds and other resources for 6G research and development. The main focus is expected to be in the deployment of 6G-enabled massive Internet of Things (IoT), interoperability issues, system architectures, energy-efficient technologies, and application of artificial intelligence and other novel techniques to improve network performance, security, and privacy.

After a careful review process, nine outstanding papers were selected for this Special Issue. The first article, "AI-Based Cloud-Edge-Device Collaboration in 6G Space-Air-Ground Integrated Power IoT" written by Wang *et al.*, demonstrates implementation of a hybrid and hierarchical cloud-edge-device collaboration architecture to adapt to different scenarios and domains. The work also suggests a queue-aware offloading algorithm to facilitate decision making optimization under incomplete information.

The second article, "Integrating Terrestrial and Satellite Multibeam Systems toward 6G: Techniques and Challenges for Interference Mitigation" written by Peng *et al.*, provides a systematic overview of efficient interference mitigation technologies focusing on two NOMA-enabled joint beamforming and resource allocation schemes to increase the minimal data rate. A future integrated scenario is also presented to validate the effectiveness of the proposed schemes.

The next article, "A Novel Wireless Resource Management for the 6G-Enabled High-Density Internet of Things" written by Shen *et al.*, proposes a novel wireless resource management technique for 6G network enabled high-density IoT services. Their experimental results demonstrate that the speed of the platform based on this solution is significantly faster than that of the traditional platform, and it is especially suitable for wireless resource management in 6G-enabled high-density IoT.

The fourth article, "Intelligence-endogenous Networks: Innovative Network Paradigm for 6G" written by Zhou *et al.*, puts forward the concept of the intelligence endogenous network (IEN), which basically aims to introduce knowledge graph and artificial intelligence technologies into networks to characterize and apply the network's multi-dimensional subjective and objective knowledge. They further introduce the basic concepts, goals, and meanings of IEN, together with its key theories and technologies.

The fifth article, "Toward Federated-Learning-Enabled Visible Light Communication in 6G Systems" written by Muhaidat *et al.*, demonstrates a detailed review of the literature on the application of federated learning (FL) in visible light communication (VLC) networks. Their work also includes a thorough overview on the main design aspects of FL-based VLC systems. Toward the end, the authors highlight some potential future research directions of FL that are envisioned to substantially enhance the performance and robustness of VLC systems.

The next article, "Quantum-Enabled 6G Wireless Networks: Opportunities and Challenges" written by Wang *et al.*, highlights a technology-driven and visionary description and exploration on how quantum information technology (QIT) can be leveraged for future 6G wireless networks. For instance, QIT can be leveraged to solve challenging wireless resource optimization problems in 6G systems. However, QIT is facing many challenges such as availability of quantum hardware and integration of QIT with ICT for 6G networks.

The seventh article, "A Prototype of Reconfigurable Intelligent Surface with Continuous Control of the Reflection Phase" written by Di Renzo *et al.*, delineates a prototype of the reconfigurable intelligent surface (RIS) that offers the capability of controlling the phase shifts. The work also includes characterization of its properties with the aid of full-wave simulations and through experimental measurements.

The penultimate article, "Satellite Based Computing Networks with Federated Learning" written by Chen *et al.*, proposes the application of FL in low Earth orbit (LEO)-based satellite communication networks. Having reviewed the state-of-the-art LEO-based SatCom and related machine learning (ML) techniques, the analysis of four possible ways of combining ML with satellite networks is carried out followed by their evaluation by simulations, which reveal that FL-based computing networks improve the performance of communication overheads and latency.

Finally, the last article, "Toward Zero-Touch Management and Orchestration of Massive Deployment of Network Slices in 6G" written by Ksentini, proposes a novel framework featuring

a distributed and AI-driven management and orchestration system for massive deployment of network slices in 6G. It is worth noting that the proposed framework is compliant with both European Telecommunications Standards Institute standards focusing on autonomous and intelligent network management and orchestration: zero touch service management (ZSM) and experimental networked intelligence (ENI). This implies that their proposed work will be leveraged to enable autonomous as well as scalable management and orchestration of network slices and their dedicated resources.

In conclusion, the Editors would like to thank all authors who submitted manuscripts to this Special Issue. The Editors wish to thank the reviewers who helped to review all of the papers in a very short timescale. We would like, in particular, to thank the Editor-in-Chief, Yi Qian, for his support to organize this Special Issue. Last but not least, it is our hope that the readers will enjoy these articles.

## Biographies

Shahid Mumtaz (smumtaz@av.it.pt) is with Instituto de Telecomunicacoes, Portugal and an IET Fellow, IEEE ComSoc and ACM Distinguished Lecturer, a recipient of the IEEE ComSoc Young Researcher Award, founder and Editor-in-Chief of IET's *Journal of Quantum Communication*, Editor-in-Chief of the *Alexandria Engineering Journal* (Elsevier), Vice-Chair, Europe/Africa Region—IEEE ComSoc Green Communications & Computing Society, and Vice-Chair for IEEE Standard P1932.1, "Standard for Licensed/Unlicensed Spectrum Interoperability in Wireless Mobile Networks." His work has resulted in technology transfer to companies and patented technology. His expertise lies in 5G/6G wireless technologies using AI/ML and digital twin (VR/XR) tools and innovation paths in industry and academia. Moreover, he worked as a senior 5G consultant at Huawei and InterDigital, where he contributed to RAN1/RAN2 and looked after the university-industrial collaborative projects

Chunxiao Jiang [S'09, M'13, SM'15] (jchx@tsinghua.edu.cn) is an associate professor in School of Information Science and Technology, Tsinghua University. He received the B.S. degree in information engineering from Beihang University, Beijing in 2008 and the Ph.D. degree in electronic engineering from Tsinghua University, Beijing in 2013, both with the highest honors. From 2011 to 2012 (as a Joint Ph.D) and 2013 to 2016 (as a Postdoc), he was in the Department of Electrical and Computer Engineering at University of Maryland College Park under the supervision of Prof. K. J. Ray Liu. His research interests include application of game theory, optimization, and statistical theories to communication, networking, and resource allocation problems, in particular space networks and heterogeneous networks.

Antti Tölli [M'08, SM'14] (antti.tolli@oulu.fi) is an associate professor with the Centre for Wireless Communications (CWC), University of Oulu, Finland. He received his Dr.Sc. (Tech.) degree in electrical engineering from the University of Oulu in 2008. From 1998 to 2003, he worked at Nokia Networks as a research engineer and project manager in both Finland and Spain. In May 2014, he was granted a five-year (2014–2019) Academy Research Fellow post by the Academy of Finland. During 2015–2016, he visited at EURECOM, Sophia Antipolis, France, while from August 2018 to June 2019 he visited the University of California Santa Barbara. He has authored numerous papers in peer-reviewed international journals and conferences and several patents, all in the area of signal processing and wireless communications. His research interests include radio resource management and transceiver design for broadband wireless communications with a special emphasis on distributed interference management in heterogeneous wireless networks. He is currently serving as an Associate Editor for *IEEE Transactions on Signal Processing*.

Anwer Al-Dulaimi (anwer.al-dulaimi@exfo.com) is a Senior Manager for Emerging technologies & Innovations and Distinguished Member of the Technical Staff in the Mobile Solutions Unit at EXFO, Montreal, Canada. He received his Ph.D. degree in electrical and electronic engineering from Brunel University, London, United Kingdom, in 2012 after receiving M.Sc. and B.Sc. honors degrees in communication engineering. His research interests include 5G and 6G networks, cloud computing, Blockchains and cybersecurity. He is the editor of IEEE Future Networks Series on 5G & 6G and guest editor for many IEEE journals. He is the chair of newly established IEEE 5G and Beyond Testbed project and the Chair of the IEEE 1932.1 Working Group "Standard for Licensed/Unlicensed Spectrum Interoperability in Wireless Mobile Networks," He is an IEEE Distinguished lecturer, Fellow of the British Institution of Engineering and Technology (FIET), Associate Fellow of the British higher education Academy (AFHEA) and registered as a Chartered Engineer (CEng) by the British Engineering Council.

M. Majid Butt [SM] (majid.butt@nokia-bell-labs.com) received the M.Sc. degree in digital communications from Christian Albrechts University, Kiel, Germany, in 2005, and the Ph.D. degree in telecommunications from the Norwegian University of Science and Technology, Trondheim, Norway, in 2011. He is a senior research specialist at Nokia Bell Labs, France, and an adjunct Research Professor at Trinity College Dublin, Dublin, Ireland. Prior to that, he has held various positions at the University of Glasgow, U.K., Trinity College Dublin, Ireland, and Fraunhofer HHI, Germany. His current research interests include communication techniques for wireless networks with a focus on radio resource allocation, scheduling algorithms, energy efficiency, and machine learning for RAN. He has authored more than 75 peer-reviewed conference and journal articles, 4 book chapters and filed over 30 patents in these areas. He was a recipient of the Marie Curie Alain Bensoussan Post-Doctoral Fellowship from the European Research Consortium for Informatics and Mathematics. He serves as an associate editor for *IEEE Communication Magazine*, *IEEE Open Journal of the Communication Society* and *IEEE Open Journal of Vehicular Technology*. He is IEEE COMSOC distinguished speaker for the class of 2022–2023.

Hafiz M. Asif [SM] (h.asif@squ.edu.om) received his Ph.D. in communication systems from Lancaster University, United Kingdom, in 2012. He worked at HW Communications Ltd., Lancaster, United Kingdom, for about one year as trainee engineer on different research and development projects. At present, he works at the Department of Electrical and Computer Engineering, Sultan Qaboos University, Muscat, Oman. He is a Chartered Engineer (CEng), IET, UK. Currently, he is the Vice Chair, Book Chapter of the IEEE Oman Chapter. His research areas include visible light communication, space time block codes, wireless communication systems, IoT, and computer networks.

Muhammad Ikram Ashraf (ikram.ashraf@nokia-bell-labs.com) received M.Sc. and Ph.D. degrees in telecommunication systems and communication engineering, respectively, from the University of Oulu, Finland. He is working as a Senior Research Specialist 5G Advanced in Nokia Bell Labs, Espoo Finland. Prior to that, he has worked as an Experienced Researcher in Network Architecture and Protocols at Ericsson Research in Jorvas, Finland. He has contributed in several technical papers, invention disclosures, and 3GPP. His research interests include 5G Advanced, AI/ML, Industry 4.0, XR, Positioning, IoT, V2X, UAV, URLLC, and TSN. He is serving as Editor of *IEEE Communication Standards Magazine* on Ultra-Low Latency, and Reliable Communications for Future Wireless Networks, Associate Editor of *IET Quantum Communication*, and Guest Editor of Elsevier, *Journal of Industrial Information Integration, Special Issue on Data/Information Integration Techniques in Industry 4.0/5.0*. Prior to that, he served as Editor of IEEE Communication Standards Magazine, Guest Editor of *IEEE Wireless Communication Magazine*, Editor of *IEEE Transactions on Cognitive Communications and Networking*, and Guest Editor of *IEEE Network (The Magazine of Global Internetworking)*.