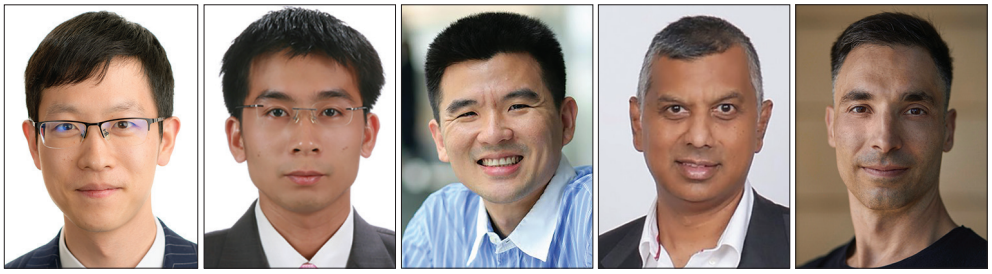
Intelligent Ultra-Reliable and Low-Latency Communications in 6G



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As one of the new communication scenarios in the Fifth Generation (5G) mobile communications, Ultra-Reliable and Low-Latency Communications (URLLC) are crucial for enabling a wide range of emerging applications, including industrial automation, intelligent transportation, telemedicine, Tactile Internet, and Virtual/Augmented Reality (VR/AR). According to the requirements in 5G standards, to support emerging mission-critical applications, the End-to-End (E2E) delay cannot exceed 1 ms and the packet loss probability should be $10^{-5} \sim 10^{-7}$. Compared with the existing cellular networks, the delay and reliability require significant improvements by at least two orders of magnitude for 5G networks. This capability gap cannot be fully resolved by the 5G New Radio (NR), i.e., the physical-layer technology for 5G, even though the transmission delay in Radio Access Networks (RANs) achieves the 1 ms target. Transmission delay contributes only a small fraction of the E2E delay, as the stochastic delays in upper networking layers, such as queuing delay, processing delay, and access delay, are key bottlenecks for achieving URLLC. Beyond 5G systems or so-called Sixth Generation (6G) systems should guarantee the E2E delay bound with high reliability.

In addition to the latency and reliability requirements, some other Key Performance Indicators (KPIs) should also be taken into account, including Spectrum Efficiency (SE), throughput, Energy Efficiency (EE), Age of Information (AoI), jitter of latency, round-trip delay, network availability, and security. To meet diverse KPI requirements, a new trend in developing communication networks is integrating domain knowledge of wireless communications, information theory, and networking into deep learning. Considering that deep learning algorithms suffer from low learning efficiency in terms of computing efficiency and sample efficiency, domain knowledge has the potential to improve learning efficiency significantly. The combination of human intelligence (domain knowledge) and artificial intelligence (learning algorithms) will be critical for achieving URLLC in 6G.

Considering the diverse application scenarios and KPIs of URLLC in 6G, the design of future intelligent communication systems requires considerable additional research efforts beyond what the community has done so far. We propose this special issue to investigate communication technologies and design methods for URLLC in 6G. We received 26 submissions, and selected six papers for this issue after a careful review process. Those papers provide visions of the different approaches toward URLLC in 6G.

The article, "Delivering Ultra-Reliable Low-Latency Communications via Statistical Radio Maps," by T. Kallehauge, A. E. Kalør, P. Ramírez-Espinosa, M. Guillaud, and P. Popovski proposes a timely framework to exploit long-range channel spatial correlation through so-called statistical radio maps, enabling URLLC communications with given statistical guarantees. The framework is exemplified in two scenarios: a location-based radio map and a latent space rendered by a channel chart, where the distribution of channel capacity is predicted.

The article, "Quantum Machine Intelligence for 6G URLLC," by F. Zaman, A. Farooq, M. A. Ullah, H. Jung, H. Shin, and M. Z. Win investigates the potential of variational quantum computing and quantum machine learning (QML) for 6G URLLC by utilizing the advantage of quantum resources, such as quantum superposition, quantum entanglement, and quantum parallelism. In the case study, the quantum approximate optimization algorithm is applied in URLLC task offloading optimization, which is an NP-hard combinatorial decision problem.

The article, "WiserVR: Semantic Communication Enabled Wireless Virtual Reality Delivery," by L. Xia, Y. Sun, C. Liang, D. Feng, R. Cheng, Y. Yang, and M. Ali Imran proposes a novel framework, namely WIreless SEmantic deliveRy for VR (WiserVR), for delivering consecutive 360° video frames to VR users. Deep learning-based multiple modules are well-devised for the transceiver in WiserVR to realize high performance feature extraction and semantic recovery. Implementation and initial simulations are provided, followed by associated open issues and corresponding solutions.

The article, "Toward Industrial Metaverse: Age of Information, Latency and Reliability of Short-Packet Transmission in 6G," by J. Cao, X. Zhu, S. Sun, Z. Wei, Y. Jiang, J. Wang, and V. K. N. Lau revisits the coupled relationship of the key performance indicators (KPIs), i.e., AoI, latency, and reliability in the 6G URLLC, where Industrial metaverse is considered as an emerging paradigm of the next generation industry transformation. The co-design of sensing, communication, control, and computing is presented to realize the required real-time intelligence.

The article, "Machine Learning for 6G Enhanced Ultra-Reliable and Low-Latency Services," by Y. Liu, Y. Deng, A. Nallanathan, and J. Yuan categorizes the 6G URLLC vision into three connectivity characteristics: ubiquitous connectivity, deep connectivity, and holographic connectivity, with their corresponding unique QoS requirements. Then, the authors identify potential challenges in meeting these connectivity requirements, and investigate promising ML solutions to achieve the intelligent connectivity for the 6G URLLC service. The implementations of the ML algorithms to guarantee the QoS requirements for different URLLC scenarios are discussed.

The article, "Orthogonal Time Frequency Space and Predictive Beamforming-enabled URLLC in Vehicular Networks," by W. Yuan, J. Zou, Y. Cui, X. Li, and J. Mu proposes to use the new orthogonal time frequency space (OTFS) and sensing-assisted predictive beamforming framework for supporting URLLC in high mobility scenarios. Several open problems and future studies are summarized to highlight the challenges in theoretical research and practical implementation of the developed URLLC solution.

We would like to convey our gratitude to all the authors (irrespective of whether their papers were accepted or rejected) for their high-quality submissions that made this Special Issue a success. We are also grateful to the Editor-in-Chief, Professor Nirwan Ansari, for understanding the importance of this timely topic and allowing us to organize this Special Issue. Finally, we would like to acknowledge the editorial team and the anonymous reviewers for their support and contributions.

Biographies

Changyang She [S'12, M'17, SM'22] received his B. Eng degree in Honors College (formerly School of Advanced Engineering) of Beihang University (BUAA), Beijing, China in 2012 and Ph.D. in School of Electronics and Information Engineering of BUAA in 2017. From 2017 to 2018, he was a postdoctoral research fellow in Singapore University of Technology and Design. From 2018 to 2021, he was a postdoctoral research associate in the University of Sydney. He is the recipient of the Australian Research Council (ARC) Discovery Early Career Research Award (DECRA). Since 2021, he serves as the ARC DECRA fellow at the University of Sydney. His research interests lie in the areas of ultra-reliable and low-latency communications, deep learning in wireless networks, mobile edge computing, and energy efficient 5G communication systems.

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