# 5G FOR ULTRA-RELIABLE LOW-LATENCY COMMUNICATIONS


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With the expected superior performance to the current generation of mobile networks, fifth generation (5G) systems are poised to support new and diverse usage scenarios and applications, thus enriching the lives of citizens and the productivity of industry and public sectors. The widely accepted scenarios for 5G include enhanced mobile broadband (eMBB), addressing human-centric use cases for access to multimedia content, services and data; ultra-reliable low-latency communications (URLLC) with strict requirements, especially in terms of latency and reliability; and massive machine type communications (mMTC) for a very large number of connected devices typically transmitting a relatively low volume of non-delay-sensitive data.

This Special Issue (SI) of *IEEE Network* aims at presenting the most relevant scenarios, prominent research outcomes, and state-of-the-art advances of 5G systems for URLLC achieving the Third Generation Partnership Project (3GPP) targets on latency and reliability requirements to successfully deliver delay-sensitive information. In 3GPP, the performance target for control plane latency is 10 ms, and for user plane latency it is 0.5 ms for downlink and uplink directions, separately. The mobility interruption time (MIT) must be 0 ms for both intra-frequency and inter-frequency handovers for intra-New Radio (NR) mobility. Reliability, defined as success probability of transmitting a predefined number of bytes within a certain delay, depends on the usage scenario. For instance, the target reliability for the "general URLLC case" is 99.999 percent (five nines) with user plane latency of 1 ms and payload size of 32 bytes.

This SI brings together key contributions of researchers from industry and academia, which address the above challenges and sheds light on some fundamental technical aspects of 5G architectures, building blocks, and key enabling technologies for URLLC, such as ultra-low-latency air interfaces, robust waveforms, and wireless relaying; optimized high-performance unlicensed/shared spectrum solutions; dynamic network slicing, flexible virtual network functions placement at the edge, and continuous self-optimization and cognition; and packet duplication, handover, and multidimensional multi-connectivity mechanisms optimized for ultra-reliability and minimal service interruption time.

In response to the Call for Papers, a large number of manuscripts were received. The submissions underwent a rigorous review process, following which only 11 outstanding papers were selected for publication. These articles are expected to stimulate new ideas and endeavors within the global research and innovation community, in addition to providing readers with relevant background information and feasible solutions to the main technical design challenges of future 5G systems for ultra-reliable low-latency communications.

The first article, "Achieving Ultra-Reliable Low-Latency Communications: Challenges and Envisioned System Enhancements" by G. Pocovi, H. Shariatmadari, G. Berardinelli, K. Pedersen, J. Steiner, and Z. Li, presents a comprehensive analysis of system-level aspects of URLLC, and introduces new design principles of the radio interface compared to LTE, as well as novel radio resource management concepts that exploit the high degree of flexibility of the 5G physical layer characteristics.

The second article, "Ultra-Reliable Low-Latency Communication (URLLC): Principles and Building Blocks" by P. Popovski, J. Nielsen, C. Stefanovic, E. de Carvalho, E. Stroemy, K. F. Trillingsgaard, A. S. Bana, D. M. Kim, R. Kotaba, J. Park, and R. B. Sørensen, presents the fundamental principles and key enabling technologies for achieving wireless URLLC, such as framing/packetization, use of diversity, network topology, and access protocols.

In the third article, "5G Radio Network Design for Ultra-Reliable Low-Latency Communication" by J. Sachs, G. Wikström, T. Dudda, R. Baldemair, and K. Kittichokechai, the authors describe the functionality of both NR and enhanced LTE radio interfaces to provide URLLC services, and evaluate achievable latency bounds and spectral efficiency.

The fourth article, "Packet Duplication for URLLC in 5G: Architectural Enhancements and Performance Analysis" by J. Rao and S. Vrzic, investigates packet duplication (PD) mechanisms and shows how PD with dynamic control enables joint satisfactory latency and reliability requirements without increasing the complexity of next generation radio access networks (NG-RANs).

The fifth article, "Handover Mechanism in NR for Ultra-Reliable Low-Latency Communications" by H.-S. Park, Y. Lee, T.-J. Kim, B.-C. Kim, and J.-Y. Lee, proposes a conditional make-before-break handover (HO) solution to achieve zero mobility interruption time (MIT), and zero handover failure (HOF) rate by keeping the communication with the source cell until messages from the target cell are received, and exe-

cuting the HO when the link to the target cell is preferable.

The sixth article, "Zero-Zero Mobility: Intra-Frequency Handovers with Zero Interruption and Zero Failures" by I. Viering, H. Martikainen, A. Lobinger, and B. Wegmann, investigates how the zero MIT and zero HOF rate can be achieved using the LTE-NR dual connectivity (DC) feature with data and signaling radio bearers duplication, thus avoiding radio link failures, and evaluates mobility performance in terms of robustness/reliability and signaling costs.

The seventh article, "Energy Efficiency-Delay Trade-offs in 5G Ultra-Reliable Low-Latency Communications System Architectures" by A. Mukherjee, provides a perspective on various trade-offs between energy efficiency (EE) and user plane delay for 5G URLLC, and proposes new methods to improve base station on-off switching and distributed access network architectures, as well as solutions that optimize EE of discontinuous reception (DRX), mobility measurements, and handover procedures for 5G devices, without compromises on delay.

The eighth article, "Relaying-Enabled Ultra-Reliable Low-Latency Communications in 5G" by Y. Hu, M. C. Gursoy, and A. Schmeink, addresses the performance modeling and optimization of relaying-enabled URLLC networks, and shows the performance improvement of the proposed solutions with respect to the case of direct transmission (without relaying).

The ninth article, "Enabling Ultra-Reliable and Low-Latency Communications through Unlicensed Spectrum" by G. J. Sutton, J. Zeng, R. P. Liu, W. Ni, D. N. Nguyen, B. A. Jayawickrama, X. Huang, M. Abolhasan, and Z. Zhang, shows how multiple unlicensed channels could be used for reducing the time periods without access and proves that licensed-assisted access is the key to achieving URLLC in 5G unlicensed bands.

The 10th article, "Toward Low-Latency and Ultra-Reliable Virtual Reality" by M. S. Elbamby, C. Perfectoy, M. Bennis, and K. Doppler, shows the importance of millimeter-wave communications, mobile edge computing (MEC), and proactive caching, and their critical roles in meeting the most important requirements for interconnected wireless virtual reality (VR), mixed reality (MR), and augmented reality (AR).

Finally, the 11th article, "Professional Live Audio Production: A Highly Synchronized Use Case for 5G URLLC" by J. Pilz, B. Holfeld, A. Schmidt, and K. Septinus, concludes this SI with a summary of the most important requirements of live audio productions, presents what is possible to achieve with 5G URLLC mechanisms, and discusses what is needed to establish audio program making and special events (audio-PMSE) as a future 5G vertical offering.

In closing, we would like to thank all the contributors and stakeholders who have worked so tirelessly to make this SI possible. We sincerely hope this SI meets the expectations of our readers, whom this SI on 5G for Ultra-Reliable Low-Latency Communications is to serve, and will make a long-lasting impact on the networking community.

## Biographies

David Soldani (dr.david.soldani@gmail.com) received an M.Sc. degree in engineering with magna cum laude approbatur from the University of Florence, Italy, in 1994, and a D.Sc. degree in technology with distinction from Aalto University, Finland, in 2006. He was appointed visiting professor at the University of Surrey, United Kingdom, in 2014, and Industry Professor at the University of Technology Sydney (UTS), Australia, in 2016. He is now chief technology officer of Huawei Technologies (Australia). Prior to that, he served Nokia as head of 5G Technology, E2E, Global, and Huawei as head of the Central Research Institute, 2012 Labs in Europe.

Y. Jay Guo [F'14] is a Distinguished Professor and the founding director of the Global Big Data Technologies Centre at UTS). Prior to this appointment, he served as a director at CSIRO for over nine years, directing a number of ICT research portfolios. He is a Fellow of the Australian Academy of Engineering and Technology. His research interests include antennas, millimeter-wave and terahertz communications and sensing systems, as well as IoT and big data technologies. He has published over 350 peer reviewed papers and holds 24 patents.

Bernard Barani joined the European Commission responsible for implementation of research and policy issues in wireless communication. He is currently acting head of a unit in charge of research and innovation in network technologies in the CONNECT Directorate General of the EC. He is responsible for the definition and implementation of the research strategy and related policy issues in the field of future networks, and of the implementation of the 5G Public Private Partnership launched in 2013, as the flagship EC initiative in support of 5G.

Preben Mogensen is a principal engineer at Bell Labs Aalborg Department, Denmark, and a Bell Labs Fellow. He is also a part-time professor at Aalborg University and head of the Wireless Communication Networks (WCN) section. He received his M.Sc. and Ph.D. from Aalborg University in 1988 and 1996, respectively. He is currently engaged in vertical use cases for 5G including IoT, URLLC, V2X, and UAV communication. He has published more than 400 papers on wireless communication and he has over 18,000 Google Scholar citations.

Chih-Lin I is CMCC Chief Scientist of Wireless Technologies, launched 5G R&D in 2011, and leads C-RAN, Green, and Soft initiatives. She received the *IEEE Transactions on Communications* Stephen Rice Best Paper Award and the IEEE ComSoc Industrial Innovation Award. She was on the IEEE ComSoc Board and GreenTouch Executive Board, and was M&C Board Chair and WCNC SC Founding Chair. She is on IEEE ComSoc SDB, SPC, and EDB, ETSI/NFV NOC, WWRF Steering Board, and Singapore NRF SAB.

Sajal K. Das [F] is a professor in the Computer Science Department and Daniel St. Clair Endowed Chair at Missouri University of Science and Technology, Rolla. He has directed numerous funded projects, published more than 600 research articles, and co-authored many books, and holds five U.S. patents. His h-index is 78 with over 25,000 citations. He is a co-founder of the IEEE PerCom, IEEE WoWMoM, IEEE SMARTCOMP, and ICDCN conferences.