Guest Editorial Ultra-Reliable Low-Latency Communications in Wireless Networks

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ULTRA-HIGH reliability and low latency have not been in the mainstream in most wireless networks. Mobile networks have been driven so far by human-centric communications, delay-tolerant content, and non-critical services. The main target have been to boosting data rate and increasing coverage, adopting a rather best-effort networking approach. As wireless connectivity starts to get the status of a commodity, there is an increasing focus on support of services that rely critically on wireless links and therefore the reliability of the wireless connections. Next generation wireless systems, mainly 5G and beyond, are designed to provide wireless connectivity for massive machine-type communications (mMTC) and to support ultra-reliable, low latency communication (URLLC) for mission-critical services. URLLC scenarios impose stringent requirements in terms of latency (ranging from 1 ms and below to few milliseconds end-to-end latency depending on the use cases) and reliability (higher than 99.9999%). This does not mean that there are interesting applications where reliability is of paramount importance, while latency can be in the order of seconds, as in e.g. certain remote healthcare applications. Nevertheless, the coupling of low-latency networking and reliable communication is mainly driven by the need to push the technology boundaries and address a plethora of socially useful services and business domains that could benefit greatly from it. Some of the most challenging use cases are factory automation and industrial control, automated driving/flying, haptic communications, and real-time remote healthcare. URLLC is also expected to revolutionize processes in the areas of smart cities, smart farming, smart grid, remote manufacturing, and algorithmic trading. Although the URLLC constraints and the nature of real-time mission-critical applications imply the predominance of short packets and low-rate transmissions, future evolution of URLLC may also consider rate requirements. The emergence of immersive services, such as augmented and virtual reality (AR/VR), high-definition entertainment and gaming, and consumer robotics, calls for real-time, high-fidelity, broadband networks operating at latencies of few milliseconds.

To respond to this growing need, recently there has been significant activity aimed at developing the theoretical foundations and at understanding the practical implications of URLLC systems. From a theoretical standpoint, URLLC further rekindles the interest in the long standing challenge of completely characterizing the non-asymptotic fundamental tradeoffs between delay, throughput and error probability in wireless networks, including both coding delays and queuing delays. Despite various proposed analytical approaches, we are still lacking of a neat and insightful mathematical theory, which will enable us to quantify and understand the fundamental limits of low-latency communications. Furthermore, the highly variable and heterogeneous nature of network traffic together with the associated overhead should be incorporated in the conventional communication theoretic framework. From an engineering standpoint, URLLC introduces countless challenges and roadblocks in air interface design, resource allocation, network deployment, protocol stack design, and all the way up to the core network and application layer. Providing guaranteed and reliable end-to-end latency will undebatably require a departure from throughput-oriented system design towards a holistic view (network architecture, control, and data) and would require a powerful arsenal of efficient, fast, and implementable end-to-end network orchestration and optimization algorithms.

The goal of this special issue is to highlight some of the most recent advancements in the area of ultra-reliable, low-latency communications in wireless networks. The special issue is composed of eighteen papers resulting from eighty seven submissions. The first paper specifically concerns wireless channel dynamics for URLLC. A robust control inspired methodology for studying the deviation of channels from the standard spatially independent quasi-static Rayleigh fading model is proposed.

The next three papers focus on performance analysis using finite blocklength regime. Devassy *et al.* study short packet transmission in a point-to-point communication channel assuming Bernoulli arrivals, single-server queue, and variable-

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length stop-feedback coding. They evaluate the delay and peak-age violation probabilities and show their dependence on system parameters such as the frame length, the undetected error probability, and on the packet management policy. Zhou, Wolf and Motani consider a lossy joint source-channel coding problem over parallel Gaussian channels with independent quasi-static fading and derive achievability and converse bounds on the minimal excess-distortion probability for optimal finite-blocklength codes. Their results show that knowledge of the source and channel distributions at the decoder is not necessary to achieve the optimal second-order performance and that outage capacity/probability remains a valid metric even in the finite blocklength regime. Sahin *et al.* propose a framework to analyze the throughput and the error probability of IR-HARQ in correlated Rayleigh fading channels as a function of the modulation scheme.

The next three papers study the delay performance of physical layer techniques and protocols using stochastic network calculus. Schiessl, Gross, Skoglund and Caire investigate the delay performance of a multiuser multiple input, single output (MISO) system with zero-forcing beamforming with long codewords and perfect channel state information (CSI) at the transmitter as well as with finite blocklength codes and imperfect CSI. Interestingly, the channel hardening effect results in very high reliability with respect to the worst-case delay under both ideal and non-ideal assumptions. Upper bounds on the delay violation probability in downlink multiple input, multiple output - non orthogonal multiple access (MIMO-NOMA) systems is derived by Xiao *et al.* A power allocation scheme that significantly reduces the delay violation probability is also proposed. Forssell *et al.* develop a queueing model for analyzing the detection and delay performance of a feature-based physical layer authentication (PLA) protocol in mission-critical MTC networks. PLA is shown to be very effective in providing security and dealing with disassociation and Sybil attacks under sufficient number of receive antennas and relatively strong line-of-sight conditions.

The next two papers tackle the problem of coding under latency constraints. Malak, Médard and Yeh investigate the tradeoff between throughput and guaranteeable delay over point-to-point erasure channels with unreliable and delayed feedback. Using a sliding window by coding with just two packets, they propose three variations of selective-repeat ARQ protocols and show the gains and the robustness of coded ARQ with rate adaptation based on the cumulative feedback. Xiang *et al.* take a practical approach and propose a new Turbo decoding algorithm for LTE URLLC, which supports an arbitrarily-high degree of parallel processing, enabling significantly improved throughput, latency, and computational efficiency in comparison to the conventional turbo decoder while meeting the requirements of LTE URLLC.

Liu *et al.* consider short-frame full-duplex (FD) systems with carrier frequency offset (CFO) and propose an iterative semi-blind receiver with CFO and channel estimation using only a single pilot. Extensive simulation results establish the performance gains in terms of bit error rate, mean square errors of channel and CFO estimation and output signal-to-interference-and-noise ratio with reduced training overhead compared to similar methods. Jain, Kumar and Panwar use stochastic geometry to analyze the probability, duration, and frequency of blockage events in millimeter wave systems employing macrodiversity. This work reveals the importance of dynamic blockage in network dimensioning and show that the density of base station required to satisfy the URLLC constraints is much higher than that obtained by capacity or coverage requirements. Ayoughi, Yu, Khosravirad, and Viswanathan tackle the problem of interference management in a multiple interfering broadcasts network and propose two protocols for improving the scalability of Occupy CoW in large networks. The performance improvement leverages full frequency reuse and successively decoding and cancellation of as much inter-cell interference as possible by actuators.

The next three papers specifically concern radio resource management (RRM) issues. Tang, Shim, and Quek consider service multiplexing and revenue maximization in a cloud RAN (C-RAN) with multiple unicast URLLC and multicast eMBB slices. The revenue maximization problem with slice request admission is formulated as a mixed-integer nonlinear programming (MINLP), whose solution results in significant power consumption and revenue gains. Elayoubi *et al.* explore several resource allocation and retransmission schemes for both deterministic packet generation and sporadic traffic. They also show how to choose between individual reservation and contention-based reserved resources schemes for the lowest possible resource consumption. RRM for low-latency vehicular communication is considered by Guo, Liang, and Li. The authors use effective capacity to characterize the delay violation probability for vehicle-to-vehicle (V2V) links and develop spectrum reuse and power allocation algorithms to maximize the sum ergodic capacity of vehicle-to-infrastructure (V2I) links while guaranteeing V2V latency requirements.

The focus of the next paper is on network protocol design and Abbasloo, Xu, and Chao propose a flexible low-latency cellular congestion control protocol combining in-network active queue management schemes and throughput-oriented transport control protocols (TCPs). Extensive evaluations in both real-world environment and trace-based emulations show that the proposed scheme may outperform state-of-the-art TCP mechanisms, such as PCC-Vivace, Google's BBR, Verus, Sprout, TCP Westwood, and Cubic, in terms of average delay, jitter, and 95th percentile packet delay.

The last two papers present two important URLLC use cases. Jiang *et al.* explore packet detection and synchronization algorithms with a very short preamble (one OFDM symbol) for wireless industrial control. The theoretical analysis is supported by experiments in a real factory-like environment, showing that the proposed preamble guarantees perfect accuracy up to 20 m range and, when the differential detection is employed, frequency offsets up to 1200ppm can be tolerated. Finally, Tinnakornsrisuphap *et al.* consider end-to-end design of 5G industrial networks for factory automation, study the suitability and performance tradeoffs of coordinated multipoint techniques, and validate the proposed framework using a prototype system.

In conclusion, we would like to thank the authors of all submitted papers, many of which could not be accommodated

in this issue, and they highly appreciate the high-quality and timely work of the reviewers. The mentoring and the support provided by Prof. Gunnar Karlsson, JSAC Senior Editor, by Prof. Muriel Médard, previous Editor-in-Chief, and by Prof. Raouf Boutaba, Editor-in-Chief, are greatly acknowledged. Special thanks are due to Janine Bruttin, JSAC Executive Director, Lauren Briede, and Laurel Greenidge for their support and assistance in the preparation of this issue.

We hope that this issue will encourage researchers to continue working at this exciting and influential area, which holds promise to change the way future communication networks are designed and deployed.

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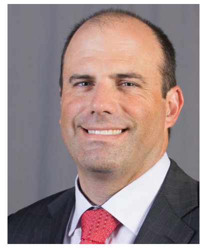

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