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Ultra-Reliable Low-Latency Communications: Foundations, Enablers, System Design, and Evolution Towards 6G

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Contents

Ultra-Reliable Low-Latency Communications: Foundations, Enablers, System Design, and Evolution Towards 6G

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ABSTRACT

Wireless communication has traditionally been designed to connect human users. The main design goal was to maximize the data rate while guaranteeing moderate reliability and latency targets dictated by the limitations of human senses. The application of wireless connectivity for machine to machine communications, typically known as machine-type communications (MTC), has been growing in the past decade due to its flexibility, scalability and ease of use. It is also driven by the proliferation of Internet of Things (IoT)

Nurul Huda Mahmood, Italo Atzeni, Eduard Axel Jorswieck and Onel Luis Alcaraz López (2023), "Ultra-Reliable Low-Latency Communications: Foundations, Enablers, System Design, and Evolution Towards 6G", Foundations and Trends® in Communications and Information Theory: Vol. 20, No. 5-6, pp 512–747. DOI: 10.1561/0100000129.

nodes and applications, with several billions of connected devices expected by the next decade.

The fifth-generation (5G) New Radio (NR) wireless system has introduced two distinct services classes to support MTC, namely massive machine-type communications (mMTC) and the ultra-reliable low-latency communications (URLLC). Out of these, designing URLLC solutions is the most challenging given that it aims to provide dependable connectivity for mission-critical applications in industrial scenarios, process engineering and other similar verticals.

URLLC aims to guarantee very high reliability and very low latency, and therefore the *outage performance* replaces the average performance as the main design criterion. This calls for a new approach to the communication- and information-theoretic fundamentals of wireless system design. Different theoretic foundations of URLLC have so far been treated in individual and disconnected works that fail to provide a meta-level understanding of this topic. This monograph aims at filling this gap by presenting a comprehensive coverage of the topic including the motivation, theory, practical enablers and future evolution. The unified level of details in this monograph is aimed at providing a balanced coverage between its fundamental communication- and information-theoretic background and its practical enablers, including 5G NR system design aspects. Finally, this monograph offers an outlook on URLLC evolution in the sixth-generation (6G) era towards dependable and resilient wireless communications.

1

Introduction

Wireless communications can be broadly categorized into human-type communications (HTC) and machine-type communications (MTC) [292]. The former includes voice calls, mobile broadband access, and other communications involving humans; whereas the latter comprises the wide range of scenarios where machines communicate with each other or with the network in the absence of direct human involvement. Wireless networks were predominantly designed to support HTC until the fourth-generation, though Long-Term Evolution (LTE) introduced some preliminary features to support MTC, such as LTE for MTC and narrowband Internet of Things (IoT).

MTC services are inherently different and more diverse compared to HTC services and introduce novel design challenges in wireless networks. Typical MTC applications involve sensors or IoT nodes sending periodic or event-triggered monitoring messages to the network. Hence, the traffic is usually sporadic with small payloads and skewed towards the uplink direction, as opposed to the downlink heavy HTC traffic with larger payloads [91].

MTC can be broadly categorized into massive machine-type communications (mMTC) and critical MTC or ultra-reliable low-latency communications (URLLC). MMTC refers to communications involving a massive deployment of sensors or IoT nodes with relatively relaxed quality-of-service (QoS) requirements in terms of the packet error rate and latency. The devices themselves are, in most cases, simple and low-cost with constrained energy sources and computational capabilities. The main design challenges are thus related to designing simple, low-power, and efficient access and transmission schemes for a large number of devices. On the other hand, *URLLC mandates very high reliability and low latency to support mission-critical applications* such as industrial automation, healthcare, intelligent transportation systems, and high-fidelity audio systems [289]. The current fifth-generation (5G) New Radio (NR) is the first wireless standard designed to natively support multi-service communications [196]. In addition to serving conventional HTC through the enhanced mobile broadband (eMBB) service class, 5G NR supports MTC through the newly introduced URLLC and mMTC service classes.

Among the three 5G NR service classes, URLLC is arguably the most challenging [248]. Designing URLLC solutions to simultaneously guarantee reliability in the order of 99.999% and end-to-end (E2E) latency in the order of 1 ms requires a sharp departure from the conventional communication-theoretic foundations conceived on the basis of the average performance [51], [181]. Furthermore, URLLC is also the area with the most interesting research questions and potential impact, owing to its central role in many important and emerging vertical sectors, such as manufacturing and health care.

URLLC was first conceived as a novel service class of the 5G NR standard [26]. This was followed by a number of practical URLLC enablers and system design enhancements, many of which were also included in the early 5G NR standard [236]. Examples include revised numerology with the capability to scale the sub-carrier spacing (SCS) and consequently reduce the transmission time interval (TTI) duration [148] and mini slots with a smaller number of symbols to reduce the transmission latency [273], puncturing and preemptive scheduling to overlay high-priority URLLC transmissions to reduce the channel access latency [148], multi-connectivity to enhance the transmission reliability [201], and others. In addition, new applications and enablers constantly emerge from both academic research and 3rd Generation Partnership Project (3GPP) standardization.

The communication- and information-theoretic foundations and challenges of URLLC have started being explored following its initial introduction. Durisi *et al.* provided the information-theoretic principles of transmitting short data packets with low latency and ultra-high reliability [103]. Bennis *et al.* [51] proposed to decompose URLLC into three basic building blocks, namely tail, risk, and scale, highlighting a set of communication- and information-theoretic tools that can be used to analyze them. López *et al.* [181] delved into such and many other tools and methodologies for designing and analyzing URLLC systems, while providing several examples focused on the physical layer (PHY) and medium access control (MAC) layer. Meanwhile, Swamy *et al.* [304] revisited the wireless channel characteristics and dynamics in the context of the strict demands imposed by URLLC services and proposed solutions to bound the channel model uncertainty in order to ensure URLLC.

Another line of research considers variable-length stop feedback (VLSF) codes that comprise simple schemes such as automatic repeat request or hybrid automatic repeat request (HARQ), which provide an efficient way to ensure reliable reception of the data packet over fading channels. The suitability of VLSF codes for URLLC is studied in [253]. It turns out that it is important to optimize the transmission of signaling information, as well as to exploit various sources of diversity. Very recently, the performance of VLSF codes in multiple and random access channels is studied and compared to the Gaussian MAC [337]. While the first information-theoretic works on channels with noiseless feedback date 50 years back [188], recent works consider how to achieve the reliability exponent for unknown channels [313] or for noisy one-way and two-way channels [240].

1.1 Historical Background of MTC

Though MTC has been implemented since the second-generation era [80], it was incorporated as a part of the system design only in the fourth generation LTE. LTE for MTC was first introduced in 3GPP Release 12 as a dedicated radio technology standard to specifically enable MTC and IoT applications, which was then followed by the low-power wide-area network radio technology narrowband IoT in 3GPP Release 13. Instead of having different standards and radio technologies for different use cases, 5G NR design integrated these technologies under a unified system design served by different service classes.

There are two major motivations behind incorporating dedicated support for different service classes in wireless systems, namely technological needs and market demand. With the proliferation of MTC and IoT applications in a wide range of use cases, there is a growing demand to have a unified radio technology that can enable the diverse connectivity needs of these applications. On the other hand, the penetration rate of HTC exceeded 100% in most advanced markets while the average revenue per user was decreasing, forcing telecom operators to look for new markets. The huge growth potential of the MTC/IoT market with a forecast of billions of connected devices in the coming decade provides a natural expansion zone for filling this demand.

At the same time, the industrial and manufacturing sector witnessed the emergence of the fourth industrial revolution, also known as Industry 4.0. Industrial communication systems adopted in factory automation, manufacturing, and process control that interconnect controllers, sensors, actuators, input/output devices, and other industrial equipment are an integral part of Industry 4.0. Such communication networks, first introduced in the 1980s, have typically been implemented using proprietary fieldbus protocols. Today it has evolved to wired Ethernet-based fieldbus systems such as PROFINET Isochronous Real Time that can support industrial automation applications requiring very high reliability and low latencies [52]. The proprietary nature of most of the existing fieldbus solutions limits their wide adoption. The IEEE 802.1 time sensitive networking (TSN) standards aim to address this issue by introducing a set of common standards that can provide deterministic connectivity through IEEE 802 networks, i.e., guaranteed packet transport with bounded latency, low packet delay variation, and low packet losses [257].

The wired nature of existing solutions providing deterministic connectivity limit flexibility, scalability, and deployment options and lead to high capital and operational expenditures for cabling installation and maintenance [75]. Since the last decade, wireless technologies like wireless local area network, ZigBee and Bluetooth, as well as their proprietary extensions such as Wireless Interface to Sensors and Actuators and Highway Adressable Remote Transducer have also been used as fieldbus systems [114], [324]. However, these technologies operate in a crowded unlicensed spectrum with unpredictable interference levels and are not capable of enabling dependable communications supporting applications requiring very high reliability and low latency [324]. The URLLC service class introduced in 5G NR is a first attempt in introducing a common wireless standard to enable deterministic connectivity for industrial communication systems and other verticals. The initial URLLC outlined in 3GPP Release 15 had limited capabilities, but these are being progressively improved in every subsequent releases [118], [258].

1.2 URLLC Use Cases

The multi-service support in 5G NR extends its capabilities far beyond conventional cellular broadband connectivity to enable new use cases in many vertical domains, such as manufacturing industries, intelligent transportation systems, health-care, agriculture, energy, smart societies, and many other sectors. In this section, we briefly discuss several URLLC use cases in different vertical sectors.

1.2.1 Connected Industries and Automation

The industrial domain is a very diverse field with many heterogeneous use cases representing diverse requirements. The manufacturing process, QoS requirements, plant size, deployment scenarios, etc., all may be very different for different sectors. However, URLLC solutions for the industrial communication networks interconnecting the different elements and devices, such as controllers, sensors, and actuators, in each of these industries may lead to substantial improvements and optimizations. Moving from 5G towards beyond-5G/sixth-generation (6G) systems, URLLC service class (and its evolution) has the potential to converge

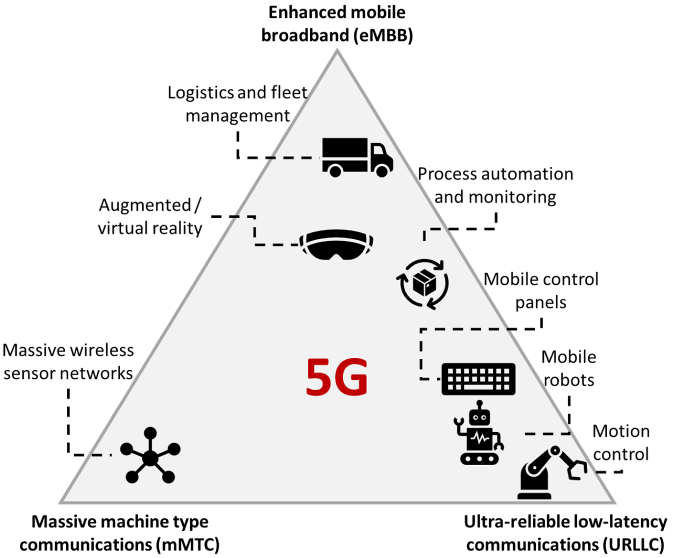
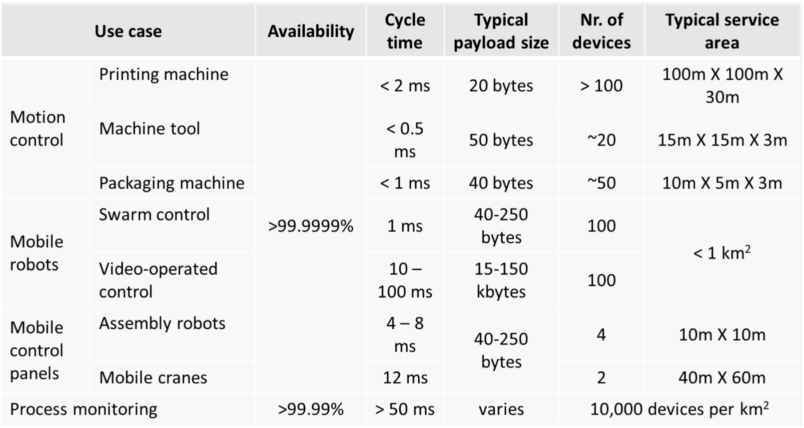


Figure 1.1: Different industrial use cases and their relative placement with respect to the three 5G NR service classes.

to a unified deterministic and resilient wireless connectivity solution. In parallel with the trend towards TSN as a unified (wired) Industrial Ethernet solution, beyond-5G systems may, for the first time, enable direct and seamless wireless communication from the field level to the cloud [10].

Promising URLLC applications range from logistics for supply and inventory management, automated guided vehicles (AGVs) through robot and motion control applications, to operations control and accurate localization. Moreover, integration of TSN features within 5G will enable it to easily replace wired connectivity with wireless solutions in certain parts of an industrial communication system, while interoperating with existing infrastructure that need not be replaced [121]. Figure 1.1 below presents an overview of selected industrial use cases, and their operational and functional requirements are outlined in Table 1.1.

Table 1.1: Operational and functional requirements for different industrial use cases [10].



Use case		Availability	Cycle time	Typical payload size	Nr. of devices	Typical service area
Motion control	Printing machine	>99.9999%	< 2 ms	20 bytes	> 100	100m X 100m X 30m
	Machine tool		< 0.5 ms	50 bytes	~20	15m X 15m X 3m
	Packaging machine		< 1 ms	40 bytes	~50	10m X 5m X 3m
Mobile robots	Swarm control		1 ms	40-250 bytes	100	< 1 km^2
	Video-operated control		10 – 100 ms	15-150 kbytes	100	
Mobile control panels	Assembly robots		4 – 8 ms	40-250 bytes	4	10m X 10m
	Mobile cranes		12 ms		2	40m X 60m
Process monitoring		>99.99%	> 50 ms	varies	10,000 devices per km^2	

1.2.2 Massive Digital Twin

A digital twin (DT) provides a real-time representation of physical objects in the virtual world. DTs are already becoming an integral part of manufacturing by rendering digital replicas of production/manufacturing assets [217]. The applications of DTs will be further extended to include a digital representation of the (wireless propagation) environment and assets beyond manufacturing; leading to the massive DT use case [136], [241]. A vast array of IoT devices collecting real-time and multi-source data allows the digital replicas to dynamically update and change along with their physical counterparts. To enable this, massive DT will require URLLC with high data rates, thereby imposing novel design challenges. The desired reliability and latency requirements of a DT implementation directly relates to the chosen level of abstraction, and the choice of DT modeling fidelity (i.e., how closely the model represents and follows the reality) is primarily driven by the use case [319].

1.2.3 Swarm Networking

Self-driving vehicles in the shop floor, e.g. AGVs, rely heavily on wireless communications for critical applications such as collision avoidance and control information interchange. Coordinated autonomous mobility in the shop floor, e.g., AGVs collaboratively carrying a large object, will be common in the future [70]. Such autonomous collaborative tasks will require a large number of sensors, actuators, and edge systems integrated within the autonomous vehicles and communicating with one another. This in turn increases the demand on the scale, complexity, and QoS of the connectivity within the AGV or swarm of vehicles, and between the vehicle/swarm and the serving network. Beyond the manufacturing shop floor, swarm networking use cases will also have applications in connected logistics and autonomous supply chains (e.g., swarm of supplying drones). AGV-based collaborative robots used for critical industrial processes grinding, sanding and product assembly will require URLLC with latency and packet error rates as low as 0.25 ms and 10^{-9}, respectively [239].

1.2.4 Immersive Experience

The ability to transmit multi-sensory information (audio, video, haptic, etc.) through Tactile Internet in real-time will pave the way towards immersive-experience use cases, where humans will be able to interact with other humans and/or digital assets (e.g., DTs) using all senses [24]. Examples of immersive-experience use cases in industrial scenarios include human-in-the-loop networks, where human operators can remotely interact and operate physical objects located in difficult and/or hazardous to-reach locations, and mixed-reality co-design, where designers can interact with DTs and other digital objects to design and digitally prototype new products before real-life prototyping. Such use cases will require E2E latencies in the order of 10 ms round-trip time (RTT) with a 10^{-5}–10^{-6} block error rate (BLER) target [24].

1.3 State of the Art in URLLC

URLLC was first introduced in 2015 by the International Telecommunications Union (ITU) as one of the three service classes of IMT-2020 system [147]. It was envisioned to have stringent requirements in terms of throughput, latency, and availability for applications such as wireless control of industrial manufacturing or production processes andtransportation safety. Following the ITU recommendation, it was adopted by 3GPP as part of the 5G NR Release 15 standard [2]. Since then, a number of tutorials and survey papers have been published on this topic, which are summarized in the following.

1.3.1 URLLC in 3GPP Standardization

From the standardization point of view, [118] provides an overview of the 5G NR Releases 16 and 17 features, including those focused on URLLC and industrial IoT such as time sensitive communications, enhanced location services, and support for non-public networks (NPNs). Focusing specifically on URLLC, [171] presents an overview of the URLLC features in 5G NR from Release 15 to Release 17 such as improved feedback mechanisms, intra-user equipment (UE) multiplexing, prioritization of traffic, support of time synchronization, new QoS-related parameters, and coexistence with unlicensed bands.

1.3.2 URLLC Use Cases

Critical industrial IoT automation with strict latency and reliability demands in smart factories is among the most important use cases of 5G URLLC [128]. The work in [189] describes the drivers for future industrial wireless systems along with the role of 5G URLLC and its industrial-centric evolution towards meeting the strict performance standards of factories. Furthermore, [295] discusses the key technical requirements and architectural approaches for the Tactile Internet, another important URLLC use cases, and presents the role of wireless access protocols, radio resource management aspects, next-generation core networking capabilities, edge cloud, and edge artificial intelligence (AI) capabilities in supporting the Tactile Internet. An overview of the 5G NR functionalities for URLLC and how they aim to guarantee ultra reliability and low latency for the Tactile Internet services and haptic communication applications is provided in [272]. Further focusing on Tactile Internet applications, [220] studies means to ensure URLLC at the fronthaul via multipath diversity and erasure coding of the MAC frames under a probabilistic model.

1.3.3 Fundamentals of URLLC

The principles for supporting URLLC from the perspective of the traditional assumptions and models applied in communication-/information-theory are discussed in [253] along with their application in designing access protocols and diversity sources. It is concluded that there is a need to optimize the transmission of signaling information and the use of different diversity sources to enable URLLC with efficient utilization of resources. The work in [256] provides a communication-theoretic model for the non-orthogonal sharing of random access network (RAN) resources among URLLC, eMBB, and mMTC services via network slicing that accounts for the heterogeneous requirements and characteristics of different service classes. It also introduces the concept of reliability diversity as a design principle that leverages the different reliability requirements across the services to ensure the performance guarantees of each service with RAN slicing. Unlike conventional communication applications with long data packets, most URLLC applications involve transmitting novel traffic types that use short packets. The information-theoretic principles governing the transmission of short packets in URLLC are detailed in [103], which also illustrates their application in optimizing the transmission of control information. It is concluded that new principles are needed for the design of wireless protocols supporting short packets.

1.3.4 URLLC Design/Analysis Tools

The work in [248] discusses some of the challenges of achieving URLLC, particularly in the downlink direction, such as those related to the reliability requirements for both data and control channels, the need for accurate and flexible link adaptation, reducing the processing time of data retransmissions, and the multiplexing of URLLC with other services. It further proposes solutions to these challenges covering different aspects of the radio interface, which are then validated through system-level simulation results. The work in [51] highlights that URLLC mandates a departure from the conventional average utility-based network design approach to a principled and scalable framework considering the tail of the distribution of various parameters of interest (e.g., delay, reliability, and packet size) while making decisions under the uncertainty due to the stochastic nature of wireless networks. It further introduces various URLLC enablers and presents several techniques and methodologies to ensure that the URLLC requirements are met. The more recent tutorial [181] presents several statistical tools and methodologies, such as reliability theory, short packet communications, tail approximations, rare event simulations, and stochastic geometry, which are useful for designing and analyzing URLLC systems. It further complements the discussion on the tools with novel application examples focused on the PHY and MAC layer.

1.3.5 URLLC Enablers

The work in [244] presents a survey of various low-latency enablers at the RAN, core network, and network caching elements alongside a general overview of several 5G cellular network technology components such as software defined network, network function virtualization, and multi-access edge computing. Moreover, [303] provides a comprehensive discussion on the PHY and MAC enablers of URLLC and identifies the potential of utilizing the unlicensed bands alongside the licensed ones for URLLC applications. The feasibility of various diversity techniques (in particular multi-connectivity approaches) in ensuring URLLC is discussed in [296], which also proposes a multi-connectivity algorithm for multi-cell multi-user systems based on matching theory. The work in [301] presents an extensive survey of multi-connectivity for URLLC. Specifically, it identifies the main scheduling categories, compares different network architectures, and considers different layers for implementing multi-connectivity. At higher layers, the role of edge computing based on distributed computing, storage, and control services closer to end-network nodes in enabling URLLC for mission-critical applications is explored in [107]. Similarly, [266] surveys the literature on new E2E solutions and the creation of URLLC services in current and future 5G networks, also classifying them according to the enabling technologies and methods used to achieve success in terms of latency and reliability.

1.3.6 Radio Resource Management for URLLC

Owing to its specific requirements, optimization problems for the optimum resource allocation in URLLC applications need to be approached in a different way. In this regard, [289] analyzes the delay and packet loss components in URLLC and explores appropriate tools to design radio resource allocation under constraints on delay, reliability, and availability. The work in [72] argues that the consumption of communication resources and the control subsystem performance are mutually dependent in URLLC. Hence, it is critical to integrate URLLC and control subsystems by formulating a communication and control co-design problem to optimize the overall system performance. Different resource allocation schemes for (re)transmissions with the aim of meeting the URLLC requirements with low resource consumption are investigated in [106]. A review of packet scheduling algorithms for URLLC in 5G-and-beyond systems covering centralised, decentralised, and joint scheduling techniques is presented in [131].

1.3.7 Coding Schemes for URLLC

Coding schemes specific for URLLC also received particular attention. The works in [294], [341] review different channel coding techniques for URLLC and provide a comparative study of their performance and complexity. On the other hand, [57] describes the encoding process of polar codes adopted by 3GPP as a channel coding scheme in the 5G standard and presents an elaborate framework that applies novel coding techniques to provide a solid channel code for NR requirements, with particular attention to rate flexibility and low decoding latency. The design of low-density parity check (LDPC) codes with short blocklength and fast convergence for URLLC applications is proposed in [331]. Joint coding schemes that can simultaneously accommodate URLLC and eMBB transmissions under different communication scenarios, such as point-to-point (P2P) channels, broadcast channels, interference networks, cellular models, and cloud-RANs, are discussed in [232] from an information-theoretic perspective.

1.3.8 Applications of ML/AI to URLLC

Machine learning (ML) and AI techniques are becoming more and more popular in the field of wireless communications. This is driven by their success in other fields (e.g., image processing, speech recognition, and natural language processing) and by the advances in their computational efficiency. Following this trend, the use of ML/AI tools has been investigated and promoted to address URLLC problems. The application of supervised/unsupervised learning by developing data-driven resource management for URLLC is surveyed in [275]. However, directly applying existing ML tools as an enabler for URLLC may not be efficient due to the stringent QoS requirements, the dynamic nature of most URLLC use cases (which leads to the training and validation samples being drawn from different distributions), and overhead in terms of latency. These challenges can potentially be addressed by integrating domain knowledge with ML tools. For example, [288] illustrates how to improve the performance of supervised/unsupervised deep learning and deep reinforcement learning (DRL) algorithms for URLLC by applying model-based analytical tools and cross-layer optimization frameworks.

1.3.9 UAV/RIS-Aided URLLC Systems

The adoption of additional network elements such as unmanned aerial vehicles (UAVs) and reconfigurable intelligent surfaces (RISs) as enablers for URLLC has also been explored in the literature. For instance, [208] discusses UAV-enabled networks with special emphasis on the research advancements in UAV-enabled URLLC networks. In addition, [132] investigates the average achievable rate and error probability of RIS-aided systems in the finite blocklength (FBL) regime considering industrial URLLC scenarios as a specific application. The combination of UAVs and RISs to deliver short packets is explored in [261], which also proposes a computationally efficient optimization algorithm to minimize the total decoding error rate and find the optimal position and blocklength of the UAV.

1.3.10 URLLC Evolution Towards 6G

The URLLC evolution towards 6G will impose higher reliability, lower latency, and additional QoS guarantees. Moreover, URLLC is expected to expand into multiple service classes combining the three basic service classes of 5G, giving rise to extreme URLLC, scalable URLLC, and broadband URLLC [24], [250]. The work in [241] examines the limitations of 5G URLLC and the key research directions for URLLC evolution towards 6G. It envisions that this evolution will leverage recent advances in ML for faster and more reliable data-driven predictions, utilize non-radio frequency signals to enhance the reliability, and emphasize communication and control co-design as a holistic system-design principle. On a similar note, [198] discusses the main drivers, key requirements, and potential enabling technologies for both MTC and URLLC towards 6G. Focusing specifically on future URLLC deployment in industrial production modules, robots, and vehicles, the design of short-range wireless isochronous real-time communication capabilities in a sub-network aimed at life-critical applications in future 6G networks is presented in [15]. We note that a special issue on the evolution of URLLC in the 6G era, entitled "xURLLC in 6G: Next Generation Ultra-Reliable and Low-Latency Communications", will be published in the *IEEE Journal on Selected Areas in Communications* [287] in the third quarter of 2023. This special issue will contain twenty articles covering different aspects of next-generation URLLC, including novel methodologies and innovative technologies needed to solve the resulting research problems.

1.4 Motivation of This Monograph

Despite the timely contribution of the relevant works on URLLC listed above (and other similar surveys/tutorials on this topic), there are still three important gaps in the literature. First, there is a lack of a comprehensive and unified coverage on the communication- and information-theoretic fundamentals of URLLC, as well as the theoretical tools that can be used to analyze it and design its various enablers, despite being covered sporadically in a number of articles. Second, there is room to provide a meta-level understanding of the motivations and the theoretical basis behind the wide range of URLLC enablers discussed in the literature. Third, few of the existing works discuss how (some of) the various enablers interact with each other and how they can be successfully combined into a solid and sustainable system design. This monograph aims at filling these gaps by presenting a complete, self-contained overview of URLLC, including the motivation, foundations, enablers, system design, and evolution towards 6G. It is written at a level of details approachable to an average early-stage researcher, treating the subject matter in sufficient details.

1.4.1 Contributions

The main contributions of this monograph can be summarized as follows.

- In this section, we provide an introduction to MTC, URLLC, and the 5G NR standardization aspects, including the historical motivation behind URLLC, and the detailed research challenges of ensuring high reliability and low latency simultaneously.

- In Section 2, we discuss the communication- and information-theoretic foundations of URLLC and the differences with classical information theory. Specifically, Section 2.1 describes the design challenges for URLLC, explaining the sources of randomness, impact of fading, and key properties. Section 2.2 focuses on the communication-theoretic aspects of URLLC, describing the transition from average capacity to outage capacity and age of information (AoI). Section 2.3 presents the information-theoretic aspects of URLLC, including the fundamental limits of multiple access channels, FBL theory, control and data encoding in short packets, channel codes for FBL transmission, and variable length codes for short packets with feedback. Lastly, Section 2.4 defines the fundamental trade-off between high reliability and low latency, describing the effective capacity and energy efficiency, the rate-reliability-latency trade-off, and the trade-offs at the MAC layer.

- In Section 3, we present some key URLLC enablers. Specifically, Section 3.1 describes the URLLC enablers from a system design perspective, including specific high-reliability and low-latency enablers. Section 3.2 focuses exclusively on multiple-input multiple-output (MIMO) communications for URLLC, illustrating statistical channel modeling, channel estimation and beamforming design, massive MIMO, joint transmission coordinated multipoint (JT-CoMP) and cell-free massive MIMO, and high-frequency communications. Lastly, Section 3.3 presents URLLC-grade resource allocation, covering bounds and distribution tails, extreme value theory, risk management, and meta probability.

- In Section 4, we present uplink multiple access and user scheduling protocols designed to meet the challenges associated with URLLC. Section 4.1 describes grant-based multiple access schemes, including the conventional grant-based scheme, semi-persistent and preemptive scheduling, and fast-uplink multiple access. Section 4.2 discusses grant-free uncoordinated access, focusing on enhanced collision avoidance/resolution, enhanced multi-user detection, and their co-design. Section 4.3 focuses on schemes based on non-orthogonal multiple access (NOMA). Section 4.5 deals with massive and random access in the FBL regime. Lastly, Section 2.2.2 introduces latency- and AoI-aware scheduling.

- In Section 5, we show several concrete examples of URLLC system design building on some of the tools and enablers characterized in the previous sections. Section 5.1 presents an integrated functional architecture for special-purpose URLLC network focusing on the lower Open Systems Interconnection (OSI) protocol layers. Section 5.2 discusses the power control with reliability guarantees in the FBL regime and provides quantitative insights on the extra power that is needed in comparison with the conventional Shannon (asymptotic) approach. Section 5.3 introduces and analyzes the rate and power allocation in single-antenna NOMA networks, which are exploited to support per-user reliability requirements. Section 5.4 describes an AoI-aware resource allocation scheme for vehicular networks based on multi-agent, multi-task reinforcement learning, where the proposed design based on ML achieves significantly low average AoI. Lastly, Section 5.5 describes the AoI minimization in energy harvesting and spectrum sharing enabled 6G networks.

- In Section 6, we present an outlook on the evolution of URLLC towards dependable communications that is expected in 6G wireless systems and describe the key ingredients of future wireless communication systems. Section 6.1 provides an educated prediction of what 6G will be, including its key drivers, requirements and key performance indicators (KPIs), and broadband enablers for URLLC. Section 6.2 describes the expected transition from the URLLC to the more general concept of dependable communications, presenting a number of key dependability attributes and the corresponding tools from reliability theory. Lastly, Section 6.3 discusses TSN, from the wired version applied in Industry 4.0 to its wireless evolution that is currently under development as TSN-over-5G.

The content of this monograph is covered in a self-contained manner. Except for a basic background in wireless communications, no other prerequisite knowledge is required from the reader. Both fundamental concepts and more advanced research-oriented topics will be presented. The structuring is purposely chosen to strike a balance between the communication-/information-theoretic foundations and the practical aspects of URLLC, with the main objective of producing a monograph that will appeal to a wide audience base. Each section ends with a list of key points, which provide a summary of the section and can be used by the reader to decide what to read in detail.

1.4.2 Target Audience

This monograph has three main groups of target audiences in mind.

- *Early-stage researchers* intending to embark on URLLC research. This monograph will provide a thorough and comprehensive background on the subject, a complete picture of the landscape of current URLLC solutions, and some insights on existing and future interesting open research questions. We will pay attention to restrict the level of mathematical details within the reach of an average early-stage researcher.

- *Graduate students* intending to get an introductory overview of URLLC and the related concepts. They may selectively approach the first part of this monograph (i.e., skipping some of the theoretical and mathematical details) without any loss of general comprehension.

- *Researchers and professionals* (from both academia and industry) interested in the state-of-the-art, the research challenges, the 5G NR standardization aspects, and the expected evolution of URLLC may use it as a comprehensive reference on URLLC.

More generally, anyone in the field of wireless communications for 5G and beyond-5G systems, from newcomers to experts, will benefit from this monograph. Due to the wide spectrum of current and emerging URLLC applications and the growing interest in beyond-5G and 6G wireless systems, we believe this monograph will attract a huge interest from both academia and industry as well as a large number of citations.

1.5 Key Points from Section 1

- MTC, which comprises scenarios where machines communicate with each other or with the network in the absence of direct human involvement, can be broadly categorized into mMTC and URLLC. These, together with eMBB, are novel service classes introduced in the 5G NR standard.

- MMTC refers to communications involving a massive deployment of sensors or IoT nodes with relatively relaxed QoS requirements, whereas URLLC mandates very high reliability and low latency to support mission-critical applications.

- Designing URLLC solutions to simultaneously guarantee reliability in the order of 99.999% and E2E latency in the order of 1 ms requires a sharp departure from the conventional communication-theoretic foundations conceived on the basis of the average performance.

- URLLC use cases include connected industries and automation, massive DT, swarm networking, and immersive experience.
- This monograph presents a comprehensive coverage of the URLLC subject. In Section 2, we discuss the communication- and information-theoretic foundations of URLLC. In Section 3, we present some key URLLC enablers. In Section 4, we present uplink multiple access and user scheduling protocols. In Section 5, we show several concrete examples of URLLC system design. Lastly, in Section 6, we present an outlook on the evolution of URLLC towards dependable communications that is expected in 6G wireless systems.

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