

BEYOND 5G URLLC EVOLUTION: NEW SERVICE MODES AND PRACTICAL CONSIDERATIONS

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Abstract – *Ultra-Reliable Low Latency Communications (URLLC) arose to serve Industrial IoT (IIoT) use cases within 5G. However, currently, it has inherent limitations in supporting future services. Therefore, in this article, based on state-of-the-art research and practical deployment experience, from two distinct test networks from Finland and South Korea, we introduce and advocate for three variants of critical Machine-Type Communications (MTC), namely, broadband, scalable and extreme URLLC. Moreover, we discuss use cases and key performance indicators and identify two critical technology enablers for each new service class. Finally, we bring practical considerations from the IIoT testbed and provide an outlook towards new research directions.*

Keywords – Beyond 5G, industrial IoT, service modes, testbed, URLLC

1. INTRODUCTION

Mobile communication technologies have experienced great success since their inception for the current Fifth Generation (5G). 5G technologies continue their evolutionary path after 2020 (beyond 5G, B5G) to extend the service scenarios and features, finally converging to the Sixth Generation (6G) by 2030. Research groups have commenced their research initiatives into 6G communications [1-3]. Global 6G research activities are proliferating, aiming to shape what 6G will be. Triggered by the 6G Flagship in Finland, in June 2019, the IMT-2030 Promotion Group was established in China. In June 2020, Japan published its B5G promotion strategy, and, in August 2020, Korea announced its 6G R&D strategy. More regions are likely to join efforts for B5G from 2021 under international coordination. With the emergence of 6G, the networks will deliver new services to satisfy unprecedented requirements and user experiences, enabling the vision of a data-driven connected society.

In this evolutionary path, 5G major services, namely enhanced Mobile Broadband (eMBB), Ultra-Reliably Low Latency Communication (URLLC) and massive Machine-Type Communication (mMTC), are being pushed against stricter requirements giving rise to new Key Performance Indicators (KPIs) (e.g., End-to-End (E2E) latency and reliability,

positioning, mobility, energy consumption and coverage) due to increased demand of emerging services such as holographic telepresence, digital twins, industrial automation, remote surgery, extended Reality (XR), pervasive connectivity and tactile communications. In addition, industry 4.0 has triggered the combination of operation and information and communication technologies with Cyber-Physical Systems (CPSs), accelerated by advanced wireless communications and Industrial Internet of Things (IIoT) services. Such demands motivated the 3rd Generation Partnership Project (3GPP) to standardize service requirements and critical features to support various vertical domains. IIoT is one of the solid pillars for 5G and B5G, as evinced by 3GPP ongoing work on enhanced features of IIoT and URLLC proposed in Release 17 [4]. These are the first steps towards attending IIoT and B5G requirements despite these efforts.

Current 5G URLLC technology has inherent limitations to fully support future services with a stricter data rate, connectivity and latency requirements. These shortcomings emerge because the three services in 5G have conflicting configurations that should evolve to support a holistic framework. URLLC evolution requires less than 1 ms latency and reliability higher than $1 \cdot 10^{-5}$ (five 9s). At the same time, it should address higher data rates and massive connectivity. To cope with conflicting configuration and timely evolution, we

propose three URLLC variants: broadband, scalable and extreme, as illustrated in Fig. 1.

- **Broadband URLLC** comprises a blend of URLLC and eMBB requirements.
- **Scalable URLLC** incorporates the features of legacy mMTC, and
- **Extreme URLLC** deals with the strictest requirements.

Next, for each of the proposed URLLC variants, we detail the drivers, use cases and technical requirements.

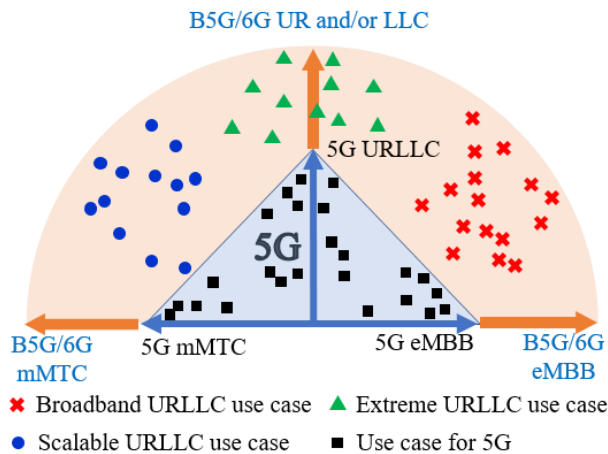


Fig. 1 – URLLC evolution and new service classes: broadband, scalable and extreme URLLC.

2. URLLC EVOLUTION – SYSTEM DESIGN PERSPECTIVE

2.1 Drivers and use cases

5G provides connectivity to various verticals under the three usage scenarios (i.e., eMBB, URLLC and mMTC). However, it cannot still deliver a realistic, volumetric and immersive sense of experience. One of the critical drivers for URLLC evolution is the tactile Internet, which relies on CPS and cyberspace concepts to become a reality and gain market penetration [5]. The tactile Internet branches into broadband immersive and narrowband with haptic feedback [6]. The cyberspace-based tactile Internet involves advanced video transmission, while the latter only requires control of information exchanges. For example, humans feel as if, beyond observation, they touch and directly interact with physical objects on the other side of the network. Such an effect emerges from the combination of advanced video technologies, e.g., 360-degree stereoscopic Ultra-High Density (UHD) with six degrees of freedom (6DoF), and haptic feedback, e.g., arising from various tactile sensors. The CPS-based

tactile Internet enables the implementation of digital replicas, e.g., using advanced video technology, in one place. While connected to its physical object at another location through the network, someone manipulating (using wearables) the digital replica has the same effect on the physical object. Haptic feedback helps people participate and interact with the actual physical object quickly.

URLLC service classes cover many other use cases related to future Intelligent Transport Systems (ITSs), future factories and control of unmanned swarms of aerial vehicles or robots. Among ITS, autonomous driving is a prominent example of combining sensors, cameras, radars, Artificial Intelligence (AI) and Vehicle-to-everything communication (V2X) technologies. V2X plays a pivotal role in providing car-mounted AI with the environment of smart roads, automated highways, or smart autonomous intersections.

Based on the gathered data from its sensors and environments, real-time AI enables (once deemed impractical) autonomous driving. However, 5G cannot fulfil some of the envisioned future factory architecture use cases. For instance, factory automation demands an E2E latency of less than 0.5 ms and extremely reliable Block Error Rates (BLERs), e.g., $1-10^{-9}$. Table 1 shows some representative URLLC evolution use cases expected in B5G systems.

2.2 Key Performance Indicators (KPIs)

Simultaneously providing human sense-related services to multiple users requires more stringent KPIs to satisfy the heterogeneous URLLC service classes than homogeneous classes in 5G. Thus, the URLLC evolution began in Release 17 of 3GPP after completing 5G Phase 1 (Release 15) and Phase 2 (Release 16) technical specifications. Phase 1 mainly focused on eMBB, and Phase 2 handled mMTC and URLLC. 5G Phase 2 URLLC supported vertical industries starting with industrial automation. URLLC evolution will support more diverse vertical industries and improved use cases. The URLLC evolution no longer focuses solely on low latency and high reliability. New emerging use cases demand URLLC, eMBB and mMTC characteristics (high traffic volume or high user density) either individually or simultaneously. Fig. 2. illustrates the service class evolution compared to a 5G URLLC and presents an overview of the critical KPIs towards 6G. Moreover, Table 2 compares 5G URLLC and URLLC evolution use cases

and their respective KPIs based on the standardization activities from Release 15 to Release 17 [7], [8]. Even though latency and reliability are inherent in URLLC, the evolution encompasses conventional KPIs and introduces new KPIs. Fig. 2 also shows energy efficiency and security as critical KPIs. However, due to conciseness, we point the reader towards [3,5] for a comprehensive discussion on those KPIs.

Reliability: URLLC envisions replacing wired with wireless connections, while maintaining wireline quality. This vision aligns with demands from manufacturing and medical use cases with haptics. For example, as shown in Table 1, telesurgery, automated guided vehicles, and manufacturing processes for future factory automation require reliability up to $1 \cdot 10^{-9}$ (contrasted with the current 5G BLER target of $1 \cdot 10^{-5}$).

Low latency: E2E Round Trip Latency (RTL) measures the time required to transfer information between application layers at the source device and destination. It includes request, reply, and all propagation and processing delays. For example, tactile Internet haptic feedback requires E2E RTL within 20 ms to prevent cybersickness. On the other hand, haptic steering requires stringent E2E RTL. For instance, the reaction time of the touch screen must be within 1 ms to achieve an unnoticeable displacement of 1 mm between the finger and the object to be moved [10]. To achieve such short E2E latencies, every protocol layer from both sides of RAN and core should strive to reduce its latency.

Scalability: It supports several (10s of thousands) URLLC connections with distinct requirements. In addition, it requires novel orthogonal and non-orthogonal heterogeneous resource allocation solutions for service coexistence.

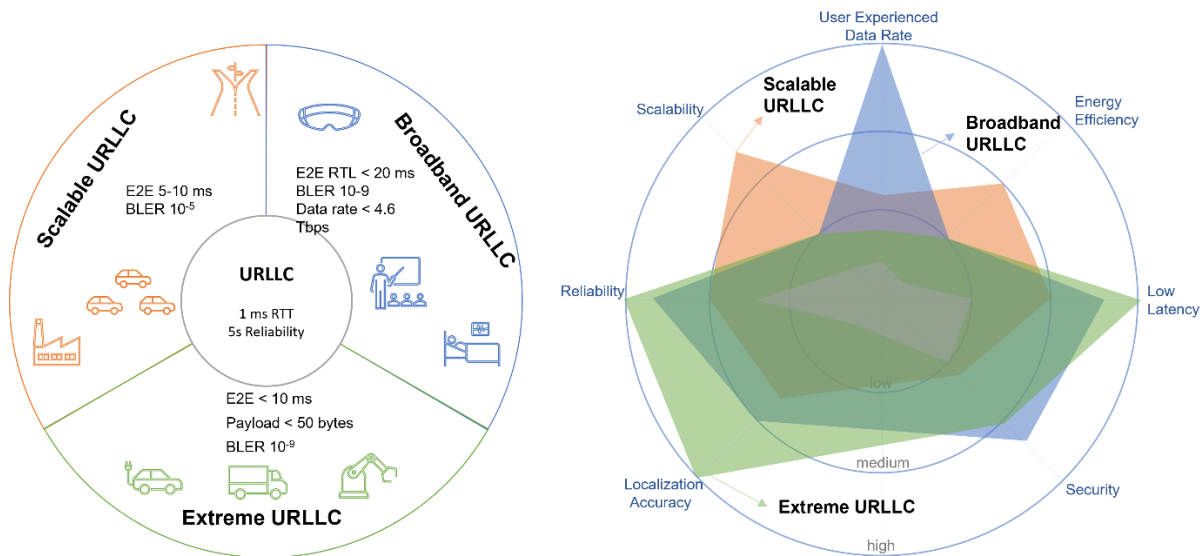


Fig. 2 – (left) URLLC new service classes and typical KPIs. (right) A spiderweb of the critical KPI towards 6G [1-3]. 5G URLLC KPIs are depicted in the centre as a comparison.

Table 1 – URLLC evolution: new service classes use cases and KPIs. The cycle time includes the downlink and uplink transport time and their application layer process time at the factory site.

Applications		Use cases	KPIs [2,7-8,10-12,19]	Class
Broadband tactile Internet with haptic feedback	CPS-based	Telesurgery, remote driving	E2E RTL < 20 ms BLER 10 ⁻⁹ Data rate > 10 Gbps	Broadband URLLC
		Holographic telesurgery	E2E RTL < 20 ms BLER 10 ⁻⁹ Data rate < 4.6 Tbps	
	Cyber-space based	Digital real estate, eCommerce, eTourism, eConference, eEducation, eGames	E2E RTL < 20 ms BLER 10 ⁻⁵ - 10 ⁻⁶ Data rate > 10 Gbps	
		Holographic education/training	E2E RTL < 20 ms BLER 10 ⁻⁵ - 10 ⁻⁶ Data rate < 4.6 Tbps	
	CPS-based	Cooperative factory automation	E2E RTL < 20 ms	Scalable

Applications		Use cases	KPIs [2,7-8,10-12,19]	Class
Narrowband tactile Internet with haptic feedback	Others	Wearables/exoskeletons for healthcare, heavy-labour, and mission-critical	BLER $10^{-5} - 10^{-6}$	
Future ITS	Fusion	Autonomous driving	E2E 5-10 ms	
	V2X	Smart highway, Smart road, Smart intersection	BLER 10^{-5}	
Future factory	Factory automation	Motion control	Cycle time < 0.5 ms Payload <50 bytes	Extreme URLLC
		Automated guided Vehicles	E2E 10-50 ms Payload < 300 bytes BLER $10^{-6}-10^{-9}$	
		Manufacturing process	E2E < 10 ms Payload < 50 bytes BLER 10^{-9}	

Table 2 – Standardization phases for 5G URLLC use cases and KPIs (based on [2,7-8,10-12,19])

3GPP Rel.	Service (use cases)	URLLC KPIs		eMBB KPIs	mMTC KPIs	New KPIs
		Reliability (%)	Max E2E Latency (ms)	Data Rate (Mbit/s)	Connection Density (UEs/km ²)	Clock Synchronicity (μs)
Rel.15 (5G Phase 1)	Discrete/Process automation (remote control)	1 - 10^{-5}	10 / 60	10 / 1-100	100,000 / 1,000	Not defined
	Electricity distribution automation (medium/high voltage)	1 - 10^{-5}	40 / 5	10	1,000	
	Entertainment (AR/VR/XR)	1 - 10^{-5}	7 - 15	250	-	
Release 16 (5G Phase 2)	Factory automation (motion control)	1 - 10^{-6}	0.5 - 2	1	100	0.9
	Electricity distribution automation (grid fault – automated switching)	1 - 10^{-6}	5	1.5	20	-
	Central power generation automation (wind power plant – control traffic)	1 - 10^{-9} (wired)	16	-	1,000	-
Release 17 (5G evolution)	Wired to wireless 1Gbps link replacement in factory	1 - 10^{-6}	1	250	2 - 5	-
	UHD video for robotic aided surgery / telesurgery	1 - 10^{-6}	1/20	50,000 / 6,000	1 / 2	50
	Audio streaming live performance/ outside broadcast contribution - uncompressed UHD video	1- 10^{-6} / UL:1- 10^{-10} , DL:1- 10^{-7}	0.75/400	UL: 0.5, DL: 1 / UL: 12,000, DL: 20	100 - 200 / 1	1

Localization accuracy: This becomes a key component in B5G, especially IIoT applications that require precise control of autonomous objects. 5G NR targets a localization accuracy of around cm-level, enabling positioning as a service solution [11].

User experienced data rate: The 5G requirement of the user experienced data rate was 100 Mbps. As the XR technology advances, the data rate requirement becomes much higher. Even if the source data compression was considered in the applications not using the 6DoF, the required data rate of the advanced human perception level and ultimate VR is 11.94, 50.39, and 95.55 Gbps. Full-colour 3D holograph demands a larger bandwidth, up to 1 Tbps [12].

3. NOVEL SERVICE CLASSES IN B5G

We propose three new service classes to meet the demands of URLLC evolution, as discussed in Section 2 and illustrated in Fig. 2. Herein, we detail the crucial components of each new service class.

Broadband URLLC: Smartphones propelled the 4G industry, but they will not play the same role in the 5G era and beyond. We envisage that more advanced and diverse user equipment will appear and drive the B5G industry. Recently, new outstanding technologies are under development in display and user interface, such as 4K/8K UHD, 6DoF, hologram, haptics, wearables, and gesture recognition. These technologies will trigger the development of various types of user equipment and propel the B5G use cases. Ultimately, advanced video devices equipped with a haptic interface could provide users with a realistic, volumetric and immersive sense of experience. Together with video technologies, haptic interaction generates new verticals in every application field. eMBB or URLLC alone cannot meet the demands of these new applications. Hence, the need for a scenario merging their inherent characteristics.

Scalable URLLC: We need to boost connection density while still guaranteeing reliability and low

latency. There is no doubt that the number of connected IoT devices will increase dramatically in the upcoming decade. We expect haptic interfaces, especially in the smart manufacturing industry and the personal health monitoring system, to be mounted on these IoT devices (e.g., sensors, machines, connective vehicles). As a reference, 5G mMTC requirements are, e.g., connection density up to one device per m^2 , an RTL of less than 10 seconds with a payload of 20 bytes, and ultra-low cost. However, scalable URLLC envisions providing users with tangible experience in an ultra-reliable and ultra-responsive manner. Therefore, we expect a much higher connection density, bandwidth, data rate, and low latency experience (in the order of 10 ms) – see Table 2.

Extreme URLLC: Exciting new applications (see Table 2) impose extreme latency and reliability requirements. Extreme URLLC aims to offer deterministic, wired-like connectivity. For instance, Ethernet-based time-sensitive networks guarantee $1-10^{-9}$ reliability and less than 10 ms E2E latency.

4. URLLC EVOLUTION: SIX KEY BUILDING BLOCKS

This section discusses six critical enablers for the new service classes to meet the diverse KPIs discussed in Section 2 and Section 3, and Table 3 summarizes some of the research directions.

4.1 Broadband URLLC

As this service mode requires high data rates, we foresee the need for efficient modulation and coding solutions to handle large packets with reduced decoding complexity. In addition, broadband URLLC will rely on wide bandwidths, available at millimetre wave and THz bands, to meet the required data rates. Next, we discuss some challenges in these areas.

Intelligent modulation and coding: Broadband URLLC services require enhanced spectral efficiency and wider communication bandwidths. Contrary to 5G URLLC, broadband URLLC handles larger packets alleviating the penalty incurred due to finite block-length coding. Modulation and coding schemes help approach the channel capacity. Conventionally, channel coding schemes have been used to maximize channel capacity over binary flat channels. Non-binary codes are beneficial to the lossless reception of coded symbols at the cost of decoding complexity. In addition, interleaving schemes randomize the different error protection

levels of higher-order modulation symbols and multipath fading selectivity. The traditional code design based on the coding theorem utilizes the mapping between the selectivity profiles and the achievable code rates. For instance, the polar code constructions could be designed depending on the fading selectivity under successive cancellation decoding [13]. Recently, code constructions have been designed using Artificial Intelligence (AI) techniques such as reinforcement learning and a genetic algorithm. AI-driven approaches are suitable solutions for finding the best code in a flat channel. Inferring the effective Signal-to-Noise Ratio (SNR) from the pairs of the channel profile and a code based on statistical approaches yields further coding gain. Non-binary codes are beneficial to the lossless reception of coded symbols despite increased decoding complexity.

Terahertz (THz): Broadband URLLC services require wide frequency bandwidths potentially available in millimetre and THz frequency bands to deliver mobile broadband within ultra-low latency [9]. Land mobile and fixed services shall operate in some frequency bands between 275–450 GHz. A higher carrier frequency shortens coverage due to increased path loss. Ultra-massive MIMO provides coverage extension through denser antenna arrays by boosting beamforming gain and improved spectral efficiency by offering higher spatial resolution. Multiple-point transmission and specular reflecting surfaces can handle propagation blockage. Channel measurements in THz bands are not comprehensively available to identify their full characteristics. The channel modelling should help promote physical layer design by incorporating reconfigurable intelligent surfaces [14]. As the THz band scales up the number of subcarriers, the peak-to-average power ratio and the complexity of the Fourier transform increase. Accordingly, wider subcarrier spacing or single carrier modulation are potential solutions to address these challenges of THz communications.

4.2 Scalable URLLC

As the number of URLLC users grows in scalable URLLC, the Channel State Information (CSI) acquisition overhead becomes unattainable. We identify fingerprinting mapping and efficient random access as promising solutions to mitigate such an issue, as we shall detail next.

Fingerprinting mapping: In an average sense, the CSI acquisition relies on Reference Signal (RS)-based channel measurements and reports.

Therefore, channel measurements may be unreliable if the radio link undergoes instantaneous deep fading. For eMBB services, HARQ retransmission and open-loop link adaptation schemes guarantee link reliability. On the other hand, a URLLC service's link reliability resorts to frequent RS transmission and measurement reports and large scheduling margins despite reduced spectral efficiency. Furthermore, in massive URLLC devices, the limited resources are not enough to handle substantial control overheads. Therefore, scalable URLLC requires enhanced CSI acquisition schemes to meet the stringent latency and reliability requirements and scalable connections. One new approach is position-based CSI acquisition. Fingerprint-based positioning estimates location information using a fingerprint map based on statistics of channel status, i.e., Received Signal Strength (RSS), Angle of Arrival (AoA), Time of Arrival (ToA) and amplitudes and phases of channel coefficients [15]. According to a device's location, the search for the CSI, available in the fingerprint map, does not incur significant control overheads.

Random access: 5G NR employs grant-free access and 2-step random access for URLLC and mMTC services to reduce the control signalling overheads and access latency. However, those access schemes may cause an increased probability of preamble and data collisions without contention resolution and resource scheduling. In [16], NOMA, in conjunction with grant-free access, resolve overlapped transmissions with advanced receivers and further enhance reliability and resource efficiency. However, new challenges arise from resource utilization in handling preamble collisions among scalable URLLC devices with diverse requirements. For instance, the preamble allocation's adaptive algorithms can resort to stability constraints of temporal traffic dynamics.

4.3 Extreme URLLC

To meet the ever more stringent requirements in extreme URLLC, we foresee the use of localization information with distributed multi-antenna systems. In addition, programmable reflective surfaces and efficient coding are promising solutions to enhance diversity towards extreme URLLC.

Location-based, distributed, multi-connectivity: B5G systems foresee evolution towards even higher frequency ranges, wider bandwidths, highly dense deployments, massive antenna arrays, and

reflective surfaces. In turn, these features will enable sensing solutions with fine range, Doppler, and angular resolutions and localization to a cm-level degree of accuracy [17]. Side-information (particularly sensing and location knowledge) can improve wireless communication Radio Resource Management (RRM) procedures. Location-awareness can reduce overhead and latency by helping to predict radio channel quality. The protocol stack can overlay the location information [15]. The physical layer permits mitigating interference, controlling the signalling exchange overhead and reducing the corresponding latency and feedback delay penalties. In addition, position knowledge can reduce the beam management (alignment) overhead and help design proactive beamforming techniques and proactive edge-cloud offloading of expensive computations.

Nevertheless, position information can also improve multi-connectivity resource allocation efficiency by supporting the allocation of parallel stream communications [18]. Thus, spatial and temporal wireless channel prediction becomes crucial for proactive resource management in future wireless networks. As a result, AI/ML solutions are increasingly popular to cope with challenges in wireless communication systems by leveraging the unprecedented availability of data and computing resources.

Ubiquitous diversity: As severe channel variations require a high SNR at the receiver end, transmitting and receiving diversity schemes using multiple antennas and large frequency bandwidth resource allocation are the most powerful tools to lower the SNR loss equivalent to fading margins unless a situation for line-of-sight transmission occurs [18]. In a smart industrial factory, installing massive multiple antennas belonging to the base station is feasible, obtaining spatial receive diversity. A programmable environment can enhance diversity via controllable reflective surfaces or large antenna arrays. However, acquiring space and frequency diversity on the downlink requires careful design considerations. The signal mapping design of a massive transmit diversity scheme in conjunction with wide bandwidth resource allocation could effectively enhance reliability. For extreme URLLC, a channel code with a very low rate is desirable with an expected block error rate (or codeword error rate) lower bound as low as 10^{-9} . To achieve such a figure with a low Signal-to-Interference-plus-Noise Ratio (SINR), a steep waterfall characteristic of

BLER curves with an extremely low error floor is critical. Therefore, a low rate codeword may occupy substantial resources to achieve spatial and frequency diversity needed to meet extreme URLLC

requirements. Since longer channel codewords lead to longer latency, a large bandwidth could help solve the extreme URLLC latency aspects.

Table 3 – Some research directions for the new service modes

	Challenges	Requirements	Tools
Broadband URLLC	<ul style="list-style-type: none"> • Combatting the fading selectivity of the channels for high modulation and coding order • Reducing decoding complexity 	Fading selectivity profile, CSIT, CSIR, QoS requirements	Polar codes, graph and cluster-based decoders, genetic algorithms, reinforcement learning, non-binary codes
Scalable URLLC	<ul style="list-style-type: none"> • Design CSI acquisition solution exploiting statistical channel information in distributed systems serving a massive number of users • Novel random access solutions for massive access with fast preamble resolution 	Local CSIT, global statistical CSI, QoS requirements, traffic, localization	Traffic prediction, joint user detection and decoding, localization, fingerprinting mapping, predictive RRM
Extreme URLLC	<ul style="list-style-type: none"> • Design beamforming solutions exploiting statistical channel information for agile response in distributed systems (e.g., multi-connectivity, distributed MIMO, DAS). • Location-based beamforming directs the energy towards the desired direction with proper phase-shifting 	Local CSIT, global statistical CSI, QoS requirements, traffic, localization, Doppler shift mapping	Traffic prediction, interference mapping, localization, fingerprinting mapping, CSI-limited beamforming, ray-tracing

5. CHALLENGES RAISED FROM EXPERIMENTAL 5G-BASED INDUSTRIAL IOT TESTBED

The current manufacturing industry has undergone a revolution toward smart factories that move from the traditional manufacturing system to connected manufacturing systems that use data to cope with increasing business demands. The smart factory with connected manufacturing systems should be flexible, optimize its performance, self-adapt in real-time, and automatically run entire production processes. The primary role of IoT smart factory is the collection of manufacturing data in a transparent, extensive, and interactive way. Based on 5G URLLC, IIoT can provide wireless data transmissions with very low latency and high reliability and the improved capability for real-time monitoring and control of assets and equipment, quality of processes and factory resources, enhanced flexibility, and self-adaptability in the factory environment.

With the aim of practical implementations, test networks have emerged in recent years. For instance, the 5G Test Network (5GTN –

<https://5gtn.fi/>) is an accessible and flexible academic 5G infrastructure available for trials and demonstrations. 5GTN comprises a radio access network operating on licensed 4G LTE and 5G bands and virtualized evolved packet core, leading to 6GTN, e.g., THz communications.

ETRI developed a 5G-based Industrial IoT Testbed implementing a factory environment demonstrating several smart manufacturing services. In addition, the testbed fulfils the 3GPP's requirements for 5G systems in terms of latency and reliability, and reliability, as illustrated in Fig.3 and Table 4.

ETRI's Industrial IoT Testbed can provide less than 0.5 ms one-way latency over the radio interface, and the transmission reliability over the radio interface is more than $1-10^{-6}$ (BLER) in both UL and DL. In addition, the testbed can support the manufacturing applications with a cycle time of less than 4 ms and accommodate more than one connection/m².

Table 4 – Comparison of measured performance and 3GPP requirements

	3GPP requirements	Achieved performance
One-way latency over the radio interface	0.5 ms in UL 0.5 ms in DL	0.39 ms in UL 0.5 ms in DL
Round-trip end-to-end latency (with MEC)	N/A	3 – 4 ms
Reliability (1-BLER) over the radio interface	99.9999% in UL 99.9999% in DL	99.99993% in UL 99.99995% in DL
Connection density	1 UE/m ² = 900 UEs / (30x30m service area)	Supports more than 900 UEs / (30x30m service area)

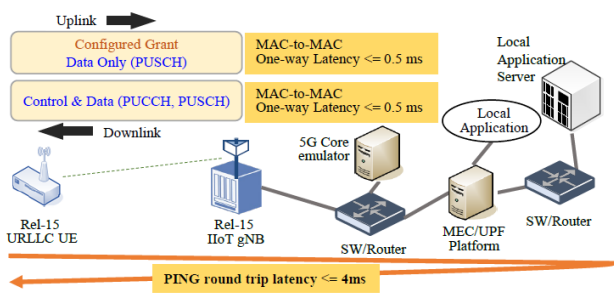


Fig. 3– Configuration of ETRI’s industrial IoT testbed

6. CONSIDERATIONS AND OUTLOOK

Due to the growing demands from various industrial verticals, URLLC must evolve beyond latency and reliability, comprising a more extensive set of KPIs. By encompassing features from mMTC and eMBB, we propose three new service classes: broadband URLLC, scalable URLLC, and extreme URLLC. The new service classes are presented based on such demands with solid support from test network deployments pushing the limits of current standards. For instance, the current 5G standard determines the minimum E2E latency required for some use cases in factory automation and the HMI category as 0.5 ms or 1 ms [7]. Thus, 0.5 ms becomes the one-way latency necessary over the radio interface for 3GPP 5G systems. However, in practice, state-of-the-art ETRI’s IoT testbed, based on the latest 5G release, shows a one-way E2E latency of 1.5 - 2 ms. In this scenario, it is almost impossible to achieve E2E latency (i.e., over the radio interface latency, processing times and other delays across different layers) of less than 0.5 or 1 ms using the current 5G implementation, which motivates extreme URLLC service mode development.

A massive number of floor devices and equipment need simultaneous, real-time monitoring and control in a large-scale factory. Hence, it motivates a higher connection density than the one foreseen in B5G. Although ETRI’s IoT testbed accommodates more than one connection/m², it cannot cover the large area and provide URLLC services to several

devices simultaneously, evincing the need for scalable URLLC.

Current XR applications demand high throughput and low latency to avoid cybersickness. The requirements have become even more strict towards the tactile Internet. In a medical-related trial implemented in the 5GTN, the E2E latency measured utilizing 5G showed less than 10 ms latency and 500 Mbps throughput. These metrics are more extensive than the requirements described in Section 2, which motivates developing broadband URLLC as a service mode.

We have identified key research areas essential for each new mode, leading to many research directions. For broadband URLLC, the desired spectral efficiency and latency urge new coding and modulation schemes, particularly non-binary, lossless codes, besides large bandwidths towards THz. However, very high carrier frequencies bring about challenges related to beamforming and beam management, subcarrier allocation, and energy consumption, besides propagation impairments, e.g., the need for strong Line-of-Sight (LoS). For scalable URLLC, it is imperative to reduce the overhead signalling for random access, CSI acquisition, and scheduling, leading to increased latency and low reliability and throughput due to, e.g., collisions. Traffic-based predictive radio resource management emerges as a strong candidate solution able to deal with dynamic traffic and the massiveness of the network. To support extreme URLLC, we foresee the need for ubiquitous diversity and multi-connectivity, in which beamforming and connection rely on the position knowledge as side information to enhance robustness. Based on the growing demands and supported by real test network deployments, the need for the proposed service classes is evident. Finally, we point out many open research questions (e.g., related to the trade-offs between latency, reliability, scalability, localization accuracy and data rate) instrumental to the URLLC evolution.

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