REMOTE MONITORING OF SMART FACTORY OVER AN INTERCONTINENTAL LINK: VISTAS FROM ETRI-OULU COLLABORATION PROJECT

Nurul Huda Mahmood[1*], Hossein Rezaei[1], Gweon Do Jo[2], Hyun Kyu Chung[2], Ari Pouttu[1] and Matti Latva-aho[1]

[1]Centre for Wireless Communications, University of Oulu, POBOX4500, Oulu 90014, Finland
[2]Electronics and Telecommunications Research Institute, 218 Gajeong-ro, Yuseong-gu, Daejeon, 34129, Korea

[*]Corresponding author, email: NurulHuda.Mahmood@oulu.fi

Abstract *– While the fifth generation (5G) New Radio wireless system is being deployed across the globe, the wireless research community has started exploring what will the sixth generation (6G) be? 6G is expected to cater to societal and economic needs by integrating the biological, physical, and virtual worlds with the networks. The notion of multi-service communication introduced in 5G will be further diversified and expanded to include new service classes representing novel and emerging use cases that were not considered as a part of the 5G landscape. Ultra-reliable low-latency communications (URLLC) and their evolution in 6G are of particular interest given their prominent role in enabling future industrial Internet of Things (IIoT) applications. During 2020 – 2022, ETRI from South Korea and the University of Oulu from Finland convened a joint project to explore URLLC evolution towards the 6G era. This article summarized the key highlights of the project and outlines its main findings. The project involved a study of future URLLC service classes and their potential enablers, along with a demonstration of remote monitoring of a smart factory over an intercontinental link. The project's proof-of-concept was able to demonstrate remote monitoring of ETRI's IIoT testbed from Finland at sub-300 ms service round trip time.*

Keywords *– 5GTN, 6G, beyond 5G, industrial Internet of Things, smart factory, URLLC.*

1. INTRODUCTION

Since their inception, mobile communications networks have historically catered to predominantly human users. The current Fifth Generation (5G) New Radio (NR) initiated a shift from this paradigm by introducing two novel service classes dedicated to machine type communications (MTC), namely ultra-reliable low-latency communications (URLLC) and massive MTC (mMTC). This paves the way towards having a single wireless system providing wireless connectivity to a wide variety of applications in various vertical sectors.

Since the world's first commercial success of 5G NR in Korea and its subsequent launching around the globe, the research community is continuing investigation into its evolution in beyond 5G (B5G) to extend the service scenarios and features. The objective is to finally converge to the next phase of mobile communications, the Sixth Generation (6G), by 2030. The first large-scale 6G research project – 6G Flagship[1] – was initiated by the University of Oulu in 2018 [1]. Since then, global 6G research activities are proliferating, aiming to shape what 6G will be in the long term while 5G NR continues to evolve with further refined scenarios, service classes and solutions [2] [3] [4] [5].

URLLC is arguably the most challenging of the three 5G NR service classes due to its stringent requirements. It mainly targets Industry 4.0 and other similar verticals requiring highly dependable connectivity [6]. Industry 4.0 focuses on two growing needs: *mass customization* and *efficiency*. The former requires flexible production lines that can dynamically adapt to the production demand; whereas the latter requires greater flexibility to execute different production orders such that the production capacity is not underutilized. Towards this end, it is desirable to have a single open, flexible, and converged network architecture.

The URLLC service class and its enabling technologies introduced in the first 5G NR release are merely the first steps in this direction, and further evolution and advancements are needed to meet the final goal. The increased demand of emerging services such as holographic telepresence, digital twins, industrial automation, remote surgery, extended reality (XR), pervasive connectivity, and tactile communications is pushing URLLC against stricter reliability and latency requirements, as well as giving rise to new key performance indicators (KPI)s (e.g., end-to-end (E2E) latency and reliability, positioning, mobility, energy consumption, and coverage). Therefore, URLLC technologies in B5G and 6G networks should include various mechanisms to enable a converged wireless network that can provide end-to-end seamless quality

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[1] https://www.6gflagship.com/

of service (QoS) guarantees for Industry 4.0 and other similar applications [7].

As major research and development (R&D) entities in South Korea and Finland, ETRI and the University of Oulu (UOULU) held the first research collaboration project on 6G between the two countries from May 2020 to April 2022. The project specifically investigated URLLC evolution in B5G/6G networks and demonstrated remote monitoring of ETRI's Industrial IoT (IIoT) testbed from UOULU's 5G test network (5GTN) over an inter-continental connection. The highlights and the lessons learnt from this recently concluded project are presented in this paper.

The rest of this paper is organized as follows. To cope with conflicting configuration and timely evolution, we propose three URLLC variants in Section II, namely broadband, scalable, and extreme URLLC. Section III presents two URLLC enabling technologies: fast polar encoder/decoder for short packet transmissions, and a predictive link adaptation scheme. The remote control of ETRI's IIoT test bed from 6G Flagship's 5GTN is detailed in Section IV, before finally concluding the paper in Section V.

2. URLLC EVOLUTION – SYSTEM DESIGN PERSPECTIVE

2.1 Drivers and Key Performance Indicators

The development of IIoT use cases towards the 6G era is motivated by various drivers spanning across multiple vertical sectors. A few relevant use cases and their corresponding key performance indicators (KPI) are highlighted in this sub-section.

Massive digital twinning: 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. DTs operate through a vast array of IoT devices collecting real-time and multisource data, which will in turn require dependable wireless connectivity solutions with high data rates [8]. ***Swarm networking:*** Self-driving vehicles on the shop floor, e.g., automated guided vehicles (AGV), rely heavily on wireless communications for critical applications such as collision avoidance and control information interchange [9]. Such autonomous collaborative tasks will require many sensors, actuators and edge systems integrated within the autonomous vehicles and communicating with one another, thereby increasing the demands on the scale, complexity and QoS of the connectivity. ***Immersive experience:*** The ability to transmit multisensory 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 [5]. Such applications will truly push to a new service domain requiring broadband connectivity with URLLC guarantees.

Since the URLLC evolution will support more diverse vertical industries and improved use cases, low latency and high reliability will no longer be the sole KPI. New emerging use cases demand more stringent targets for these KPIs along with novel KPIs. For example, applications like AGVs and high precision manufacturing processes for future factory automation require reliability up to $1\text{-}10^{-9}$, in contrast with the current 5G target of $1\text{-}10^{-5}$. Similarly, Tactile Internet haptic feedback requires E2E round trip latency (RTL) within 20 ms to prevent cybersickness, which translates to link-level latencies below 1ms [10]. In terms of the novel KPIs, URLLC services in B5G/6G networks will need to support scalability (i.e., supporting a large concentration of devices), high data rates [11] and high-precision localization [12], among others.

2.2 Novel Service Classes in B5G

In order to support the emerging IIoT use cases and their novel KPI requirements, we propose three extensions of the URLLC service class in B5G/6G networks, as illustrated in Fig. 1. These are:

i) **Broadband URLLC** catering to scenarios requiring ultra high definition data rates of at least 25 Mbps for two-way telepresence, $1\text{-}10^{-3}$ to $1\text{-}10^{-5}$ reliability and below 5 ms latency to avoid cyber-sickness.

ii) **Scalable URLLC** for applications requiring URLLC connectivity for many devices. The reliability and latency requirements will be similar to 5G NR (i.e., around $1\text{-}10^{-5}$ reliability and 1 ms latency), albeit with a connection density of up to 10 devices/m^3.

iii) **Extreme URLLC** catering to exciting emerging applications requiring deterministic, wired-like connectivity, for instance, reliability guarantees in the order of $1 - 10^{-7}$ 1to $1 - 10^{-9}$, along with sub-ms latency. However, the data rate and connection density requirements in this case are expected to be moderate.

3. KEY TECHNOLOGY ENABLERS OF URLLC EVOLUTION IN 6G

The new URLLC evolution service classes introduced in Section II will be realized by adopting novel technology enablers in 6G. One such enabler investigated in the joint ETRI-UOulu collaboration project is briefly discussed in this section.

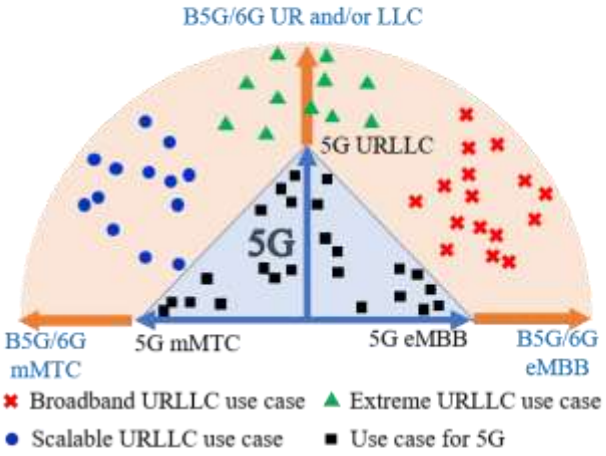

***Fig. 1** – New URLLC evolution service classes: broadband, scalable and extreme URLLC.*

3.1 Coding for Short Packets

URLLC services, especially extreme and scalable URLLC, will mostly require short payload transmissions. This calls for a rethinking of the channel codes, which have been traditionally designed for large packets. Polar codes have been approved by 3GPP as a channel coding scheme for short packet transmission in 5G and beyond. Polar codes can achieve the binary memoryless channel capacity with an explicit construction and can be implemented with low complexity using successive cancellation (SC) decoding algorithm ***[13]***.

A polar code $P(N,k)$is a code sequence containing N symbols carrying k information bits. Therefore, the code rate is calculated as $R = {}^{k}/_{N}$. The remaining $N - k$ bits, called frozen bits, are set to a predetermined value (usually zero) at the encoder side. Channel polarization is proposed in [14] as a way to construct code sequences in order to achieve symmetric channel capacity $\big(I(W)\big)$ of binary-input discrete memoryless channel (B-DMC) W under SC decoding. Out of N channels, each channel W_i^N $(1 < i \leq N)$ tends to be either completely reliable $\big(I(W_i^N) \rightarrow 1\big)$ or completely unreliable $\big(I(W_i^N) \rightarrow 0\big)$ as the codelength N grows. Using the polarization kernel $G_2 = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}$ as the mathematical foundation, a polar code of length N can be constructed by the transformation matrix $G_N = G_2 \otimes n$ which is the n-fold Kronecker product of G_2. While for $n \rightarrow \infty$ this construction creates channels that are either perfectly noiseless or completely noisy, for smaller values of n the synthetic channels polarization may be incomplete, generating intermediary channels that are only partially noisy.

The SC algorithm for decoding polar codes can be represented as a depth-first binary tree search with priority to the left branch. The leaf nodes are the N bits to be estimated. The soft information (Log-Likelihood Ratios (LLRs)) on the received code bits is input at the root node, with a decoding complexity of $O(N\log_2(N))$. SC is the very basic decoding algorithm for polar codes and suffers from a large decoding latency. Different approaches have been proposed in various research works to decrease the latency of SC algorithm. The simplified-SC (SSC) is proposed in [15] to increase the decoding throughput with no effect on error-correction performance. Maximum-likelihood nodes (ML-SSC) introduced in [16] could increase the throughput of SSC up to three folds. The work in [17] proposed some new node patterns corresponding to particular frozen-information bit sequences to further prune the binary tree. At the cost of losing some error-correction performance, altering the polar code construction is another way to further reduce the latency of polar codes [18].

In order to further minimize the latency without jeopardizing the throughput, we propose a novel parallelization algorithm called Ultra-Fast SSC (UF-SSC), which parallelizes multiple processing nodes at different levels of the binary tree and prunes it further to decrease the latency [19]. This algorithm is validated by FPGA implementation. **Error! Reference source not found.** summarizes the FPGA utilization and performance comparison of different SSC schemes for an example polar code of length N=1024 and rate R = 1/2. An important point that a designer needs to consider when conducting a hardware implementation, is that the channel and internal LLRs need to be quantized. In **Error! Reference source not found.** the quantization format is considered as $Q\big(Q_i, Q_c, Q_f\big)$, where $Q_i, Q_c,$and Q_f are the number of quantization bits for internal, channel and fraction bit sizes of LLRs, respectively. A bit size of zero for the fraction bits implies that fractions are rounded to the nearest integer. LLR quantization has a minor effect on error-correction performance when we consider proper number of bits. For instance, Fig. 2 compares the frame and the bit error rate of floating-point and quantized performance of UFSSC for a $P(512, 256)$ polar code using (6,6,0) quantization format. The error rates overlap with each other, demonstrating that the effect of quantization is negligible.

4. REMOTE MONITORING OF ETRI'S SMART FACTORY FROM OULU

Alongside the theoretical investigations, the ETRI-UOulu collaboration project also implemented a proof of concept demonstrating the establishment of an intercontinental link to remotely connect ETRI's 5G IoT testbed with UOulu's 5G test network (5GTN).

Table 1: FPGA utilization and performance comparison of P(1024,512) and R = 1/2

Work	FPGA Family	Q (Q_i, Q_c, Q_f)	LUTs	Reg.	RAM (kbits)	f (MHz)	L (CCs)	T/P (Mbps)
[16]	Altera	(6, 5, 1)	23,020	1,024	42.8	103	220	240
[18]	Altera	(6, 5, 1)	23,353	5,814	43.8	103	204	259
Our work	Xilinx	(7, 6, 0)	18,982	3,384	37.7	94.36	123	393

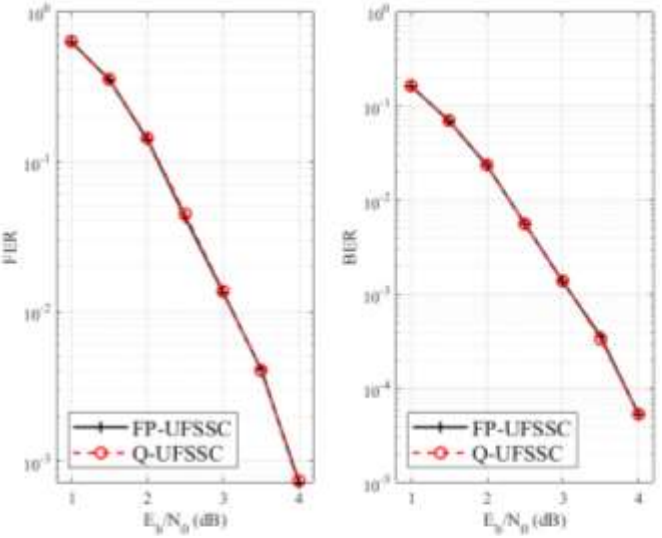

Fig. 2: Floating-point versus quantized FER and BER performance of UFSSC.

4.1 *ETRI's 5G IIoT Testbed*

Based on 3GPP Rel-15/16 5G specifications, ETRI has developed a 5G-based IIoT testbed, which is comprised of NR-URLLC UE, NB-IoT UE, IIoT gNB, EPC and 5G-Core emulator, and MEC platform and then deployed it in a Model Factory environment. The testbed fulfills the 3GPP's requirements for 5G systems in terms of latency and reliability, as illustrated in Fig. 3. ETRI's IIoT testbed can provide less than 0.5 ms one-way latency over the radio interface and the transmission reliability over the radio interface more than $1\text{-}10^{-6}$ (BLER) in both UL and DL. In addition, the testbed can support the manufacturing applications with a cycle time of less than three (3) ms and accommodate more than one connection/m^2.

4.2 *Oulu's 5G Testbed*

University of Oulu's 5G Test Network (5GTN – https://5gtn.fi/) is a carrier-grade accessible and flexible academic 5G network available for trials and demonstrations. The Full-scale 5GTN supports using 5G devices, higher frequency bands, cognitive management functionalities, system testing tools for new solutions. Its feature evolution follows 5G research and standardization progress, acting as verification platform for theoretical 5G research. The cellular devices part of the network is composed of 30 LTE small cells (700 MHz, 2.1, 2.3, 2.6, 3.5 GHz) and 2 macro cells (2.3 GHz). The network has two 5GNR base stations (3.5 GHz) and 5G enabled mobile phones from several vendors. The network is currently being complemented by mmWave (24-28 GHz) 5G NR base stations as well as with 36 remote radio head (RRH) based cloud RAN 5G NR devices.

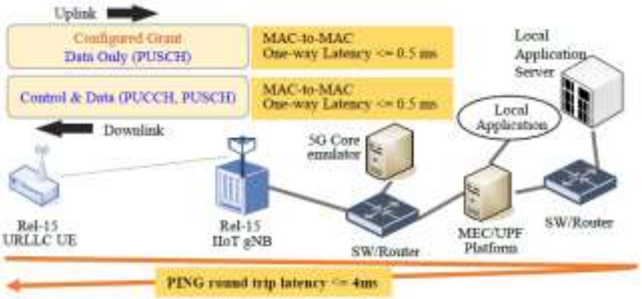

Fig. 3: Configuration of ETRI's industrial IoT testbed

4.3 *Interconnection Service Demonstration*

5G Testbeds in Korea and Oulu are inter-connected via an inter-continental layer 2 virtual private network (L2VPN) connection, as shown in Fig. 4. The average PING Round Trip Time (RTT) between 5GTN and 5G IIoT Testbed in Model Factory is about 280ms. As shown in Fig. 4, two remote control & monitoring office in ETRI (Korea) and UOulu (Finland) are connected to the Model Factory in this demonstration, and the following application services are provided from the remote offices:

Remote Services from Domestic Area (ETRI's monitoring office in DaeJeon, Korea)

- Remote real-time operation of MES (Manufacturing Execution System)
- Remote real-time control and monitoring with portable Supervisory Control and Data Acquisition (SCADA) control panel

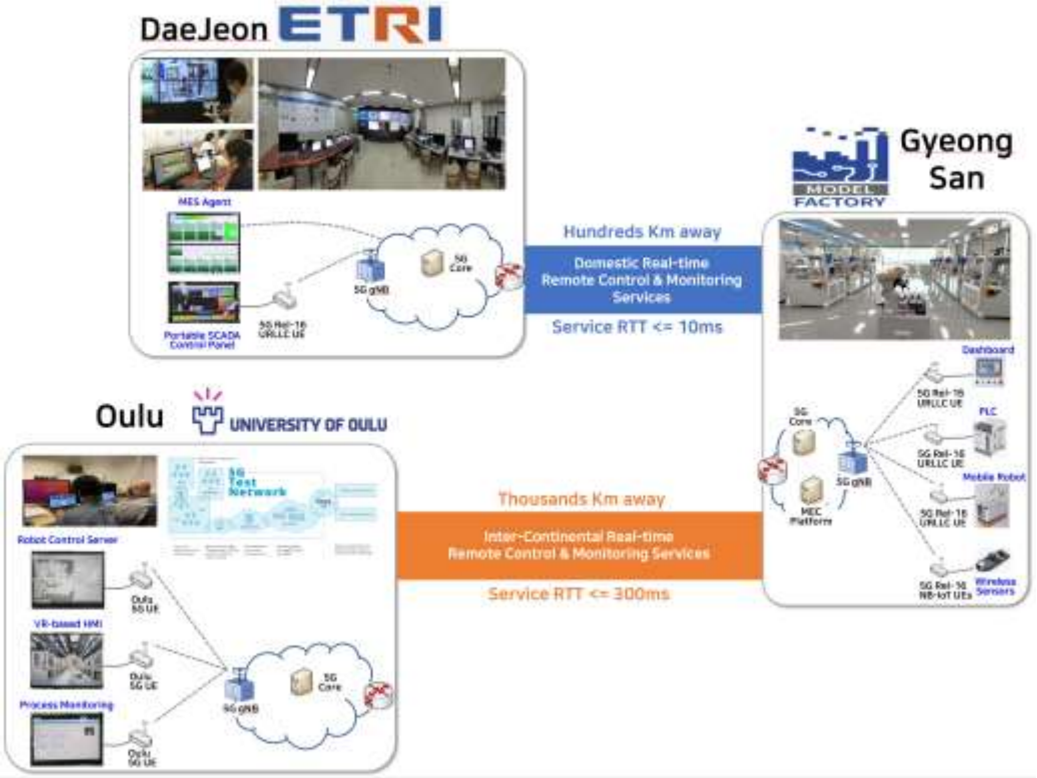

Fig. 3- Remote Service Demonstration

Remote Services from abroad (UOulu's 5GTN in Oulu, Finland)

- Remote real-time control & monitoring of KUKA mobile robot
- Remote real-time factory and process monitoring with VR-based HMI
- Remote real-time process monitoring based on data gathered from wireless sensors in the factory.

Results from the service demonstration reveals that very low service RTT of less than 10 ms can be achieved for the domestic remote monitoring applications in a practical setting, which is sufficient to meet the demands of most emerging scalable and broadband (and even some extreme) URLLC applications.

On the other hand, the service RTT is several hundreds of ms for the intercontinental remote monitoring, due to the large physical distance, and the placement of several interconnect routers between the two end points. Nonetheless, non-critical control applications like controlling KUKA mobile robots and real time process monitoring based on wireless sensor data are still possible. In addition, remote monitoring with virtual reality based human machine interaction was also realized.

5. CONSIDERATIONS AND OUTLOOK

The next generation of wireless network, 6G, will be designed to serve a diverse set of use cases and scenarios addressing important vertical sectors such as IIoT. This paper presented some highlights and an overview of the findings of the joint ETRI-University of Oulu collaborative projectinvestigating what 6G will mean for IIoT networks. Due to the growing demands, URLLC must evolve beyond the latency and reliability comprising a more extensive set of KPIs. To address these emerging needs, we propose three new service classes dedicated to URLLC, namely: broadband URLLC, scalable URLLC, and extreme URLLC. We further present two novel technology enablers for these challenging service classes, such as fast and reliable channel codes for short packets, and predictive resource management algorithms. Finally, we present the experience from our test bed demonstration linking University of Oulu's 5GTN in Finland with ETRI's model factory in Korea. We demonstrate that such intercontinental link can support remote real-time process monitoring based on data gathered from wireless sensors in the factory with service RTT delays of less than 300 ms.

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