5G URLLC evolving towards 6G: research directions and vision

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***Abstract*—** This paper presents a vision and research directions for 5G URLLC evolving towards 6G URLLC. 5G offers fundamental differences from the former generation in that it aims for industrial applications. URLLC, one of the novel service scenarios 5G introduced, addresses stringent latency and reliability requirements for mission-critical and industrial applications. The application of 5G URLLC to smart factories triggers the introduction of a shared factory concept. And URLLC will keep evolving until 6G URLLC emerges in the market with more robust performance around 2030. Although satellite communication has gained significant importance owing to its capability to deliver a broader coverage than terrestrial networks, the application of the LEO satellite mesh network shall be beneficial to reduce the latency over long-distance communication links. LEO satellite mesh network will play a pivotal role in delivering 6G URLLC service.

Keywords—6G, 5G, latency, reliability, URLLC, vision

I. INTRODUCTION

We are living in a connected world thanks to wireless communication technologies, so-called 4G/LTE & 5G. Hundreds of billion things of IoT might be further included in the connections, which means more advanced technologies and communication services shall be infused into our everyday routines [1]. Ordinary people often pose a question about the difference between 4G & 5G. Presumably, they could not have identified truly transformative applications in their smartphones supporting 5G. To give them a quick answer, we need to review the history of mobile communication technologies.

When we look back on the history of mobile comm, all of the new generations typically occur every 10 years. The mobile voice communication service that emerged in the first generation was not of good quality. Users had to put up with frequent call drops, cross talks, and low voice quality. The mobile voice service was not satisfactory to users until the second generation appeared. The second generation (2G) offered much better quality than before thanks to digital technologies. In a similar way, the mobile internet service that emerged in the third generation (3G) was not successful in the market until the fourth generation (4G) appeared in terms of tech and business. 4G has been widely accepted as a fast & stable communication service.

Likewise, the fifth generation (5G) offers some fundamental differences from 4G, and it has implications that will be polished until 6G. The keywords of 5G in terms of services should be industry, vertical, convergence, etc. Industrial application is one of the representative services of 5G. Up until 4G, when the main goal of service has been human-to-human or human-to-machine interaction, most people have enjoyed the advanced features and services that their smartphones offer. However, ordinary people could not have any brand-new transformative services in sight with their 5G phones, because new changes visible through the hand-held phones are just a minor subset of big changes that 5G brings about. In 5G and beyond, the user equipment will be diversified to integrate with vehicles, UAVs, sensors, wearables, HMD, holographic devices, etc [2, 3].

According to the recent trend in the industrial sector, machine-to-machine (M2M) type communication is gaining significant importance. M2M type communication closely relates to mission-critical applications with an emphasis on ultra-reliability and low latency, such as factory automation, unmanned aerial vehicle control, telesurgery, automated guided vehicles, and remote driving. URLLC is one of the novel service scenarios introduced in 5G aiming to address stringent latency (1ms) and reliability requirements (BLER of 10^{-5}) for applications in industrial sectors and their vertical domains [4]. In the next generation wireless services, i.e. 6G, ultra-reliability and low-latency for mission-critical applications shall require ever more stringent requirements.

The rest of the paper is organized as follows: Section II addresses the vision of URLLC application to the smart factory, which will evolve along with 5G and beyond, and introduces the concept of a shared factory. Section IV identifies research directions for 6G URLLC and addresses the application of LEO satellites for reducing the latency over long-distance communication links. We make a conclusion with discussion issues for further studies in Section V.

II. SMART FACTORY AND 5G URLLC

The smart factory is a concept to create a hyper-flexible, self-adapting manufacturing capability. Recent innovations such as AI, big data, automation, industrial IoT (IIoT), robotics, and AR/VR are revolutionizing the manufacturing sectors. They make factories smarter and more efficient than before, which means most current factories have problems and limitations to improve. Smart factory delivers a highly digitized factory. It continuously collects and shares data through connected machines, devices, and production systems. The data can be used by self-optimizing devices or across the factories to address issues proactively, improve manufacturing processes and respond to new demands in the market. IIoT communication networks based on 5G connect people and things systematically during the manufacturing process. We expect the IIoT network plays an important role in realizing the advanced features in the smart factory.

5G wireless technologies support ultra-reliable low-latency communication scheme so-called URLLC. It is significant to support mission-critical applications, especially in the factory. Communication errors & delays can bring enormous loss & confusion in the manufacturing process. 5G-based IIoT network offers a unified solution to provide wireless connections between factory-to-factory, factory-to-office, factory-to-vehicle, factory-to-public internet, and connections among the devices in the factory. As a unified approach to connecting everything, anywhere, anytime supporting ultra-reliability and low-latency simultaneously, 5G is prominent to meet such requirements for Industrial IoT, thanks to the URLLC feature.

We investigated how the 5G can apply to the factory, and how the factory evolves based on the 5G. We envision 5G-based smart factory will be evolving through 3 phases. In phase 1, 5G will apply to the area to which the wired network cannot apply. Mobile robot control, portable devices such as AR/VR HMI, and portable control panels are typical examples requiring wireless connections. Furthermore, it is preferable to connect a massive number of sensors with wireless connections because the wireline requires significant installation costs when the number of sensors becomes enormous. The wireless solution is beneficial to offer flexible and timely deployment. It is possible to deploy almost everywhere in principle and easy to reconfigure the facilities.

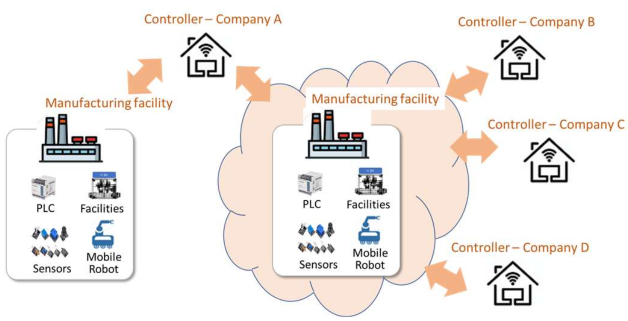

Fig. 1. The concept of a shared factory

In phase 2, we consider a case that 5G URLLC wireless connections are available everywhere outside the factory, 5G enables remote control and monitoring, while the operator is moving everywhere. Then, the control systems do not have to be co-located in the factory. They can be installed almost everywhere. Furthermore, we think of more than remote controlling in phase 2. As we removed control systems, the factory consists of facilities for manufacturing only. Thus, a number of companies having their own control systems can share a certain factory to produce their own products as shown in Fig. 1. This is a typical use case, in phase 2 we identified. The concept of a shared factory has been motivated by the success of sharing economies such as transportation and accommodation. It inherits from the concept of manufacturing resource sharing. The revolutionized mobile communication services and information technologies can help manufacturers share their manufacturing resources on the network with relatively low costs [5].

In phase 3, all of the wireless connections will replace the wireline connections in the factory. I assume this will improve the efficiencies in the industrial sectors so much. Unfortunately, the current 5G technology cannot realize the full wireless factory at the moment, because it cannot outperform the current wireline schemes such as Industrial Ethernet, Profinet, and SERCOS in terms of reliability and latency. We envision that 6G will support 100us latency and 10^{-9} block error rate at least to provide extreme performance comparable to the current wireline schemes. And also, 6G has to support a massive number of devices in a large-scale mega-factory, while all the devices are under real-time control. We expect to see the full wireless factory in the future when 6G emerges around 2030. In this context, we need to do research on the enabling technologies going beyond 5G capability supporting phase 3.

III. Towards 6G URLLC

3GPP identified the requirements for interconnection between terrestrial 5G and satellite systems in release 16 study item of the non-terrestrial network (NTN). 3GPP defined the fundamental functions of NTN based on 5G New Radio in release-17, which supports New Radio based satellite access deployed in FR1(Frequency Range1) bands serving handheld devices for global service continuity. Further enhancements for NTN will be included in release 18 [6].

Leveraging the use of low-Earth orbit (LEO) satellites is one of the fundamental research directions towards 6G services. In this context, wireless terrestrial networks that connect UE's and base stations in 2 dimensions shall evolve to extend their coverage to 3 dimensions supporting connectivity with satellites, UAVs, and aircraft. The use of satellites will support worldwide access to mobile 5G/6G services and drive explosive growth in the satellite industry [6]. It will deliver extensive coverage supporting access to flying taxis, drones, aircraft, ships, and public safety zones with low cost and high-speed data rates.

Low latency for mission-critical applications in 6G shall require ever more stringent requirements than 5G. The current 5G NR system can offer less than 0.5 ms one-way latency over the radio interface and sub-10 ms end-to-end (E2E) latency. The use cases in 6G such as factory automation and remote surgery are expected to require lower than 0.5 ms E2E latency, which is far more stringent than before [7]. Although 5G is a good solution for smart factories, much more stringent requirements are being proposed in the field.

Authors in [8] addressed that the average PING round-trip-time (RTT) between Oulu in Finland and Gyeongsan in Korea measured sub-300ms in the test demonstrating intercontinental factory monitoring using their 5G testbeds. Most latency occurs in the wireline due to the geographical distance and many routers interconnecting fiber optic cables, while only a few tens of milliseconds are spent in the wireless zone. Long distance results in long latency. That is the nature of propagation over fiber and air. Long latency should restrict the scope of feasible URLLC services. In terms of end-to-end latency, the delay in the wireline shall be much longer than that of the radio interface. It implies that the future technologies for URLLC need to incorporate the schemes for optimizing the wireline network to diminish the end-to-end latency.

What can we do for diminishing the long latency that long wireline brings about? The adoption of mobile edge computing (MEC) is a common approach to decrease the end-to-end wireline latency and enhance the quality of experience for end users. However, this paper focuses on the use of low earth orbit (LEO) satellites aiming for low-latency solutions. Satellite communication has been considered to require higher costs with longer latency than land mobile communication. However, the recent technological achievements in the satellite industry have diminished the operation cost of satellites remarkably, and it is not a big deal when using LEO instead of MEO (medium earth orbit) and GEO (geostationary earth orbit) satellites.

In the case of intercontinental connection using fiber optic cables, we cannot expect straight-line deployment from end to end. As we know, global fiber networks are installed underground and under the seas in a quite complicated way. The packets should stop by many routers and detours along with the global topography to arrive at the destination. Furthermore, we need to notice that the propagation speed of the light in optical fibers is about 200000 km/s, i.e. 2/3 of the light speed in the air. The growth of novel commercial solutions providing global internet access using mass satellite constellations is being witnessed in the market. Starlink, one of the large satellite constellations using a low earth orbit to deliver broadband internet, allegedly consists of over 3,300 satellites in low earth orbit with a possible later extension to 42,000. The service provider seems to deliver about 50 Mbps with 40 - 60 ms latency [9-10].

All satellites can communicate with each other directly using inter-satellite links. Real-time links between satellites can promise quicker delivery of data across the globe especially when the links are established as shortly as possible from end to end. The satellite mesh network might outperform the conventional optic fiber networks in a certain condition, or shall be a splendid complement in terms of latency. It is clear that the optimal algorithms for routing inter-satellite links and inter-satellite handover shall be fundamental components for future 6G URLLC applications. Actually, we are familiar with the mesh network, a system of wireless access points that can all communicate with each other thanks to the interconnectivity between all nodes. The routing algorithms used in mesh networks can apply to satellite links in a similar way.

IV. CONCLUSIONS

Satellite communication has gained significant importance owing to its capability to deliver services anywhere, i.e. provide coverage in areas that are unreachable by conventional terrestrial networks. However, we went through the application of the LEO satellite in order to diminish communication latency, especially in long-distance links. The use of satellite communication may not fall within the coverage enhancement only. Compared to conventional optic fiber networks, the inter-satellite links shall be beneficial to long-range communication with lower latency or a good complement at least in terms of the latency. Satellite communication shall be a strong candidate technology delivering 6G URLLC service. As the machine learning technologies have shown great potential in many regions recently, it shall be worth trying to apply machine learning to routing algorithms for inter-satellite mesh networks.

Commercial deployments providing global internet access using LEO satellite constellation are being witnessed in the market. SpaceX, OneWeb, amazon, and Geely are the companies operating commercial satellites to offer global internet access. Their systems are based on their own specifications and protocols, which means it is too early to mention the compatibility among their devices. 3GPP is working on further enhancement of NTN in release-18. It is expected that the NTN standard shall be polished until 6G emerges in the market around 2030. On the commercial launch of 3GPP NTN in the near future, the incompatibility between 3GPP NTN and other commercial systems that have survived in the market shall be an issue. Will 3GPP NTN compete with them or cooperate as a complementary partner for success in the market? That must be a matter of interest for the time being.

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