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A Study on the Current Status and Development Trends of Key 5G URLLC Technologies

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Abstract. With the deepening of digital transformation in all sectors, traditional mobile communications are no longer suitable for meeting the low-latency and high-reliability requirements of specialized services, and URLLC has become one of the main research directions for current 5G communication technology. After many years of standardisation, URLLC has undergone several protocol revisions, and the relevant wireless transmission technologies have matured and found extensive applications in manufacturing, transportation and power, etc. However, in actual operation, URLLC still has many deficiencies, such as conflicts in multi-service scheduling, interference from communications in unlicensed frequency bands, and performance degradation at high speed and high frequency; thus, it is difficult to meet the rising demand for real-time control services in the future. Based on the results of previous research, this paper will systematically introduce the core technologies and typical application scenarios of URLLC, summarize the current deficiencies in this technology, and analyze the future development direction of URLLC to provide a foundation for subsequent technical optimisation and practical application.

Keywords: 5G URLLC technologies, current status, development trends

1. Introduction

With the development of network intelligence and industrial digitalisation, all parts of the industry have been placing higher and higher demands on the latency, reliability and stability of communication networks. Traditional mobile communications have focused mainly on expanding the speed and coverage of the network, but cannot meet the very high requirements for transmission timeliness and quality in applications such as industrial control, autonomous driving and real-time power grid protection. Based on the above, URLLC is one of the necessary attributes of 5G, and due to its low-latency and high-reliability transmission characteristics, it has been applied to various areas for intelligent upgrades.

Currently, URLLC has been standardised in several editions, and traditional wireless-layer technical solutions have formed a mature framework that can meet the operational requirements of most low-latency services to some extent at present. However, with the continuous expansion of application scenarios, such as high-speed mobility, high-frequency communication and large-scale concurrent terminal scenarios, the existing URLLC technology is gradually showing problems such

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as performance deficiencies, scheduling conflicts, severe interference and low resource utilization, and is unable to meet the development requirements of next-generation high-precision control services.

To give a general introduction to the current situation and future prospects of URLLC technology, the four parts of this paper are as follows: Key Technologies for URLLC, Typical Application Scenarios, Current Technical Limitations, and Future Development Directions. It has listed the strengths and deficiencies of the current technology and provided a reference for continuous optimisation and large-scale application of URLLC technology.

2. Key technologies of 5G URLLC

The two goals of the URLLC technical framework are generally to achieve a low-latency and high-reliability network. Generally speaking, the three types are low-latency transmission technology, single-link high-reliability technology and cross-cell capacity enhancement technology; they all need to ensure the stable operation of services from different aspects, such as transmission mode, link quality and inter-cell coordination.

2.1. Low-latency technologies

Low-latency technology is used to achieve a millisecond-level transmission by optimising transmission parameters and scheduling methods to reduce data waiting time and transmission delay for URLLC. First, flexible OFDM digital configuration. This technology can support a large-scale sub-carrier spacing in the range of 15 kHz to 240 kHz; a larger sub-carrier spacing will result in a shorter symbol transmission duration, thereby reducing the scheduling cycle and increasing data transmission speed. Secondly, micro-slot scheduling. URLLC does not use the traditional fixed 1ms slot scheduling; instead, it has a short scheduling unit of 1-13 symbols, and as a full slot does not need to be waited for, data can be scheduled and transmitted quickly to reduce transmission latency significantly.

Thirdly, downlink pre-emptive scheduling. When urgent URLLC data arrives, the resources of the ordinary broadband service being transmitted can be preempted directly. Simultaneously, an indication message is sent to the terminal to adjust resource allocation, ensuring that high-priority real-time services are transmitted first.Fourth, authorisation-free uplink transmission. This technology does not have a request-and-authorisation interaction process like the old way. It has two modes, static configuration and dynamic adjustment, does not require signalling interaction time, and is suitable for high-frequency, small-data-volume real-time uplink services. Fifth, HARQ (High Availability Request for Quality) active pre-repetition transmission. The network reserves transmission resources in advance for several rounds, and after sending the data, it does not need to wait for a response from the receiving end. If the reception fails, a retransmission will be automatically attempted to reduce the delay caused by waiting for retransmission.

2.2. Single-link high-reliability technology

Based on the foundation of reduced latency, several technologies are used to improve the transmission stability of individual links and thus reduce packet loss and bit error rates. First, multi-antenna micro-diversity technology is used in a 2×2 and 4×4 transmission mode to increase the spatial transmission gain, compensate for signal attenuation caused by fluctuations in the wireless channel, and improve transmission stability. Second, an improved control channel design has been

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proposed. Increase the level of signalling aggregation, repeatedly transmit scheduling information, optimise signal verification mechanisms and adaptively adjust channel reporting parameters to ensure the reliable transmission of control commands and avoid service interruptions caused by lost signalling. Finally, interference suppression technology will be used to reduce signal interference from neighbouring cells and improve the quality of the signal at the terminal for a stable link.

2.3. Inter-cell macro

Inter-cell macro-diversity is a basic technology for URLLC that can increase system capacity and interference immunity by coordinating transmission across multiple transmit and receive points; several cell transceiver devices can transmit the same data packet simultaneously, and the terminal receives these multiplexed signals and combines them for decoding to solve transmission problems caused by signal obstruction and signal fluctuations. Maintain the original low-latency and high-reliability of the system, but increase its capacity by 40 per cent. In combination with single-frequency transmission and cell silence assistance, it can further enhance the efficiency of multi-cell coordinated transmission and extend the total network service area [1].

3. Typical application scenarios for and 5G URLLC

URLLC has low latency and high reliability in communication, and is now widely used in key areas such as industry, transport and power; various new types of real-time interactive services have also been introduced, forming a relatively complete ecosystem of vertical application scenarios.

3.1. Industrial automation scenarios

Industrial automation is a typical use case for URLLC, and it mainly serves Industrial Internet of Things (IIoT) services. Motion control of industrial equipment, real-time communication between devices, scheduling of autonomous mobile robots in workshops, operation of flexible and reconfigurable production lines, industrial closed-loop control, and large-scale deployment in major industrial areas such as ports and airports are all specific scenarios for URLLC. It can work with wired industrial networks to enable the compatible co-existence of wired and wireless time-sensitive services, helping factories free themselves from the constraints of extensive cabling and achieve flexible production line adjustments and intelligent manufacturing [2].

3.2. Intelligent transportation scenarios

URLLC in the transport sector mainly supports intelligent transportation and vehicle-to-everything (V2X) services, such as information exchange among vehicles, autonomous driving control, remote vehicle operation, and real-time data transmission from traffic infrastructure. Stable, low-latency communication is used to obtain real-time data on the surrounding road conditions and vehicle status for timely warnings and evasive manoeuvres; at the same time, road management authorities can monitor the operational status of the road network in real time to improve the safety and intelligence of traffic operations [3].

3.3. Power distribution scenarios

URLLC is used in the electricity industry to ensure the security and intelligent dispatch of the power grid, cover fault protection for high- and medium-voltage grids, closed-loop control of distribution

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networks, and end-to-end real-time monitoring of power systems. With a high-reliability, low-jitter transmission function, the power grid can quickly detect faults and promptly isolate them to prevent the spread of faults, ensure stable grid operation, and support the coordinated dispatch of renewable energy and the development of smart grids [4, 5].

4. Current limitations of 5G URLLC technology

Current 5G URLLC standards only support 99.999 per cent reliability and 1 ms end-to-end latency; new applications such as remote precision surgery, high-precision industrial control and coordinated drone swarms require higher reliability and sub-millisecond latency, and the existing metrics do not meet these demands. Furthermore, existing technologies only optimise the average communication quality in conventional scenarios and are not optimised for extreme signal fluctuations caused by signal obstruction, sudden interference or high-speed movement; they are prone to sudden high latency and sudden packet loss, which can lead to unstable operation of control equipment. In addition, there is a problem of resource contention among general broadband services, massive connectivity services and URLLC real-time services; ensuring the quality of real-time services requires reducing network speed and the number of connections, making it impossible to support multiple services simultaneously [6].

Existing URLLC networks focus primarily on communication transmission quality and have not been optimised to account for the operational characteristics of industrial control systems. The network only calculates a general packet loss rate and cannot distinguish the impact of different data packets on device control; even a small number of consecutive packet losses can cause devices to lose control, but the network still uses a uniform retransmission mechanism and wastes resources. Furthermore, although most control services have a certain degree of fault tolerance and transmission interval redundancy, the existing network transmits all data at the highest priority without flexible adjustment according to actual service requirements, resulting in low resource utilisation. If the sensors, controllers and actuators are deployed independently, even a short network interruption will cause a control failure; the current architecture does not have emergency switching or local control backup, and thus poses a serious operational risk [7].

5G URLLC is based on a fixed, stable channel model, and thus not suitable for dynamic real-world scenarios such as factories, high-speed mobility and drones. It cannot predict signal obstruction and link degradation in advance, and only retransmits after transmission errors occur; thus, there is an additional latency. As the network relies solely on wireless signal sampling to assess channel conditions, it is inaccurate in the presence of obstruction or high-speed movement, and frequent signal detection also consumes a considerable amount of network resources. In addition, the traditional intelligent algorithms need to upload all the raw data, which has a high latency and poor privacy; thus, they are not suitable for large-scale deployment of low-cost terminals [8].

The existing URLLC system only uses wireless radio frequency signals for optimisation of transmission; it cannot integrate visual, radar and sensor data to predict the sources of interference and thus fails to proactively reduce transmission risks. In addition, as there are no intelligent reflection-assisted transmission methods, high-frequency signals are easily blocked, and thus the link reliability is relatively low. If multiple types of perception data were directly fused for processing, it would lead to a substantial increase in energy consumption and signalling overhead, exceeding the requirements of a low-latency service, and direct implementation would be unfeasible.

The existing scheduling mechanism is only suitable for a small number of industrial devices; when a large-scale robot and drone swarm operates simultaneously, the control channel will be congested and the scheduling wait time will increase significantly. For multi-device swarm

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coordination, the current point-to-point communication mode generates a large amount of interaction data and imposes an excessive burden on the network; thus, it is not suitable for large-scale coordinated control. In addition, the resource-preemption mechanism of URLLC has continuously reduced the transmission speed of broadband services, leading to poor fairness and stability in multi-service environments.

To ensure high reliability of transmission, URLLC uses retransmission and multi-node replication extensively; as a result, spectrum utilisation efficiency is relatively low, and thus the number of supported control services per unit bandwidth is limited. High-frequency channel detection and continuous signal monitoring significantly increase the power consumption of terminal devices, reducing the battery life of sensors and mobile devices. Signal listening and collision avoidance in the unlicensed frequency band add extra latency and cause interference [9, 10].

5. Conclusion

URLLC, as a low-latency and high-reliability communication technology at the core of 5G, is an important foundation for the digitalization of industries and the intelligent development of devices. At present, URLLC has formed a mature technical system and rich industry applications, but there are still obvious shortcomings in performance limits, network architecture, intelligent sensing, large-scale adaptation, spectrum energy efficiency, etc., which make it difficult to meet future extreme real-time business needs. In the future, URLLC will continue to evolve towards higher precision, higher reliability, larger scale, and lower energy consumption through performance indicator upgrades, intelligent interference control, multi-technology integration innovation, and network architecture innovation. It will continue to empower key areas such as industry, transportation, healthcare, and energy, providing solid communication support for the high-quality development of the digital society and intelligent industry.

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