Ultra Reliable Low Latency Communications: A state of the art review*

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Abstract. The concept of Ultra Reliable Low Latency Communications describes the communication requirements of applications that demand an end-to-end latency of a few milliseconds and five-9 reliability (99,999% error-free). In this paper, we present a comprehensive survey on novel technologies and solutions focused mostly on technologies close to applications and oriented to service developers, in order to fill the gaps of previous contributions.

Keywords: URLLC · Low Latency · High Reliability · Multi-connectivity · Context Awareness · Middleware.

1 Introduction

The concept of Ultra Reliable Low Latency Communications (URLLC) [1] represents one of the three main slices of 5G (alongside enhanced Mobile Broadband and massive Machine Type Communications) and describes the communication requirements of applications that demand an end-to-end latency of a few milliseconds and five-9 reliability (99,999% error-free) [2]. Such applications include remote control (e.g. remote surgery, remote robotics, Tactile Internet), augmented reality, gaming, autonomous vehicles (drones or cars), etc. In addition, in many of these applications the user expects a high data rate (from 100 Mbps to 1Gbps). Figure 1 presents an example of one URLLC use case, Tactile Internet (in particular, vehicular remote control).

This concept has been studied in several contributions; however, most of the previous work focuses on technologies or lower layers of the protocol stack (far from service developers) and doesn't classify scientific papers addressing both latency and reliability problems at the same time. For instance, Zhang et al. [3] and Morgado et al. [4], present a variety of enabling technologies mostly focusing on lower layers and do not study concrete contributions. Elbamby et al. [5] and Antonakoglou et al. [6] study some of the enabling technologies presented in this paper, however the first one does not present or analyse contributions and the second one focuses its efforts on finding contributions for data compression

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and reduction, robust stability control, and multi-modal data streaming over the Internet. Finally, In Briscoe et al. [7] and Parvez et al. [8] work, the only focus is on latency.

In this paper, we present a comprehensive survey on novel technologies and solutions in order to fill the gaps of previous contributions and identify research opportunities in the context of transport protocols, Application Programming Interfaces (API) and middlewares. The survey focuses mostly on technologies close to applications, instead of lower layers like previous work. The methodology of the survey relies on the identification of URLLC enabling technologies. Then, we select a number of 5G related KPIs and other parameters relevant to URLLC. The parameters basically come from the 5G-PPP European initiative; however they are aligned with other world-wide activities such as 5G Americas, 5G Forum, 5G Brasil or 5GMF [9].

The output of this analysis is a new characterization of the current state of the art and the identification of research topics with high interest, such as V2X or the Internet of Drones.

This paper is organized as follows. Section 2 introduces the motivation behind the survey. Section 3 explains the classification criteria and the parameters evaluated. Then, Section 4 analyses the contributions characterize the state of the art, while Section 5 evaluates these contributions identifying possible future lines of research. Finally, in Section 6 we present our conclusions.

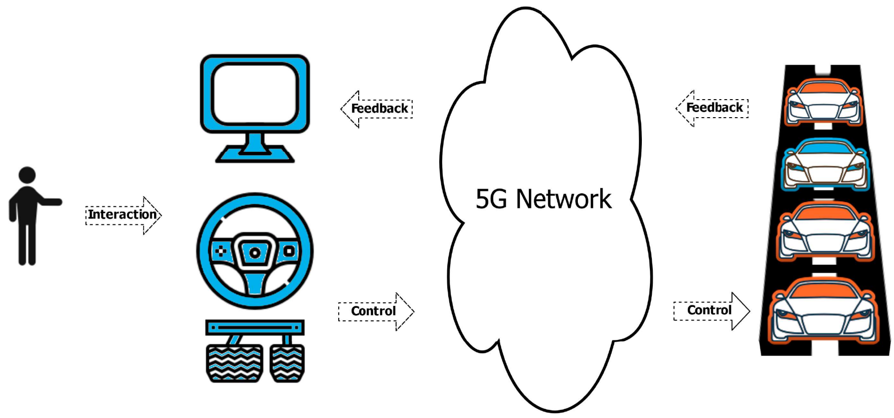

Fig. 1: URLLC use case Tactile Internet.

2 Use Cases for URLLC

The three main use cases in URLLC are remote surgery, factory automation and autonomous connected cars [10].

Remote surgery can occur during complex life-saving procedures in emergencies [11]. In such a critical scenario, networks should be able to support communication needs since any noticeable error can lead to catastrophic outcomes. Similarly, the most stringent requirements of factory automation are high reliability and low latency, since jitter is not tolerated for precise operations in factories [12]. Autonomous connected cars can only communicate via wireless networks. Such communication requires 99.999% reliability, low latency and seamless handovers to keep the car always connected and avoid misunderstanding control messages. Its importance has been recognized by the European Commission with initiatives like European Automotive - Telecom Alliance [13].

However, these are not the only existing use cases. For instance, the Internet of Drones, term coined by Gharibi [14] and Hall [15], has become a reality. The arguments for the Internet of Drones are similar to autonomous connected cars, given the need for URLLC and the use of wide area mobile networks as the main communication technology.

Likewise, Networked Action Games need a method to process the most recent messages as quickly as possible [16]. Hence, increasing confidence in transporting many recent messages thanks to redundant connections is valuable. Other examples are social network oriented videos (Periscope), Virtual reality/Augmented reality, eHealth periodic monitoring, security services, Tactile Internet, Smart Grids, etc., resulting in a wide variety of use cases (mainly) requiring low latency and high reliability.

3 Classification Criteria for previous papers

3.1 URLLC enabling technologies

There are all kinds of contributions aiming to improve latency, reliability or general performance. Based on surveys like Elbamby et al.'s [5] or Parvez et al.'s [8], the categories selected for paper work are the following.

- **Single-path protocols:** A proper communication protocol is necessary in each case to exploit the full capabilities of the network. An inefficient protocol would limit the possibility of taking advantage of network potential.
- **Multipath protocols:** Another approach is to improve communication protocols capabilities over multiple flows instead of single flows.
- **Context Awareness:** Context awareness consists in taking advantage of information outside the scope of work of a protocol to enhance its utilization and provide a better service. The network under 5G is expected to be completely context aware [17], creating interest in its development.

- **Mobile Edge Computing (MEC):** Fog and MEC computing are key enabling technologies for novel 5G requirements [18]. MEC consists in moving the cloud and some network functions closer to the user to provide services locally and consequently improve performance (e.g. reduced latency).
- **Software Defined Networking (SDN):** SDN is a novel approach that decouples architecture splitting control and data planes. SDN allows intelligent routing, flexibility, programmability and facilitates virtualization [19].
- **Network Function Virtualization (NFV):** NFV is a novel solution standardized by ETSI in 2014 [20] aiming to virtualize network functionalities. NFV decouples software functionalities from physical equipment to offer better flexibility, scalability, latency, reliability, capacity, etc.
- **Multimedia Broadcast Multicast Services (MBMS):**The growth of MBMS presents both technologies as key opportunities in 5G networks. Sending the same copy of information to multiple receivers at a given time can provide lower latencies, higher scalability and network offloading.

Some surveys have helped in the identification of the criteria. Habib et al. [21] and Li et al. [22] present studies of multipath in different layers, Mao et al. [18] and Wan et al. [23] present surveys on Mobile Edge Computing, Al-Anbagi et al.'s [24] survey focus on cross-layer approaches for delay and reliability-aware applications and, finally, Antonakoglou et al. [6] study the necessary infrastructure for Tactile Internet.

3.2 Parameters evaluated

Key Performance Indicators (KPI) Key Performance Indicators are measurements of specific network properties that help monitoring, optimizing and characterizing services. Some well-defined 5G-PPP KPIs have been extracted from the 5Genesis[1] project [26].

- **Low Latency:** *$\leq$10 ms end-to-end.*
- **High Reliability:** *>99%.*
- **High Throughput**: *peak user data rate between 1 and 10GB/s.*

Other parameters In addition to KPIs, there are a couple of qualities considered interesting in the characterization of contributions.

- **Partial Reliability**: Some critical data transmissions will focus on reliability while other data can tolerate loss in favour of lower latency.
- **Heterogeneous Networks:** An increasingly large number of different technologies with diverse characteristics coexist in current networks. A protocol's ability to work properly, to work with fairness, to adapt to changes, etc., under these circumstances of heterogeneity is a remarkable added value.

[1]European Union's Framework Programme Horizon 2020, Grant Agreement N°815178 (5Genesis) [25]

4 Analysis of the state of the art

In this section, the variety of URLLC enabling technologies solutions are presented in different subsections. Table 1 presents a comparison of the contributions for a better understanding.

Table 1: Contributions comparison.

		KPI			Other	
		Low Latency	High Reliability	High Throughput	Partial Reliability	HetNets Support
Single-path	TCP BBR [27]	✓		✓	✓	
	Luo et al. [28]	✓		✓		
	STRP [29]	✓			✓	
	Park et al. [30]	✓			✓	
Multipath	Michalopoulos et al. [31]	✓	✓	✓		✓
	Polese et al. [32]	✓		✓		✓
	Esswie et al. [33]	✓		✓		✓
	QoS-MPTPC [34]	✓			✓	
	ADMIT [35]	✓	✓	✓		✓
	PR-MPTCP+ [36]	✓	⋆	✓	⋆	✓
	MPFlex [37]		✓	✓		
	Multipath QUIC [38]	✓	✓	✓		✓
	MPRTP [39]	✓	✓	✓		
	Trammell et al. [40]	⋆	⋆	⋆	⋆	⋆
	Scharf et al. [41]		✓	✓		
	Hesmans et al. [42,43]		✓	✓		✓
Context awareness	Berhanu et al. [44]		✓			✓
	PR-MPTCP+ [36]	✓	⋆	✓	⋆	✓
	Higgins et al. [45]	✓		✓	✓	✓
	Schmidt et al. [46]	✓		✓		
	NEAT [47]	⋆	⋆	⋆	⋆	⋆
	Nielsen et al. [48]	✓	✓			✓
MEC	Zhang et al. [49]	✓				✓
	Heinonen et al. [50]	✓				✓
	Liu et al. [51]	✓	✓			✓
SDN	Awobuluyi et al. [19]	✓	✓	✓		
	G. Wang et al. [52]	✓				
	Costa-Requena et al. [53]	✓	✓	✓		
NFV	Schiller et al. [54]	✓		✓		✓
	Chantre et al. [55]	✓	✓	✓		✓
	Raza et al. [56,57]	✓	✓			
MBMS	Zhu et al. [58]		✓	✓		✓
	Chi et al. [59]		✓			✓
	Roger et al. [60]	✓				

4.1 Single-path Protocols

Some of the more remarkable contributions in communication protocols are the following. Google LLC [27] introduces a congestion control algorithm (TCP Bottleneck Bandwidth and Round-trip propagation time) which responds to actual congestion rather than packet loss and improves throughput, latency and quality of experience. Luo et al. [28] present Explicit Congestion Notification (ECN), an extension of TCP/IP enabler of Ultra-Low Latency and high throughput, that helps realize low latency in TCP. Finally, Short-Term Reliable Protocol for Low Latency Video Transmission [29] and Park et al. [30] relay in packet retransmission just for a limited amount to provide low latency with short-term reliability.

[1] When ⋆ is used, it means that the parameter can be achieved at the cost of another marked parameter.

4.2 Aggregation Methods and Multipath Protocols

There are multiple standards in this matter, as Carrier Aggregation (CA) [61], Dual Connectivity (DC) [62], LTE-WLAN Aggregation [63], IP Flow Mobility and Seamless Offload [64], Multi Access PDN Connectivity [65], LTE WLAN Radio Level Integration with IPsec Tunnel [66] or MPTCP [67]. However, in this section, the focus will be set on novel paper contributions.

With the focus set on lower layers, Michalopoulos et al. [31] presents an aggregation performed on the 5G PDCP layer and cloud-based PDCP layer to meet the requirements of high reliability and low latency, Polese et al. [32] enhance dual connectivity framework for 5G mmWave mobile networks to reduce packet loss, reduce control signaling, reduce latency and increase throughput stability and Esswie et al. [33] propose a scheduler of URLLC and eMBB packets to instantly schedule sporadic URLLC traffic and thus reduce queuing delays to achieve low latency. In middle layers, most of the work is focused on TCP improvements, like QoS-MPTPC [34], ADMIT [35] and PR-MPTCP+ [36] extensions for interactive video, video streaming and real-time multimedia applications, respectively. However, there is also work in other protocols, such as Multipath QUIC [38] , based on QUIC which takes advantage of UDP features to provide lower latency and of multi-connectivity improvements to provide higher reliability and resilience, and Multiple parallel paths for RTP [39], that increases reliability and throughput to enhance the user experience compared to RTP. When multi-connectivity is performed in the application layer, a typical approach is to use Application Programming Interfaces (APIs) to avoid the adaptation of every application. Trammell et al. [40] propose a new API solution based on message carriers and policies to make it platform and transport protocol independent (and support multipath if necessary). However, as MPTCP is the most extended multipath protocol, most API solutions are developed specifically for it, as Scharf et al. [41] or Hesmans et al. [42,43].

4.3 Context Awareness

Context awareness can benefit from environment information, as Berhanu et al. [44] work implementing a context-aware mobility robustness technique in a multi-connectivity scheme to enhance handovers in 5G; from Network context awareness, like the aforementioned PR-MPTCP+ [36]; or from application preferences, as Higgins et al. [45] and Schmidt et al. [46] Sockets solutions (multi-sockets and Sockets intent, respectively). An underexploited approach is to take advantage of, at least, two sources of information. First efforts can be found in NEAT solution [47], selecting different transport protocols through user and network information, or Nielsen et al. [48] work, selecting optimal interfaces through preferences and weight parameters.

4.4 Mobile Edge Computing (MEC)

Some of the contributions focused on MEC are the following. Heinonen et al. [50] present a prototype of a 5G network slice that selects the mobility anchor during an attach procedure from the closest network edge (and re-evaluates it in each handover). Zhang et al. [49] present a mobility-aware MEC framework for emerging 5G applications such as IoT for Intelligent Transportation, Intelligent Healthcare, etc. This solution speeds up application response (latency), improves user experience, reduces congestion, increases speed of data and exposes critical challenges for MEC that still need to be addressed, such as further improvement of efficiency and security. In fact, as highlighted by Liu et al. [51], MEC research lacks focus on reliability, the complementary aspect of URLLC. Thus, they propose a framework and algorithms to strike a good balance between both latency and reliability, offloading tasks from a single UE to multiples edge nodes.

4.5 Software Defined Networking (SDN)

SDN contributions perform a better balance between latency and reliability. Awobuluyi et al. [19] present a holistic SDN control plane approach to multimedia transmission. A QoE and context aware application takes rerouting, load balancing and adapting flows decisions in an SDN network to meet the requirements of ultra reliable low latency video streaming. G. Wang et al. [52] study the placement of SDN controllers to shorten the latency between controllers and switches in wide area networks. Finally, sometimes SDL works combined with other technologies, as in the case of Costa-Requena et al. [53] in the deployment of a modular SDN based user plane (UPF) in real testbeds for 5G. This platform allows optimized transport for low latency, throughput, reliability and MEC taking advantage of SDN flexibility and slicing.

4.6 Network Function Virtualization (NFV)

NFV is a technology highly recommended in recent cellular architectures that can easily be combined with other enabling technologies to achieve better performance. Schiller et al. [54] presents a platform with several enhancements; specifically, the MEC caching framework displays improved user Quality of Experience (e.g. latency). Chantre et al. [55] present a so-called series-parallel redundant model in an NFV architecture to enhance 5G broadcasting services. The solution obtains lower latency, higher reliability and greater effectiveness than the current parallel-series model. Finally, Raza et al. [56,57] present a vIMS (virtualized IP Multimedia Subsystem) design refactoring network function modules and resulting in significant improvements on both latency and reliability (compared with existing 3GPP IMS implementation).

4.7 Multimedia Broadcast Multicast Services (MBMS)

In the case of MBMS, the focus is set on improving reliability. Zhu et al. [58] present a new multicast protocol called MCTCP which aims to outperform the state-of-the-art reliable multicast schemes managing the multicast groups in a centralized manner and reactively scheduling flows to optimal links. MCTCP achieves improvements in both reliability and throughput. Chi et al. [59] propose enhancing multicasts transmissions by means of D2D-communication-based retransmission. They propose an efficient reliable multicast scheme for 5G networks that utilizes D2D communication and network coding to achieve 100 percent reliability. However, with the expansion of URLLC we can find some recent work also aiming to improve latency, such as that of Roger et al. [60]. They address the challenges imposed by 5G V2X services in terms of latency and reliability, which cannot generally be guaranteed using the current MBMS architecture, and propose a low-latency multicast scheme that concentrates the multicast network functionalities in layer-2 of the base stations. The goal is to decrease the end-to-end (E2E) communication latency ensuring, at the same time, the correct operation of demanding services.

5 Open research topics

In this section, we present a comprehensive evaluation to identify current research efforts and determine a possible interest in the combination of millimeter Wave, Heterogeneous Networks support, Multi-connectivity, Application Programming Interfaces, Context Awareness, Network Function Virtualization and Mobile Edge Computing.

5.1 mmWave

First of all, we found interest in the research line presented by Polese et al. [32]. There are benefits of using mmWave, such as higher bandwidth and data rates, although it also comes with substantial drawbacks; vulnerability to atmosphere or blockage, limited range, etc. Multi-connectivity might be a plausible solution to enhance its performance thanks to its redundancy power. Hence, we propose exploiting this line not in simulations, but in realistic emulations and real environments.

5.2 Heterogeneous Networks and Multi-connectivity

Another interesting characteristic is Heterogeneous Networks support. We have found that many contributions (e.g. multiconnectivity) usually address this support when enhancing latency or reliability. This importance is not a coincidence, as the 5G Network is full of heterogeneity: multiple radio access with different technologies, a variety of slices, etc. If a multipath protocol aims to be deployed in a 5G environment, it has to manage these irregularities.

This would happen both in a Dual SIM case, where the device is connected to two different providers, and under the same network provider, where it is connected through different RATs (cellular, wifi, etc.) of a same operator. One approach could be to exploit the aggregation in upper layers (above MAC or IP, e.g. Transport layer). This approach would require managing data sources in the device and at some point of the network as well. We could actually exploit most of the enabling technologies presented in order to achieve so. The solution would consist in setting up a proxy (following the idea presented by Korea Telecom [68]) which could manage the information on the network side. This proxy would take advantage of 5G Network NFV architecture to be deployed in a Virtual Network Function (VNF), providing it with high flexibility and enhanced reliability. Finally, this function could be placed in different areas of the network and, in the case of low latency needs under study, MEC could be an interesting placement to take into consideration.

5.3 Context Awareness and APIs

Following the direction presented, the importance and possibilities found in context awareness and APIs are also noteworthy. In particular, the underexploited awareness of both application and network information (as in Nielsen et al. proposed in [48]). This information could be managed in APIs not only to benefit the client side (selecting optimal interfaces or changing the data injection rate) but also the network side. In a 5G Network architecture including VNFs, context awareness could be the key to select the optimal placement of the function (close to the core, in MEC...), necessary resources according network conditions and further parameters.

5.4 Use cases as drivers for optimization

It is worth highlighting the lack of integration between solutions and use cases. The 5G standard is filled with a variety of goals in terms of use cases; autonomous cars or V2X, remote surgery, the Internet of Drones, etc., but contributions usually focus on improving concrete parameters (such as reliability, latency, both, etc.), not the full requirements of a use case. We propose turning use cases into drivers of concrete contributions, developing solutions to fully meet all requirements of selected use cases.

6 Conclusion

In this paper, we presented a comprehensive survey on a broad variety of potential contributions to URLLC. Unlike other work on this topic, we focused on higher layer technologies enhancing latency, reliability or both (alongside throughput, a non critical KPI but also important for URLLC).

Contributions have been selected based on technologies with plausible future perspectives such as novel protocols, multipath protocols, context awareness, MEC, SDN, NFV and MBMS. We have identified some lines of research regarding these enabling technologies and other qualities like the use of mmWaves and heterogeneity support, as well as the importance of contributions being driven by use cases.

Our future efforts will focus on setting up the environment presented in Section 5, combining mmWave, heterogeneous networks support, multi-connectivity, APIs, context awareness, NFV and MEC following the technological trends presented in [69] and creating a Smart Network to provide the Internet of Drones and V2X with a high performance architecture and middleware. We plan to exploit the platform 5Genesis Málaga to run experiments in a real 5G environment [25,70]

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