

# Ultra-Reliable Low-Latency in 5G: A Close Reality or a Distant Goal?

Arman Maghsoudnia  
EPFL

Eduard Vlad  
RWTH Aachen

Aoyu Gong  
EPFL

Dan Mihai Dumitriu  
Pavonis LLC

Haitham Hassanieh  
EPFL

## ABSTRACT

Ultra-Reliable Low-Latency Communication (URLLC) was introduced in 5G to meet the demanding requirements of latencies as low as 0.5 ms and reliability of 99.999 % for specific applications. Despite over a decade of discussions on URLLC, achieving these standards in real-world implementations remains challenging. We argue that it is unclear if and how URLLC can be attained and a holistic system-level perspective that addresses all the system's inherent bottlenecks is needed. Inspired by a real-world 5G testbed, we present this comprehensive vision and show how to achieve latency requirements by outlining the necessary design choices across all system layers, including the processing and radio units.

## CCS CONCEPTS

• **Networks** → **Mobile networks; Network performance analysis; Network design principles.**

## KEYWORDS

5G, URLLC, System-level analysis, System design choices

### ACM Reference Format:

Arman Maghsoudnia, Eduard Vlad, Aoyu Gong, Dan Mihai Dumitriu, and Haitham Hassanieh. 2024. Ultra-Reliable Low-Latency in 5G: A Close Reality or a Distant Goal?. In *The 23rd ACM Workshop on Hot Topics in Networks (HOTNETS '24)*, November 18–19, 2024, Irvine, CA, USA. ACM, New York, NY, USA, 10 pages. <https://doi.org/10.1145/3696348.3696862>

## 1 INTRODUCTION

Ultra-Reliable Low-Latency Communications (URLLC) is a new service introduced in 5G to support mission-critical applications with stringent demands for reliability and latency.

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for third-party components of this work must be honored. For all other uses, contact the owner/author(s).

*HOTNETS '24*, November 18–19, 2024, Irvine, CA, USA

© 2024 Copyright held by the owner/author(s).

ACM ISBN 979-8-4007-1272-2/24/11

<https://doi.org/10.1145/3696348.3696862>

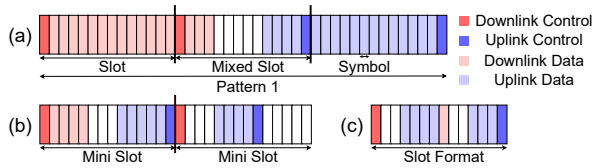
URLLC aims to deliver a 0.5 ms latency of both uplink (UL) and downlink (DL) channels (1 ms round trip) with a reliability higher than 99.99 % [8]. While the specific requirements vary across applications, sub-millisecond latency remains critical for certain use cases [3]. URLLC opens up a wide range of applications [12, 33, 52], including autonomous vehicles [22], industrial automation [13, 16], remote surgery [20], smart grids [25], virtual and augmented reality (VR/AR) [24], professional live audio production [33], and public safety communications [29, 55], where real-time communication is essential. URLLC can also improve the performance of classical applications like web browsing and gaming [44, 51].

3GPP, the standardization body for cellular networks, first introduced 5G URLLC with Release 15 in late 2017 [1]. Despite more than a decade of discussions starting in mid 2010s [58] and four years since the initial commercial deployments of 5G [34], real-world implementations of URLLC satisfying the specified requirements remain elusive. It is not entirely clear under what network architecture and configuration such latencies can be achieved. Moreover, discussions around 6G indicate even stricter latency goals of 0.1 ms uplink and downlink (0.2 ms round trip) [14, 21, 23, 45].

While there have been some practical implementations targeting URLLC, they do not achieve the latency [16, 28, 33, 42, 43] or reliability requirements [19, 56]. Most of the research on URLLC remains theoretical or based on simulations. [18, 27, 49, 56] propose reducing the time slot transmission duration to minimize latency. However, they disregard bottlenecks inherent in the system and the protocols, which impede achieving specified constraints in practice, as we will show in this paper. Moreover, many research papers assume the availability of URLLC and focus on the coexistence of it alongside other services, e.g., enhanced Mobile Broadband (eMBB) [11, 23, 26, 30, 39, 48, 57].

In this paper, we ask: *Are the latency and reliability requirements of URLLC achievable in practical 5G systems?* We argue that answering this question is non-trivial but rather exceedingly challenging due to many software, hardware, and protocol factors that can affect latency once we consider the entire system<sup>1</sup>.

<sup>1</sup>It is worth noting that we could achieve these requirements if we modified the 5G standards and implemented most layers in an Application-Specific



**Figure 1:** Possible TDD configurations: (a) *Common Configuration*, (b) *Mini Slot*, (c) *Slot Format*

To better appreciate the challenges in answering this question, consider the following example. In sub-6 GHz frequency bands, 5G specifications limit the minimum time slot duration to 0.25 ms due to scalability and bandwidth constraints [5]. However, it might take multiple time slots before a packet can be scheduled for transmission by the Medium Access Control (MAC) layer, passed to the Physical (PHY) layer, and finally transmitted on the radio as we describe in more detail in § 4, making it extremely challenging to meet URLLC requirements. On the other hand, in high-frequency millimeter wave (mmWave) bands, 5G specifications support very narrow time slots as low as 15.625  $\mu$ s [4]. However, mmWave frequencies are not reliable as they require line-of-sight to the base station, can be easily blocked, and suffer with mobility due to the directional nature of mmWave radio transmissions [32, 41]. Based on recent measurements, sub-millisecond latencies in 5G mmWave can be achieved only 4.4 % of the time rather than 99.99 % of the time [19]. Apart from the time slot duration and frequency band, many different configurations in the 5G protocol affect latency, such as Time Division Duplexing (TDD) vs Frequency Division Duplexing (FDD), period of scheduling requests, grant-based vs. grant-free uplink transmissions, TDD configurations of uplink and downlink slots, ...

In this paper, we uncover the inherent bottlenecks in the 5G system through a system-level analysis based on a real-world 5G testbed. We highlight the factors and challenges in achieving URLLC and categorize the different latency sources in a 5G system into three categories: protocol, processing, and radio latencies. We show that the latency can be bottlenecked if any of these sources are overlooked, and we emphasize the interdependency between these sources on the overall latency of the system. We then provide the system design choices needed to meet the specified latency requirements. Finally, to demonstrate the validity of our analysis, we test our arguments on a real-world 5G testbed. While we show that URLLC is, in principle, possible, the set of possible system designs is quite limited, and some might not be practical once additional factors are considered. We argue that to design a practical URLLC 5G network, further factors must be considered with real-world evaluations.

Integrated Circuit (ASIC). However, ignoring the standards means we cannot leverage the 5G infrastructure or commercial devices, making it an impractical solution.

## 2 BACKGROUND

Similar to 4G LTE, 5G New Radio uses Orthogonal Frequency-Division Multiplexing (OFDM) at the PHY layer, where the bandwidth is divided into frequency subcarriers on which data is modulated. However, unlike 4G which has a fixed subcarrier spacing (SCS), the SCS in 5G can be selected among seven numerologies ( $\mu$ ). Numerologies 0 to 2 are available in low and mid-frequencies (sub-6 GHz), known as Frequency Range 1 (FR1), while numerologies 2 to 6 are available in the so called mmWaves (24.25 to 52.6 GHz), known as Frequency Range 2 (FR2) [8]. The SCS can be derived as 15 kHz  $\cdot 2^\mu$  [4]. Regardless of the numerology, 14 OFDM symbols are grouped into a time domain *slot*, whose duration is 1 ms/ $2^\mu$ . As a result, higher numerologies are key enablers for low-latency communication in 5G.

Due to the shared nature of the wireless medium, the base station, also known as next-generation NodeB (gNB), needs to allocate the frequency and time resources to the user equipment (UE). This allocation is known as resource scheduling. After allocation, the gNB sends the results to UEs as part of the control information, which can only be sent once per slot. Consequently, in practice, the scheduling task is done just once per slot.

The data sent from the gNB to the UE is called DL data, while the data sent from the UE to the gNB is called UL data. Two forms of duplexing are defined in the 5G standard, namely TDD and FDD. In FDD, two distinct, non-overlapping, and equal frequency bandwidths are allocated for the DL and UL channels [5]. In contrast, TDD uses the same bandwidth for both, separating UL and DL temporally. As a result, TDD can change the ratio between UL and DL resources by defining time domain allocations on the fly. In terrestrial 5G networks, FDD is only supported in sub-2.6 GHz bands [5], which are usually occupied by public 5G mobile operators. Private 5G networks, consequently, are allocated the bands that only support TDD by the spectrum manager. Hence, for the URLLC applications targeted by private 5G networks, such as industrial automation [13] and hospitals [31], the only viable option is to use TDD.

Time domain slots are grouped into *periods*, and their characterization in TDD (DL, UL, mixed, or empty) depends on the configuration type, which can be either *Common Configuration* [7], *Slot Format* [6], or *Mini Slot* [2].

- **Common Configuration.** Each period in *Common Configuration* (shown in Fig. 1a), can be composed of one or two consecutive patterns. A pattern consists of several DL slots **D**, followed by one mixed slot **M**, and several UL slots **U**. The mixed slot begins with the DL symbols, followed by empty guard symbols, and concludes with the UL symbols. The use of guard symbols when switching from DL to UL is mandatory due to synchronization considerations. Hence,

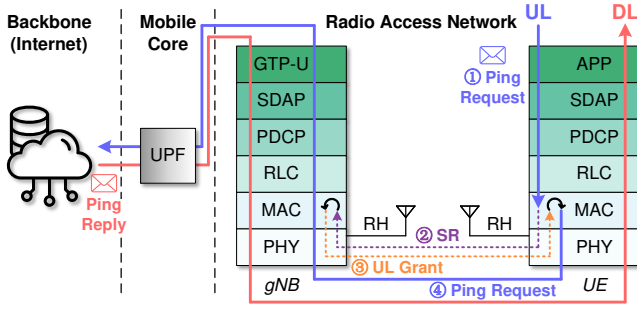


Figure 2: Journey of a Ping Request.

switching too often between DL and UL can waste resources. The standard restricts the period of the two patterns to be in the set  $\{0.5, 0.625, 1, 1.25, 2, 2.5, 5, 10\}$  ms [7].

- **Mini Slot.** When using *Mini Slot* (shown in Fig. 1b), the gNB uses the first couple of symbols of each time slot to inform the UEs of the characterization of the remaining symbols in the slot (UL, DL, or empty). The *Mini Slot* configuration provides more fine-grained allocation at the expense of increased signaling overhead.

- **Slot Format.** The *Slot Format* (shown in Fig. 1c) shares the same principle as the *Mini Slot*. The difference lies in the fact that, in *Slot Format*, the permissible formats are predefined by the standard [6]. By doing so, the gNB can reduce the signaling overhead, in exchange for more coarse-grained allocation schedules.

### 3 JOURNEY OF A PACKET

To understand the latency in a 5G system, we trace the journey of a ping request sent by a UE in a 5G network, examining the network stacks of both the UE and the gNB. Fig. 2 provides an overview of the steps discussed below.

The journey begins at the Application (APP) layer in the UE with the creation of a ping request. The UL data passes through the Service Data Adaptation Protocol (SDAP) layer for quality of service management and then the Packet Data Convergence Protocol (PDCP) layer for encryption. Next, the data moves through the Radio Link Control (RLC) layer, for segmentation and reassembly. The MAC layer manages access to the shared medium. The UE first sends a Scheduling Request (SR) (ⓑ in Fig. 2) and then sends the data after receiving a UL grant (ⓐ in Fig. 2). In the PHY layer, the data is encoded and modulated into samples. The Radio Head (RH) converts these samples into Radio Frequency (RF) signals and sends them to the gNB over the air. On the gNB side, the RH captures the signals and converts them into samples, further demodulated and decoded into the data. The gNB reconstructs the request from PHY to SDAP and encapsulates it into a General Packet Radio Service Tunneling Protocol User Plane (GTP-U) packet, forwarding it to the User Plane Function (UPF). The UPF decapsulates the payload and forwards it to the destination over IP.

The ping reply traces back the same route. However, it can be immediately scheduled for DL transmission at gNB’s MAC layer. The ping journey involves multiple steps contributing to the latency, which we explore in the following section.

### 4 LATENCY SOURCES

We divide latency sources into three main categories:

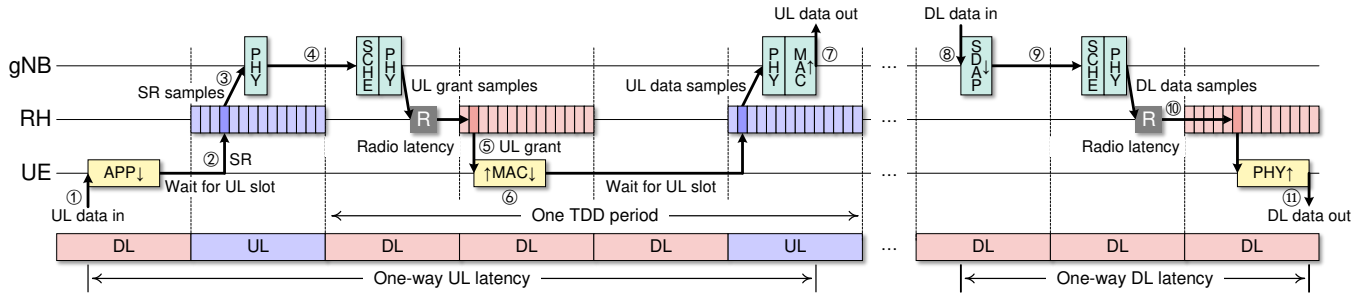
- (1) The *processing latency* consists of the time required for decision-making and data processing.
- (2) The *protocol latency* is introduced by protocol mechanisms and configurations.
- (3) The *radio latency* includes the time spent in the RH and its interaction with the PHY layer.

To analyze them, we detail the ping journey in Fig. 2 from a temporal perspective and present a breakdown in Fig. 3.

For a ping request, the UL transmission begins at the UE in ①. The UE prepares the SR, processing through the layers from APP down to PHY (APP↓), to request network resources. However, the UE must wait for the next UL slot to respect the TDD pattern. ② The UE transmits the SR in the next UL slot to the RH at the gNB side. ③ The RH passes samples to the PHY layer, where they are demodulated and decoded. The MAC layer receives the SR and schedules a UL grant for the UE. The scheduling (SCHE) does not occur right away, as it is performed periodically in every slot (cf. § 2). ④ Consequently, the grant is scheduled in the next slot. ⑤ Afterward, the gNB sends the grant to the UE as part of the control information. ⑥ After the UE receives the grant, it waits for the next UL slot and sends the ping request to the gNB (↑MAC↓). ⑦ Finally, the gNB processes the UL data samples and passes the ping request to the UPF through the layers from MAC up to SDAP (MAC↑).

For the ping reply, the DL transmission begins at the gNB in ⑧. The gNB processes the DL data through the layers from SDAP down to RLC (SDAP↓). ⑨ Again, as the scheduling is performed periodically in every slot, the data waits in the RLC layer and is scheduled in the next slot. ⑩ Next, the scheduling result specifies the DL slot where the data will be transmitted to the UE. ⑪ Finally, the UE receives the DL data in one or multiple symbols of the DL slot. It then passes the data through the layers from PHY up to APP (PHY↑).

Given the breakdown, the three latency sources are summarized as follows. (i) The *processing latency* exists in both UE and gNB (cf. ①, ④, ⑥–⑨, ⑪). This latency includes the time taken for processing data through the layers from APP down to PHY in the UE and from PHY up to SDAP in the gNB. (ii) The *radio latency* ( $\mathbb{R}$ ) also appears in both the UE (cf. ②, ⑤, ⑥, ⑪) and gNB (cf. ③, ⑦, ⑩). This latency consists of the time spent in RF chains (e.g., analog-to-digital and digital-to-analog conversions), queuing delays on interface buses, and the bus transmission time. (iii) The *protocol*



**Figure 3:** Overview of the system-level latency for the journey of a packet. A *TDD Common Configuration* with the *DDDU* pattern is used.

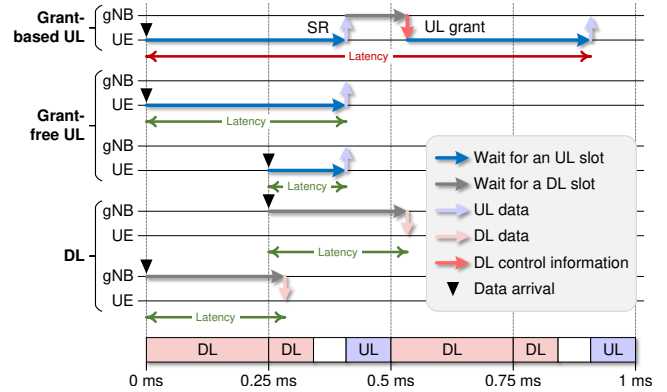
latency is the most significant, including the configurations in use (cf. ①, ④, ⑥, ⑦, ⑨). Specifically, the SR and grant procedure noticeably increases the latency of UL transmissions (cf. ② ⑤). An alternative grant-free access mechanism allocates resources to UEs without SRs, reducing latency but facing scalability issues as the number of UEs increases [9].

It is crucial to note the following points:

- *These latency sources can be influenced by numerous factors specific to the system in use.* For example, in software-based implementations of 5G, processing latency can increase or exhibit non-deterministic behavior due to the non-real-time nature of Operating System (OS) scheduling. Additionally, radio latency varies significantly depending on the interface used, such as PCIe, Ethernet, or USB, to connect the RH to the processor running the 5G stack. Furthermore, although Software-Defined Radios (SDRs) offer more flexibility compared to ASIC solutions, they introduce additional latency [53]. Another example is the duration of the TDD pattern. If the latency exceeds one TDD pattern in the above *DDDU* configuration (Fig. 2), an entire pattern is missed before the gNB can respond to the scheduling request. To address this, it is better to increase the TDD pattern duration to allow responses to scheduling requests without missing an entire pattern. However, this also increases the latency.
- *These sources are also interdependent.* It is essential to consider their interaction and adjust system requirements accordingly. For instance, the MAC scheduler must be designed to account for the total processing time in subsequent layers and radio latency. Failure to do so may result in the radio not being ready for transmission, leading to a corrupted signal. Since the sum of these delays is non-deterministic, practical implementations require the scheduler to include a margin to ensure the radio is ready on time, further increasing latency.
- *Any of these sources can bottleneck the system.* For instance, if the radio latency is 0.3 ms, halving the slot duration from 0.25 ms might not reduce latency and could even increase it.

## 5 FEASIBLE URLLC DESIGN CHOICES

In the following, we consider both theoretical and practical constraints to meet URLLC's latency and reliability. Based



**Figure 4:** Worst-case latency for the *DM* configuration.

on the tests conducted on our real-world testbed, we have reached the following conclusions.

**PHY Configuration:** We examine both the FR2 and FR1 bands. While the FR2 (mmWave) band offers slot durations as low as 15.625  $\mu$ s to reduce latency, it brings along significant drawbacks: unreliability due to line-of-sight restrictions [32, 41], high power consumption [19], and large signal bandwidth amplifying the processing-based latency. Hence, in this paper, we focus on the FR1 band (< 6 GHz), which offers slot durations of 1 ms, 0.5 ms, and 0.25 ms. Since a packet may arrive at the RLC queue just after MAC scheduling, it has to wait until it is scheduled in the next slot. As a result, the latency is at least one slot, and only the 0.25 ms slot duration can feasibly achieve the URLLC requirements.

**MAC Configuration:** We examine all the possible options: all potential *TDD Common Configurations*, *Mini-Slot Configurations*, and *FDD*.

– *TDD Common Configuration.* To explore the lowest latency for this configuration, we consider the shortest possible TDD patterns, as longer patterns increase the DL or UL duration and thus the overall latency. As explained in § 2, the minimum pattern duration for *TDD Common Configuration* is 0.5 ms, which contains only two slots that can be downlink, uplink, or mixed, i.e., *DM*, *MU*, and *DU* are the only possible configurations. For the uplink, we consider both grant-based and grant-free transmission. In grant-based, the UE has to

**Table 1:** Evaluation of the 0.5 ms latency requirement for all minimal TDD Common Configurations.

	DU	DM	MU	Mini-slot	FDD
Grant-Based UL	✗	✗	✗	✓	✓
Grant-Free UL	✓	✓	✓	✓	✓
DL	✗	✓	✗	✓	✓

send an SR before it is granted resources to transmit, as described in § 3. In grant-free, the resources are pre-allocated to the UE, and it does not need to spend time sending SR and waiting to be granted resources. This reduces latency but cannot scale to many UEs as these pre-allocated resources are limited and can be wasted if there are no uplink packets.

Our finding demonstrates that only one configuration, **DM**, satisfies the latency requirements of URLLC on both downlink and uplink for the grant-free scenario as shown in Tab. 1. We substantiate the claim in Fig. 4 by presenting the worst-case latencies for grant-free UL, grant-based UL and DL transmissions. For the UL, the worst-case latency occurs when the UE receives data just after a DL slot starts. In this case, the UE must wait for the next UL slot, before it can send the data. For the DL, the worst-case also occurs when the gNB receives data at the beginning of a DL slot: since the specific slot is already allocated for other DL data, the gNB must wait for the next DL slot to schedule the transmission. For the **DM** pattern, the worst-case latency of 0.5 ms is achieved for the grant-free UL and DL transmissions, while the grant-based UL transmission violates the latency requirement. A similar rationale can be applied to understand other conclusions presented in Tab. 1.

– *Mini-Slot Configuration:* The *Mini-Slot Configuration* in 5G standard offers a more granular scheduling (cf. § 2). Assuming a 0.25 ms time slot, this configuration achieves a latency of 0.5 ms even in the worst-case scenario for grant-based access<sup>2</sup>. However, the standard sets a target slot duration of at least 0.5 ms for the mini-slot configuration [2]. As a result, since the 0.25 ms slot duration goes against the standard’s recommendation, it needs to be evaluated in practice.

– *FDD:* Since at least one TDD configuration meets the latency and reliability requirements, the same applies for FDD, as it realizes a full-duplex channel for UL and DL.

To give an overview of the trade-offs between the viable configurations, we consider them in terms of overhead, flexibility and applicability to private 5G: FDD has a higher frequency overhead due to the duplexing distance (guard band) between UL and DL channels, while TDD has a higher time overhead from guard symbols. FDD pre-allocates UL and DL channels, limiting flexibility, unlike TDD which allows spectrum sharing between UL and DL with many possible

configurations. Among TDD options, the *Common Configuration* is the least flexible, while the mini-slot is more flexible. FDD is restricted to frequencies below 2.6 GHz and thus not possible for private 5G applications like industry automation.

It is important to note that for all viable configurations, the radio, and processing latency should be less than one slot. If this threshold is not met, an additional slot is missed, leading to a deadline violation. To meet the requirements for (i) UL and DL MAC scheduling, (ii) UL PHY decoding and DL preparation, and (iii) both UL and DL radio latency, it is essential to provide a real-world system capable of achieving these benchmarks. ASIC-based processing and radio transmission can potentially achieve them, but are less desirable as 5G moves more toward software. On the other hand, software-based processing and radio transmission using SDRs present significant challenges due to the difficulty of providing hard real-time guarantees. Hence, achieving URLLC in FR1 is feasible, but necessitates strict hardware and software requirements to meet the latency and reliability constraints.

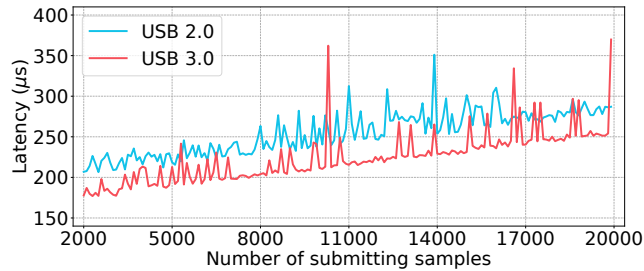
## 6 WHAT ABOUT RELIABILITY?

While this work primarily focuses on addressing the challenges of achieving low-latency in URLLC, reliability remains a critical factor that is closely intertwined with latency. Reliability in URLLC is a two-fold challenge. The first aspect stems from the unpredictable nature of the wireless channel, which can lead to packet loss. This field has been widely studied and offers a range of trade-offs to achieve the reliability [50, 54].

The second aspect, which relates more directly to our analysis, involves the non-deterministic nature of latency in certain components of the 5G system. For example, processing times can fluctuate across layers of the 5G stack, causing missed deadlines and resulting in packet loss. Another example is the delay in submitting samples to the radio and the associated radio processing time. In Fig. 5, the latency of submitting samples to the radio is shown against the number of samples for both USB 2 and USB 3 interfaces between the processor (CPU) and the RH. As seen in Fig. 5, while the linear increase in latency is expected as larger samples take longer to transmit, the more concerning spikes arise due to delays in the OS scheduling of the sample submission process. These scheduling delays, if not accounted for with sufficient margin, can cause packet loss and reliability issues.

Thus, system design must achieve a careful balance between latency and reliability, as non-deterministic latency sources can undermine the system’s ability to meet stringent reliability requirements. Some of these issues can be addressed by using, for instance, real-time kernel for the OS in software-based 5G network. Future work should focus on investigating the behavior of the non-deterministic components, and their broader impact on reliability.

<sup>2</sup>Note that any UE can send SR (one bit) at any time during the UL slot.



**Figure 5:** OS and hardware-imposed delay of submitted samples to the radio.

**Table 2:** gNB Layers' Processing and Queuing Time

	SDAP	PDCP	RLC	RLC-q	MAC	PHY
<b>Mean</b> [ $\mu$ s]	4.65	8.29	4.12	484.20	55.21	41.55
<b>STD</b> [ $\mu$ s]	6.71	8.99	8.37	89.46	16.31	10.83

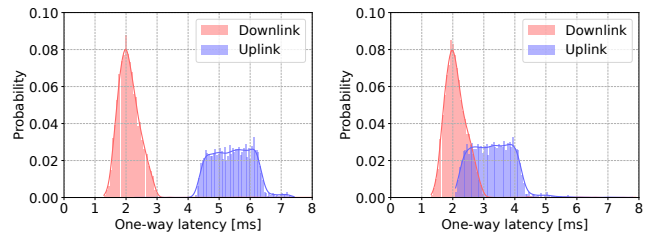
## 7 DEMONSTRATION

In this section, we validate our findings for a specific configuration. For our 5G testbed, we use a modified version of the open-source srsRAN software suite [47] as our 5G code and a USRP b210 SDR as our radio platform. The gNB code is executed on an Intel i7 CPU, providing a fully software-based 5G stack on the gNB side. We use a SIM8200EA-M2 5G modem for the UE side. The packets are uniformly generated within the pattern. We present the latency of DL and UL channels for the grant-based and grant-free UL in Fig. 6. The processing time for different layers of the gNB and the RLC queue waiting time (RLC-q) are given in Tab. 2.

We measure the latency in the n78 band with a slot duration of 0.5 ms. We employ a *TDD Common Configuration* with the **DDDU** pattern. Note that shorter time slots and **DM** pattern are not yet supported in the open-source code. Moreover, our RH uses USB which has relatively higher latency. Consequently, due to the limitations in the software and hardware in use, URLLC requirements are not met in this real-world demonstration.

Comparing the best and worst case latency of DL (Fig. 6), verifies that the initial state of the packet and the protocol-introduced latency are impactful. In the worst case, data must wait during the UL slot although it could be transmitted immediately. In contrast, in the best case, the transmission is finished in the first three DL slots of the pattern avoiding the UL slot. Moreover, since the RH in use introduces around 500  $\mu$ s latency, the transmission must be always delayed for one slot to give enough time to the RH for preparation.

In the UL channel (Fig. 6), the latency is much bigger than the DL. It is due to multiple factors. First, the UE needs more time for processing than gNB. Second, there is only one UL slot in each TDD period, increasing the waiting time. For instance, the worst case misses one TDD pattern and must



**Figure 6:** One-way latency: (a) grant-based and (b) grant-free.

wait for the next one. Third, comparing Fig. 6a and Fig. 6b, it is inferred that the SR and Grant procedure introduces significant latency, by adding one TDD period to the latency for the handshake. As seen, this one TDD period overhead can be eliminated by utilizing grant-free access.

The results showing low processing time in Tab. 2, confirm that using software-based 5G, requirements can be achieved if the fitting design choices are made. Consequently, it seems feasible to meet the deadlines (§ 5) utilizing software-based 5G deployments. Nevertheless, higher number of UEs might increase the processing times noticeably.

## 8 RELATED WORK

**Practical Studies** Fezeu et al. [19] evaluate the latency of several commercial mmWave implementations, achieving sub-millisecond round trip latency under optimal conditions. However, they note that sub-millisecond latency is only achieved in 4.4% of packets, severely violating the reliability constraint. In the sub-6 GHz bands, Wirth et al. [56] propose a PHY layer solution for 5G that achieves low latency. However, since this work predates the 5G standards, it does not incorporate the standard specifications, particularly those concerning scheduling and protocol latency, which can significantly increase the overall latency. Joint work by Nokia and Sennheiser focusing on professional audio applications [33] achieves a minimum DL latency of approximately 0.8 ms for a single UE, going higher in steps of 0.5 ms in case of retransmission. This work, however, only supports single-user point-to-point communication using a hardware-accelerated platform, of which the scalability is limited.

Additional empirical works, conduct latency evaluations in real-world campus networks [28, 42, 43] or testbeds [16, 40]: Rischke et al. [42, 43] report Round-Trip-Times (RTTs) between 12 and 40 ms, and evaluate one-way latencies ranging from 2 to 8 ms. Lackner et al. [28] find RTT latencies of 6 to 12 ms, varying significantly with different UEs. Additional work from Qualcomm [40] indicates mmWave URLLC latencies of 1.9 ms for DL and 4.0 ms for UL. Finally, Ericsson [16] demonstrate a URLLC use case for industrial automation with robots, achieving a 5 ms latency.

**Theoretical & Simulation-Based Studies** Apart from practical implementations, theoretical studies address the challenges of achieving low latency by modifying protocols and

slot configurations. For instance, Nokia [12] emphasizes the need for slotted MAC, central scheduling, and synchronization for deterministic latency. In addition, [27] discusses avoiding retransmissions to minimize latency, assuming inherent end-to-end latency within a few milliseconds. Comprehensive reviews such as [10, 15, 17, 18, 37, 38, 49] survey enabling technologies for URLLC but often overlook real-world constraints, focusing instead on idealized scenarios. For instance, either negligible processing [15, 18] or protocol-based latencies [18] are assumed. Finally, a lot of research on scheduling algorithms for URLLC, such as in [11, 23, 26, 30, 39, 48, 57], focus on managing URLLC packets alongside other services, assuming low-latency communication for a single UE and addressing scalability.

## 9 DISCUSSION & OPEN PROBLEMS

While our work takes the first steps towards answering whether URLLC requirements are achievable and how to design and configure 5G networks to achieve them, significant open research problems remain:

**URLLC in Software-Based 5G.** Compared to 5G cellular deployments with dedicated hardware accelerators and customized processing units, software-based 5G implementations are gaining increased popularity for their ability to leverage general-purpose programming languages and CPUs, which provides flexibility, ease of maintenance and updates, compatibility with commodity hardware, and the ability to run in virtualized environments [36, 47]. However, software introduces additional processing and radio delays. Moreover, the non-determinism of general-purpose OS and CPU makes it harder to achieve URLLC requirements.

**URLLC in Private 5G.** Private 5G consists of 5G deployments managed directly by private enterprises to optimize network performance for specific use cases such as campus networks, factory automation, VR classrooms, etc. These applications particularly benefit from URLLC which is harder to achieve in private 5G configurations. For example, deploying a private 5G network requires spectrum licensing, and the available bands are typically limited and mostly just supporting TDD [35]. Thus, using FDD duplexing, which has lower latency, is not possible for private 5G networks.

**URLLC in the 5G Core.** Our paper focused on the 5G Radio Access Network (RAN). To ensure URLLC is not bottlenecked by the 5G core, one solution is to replicate the core with a dedicated one for URLLC packets and another for other services like eMBB, though this increases cost and management overhead. Hence, another research question is the design of a single 5G core that handles both URLLC and other services.

**URLLC with Mini-Slots.** Our analysis shows that the mini-slot configuration can satisfy the latency requirements of URLLC and is more flexible than *TDD Common Configuration*.

However, it suffers from higher network coordination complexity due to more granular scheduling, potentially limiting the scalability. Moreover, it increases control signaling overhead, which grows with the number of UEs and reduces the system's overall efficiency. Interference management also becomes challenging due to more overlapping and asynchronous transmissions. As a result, achieving a balance between latency and scalability remains an open research problem when leveraging mini-slots.

**URLLC Scalability.** Our analysis focused on a single UE. As the number of UEs increases, factors like processing time, radio latency, contention, and scheduling complexity become more challenging. Hence, a key research problem is how to mathematically model the latency for multiple UEs in the end-to-end 5G network stack, to more accurately capture the complex interactions among these factors. Furthermore, our work shows that grant-free access is necessary in certain cases. Nevertheless, pre-allocating resources can be wasteful and may not scale to multiple UEs. Another research problem is how to predict and schedule uplink data arrivals for URLLC applications to efficiently pre-allocate resources, eliminate delays incurred in requesting, and improve scalability.

**Low-Latency in other Wireless Technologies** Existing technologies like Bluetooth [46] and Wi-Fi provide alternative solutions for URLLC but come with significant limitations. Bluetooth, with a fixed 625  $\mu$ s slot length, supports only seven devices per piconet and operates using master-slave TDD communication, limiting its scalability and flexibility [46]. Its maximum transmit power of 2.5 mW also restricts the range. Wi-Fi employs a decentralized, contention-based access mechanism, leading to unpredictable medium access delays. These characteristics make both technologies less suited for low-latency, which is specifically targeted by 5G's adaptable slot configurations and centralized scheduling.

## 10 CONCLUSION

In this paper, we argue that after almost ten years from URLLC's initial conception, it is still unclear how to achieve it in 5G. Most research on URLLC ignores critical system and protocol properties that increase the latency. We take the first steps to investigate if and how URLLC can be achieved. We provide a comprehensive analysis of latency sources in 5G and propose all possible configurations to meet URLLC's requirements. Our findings confirm that URLLC is theoretically achievable but under very specific circumstances with stringent hardware and software conditions. However, more research is required before we can deliver 5G systems that enable URLLC as highlighted in our discussion above.

**Acknowledgment:** We thank the reviewers and HotNets PC for their comments and suggestions. We also thank Raphael Cannatà and Haoxin Sun for their valuable feedback.

## REFERENCES

- [1] 3GPP. 2017. *NR; NR and NG-RAN Overall description; Stage-2*. Technical Report 3GPP TS 38.300 version 1.1.1 Release 15. 3GPP. [https://www.3gpp.org/ftp/Specs/archive/38\\_series/38.300/38300-111.zip](https://www.3gpp.org/ftp/Specs/archive/38_series/38.300/38300-111.zip)
- [2] 3GPP. 2018. *5G; Study on New Radio (NR) access technology*. Technical Report 3GPP TR 38.912 version 15.0.0 Release 15. 3GPP. [https://www.etsi.org/deliver/etsi\\_tr/138900\\_138999/138912/15.00.00\\_60/tr\\_138912v150000p.pdf](https://www.etsi.org/deliver/etsi_tr/138900_138999/138912/15.00.00_60/tr_138912v150000p.pdf)
- [3] 3GPP. 2019. *Study on physical layer enhancements for NR ultra-reliable and low latency case (URLLC)*. Technical Report 3GPP TR 38.824 version 16.0.0 Release 16. 3GPP. [https://www.3gpp.org/ftp/Specs/archive/38\\_series/38.824/38824-g00.zip](https://www.3gpp.org/ftp/Specs/archive/38_series/38.824/38824-g00.zip)
- [4] 3GPP. 2022. *5G; NR; Physical channels and modulation*. Technical Report 3GPP TS 38.211 version 17.2.0 Release 17. 3GPP. [https://www.etsi.org/deliver/etsi\\_ts/138200\\_138299/138211/17.02.00\\_60/ts\\_138211v170200p.pdf](https://www.etsi.org/deliver/etsi_ts/138200_138299/138211/17.02.00_60/ts_138211v170200p.pdf)
- [5] 3GPP. 2022. *5G; NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone*. Technical Report 3GPP TS 38.101-1 version 17.5.0 Release 17. 3GPP. [https://www.etsi.org/deliver/etsi\\_ts/138100\\_138199/138101/17.05.00\\_60/ts\\_138101v170500p.pdf](https://www.etsi.org/deliver/etsi_ts/138100_138199/138101/17.05.00_60/ts_138101v170500p.pdf)
- [6] 3GPP. 2024. *5G; NR; Physical layer procedures for control*. Technical Report 3GPP TS 38.213 version 18.2.0 Release 18. 3GPP. [https://www.3gpp.org/ftp/Specs/archive/38\\_series/38.213/38213-i20.zip](https://www.3gpp.org/ftp/Specs/archive/38_series/38.213/38213-i20.zip)
- [7] 3GPP. 2024. *5G; NR; Radio Resource Control (RRC); Protocol specification*. Technical Report 3GPP TS 38.331 version 18.1.0 Release 18. 3GPP. [https://www.etsi.org/deliver/etsi\\_ts/138300\\_138399/138331/18.01.00\\_60/ts\\_138331v180100p.pdf](https://www.etsi.org/deliver/etsi_ts/138300_138399/138331/18.01.00_60/ts_138331v180100p.pdf)
- [8] 3GPP. 2024. *5G; Study on scenarios and requirements for next generation access technologies*. Technical Report 3GPP TR 38.913 version 18.0.0 Release 18. 3GPP. [https://www.etsi.org/deliver/etsi\\_tr/138900\\_138999/138913/18.00.00\\_60/tr\\_138913v180000p.pdf](https://www.etsi.org/deliver/etsi_tr/138900_138999/138913/18.00.00_60/tr_138913v180000p.pdf)
- [9] Renato Barbosa Abreu. 2019. Uplink Grant-free Access for Ultra-Reliable Low-Latency Communications in 5G: Radio Access and Resource Management Solutions. PhD supervisor: Prof. Preben Mogenssen, Aalborg University Assistant PhD supervisors: Assoc. Prof. Gilberto Berardinelli, Aalborg University Prof. Klaus Pedersen, Aalborg University.
- [10] Rashid Ali, Yousaf Bin Zikria, Ali Kashif Bashir, Sahil Garg, and Hyung Seok Kim. 2021. URLLC for 5G and Beyond: Requirements, Enabling Incumbent Technologies and Network Intelligence. *IEEE Access* 9 (2021), 67064–67095. <https://doi.org/10.1109/ACCESS.2021.3073806>
- [11] Arjun Anand, Gustavo de Veciana, and Sanjay Shakkottai. 2020. Joint Scheduling of URLLC and eMBB Traffic in 5G Wireless Networks. *IEEE/ACM Transactions on Networking* 28, 2 (2020), 477–490. <https://doi.org/10.1109/TNET.2020.2968373>
- [12] Nihel Benzaoui. 2020. Deterministic Latency Networks for 5G Applications. *2020 European Conference on Optical Communications (ECOC)* (2020), 1–4. <https://api.semanticscholar.org/CorpusID:231851060>
- [13] Gabriel Brown, P Analyst, and H Reading. 2018. Ultra-reliable low-latency 5G for industrial automation. *Technol. Rep. Qualcomm* 2 (2018), 52065394. <https://www.qualcomm.com/content/dam/qcomm-martech/dm-assets/documents/ultra-reliable-low-latency-5g-for-industrial-automation.pdf>
- [14] Marwa Chafii, Lina Bariah, Sami Muhaidat, and Merouane Debbah. 2023. Twelve Scientific Challenges for 6G: Rethinking the Foundations of Communications Theory. *Commun. Surveys Tuts.* 25, 2 (apr 2023), 868–904. <https://doi.org/10.1109/COMST.2023.3243918>
- [15] Ericsson. 2017. *5G Techniques for Ultra Reliable Low Latency Communication*. Ericsson. [https://wp-files.comsoc.org/cscn-2017/files/2017/08/Janne\\_Peisa\\_Ericsson\\_CSCN2017.pdf](https://wp-files.comsoc.org/cscn-2017/files/2017/08/Janne_Peisa_Ericsson_CSCN2017.pdf)
- [16] Ericsson. 2019. *You Need to See Our Dancing Hexapod Demo from MWC*. Ericsson. <https://www.ericsson.com/en/blog/2019/3/dancing-hexapod-demo-a-success-at-mwc>
- [17] Daquan Feng, Lifeng Lai, Jingjing Luo, Yi Zhong, Canjian Zheng, and Kai Ying. 2021. Ultra-reliable and low-latency communications: applications, opportunities and challenges. *Science China Information Sciences* 64, 2 (20 Jan 2021), 120301. <https://doi.org/10.1007/s11432-020-2852-1>
- [18] Daquan Feng, Changyang She, Kai Ying, Lifeng Lai, Zhanwei Hou, Tony Q. S. Quek, Yonghui Li, and Branka Vucetic. 2019. Toward Ultra-reliable Low-Latency Communications: Typical Scenarios, Possible Solutions, and Open Issues. *IEEE Vehicular Technology Magazine* 14, 2 (2019), 94–102. <https://doi.org/10.1109/MVT.2019.2903657>
- [19] Rostand A. K. Fezeu, Eman Ramadan, Wei Ye, Benjamin Minneci, Jack Xie, Arvind Narayanan, Ahmad Hassan, Feng Qian, Zhi-Li Zhang, Jaideep Chandrashekar, and Myungjin Lee. 2023. An In-Depth Measurement Analysis of 5G mmWave PHY Latency and Its Impact on End-to-End Delay. In *Passive and Active Measurement: 24th International Conference, PAM 2023, Virtual Event, March 21–23, 2023, Proceedings*. Springer-Verlag, Berlin, Heidelberg, 284–312.
- [20] Andres J Gonzalez, Min Xie, Per Hjalmar Lehne, and Pål Grønsund. 2021. Achieving high throughput and low latency with 5g: A real implementation experience. *IEEE Communications Magazine* 59, 10 (2021), 84–90.
- [21] Rajesh Gupta, Dakshita Reebadiya, and Sudeep Tanwar. 2021. 6G-enabled Edge Intelligence for Ultra-Reliable Low Latency Applications: Vision and Mission. *Computer Standards & Interfaces* 77 (2021), 103521. <https://doi.org/10.1016/j.csi.2021.103521>
- [22] Saqib Hakak, Thippa Reddy Gadekallu, Praveen Kumar Reddy Maddikunta, Swarna Priya Ramu, Parimala M, Chamitha De Alwis, and Madhusanka Liyanage. 2023. Autonomous vehicles in 5G and beyond: A survey. *Vehicular Communications* 39 (2023), 100551. <https://doi.org/10.1016/j.vehcom.2022.100551>
- [23] Md. Emdadul Haque, Faisal Tariq, Muhammad R. A. Khandaker, Kai-Kit Wong, and Yangyang Zhang. 2023. A Survey of Scheduling in 5G URLLC and Outlook for Emerging 6G Systems. *IEEE Access* 11 (2023), 34372–34396. <https://doi.org/10.1109/ACCESS.2023.3264592>
- [24] Ananya Hazarika and Mehdi Rahmati. 2023. Towards an Evolved Immersive Experience: Exploring 5G- and Beyond-Enabled Ultra-Low-Latency Communications for Augmented and Virtual Reality. *Sensors* 23, 7 (2023). <https://doi.org/10.3390/s23073682>
- [25] Hongxun Hui, Yi Ding, Qingxin Shi, Fangxing Li, Yonghua Song, and Jinyue Yan. 2020. 5G network-based Internet of Things for demand response in smart grid: A survey on application potential. *Applied Energy* 257 (2020), 113972. <https://doi.org/10.1016/j.apenergy.2019.113972>
- [26] Hyoungju Ji, Sunho Park, Jeongho Yeo, Younsun Kim, Juho Lee, and Byonghyo Shim. 2018. Ultra-Reliable and Low-Latency Communications in 5G Downlink: Physical Layer Aspects. *IEEE Wireless Communications* 25, 3 (2018), 124–130. <https://doi.org/10.1109/MWC.2018.1700294>
- [27] Niklas A. Johansson, Y.-P. Eric Wang, Erik Eriksson, and Martin Hessler. 2015. Radio access for ultra-reliable and low-latency 5G communications. In *2015 IEEE International Conference on Communication Workshop (ICCW)*. IEEE, London, UK, 1184–1189. <https://doi.org/10.1109/ICCW.2015.7247338>
- [28] Thorge Lackner, Julian Hermann, Fabian Dietrich, Christian Kuhn, Mario Angos, Johannes L Jooste, and Daniel Palm. 2022. Measurement and comparison of data rate and time delay of end-devices in licensed sub-6 GHz 5G standalone non-public networks. *Procedia CIRP* 107 (2022), 1132–1137.
- [29] Jingya Li, Keerthi Kumar Nagalapur, Erik Stare, Satyam Dwivedi, Shehzad Ali Ashraf, Per-Erik Eriksson, Ulrika Engström, Woong-Hee Lee,



- and Thorsten Lohmar. 2022. 5G New Radio for Public Safety Mission Critical Communications. *IEEE Communications Standards Magazine* 6, 4 (2022), 48–55. <https://doi.org/10.1109/MCOMSTD.0002.2100036>
- [30] Jing Li and Xing Zhang. 2020. Deep Reinforcement Learning-Based Joint Scheduling of eMBB and URLLC in 5G Networks. *IEEE Wireless Communications Letters* 9, 9 (2020), 1543–1546. <https://doi.org/10.1109/LWC.2020.2997036>
- [31] Andrea Moglia, Konstantinos Georgiou, Blagoi Marinov, Evangelos Georgiou, Raffaella Nice Berchiolli, Richard M. Satava, and Alfred Cuschieri. 2022. 5G in Healthcare: From COVID-19 to Future Challenges. *IEEE Journal of Biomedical and Health Informatics* 26, 8 (2022), 4187–4196. <https://doi.org/10.1109/JBHI.2022.3181205>
- [32] Yong Niu, Yong Li, Depeng Jin, Li Su, and Athanasios V. Vasilakos. 2015. A survey of millimeter wave communications (mmWave) for 5G: opportunities and challenges. *Wireless Networks* 21, 8 (01 Nov 2015), 2657–2676. <https://doi.org/10.1007/s11276-015-0942-z>
- [33] Nokia and Sennheiser. 2020. *Low Latency 5G for Professional Audio Transmission*. Nokia and Sennheiser. [https://d1p0gxnqcu0lvz.cloudfront.net/documents/Nokia\\_Low\\_Latency\\_5G\\_for\\_Professional\\_Audio\\_Transmission\\_White\\_Paper\\_EN.pdf](https://d1p0gxnqcu0lvz.cloudfront.net/documents/Nokia_Low_Latency_5G_for_Professional_Audio_Transmission_White_Paper_EN.pdf) Accessed on October 26, 2024.
- [34] European 5G Observatory. 2018. Commercial 5G launches – 5G Observatory. <https://5gobservatory.eu/overview-5g-commercial-launches/> Accessed on October 26, 2024.
- [35] European 5G Observatory. 2020. 5G private licences spectrum in Europe. <https://5gobservatory.eu/5g-private-licences-spectrum-in-europe/> Accessed on October 26, 2024.
- [36] OpenAirInterface. 2024. OpenAirInterface: 5G software alliance for democratising wireless innovation. <https://openairinterface.org/>
- [37] Imtiaz Parvez, Ali Rahmati, Ismail Guvenc, Arif I. Sarwat, and Huaiyu Dai. 2018. A Survey on Low Latency Towards 5G: RAN, Core Network and Caching Solutions. *IEEE Communications Surveys & Tutorials* 20, 4 (2018), 3098–3130. <https://doi.org/10.1109/COMST.2018.2841349>
- [38] Petar Popovski, Jimmy J. Nielsen, Cedomir Stefanovic, Elisabeth de Carvalho, Erik Strom, Kasper F. Trillingsgaard, Alexandru-Sabin Bana, Dong Min Kim, Radoslaw Kotaba, Jihong Park, and Rene B. Sorensen. 2018. Wireless Access for Ultra-Reliable Low-Latency Communication: Principles and Building Blocks. *IEEE Network* 32, 2 (2018), 16–23. <https://doi.org/10.1109/MNET.2018.1700258>
- [39] Yerra Prathyusha and Tsang-Ling Sheu. 2022. Coordinated Resource Allocations for eMBB and URLLC in 5G Communication Networks. *IEEE Transactions on Vehicular Technology* 71, 8 (2022), 8717–8728. <https://doi.org/10.1109/TVT.2022.3176018>
- [40] Qualcomm. 2020. *Making 5G NR a Reality*. Technical Report. Qualcomm. [https://www.qualcomm.com/content/dam/qcomm-martech/dm-assets/documents/powerpoint\\_presentation\\_-\\_making\\_5g\\_nr\\_a\\_reality\\_february\\_2020\\_web.pdf](https://www.qualcomm.com/content/dam/qcomm-martech/dm-assets/documents/powerpoint_presentation_-_making_5g_nr_a_reality_february_2020_web.pdf)
- [41] Sundee Rangan, Theodore S. Rappaport, and Elza Erkip. 2014. Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges. *Proc. IEEE* 102, 3 (2014), 366–385. <https://doi.org/10.1109/JPROC.2014.2299397>
- [42] Justus Rischke, Peter Sossalla, Sebastian Itting, Frank HP Fitzek, and Martin Reisslein. 2021. 5G campus networks: A first measurement study. *IEEE Access* 9 (2021), 121786–121803.
- [43] Justus Rischke, Christian Vielhaus, Peter Sossalla, Sebastian Itting, Giang T Nguyen, and Frank HP Fitzek. 2022. Empirical study of 5G downlink & uplink scheduling and its effects on latency. In *2022 IEEE 23rd International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*. IEEE, Belfast, United Kingdom, 11–19.
- [44] William Sentosa, Balakrishnan Chandrasekaran, P. Brighten Godfrey, Haitham Hassanieh, and Bruce Maggs. 2023. DChannel: Accelerating Mobile Applications With Parallel High-bandwidth and Low-latency Channels. In *20th USENIX Symposium on Networked Systems Design and Implementation (NSDI 23)*. USENIX Association, Boston, MA, 419–436. <https://www.usenix.org/conference/nsdi23/presentation/sentosa>
- [45] Changyang She and Yonghui Li. 2024. *Ultra-Reliable and Low-Latency Communications in 6G: Challenges, Solutions, and Future Directions*. Springer International Publishing, Cham, 27. [https://doi.org/10.1007/978-3-031-37920-8\\_24](https://doi.org/10.1007/978-3-031-37920-8_24)
- [46] Bluetooth SIG. 2024. *Bluetooth Core Specification v5.3*. Technical Report. Bluetooth SIG. <https://www.bluetooth.com/specifications/specs/core-specification-5-3/>
- [47] Software Radio Systems. 2024. srsRAN Project: Open source RAN. <https://www.srsran.com/>
- [48] Rana M. Sohaib, Oluwakayode Onireti, Yusuf Sambo, Rafiq Swash, Shuja Ansari, and Muhammad A. Imran. 2023. Intelligent Resource Management for eMBB and URLLC in 5G and Beyond Wireless Networks. *IEEE Access* 11 (2023), 65205–65221. <https://doi.org/10.1109/ACCESS.2023.3288698>
- [49] Gordon J. Sutton, Jie Zeng, Ren Ping Liu, Wei Ni, Diep N. Nguyen, Bee-shanga A. Jayawickrama, Xiaojing Huang, Mehran Abolhasan, Zhang Zhang, Eryk Dutkiewicz, and Tiejun Lv. 2019. Enabling Technologies for Ultra-Reliable and Low Latency Communications: From PHY and MAC Layer Perspectives. *IEEE Communications Surveys & Tutorials* 21, 3 (2019), 2488–2524. <https://doi.org/10.1109/COMST.2019.2897800>
- [50] Michal Sybis, Krzysztof Wesolowski, Keeth Jayasinghe, Venkatkumar Venkatasubramanian, and Vladimir Vukadinovic. 2016. Channel Coding for Ultra-Reliable Low-Latency Communication in 5G Systems. In *2016 IEEE 84th Vehicular Technology Conference (VTC-Fall)*. IEEE, Montreal, QC, Canada, 1–5. <https://doi.org/10.1109/VTCTFall.2016.7880930>
- [51] Talal Touseef, William Sentosa, Milind Kumar Vaddiraju, Debopam Bhattacharjee, Bala Chandrasekaran, P. Brighten Godfrey, and Shubham Tiwari. 2023. Boosting Application Performance using Heterogeneous Virtual Channels: Challenges and Opportunities. In *22nd ACM Workshop on Hot Topics in Networks (HotNets)*. ACM, Cambridge MA USA, 139 – 146. <https://doi.org/10.1145/3626111.3628193>
- [52] Mikko Uitto and Antti Heikkinen. 2021. Evaluation of live video streaming performance for low latency use cases in 5g. In *2021 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*. IEEE, IEEE, Porto, Portugal, 431–436.
- [53] Tore Ulversoy. 2010. Software Defined Radio: Challenges and Opportunities. *IEEE Communications Surveys & Tutorials* 12, 4 (2010), 531–550. <https://doi.org/10.1109/SURV.2010.032910.00019>
- [54] Sutharshun Varatharajan, Marcus Grossmann, and Giovanni Del Galdo. 2022. 5G New Radio Physical Downlink Control Channel Reliability Enhancements for Multiple Transmission-Reception-Point Communications. *IEEE Access* 10 (2022), 97394–97407. <https://doi.org/10.1109/ACCESS.2022.3206027>
- [55] Mojca Volk and Janez Sterle. 2021. 5G Experimentation for Public Safety: Technologies, Facilities and Use Cases. *IEEE Access* 9 (2021), 41184–41217. <https://doi.org/10.1109/ACCESS.2021.3064405>
- [56] Thomas Wirth, Matthias Mehlhose, Jens Pilz, Bernd Holfeld, and Dennis Wieruch. 2016. 5G new radio and ultra low latency applications: A PHY implementation perspective. In *2016 50th Asilomar Conference on Signals, Systems and Computers*. IEEE, Pacific Grove, CA, USA, 1409–1413. <https://doi.org/10.1109/ACSSC.2016.7869608>
- [57] Hao Yin, Lyutianyang Zhang, and Sumit Roy. 2021. Multiplexing URLLC Traffic Within eMBB Services in 5G NR: Fair Scheduling. *IEEE Transactions on Communications* 69, 2 (2021), 1080–1093. <https://doi.org/10.1109/TCOMM.2020.3035582>
- [58] Shunqing Zhang, Xiuqiang Xu, Yiqun Wu, and Lei Lu. 2014. 5G: Towards energy-efficient, low-latency and high-reliable communications networks. In *IEEE International Conference on Communication Systems*,

