Optimizing 5G-based Teleoperation: Synergy of Vulnerable Road User Awareness and Advanced Traffic Management Systems

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Abstract—**The Transport and Logistics (T&L) sector faces numerous challenges, including the search for qualified personnel, as well as improving driver safety and work-life balance. Teleoperation emerges as the technology able to address these challenges. Thanks to 5G connectivity and network slicing, operating vehicles remotely from a Teleoperation Center (ToC) is becoming a reality. The European project 5G-Blueprint, funded by the European Union, has demonstrated the feasibility of 5G-based teleoperation, even in a cross-border context. Despite the fact that 5G and network slicing enable reliable and low-latency transmission of video data from cameras installed on Teleoperated Vehicles (ToVs) to ToC, the perception of the surrounding environment is different for the teleoperator compared to the driver who is physically present in the vehicle. In this paper, we introduce a real-world system that showcases synergy among different teleoperation elements, including intelligent traffic lights (iTL) and Vulnerable Road Users (VRU), aimed at supporting teleoperation by improving remote driver's situational awareness. This synergy enhances the environmental perception of the teleoperator, bridging the gap between their experience and that of an in-vehicle driver. First, we evaluate the performance of a real-world 5G network with network slicing, based on actual data and testing scenarios conducted in both industrial and urban areas with 5G Standalone (5G SA) coverage. Then we validate the 5G capabilities for enabling a real-world system that showcases synergy among different teleoperation elements.**

Index Terms—**5G, Network slicing, Teleoperation**

I. Introduction

The European Transport and Logistics (T&L) sector faces a number of different challenges, including the need to reduce emissions in alignment with environmental regulations and the critical lack of qualified personnel in various roles, such as truck drivers [1]. The T&L sector also faces issues related to the safety and work-life balance of drivers, the safeguarding of human life on the roads, and the overall security of road transport [1]. These multifaceted challenges require innovative and effective solutions, where advanced telecommunication strategies and digitalization play crucial roles. In this context, Teleoperated Vehicles (ToVs) emerges as a noteworthy innovation, offering the potential to improve both driver and road safety, through the effective intervention of teleoperators in challenging situations. Additionally, ToVs can optimize logistics operations by enabling remote vehicle control from a Teleoperation Center Teleoperation Center (ToC). The success of teleoperation fundamentally depends on high-performance connectivity e.g., end-to-end latency less than 50ms and uplink (UL) bandwidth more than 5Mbps [2]. These high-performance are essential for maintaining fast, safe, and reliable communication between ToVs and ToC under all circumstances [2]. To address the need for such high-performance connectivity, 5G is a good candidate. 5G offers extremely low latency (1-10 ms), near absolute reliability (99.999%), and an impressive data transfer capacity (up to 20 Gbps) [3]. These goals are achieved by constructing logical and virtual networks, known as network slices, which overlay the common network infrastructure [4]. Therefore, thanks to the implementation of Ultra-Reliable Low Latency Communications (uRLLC), enhanced Mobile Broadband (eMBB), and massive Machine-Type Communications (mMTC), 5G and B5G are capable of delivering ToVs in the same network where other services are running. Network slicing is able to maintain isolation between slices (e.g., the load of eMBB does not interfere with the performance of uRLLC) and guarantee Key Performance Indicators (KPIs), as latency, UL throughput, and reliability (based on packet loss). In this context, the 5G-Blueprint project has designed, executed, and demonstrated technical solutions to support continuous cross-border road transport teleoperation using 5G. Nevertheless, the application of teleoperation is not limited only to the remote control of vehicles and the high-quality network. For the successful implementation of ToVs on our roads, it is essential to provide advanced services that enhance the teleoperator's awareness of the surrounding environment of the ToVs. These services include improved perception for the remote driver through features like advanced notifications and dashboards, as well as integration into the teleoperation chain to allow for automatic adjustments in the maneuvering process. To effectively promote the adoption of ToVs, it is essential to construct an ecosystem capable of mix-matching the safety of all categories of road users with the improved driving experience of ToVs from a ToC, aiming to limit dangerous scenarios as much as possible. In this paper, we introduce a mechanism developed in the 5G-Blueprint project that aims to improve Vulnerable Road Users (VRUs) security and increase VRUs awareness among ToVs operators through the use of 5G communication and network slicing. This mechanism has been tested in real-world scenarios. Additionally, we will describe and evaluate, using real-world data, how 5G and network slicing facilitate the implementation of Intelligent Traffic Lights (iTL), thus enhancing both the safety and efficiency of road transport.

II. Overview of the 5G-Blueprint project

The 5G-Blueprint project, funded by the European Union, aims to develop, test, and validate an integrated framework that combines a robust technical architecture with viable business and governance models [5]. This framework is designed to facilitate seamless and uninterrupted cross-border teleoperated transport, utilizing the advanced capabilities of 5G connectivity, as defined in the 3GPP Release 16 standards [6]. The technical mission of the project is to deploy a real prototype for a teleoperated transport system. This prototype demonstrates end-to-end transportation of vehicles within real-life scenarios, including those scenarios that span country borders. A key element of this system is the integration of cameras and sensors that, combined with the features of 5G technology, enable efficient and instantaneous remote driving operations,

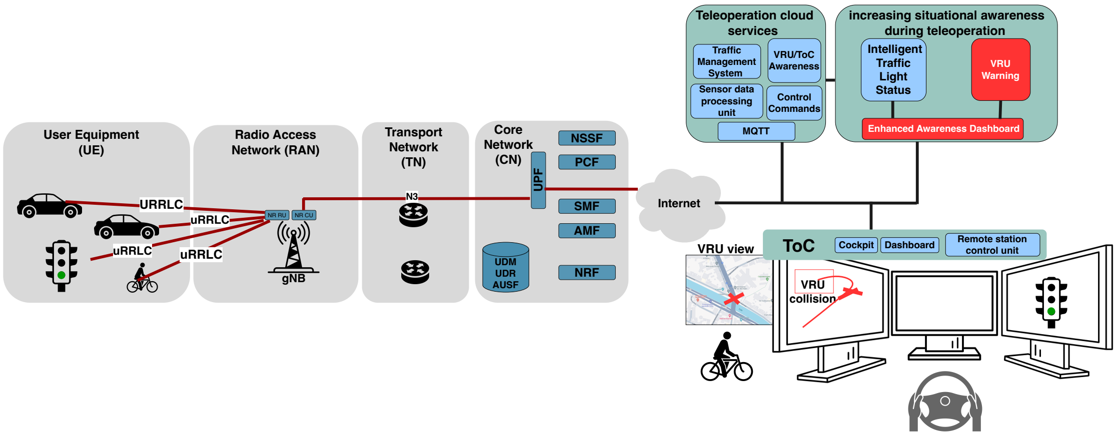

Fig. 1. High-level architecture of 5G-enhanced synergy between different teleoperation elements, including iTL and VRUs.

enhancing safety protocols. To address the intricacies of cross-border operations, which often involve coordination between different network operators, pilot sites have been established in strategic port locations across Vlissingen (NL), Antwerp (BE), and Zelzate (BE-NL) [7]. These sites are essential in examining the challenges and complexities inherent in transport and cross-border operations. In order to demonstrate the practical applications of teleoperation in various vehicles, including trucks, vessels, and skid steers, 5G-Blueprint has introduced multiple use cases [7]. 5G-Blueprint explores and addresses regulatory challenges associated with deploying teleoperated transport systems that leverage 5G connectivity, particularly in cross-border contexts. The outcomes of the 5G-Blueprint project, encompassing both its technical achievements and the insights gained from validation efforts, are intended to identify strategies to be accomplished to ensure that the teleoperated transport system aligns with regulations. This contribution will serve as a foundational blueprint for future collaborations in the realm of 5G-enabled Connected and Automated Mobility (CAM) among public, private, and semi-private entities, including ports. Furthermore, the project opens up new perspectives on security requirements and the development of secure CAM system architectures, emphasizing the crucial importance of ensuring the safety of the entire teleoperation ecosystem. To achieve this goal, the 5G-Blueprint project introduces Enabling Functions (EFs) [7].

A. *Enabling Functions*

Environmental perception of the teleoperator is one of the most significant issues that need to be addressed to reinforce teleoperation safety. The teleoperator is required to: i) surpass the inherent difficulties in fully understanding the surrounding environment; ii) demonstrate abilities in executing complex maneuvers in variable environments, such as the dynamics of urban spaces or distinct industrial areas; iii) rapidly respond to frequent changes of the traffic conditions, like deteriorating weather or the appearance of unexpected obstacles such as traffic lights, and the unpredictable behaviors of other road users; iv) adeptly integrate effective bidirectional communication with intelligent road infrastructures e.g., iTL, crucial for an efficient teleoperation system.

The situational awareness of a teleoperator is inevitably reduced than the one in-vehicle. This is due to the absence of immediate perceptual feedback such as acceleration, inclination, and the responses of the vehicle to specific driving actions, like steering or braking.

The images transmitted from cameras installed on the ToVs may not be sufficiently detailed or profound to provide a remote driver with an accurate perception of the environment. Such quality issue affects the ability to accurately assess the distance and speed of objects, or recognition of road signs and other important driving elements e.g., the camera feed might have difficulty identifying a pedestrian in low light conditions, making it challenging for the remote driver to safely navigate around them. This limitation could be attributed to the inherent constraints of the cameras, such as insufficient resolution. As a result, the visual representation perceived by the operator may not precisely correspond to what would be experienced driving in-vehicle, with potential repercussions on the ability to make quick and safe decisions from the teleoperator.

Therefore, transferring the driving task from an internal driver to a remote driver necessitates the creation of an advanced technological ecosystem, capable of compensating for the loss of sensory perceptions. The development of such an advanced technological ecosystem must be achieved through the enhancement of visual and sound-based alert systems and the improvement of teleoperator support tools. Only then it can be ensured that teleoperation is not only feasible but also compliant with road safety standards.

In the context of the 5G-Blueprint project, several EFs are being developed and tested to support the use cases, delivering a complete ecosystem to support the operator during the execution of tasks and enhance road safety [5], [7]. In particular, in Section III and Section IV we illustrate and evaluate two EFs: i) VRUs interaction and ii) Time slot reservation at intersection. For simplicity, In the 5G-Blueprint project, the experiments and the evaluation of these two EFs are part of two different real-world scenarios. However, in this paper, we present and analyze the results and overall capabilities of the joint system.

B. *Scenario*

The scenario depicted in Figure 1 illustrated how ToVs controlled by teleoperators located at ToC can safely coexist on urban roads together with VRUs, and iTL utilizing 5G technology and network slicing. Thanks to network slicing, it is possible to manage the network to ensure that safety messages receive the highest priority within the network. That means that safety messages have priority over other services that are using the network. Within this scenario, various User Equipments (UEs), such VRUs, iTLs, and ToVs, share the same 5G infrastructure, but different slices of the network. As illustrated in Table I, the eMBB slice is attributed to the upstream of the data from the cameras in the ToVs to the ToC. The upstream of the cameras requires guaranteed UL throughput in teleoperation scenarios. On the other hand, the uRLLC slice is dedicated to critical messages, such as collision detection awareness for VRUs and ToVs, and the communication between iTL and ToC. In order to achieve this synergy, the 5G network must meet the requirements for both slices simultaneously. Data regarding the position, velocity, and trajectory of ToVs and VRUs are transmitted to a cloud-based system capable of estimating expected collision times and points. This segment of the scenario is discussed in Section III. Simultaneously, iTLs communicate their status to the ToC e.g., red light or green light. This last segment of the scenario is discussed in Section IV. As a result, the teleoperator, in addition to receiving visual data from cameras installed on the ToVs, is promptly alerted about i) the presence of nearby VRUs, ii) potential collision scenarios, and iii) the status of traffic lights that regulate urban traffic flow. These alerts significantly enhance the situational awareness of teleoperators, substantially improving road safety. Timely cooperation among multiple road elements is particularly crucial in situations where adverse weather conditions or visual obstructions may hinder the clear view of teleoperators in traffic conditions. On the other hand, VRUs receive automatic notifications on their devices e.g., smartphones when ToVs approaches. These alerts are designed to promote increased vigilance among VRUs, especially at intersections or when the ToVs are in proximity of the VRUs.

C. Network Requirements

To ensure synergy and effective interaction between ToVs, traffic participants such VRUs, and road elements such as iTL, several network requirements must be met. The following requirements are essential to ensure seamless communication, situational awareness, and safety in urban road environments:

1) **Low Latency Communication**: To facilitate real-time interaction and control, the network must provide low-latency communication between the ToC and the ToVs. Minimal delay in transmitting control commands and safety messages is a must to respond promptly to dynamic situations on the road. The 5G-Blueprint project has defined a maximum end-to-end latency of 30ms between the ToVs and the ToC [2].
2) **High Reliability**: The network should guarantee high reliability to prevent communication failures or data loss. This is critical for maintaining continuous communication between the ToC and the ToVs, especially in safety-critical scenarios.
3) **Bandwidth Scalability**: The network should be capable of scaling its bandwidth to accommodate the exchange of high-definition video streams, sensor data, and other information. This ensures that the teleoperator receives clear and real-time feedback from the ToVs.
4) **Network Slicing**: Implementing network slicing mechanisms is necessary to prioritize safety-critical messages over less critical data traffic. This prioritization guarantees that safety-related information always receives the highest level of attention from the network.
5) **Seamless Coverage**: To support teleoperation in diverse urban areas, the network must provide seamless coverage. This means minimizing connectivity gaps and ensuring reliable communication even in areas with varying signal strengths.

Table I provides the list of the KPIs that we will use to evaluate their successful implementation in both segments of the scenario, such as i) VRUs interaction and ii) Time slot reservation at intersection. Furthermore, Table I contain the network requirement defined from the 5G-Blueprint project.

TABLE I
NETWORK REQUIREMENTS AND KEY PERFORMANCE INDICATORS

KPI	Camera stream	VRUs and iTL messages
Service Type	Uplink	E2E
Network Latency	< 50 ms	< 35 ms
Network Service Interruption	< 150 ms	< 150 ms
Bandwidth Requirement	> 5 Mbps < 25 Mbps	< 2 Mbps
Slice Type	eMBB	URLLC

III. VULNERABLE ROAD USERS INTERACTION ASSESSMENT

In this section, we present the methodology and experimental setup for assessing the interaction between VRUs and ToVs. For that purpose, one mobile application and a cloud service have been developed. Our study aims to determine whether the uRLLC slice of the 5G Standalone (5G SA) network can provide the necessary performance to establish a teleoperation support ecosystem, ensuring compliance with current road safety regulations. The 5G SA network used for our test is a real large-scale testbed provided by a mobile operator, ensuring the realism and scalability of our experiments. We evaluate the performance of VRUs awareness system over 5G using the KPIs in Table II, and the network requirements in Table I.

A. Experiment

To conduct our experiments, we employed two identical mobile devices, specifically the Oppo X5 Pro 5G[1], for all testing purposes, involving both ToVs and VRUs, as shown in Figure 2. One of these devices was equipped with a 5G SA SIM card, directing traffic through the uRLLC slice to the exchange service running in the cloud, while the other device was equipped with a standard commercial 4G SIM card, serving as a benchmark for comparative analysis. These 5G devices were meticulously configured to establish a connection with the 5G SA network.

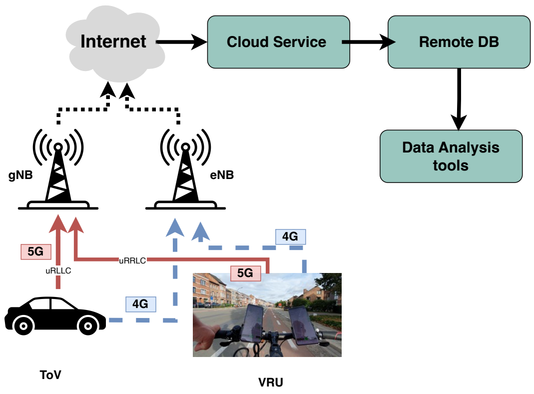

Fig. 2. Experiment Setup.

For the VRUs tests, we conducted two different usage scenarios:

- **Optimal Conditions:**
  1) Pedestrian: The mobile device was manually held.
  2) Cyclist: The mobile device was securely mounted on the handlebar.

[1] Oppo X5 Pro 5G:https://www.oppo.com/en/smartphones/series-find-x/find-x5-pro/specs/

- **Realistic Usage Scenarios:** The mobile device was either placed in a backpack or carried in a pocket.

Each scenario has been tested in urban and industrial public areas. Since we ran our experiments in a public area, a regular vehicle was operated by a human driver, emulating the ToVs scenario. VRUs, including both pedestrians and cyclists, approached ToVs paths from both perpendicular and longitudinal angles, simulating potential collision scenarios and subsequently triggering collision warnings. To evaluate the effectiveness of the system, each individual mobile application logged various user activities and data communication characteristics. These logged data points were stored in a centralized data repository for the evaluation of the KPIs.

B. Evaluation and Discussion

To evaluate the Service Continuity of the mobile application, we used a crash monitoring tool (Crashlytics[2]).

During the experiments, the apps reported 1.75 crashes and 11.8 non-fatal errors e.g., messages fail to be delivered immediately, per user per month. Assuming an average restart time of 1 minute, the total availability of the apps was 99.99%.

The Service Continuity of the cloud service is evaluated by a crash monitoring tool. During the experiments, no crashes were reported (100% uptime).

Service Continuity (Network Awareness) is evaluated based on the percentage of times the radio connection has an Reference Signals Received Power (RSRP) of -105 dBm or higher, which is considered sufficient for a reliable connection [8]. Our analysis, as detailed in Table III-B, revealed that the device attached to the 5G SA network in the uRLLC slice consistently exhibited higher RSRP values than their 4G counterparts in all assessed scenarios. Notably, the median RSRP values for 5G SA (uRLLC) outperformed those of 4G by a significant margin in both industrial and urban settings, as well as under optimal and realistic conditions. This suggests a stronger and more reliable signal for 5G SA (uRLLC), which is crucial for applications where timely and reliable communication is essential, such as in systems designed to alert UEs of critical events.

To statistically validate our observations, we employed the Kruskal-Wallis and Wilcoxon tests [9][10], given the non-normal distribution of our data. Both tests yielded p-values (2.2×10^{-16} and 2×10^{-16}, respectively), which are substantially lower than the conventional alpha level of 0.05. This strongly rejects the null hypothesis, confirming that the observed differences in RSRP values between the two network technologies are statistically significant.

Table IV shows the comparison in terms of reliability between 5G SA (uRLLC) and 4G networks, revealing that while both technologies exhibit high reliability in industrial settings, 4G consistently surpasses the 99% of reliability in all conditions. This marginally higher reliability of 4G is crucial where even a small percentage can impact the safety and efficiency of communication systems. Substantiated by p-values of 2.2×10^{-16} and 2×10^{-16} from the Kruskal-Wallis and Wilcoxon tests respectively, the statistical evidence strongly indicates that 4G currently holds a modest yet critical advantage in service continuity.

Looking forward, as 5G technology continues to evolve, it is anticipated to surpass the reliability of 4G, offering enhanced service continuity for VRUs and teleoperation applications.

Latency is a critical performance metric in network communication, especially for applications that rely on timely message delivery, such as those intended to ensure the safety of VRUs and operation of ToVs. The data in Section V show that 5G SA (uRLLC) roundtrip times in industrial areas are consistently below than in urban areas, with a mean roundtrip time of 166.5 ms. In urban areas, however, the mean latency (described in Table II) increases to 241.5 ms. When considering optimal vs. realistic conditions, 5G SA(uRLLC) again maintains roundtrip times below than optimal conditions but slightly exceeds it under realistic conditions. In comparison, 4G network latencies are significantly higher in both industrial and urban settings. These p-values indicate a very strong likelihood that the observed latency improvements with 5G SA uRLLC are not due to random chance but are a result of the inherent capabilities of the 5G technology. Given the nature of the applications, the reduction in latency with 5G SA uRLLC could translate into enhanced safety for VRUs and improved operability of ToVs. The confirmed statistical significance of these results underscores the importance of adopting 5G technology in scenarios where low latency is paramount.

IV. Intelligent Traffic Light Assessment

The synergy between iTL (intelligent Traffic Light) and ToVs systems is a critical aspect of modern urban traffic management. The UL presents a challenge in such synergy as the network must handle i) a high flow of video packets, ii) other sensors data from ToVs and iii) several devices connected to the network. Network slicing is a key technology that enables the coexistence of iTL and ToVs systems by prioritizing security messages within the network. A robust 5G system isolates network slices to ensure proper performance for i) teleoperation that mainly depends on UL and eMBB, and ii) VRUs and iTL that use uRLLC. To evaluate the capability of 5G SA technology to handle communication and coordination, we conducted a comprehensive evaluation of a real-world 5G network enabled with network slicing. This evaluation aims to thoroughly examine the capabilities and performance of different network slices, such uRLLC and eMBB emphasizing the importance of efficient UL communication and optimal utilization of network resources. The evaluation of the slicing performance for iTL takes place within an urban environment, aligning with the assessment of interactions with VRUs) detailed in Section III. The consistency between the 5G network infrastructure, the network slicing configurations, and the environmental conditions described in Section III ensure comparability with iTL test scenarios. Therefore, we can analyze scenarios in which these two systems coexist within the same network infrastructure.

A. Experiment

We conducted an experiment using two (UEs) devices, each connected to separate Peplink routers. These Peplink routers are connected to the same gNB and are equipped with distinct SIM cards. One SIM card is dedicated to uRLLC slice, while the other connect to the eMBB slice.

For performance evaluation, we relied on two KPIs: UL throughput and Round-Trip Time (RTT) latency. Traffic generation is performed through the use of the Iperf3[3] tool, while RTT latency measurements were conducted (simultaneously to Iperf3) via ping tests.

In the initial phase, our focus was on examining the performance of each network slice individually, aiming to establish baseline benchmarks for subsequent comparative analysis. Results derived from this phase are categorized as "NO_impact", forming a reference point for network performance under standard operational conditions.

In the second phase, our focus shifts towards evaluating the overall performance of the 5G network, specifically the ability

[2]Crash monitoring tool: https://firebase.google.com/docs/crashlytics

[3]Documentation : https://iperf.fr

TABLE II
KEY PERFORMANCE INDICATORS (KPIS)

KPI Category	Description
Service Continuity	Percentage of time during which smartphone apps were operational during each field trial.
Service Continuity (MQTT service)	Percentage of time during which MQTT service was operational.
Service Continuity (Network Awareness)	Percentage of times the radio connection was reliable enough to timely warn VRUs.
Reliability	Number of messages made available via MQTT Broker with position of VRU, and potentially warning, per hour.
Latency	Roundtrip time for messages exchanged with MQTT server.

TABLE III
COMPARISON OF RSRP (DBM) OF 5G SA URLLC AND 4G ACROSS DIFFERENT OPERATIONAL SETTINGS AND CONDITIONS.

Operational Setting	5G SA URLLC RSRP 1st Qrt	5G SA URLLC RSRP Median	5G SA URLLC RSRP Mean	5G SA URLLC RSRP 3rd Qrt	4G RSRP 1st Qrt	4G RSRP Median	4G RSRP Mean	4G RSRP 3rd Qrt
Industrial	-90	-80	-81.1	-72	-88	-83	-82.8	-77
Urban	-95	-87	-87.7	-80	-100	-93	-91.6	-85
optimal	-92	-82	-83.0	-74	-93	-86	-86.2	-79
Realistic	-97	-89	-87.2	-76	-96	-90	-89.6	-85

TABLE IV
COMPARISON OF RELIABILITY (%) OF 5G SA URLLC AND 4G ACROSS DIFFERENT OPERATIONAL SETTINGS AND CONDITIONS.

Operational Setting	5G SA URLLC Reliability				4G Reliability			
	1st Qrt	Median	Mean	3rd Qrt	1st Qrt	Median	Mean	3rd Qrt
Industrial	100%	100%	99.0%	100%	100%	100%	99.6%	100%
Urban	100%	100%	96.8%	100%	100%	100%	99.6%	100%
optimal	100%	100%	98.4%	100%	100%	100%	99.9%	100%
Realistic	100%	100%	97.9%	100%	100%	100%	99.7%	100%

TABLE V
COMPARISON OF ROUNDTRIP TIMES (MS) OF 5G SA AND 4G ACROSS DIFFERENT OPERATIONAL SETTINGS AND USAGE CONDITIONS.

Conditions/Settings	5G SA URLLC Roundtrip Time				4G Roundtrip Time			
	1st Qrt	Median	Mean	3rd Qrt	1st Qrt	Median	Mean	3rd Qrt
optimal	109	122	195.6	162	175	228	300.8	398
Realistic	112	132	205.1	169	216	350	374.6	445
Industrial	102	119	166.5	148	171	197	233.4	232
Urban	119	148	241.5	195	255	377	402.7	462

of the network to hold and isolate both the eMBB and uRLLC slices configured on the gNB. During this phase, we aim to replicate extreme operational scenarios, such as having multiple ToVs and iTL utilizing the uRLLC slice for streaming video packets and messages to the ToC, while multiple UEs devices simultaneously utilized the eMBB slice. This allowed us to assess the resilience and reliability of these network slices within the 5G infrastructure, centered around the gNB. The outcomes from this phase are categorized as "YES_impact".

B. Results and Discussion

We show the output of our experiments in Figure 3, and Figure 4. Figure 3 shows the results related to the latency and Figure 4 shows the results related to the throughput. In our evaluation, we observed the following:

- **Latency eMBB Slice**: Under normal conditions ("NO_impact"), the eMBB slice demonstrates stable performance with low latency and minimal variability, showcasing robust capability. However, when exposed to high-load conditions ("YES_impact"), latency significantly increased to 181.50ms, suggesting a potential limitation in latency-sensitive for eMBB applications, especially crucial for prompt data transmission.
- **Latency uRLLC Slice**: In normal conditions ("NO_impact"), the uRLLC slice exhibited consistently low-latency performance (42-44ms), essential for real-time data transmission. Even under high-load conditions ("YES_impact"), the network shows low latency, though with a slight increase, emphasizing the influence of network slicing configurations in loaded environments.
- **UL Throughput**: The eMBB slice maintained robust and consistent throughput performance in normal conditions, while in high-load conditions, eMBB slice showed a slight decrease but remained relatively stable. The uRLLC slice exhibited commendable performance in normal conditions but experienced a decline in throughput performance under the YES_impact scenario.

Based on our analysis, it becomes clear that the current implementation of network slicing demonstrates both strengths and areas that could benefit from improvement. The eMBB slice, tailored to handle high-throughput demands, consistently delivered impressive bitrate performance across various scenarios. Its performance under normal conditions was particularly robust, showcasing its ability to efficiently manage high data loads. However, during high-load scenarios, we observed a significant increase in latency. This suggests that while the eMBB

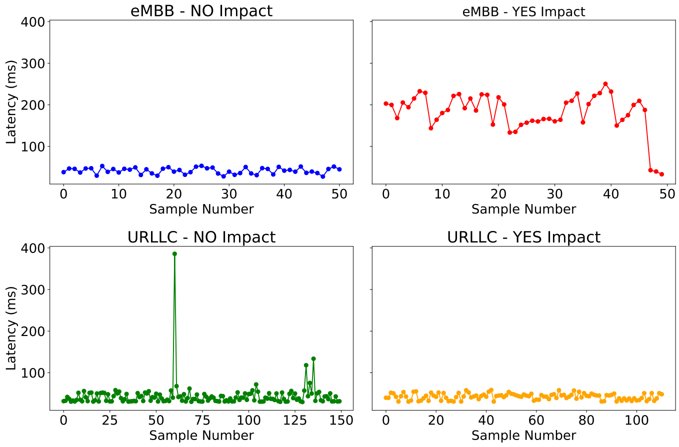

Fig. 3. Latency of the eMBB slice and uRLLC slice.

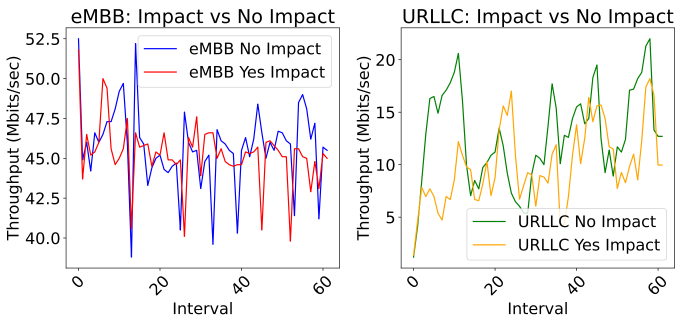

Fig. 4. Throughput.

slice excels in throughput, there is room for optimizing its latency management, especially for applications where timely data transmission is critical.

Conversely, the uRLLC slice, designed for ultra-low latency scenarios, effectively maintained low-latency performance under normal conditions. Nevertheless, when subjected to high-stress conditions, this slice exhibited notable fluctuations in both latency and throughput. This variability, especially in latency, raises concerns about the slice's reliability in consistently delivering the ultra-low latency required for critical applications.

The performance of network slices under high-load conditions also highlights the importance of slice isolation. Effective isolation is crucial to ensure that the performance of one slice does not negatively impact another. Our evaluation suggests that while there is some level of isolation, the effects of high-load conditions on different slices indicate a need for more refined isolation mechanisms. This is essential to guarantee that each slice can independently meet its specific service requirements, regardless of the overall network load.

V. Conclusion

In this work, we have discussed the necessity of creating synergy among various traffic participants and road elements, such as VRUs and iTL, with the teleoperators of ToVs to make teleoperation feasible and aligned with road safety standards. Within the scope of the European project 5G-Blueprint, numerous enabling functions have been developed to assist the teleoperator and make their perception during teleoperation as similar as possible to that of a driver inside the vehicle. We have presented two real-world experiments for the safety of VRUs and intelligent traffic lights, evaluating their effectiveness. Furthermore, we have assessed the performance of a large-scale, real-world 5G network enabled with network slicing to gauge the network's capacity to support these services. From our results, a clear difference in terms of latency emerges between the uRLLC slice of the 5G network and the 4G network, confirming the crucial role of 5G in serving critical communications. However, our findings also reveal that the 4G network provides greater reliability compared to 5G, even in cases where 5G coverage is better in terms of RSRP. This discrepancy is attributed to the higher frequency transmission nature of 5G, rendering it more susceptible to signal noise and distortion. In the context of teleoperation, signal distortion can be triggered by the passage of large vehicles near the ToVs. A potential solution to this issue could involve deploying several small cells within the same area, however, this may incur significant economic costs for telecommunication companies. This is why solutions such as O-RAN have the potential to facilitate the deployment of multiple small cells in critical areas at a reduced cost [11]. O-RAN, characterized by its open architecture, effectively mitigates the issue of vendor lock-in, facilitating a more collaborative ecosystem among vendors and operators [11].

Acknowledgments

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